ANIDOLIC DAYLIGHTING SYSTEM FOR DEEP-PLAN ARCHITECTURE OF AUTOMOTIVE WORKSHOP IN THE TROPICS

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DEDICATION

This thesis is dedicated to my family, who have always love and support me mentally and financially throughout my postgraduate school journey. I also dedicate to my supervisor and university friends who has support each other during this journey.

ACKNOWLEDGEMENT

I want to sincerely thank everyone who assisted with my thesis. Without their assistance, this thesis cannot be finished.

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ABSTRACT

Lighting is crucial for everyday task. When there is no availability of daylight, electrical artificial lighting is the replacement of daylight. Daylight is a free resource that is always available to us, therefore people should make good use of it. Human health and psychological responses, particularly in mood and productivity, gain greatly from daylight. In addition, daylighting systems are considered while designing buildings to provide optimum lighting effects while also promoting environmentally friendly construction. To lessen the demand for artificial lighting, a number of daylighting systems have been created to bring daylight into areas. For deep-plan design, the section with a lengthy floor area where the deeper space is not getting daylight from a side window has to be illuminated. Therefore, a passive prototype for a daylight transporter system like the ADS is able to gather and route daylight to a particular interior space. VELUX Daylight Visualizer is being utilised to test with the space using ADS in terms of determining the system's performance. In order to determine the fundamental knowledge of the properties of the light-pipe duct, a simple 3D model is being tested with certain configuration variables of the daylight transporter system. Finally, the performance is assessed using the daytime illumination and contrasted to create a configuration for the deep plan.

ABSTRAK

Pencahayaan sangat penting untuk aktiviti harian, manakala cahaya elektrik telah digunakan dalam keadaan yang tidak disinar oleh cahaya siang. Cahaya siang ialah sumber percuma yang tersedia untuk pengunaan setiap hari yang sepatutnya kita hargai. Tidak dapat dinafikan bahawa cahaya siang membawa manfaat untuk kesihatan manusia dan reaksi psikologi, khususnya dari segi mood dan produktiviti. Selain itu, parameter reka bentuk seni bina telah mempertimbangkan sistem pencahayaan siang yang akan memberikan kesan pencahayaan yang tepat kepada bangunan, sekaligus mempromosikan bangunan dan lingkungan yang lestari. Terdapat pelbagai jenis sistem pencahayaan siang telah dikembangkan untuk membawa cahaya siang ke dalam bangunan untuk mengurangkan keperluan cahaya elektrik. Seni bina pelan dalam, iaitu ruang yang mempunyai luas lantai panjang dan mendalam sehingga tidak dapat menerima cahaya siang dari tingkap tepi amat memerlukan sistem pencahayaan siang untuk menangani masalah ini. Seterusnya, sistem pengangkut cahaya seperti sistem anidolik merupakan prototaip pasif yang dapat mengumpul dan memimpin cahaya siang ke kawasan dalaman tertentu. Untuk mengetahui prestasi sistem, VELUX Daylight Visualizer telah digunakan untuk menguji ruang dengan penggunaan sistem anidolik. Model 3D asas telah diuji dengan pemboleh ubah khusus konfigurasi sistem anidolik untuk mengetahui pemahaman asas mengenai ciri saluran paip cahaya. Akhirnya, prestasi iluminasi cahaya telah dinilai dengan menbandingkan keputusan untuk mendapatkan konfigurasi yang sesuai untuk pelan dalam.

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LIST OF ABBREVIATIONS

3D	-	Three-dimensional
ADS	-	Anidolic Daylighting System
BCA		Building and Construction Authority
DOSH	-	Department of Occupational Safety and Health
WPI	-	Work Plan Illuminance
ZEB	-	Zero Energy Building

CHAPTER 1

INTRODUCTION

1.1 Problem Background

Daylight generated from sun, is a free, safe, and natural resource. The technique of employing daylight to provide the right lighting effect in buildings, such as supplying enough illumination for job areas or preventing its occurrence in particular instances, is known as daylighting (Costanzo, V., Evola, G., & Marletta, L., 2017). Daylight illuminate areas that provide building inhabitants a different mood. Daylighting studies are now included in architectural design as architects create the ambiance that is appropriate for the space's intended use. According to study by Mirrahimi, S., Ibrahim, N. N., & Surat (2013), daylighting should be considered when designing buildings since it influences students' health. Researchers discovered that daylighting improves the atmosphere of the workspace as well as human health and psychological responses including mood, presentation, and productivity.

Additionally, properly utilised daylighting enhances a building's sustainability. This is so that replacing artificial lighting with natural illumination can reduce the amount of energy used for it. Sustainability building has been practiced over decades that concern for the environment. Therefore, the use of natural lighting with the application of daylight technology in buildings do contribute in environment sustainability at the same time, increase human activities performances in such building. Thus, the use of daylight can be great strategy to replace artificial lighting to have a better environment for human.

Deep-plan architecture describes buildings with lengthy, deep plans that typically don't have enough natural light in the centre of the building. It's difficult to design a room with the appropriate environmental qualities while also using less energy in buildings (Al-Ashwal, N. T., & Budaiwi, I. M., 2011). Architectural constructions must incorporate lighting into their designs, yet it can be difficult to deliver light into a dark space inside a building. Architectural designers should consider adding daylight to a building's interior deep spaces since it can reduce energy use and improve user performance (Roshan, M., Mohammadi, M. P., & Kandar, M. Z. B., n.d.).

The amount of light entering a building via a window depends on the sky, although it does not penetrate very far (Roshan, M., Mohammadi, M. P., & Kandar, M. Z. B., n.d.). Malaysia has a tropical climate; therefore, the sky is frequently cloudy or in between, with scorching sun during the day. Due to the intense glare and radiating heat, construction professionals frequently avoid using sunshine in these situations. Therefore, certain daylighting technologies are designed that may bring in daylight while still avoiding the drawbacks of sunlight. According to Hansen, V.G. (2006), light transport technologies are necessary in deep-plan architecture since simple windows or skylights cannot adequately convey sunshine into the building's deep space.

1.2 Problem Statement

No doubt, in order to comply with local authority rules and regulations, every building must have openings like windows. In most cases, the apertures created for light and ventilation do not have a further investigation for getting enough daylighting. Due to changes in interior architecture, the daylighting potential offered by vocations frequently becomes less helpful (Vaidya, P. et al., 2004). These occurrences are typically the result of post-installation furniture rearrangement or space refurbishment. Artificial lighting is frequently used as a method to give lighting in these areas.

A typical automotive workshop has a complex layout since it needs room for the vehicles, machines, and users. Due to the exact nature of the activity, it is sometimes necessary to use a lot of artificial illumination in order to have a perfect visual sight. For deep-plan design, when the area is bigger than the daylight redirection distance from windows, a high amount of artificial lighting, such as electric lighting, is required (Heng, C.Y.S., Lim, Y.W., & Ossen, D.R., 2020). In addition, the workshop's lack of openings which should be avoided to prevent dust in the area and to minimise glare and visual discomfort for users is another factor contributing to the large quantity of artificial lighting provided.

Due to the other existing level above, a deep-plan design with many floors is not possible to construct openings from the top like skylights. The most direct answer in such a situation is to use artificial illumination. Due to these issues, the issue of deep-plan design is concentrated on supplying enough daylight to provide a better working environment. The goal of daylight harvesting is to reduce the quantity and quality of artificial illumination. For the best performance, the daylighting system has to be able to illuminate a certain deep-plan region where daylight from side windows cannot reach.

1.3 Research Aim

This thesis aims to enhance daylight performance and provide sufficient daylight illuminance in deep-plan architecture in tropical climate.

1.4 Research Questions

The research questions are:

(a) What is the optimum orientation for installation of ADS in tropical climate?

(b) What design parameters affect the efficiency of ADS?

(c) What is the ideal configuration design of ADS in daylight performance of deep-plan in tropical climate?

1.4.1 Research Objectives

The objectives of the research are:

(a) To investigate daylight performance efficiency of different façade orientation with installation of ADS.

(b) To evaluate the design variables of ADS that influence daylight performance.

(c) To determine configuration of ADS with optimum daylight performance in deep-plan architecture in tropical climate.

1.5 Research Scope

The study focuses on daylighting in deep-plan architecture that achieves visual comfort for users in the space by the ADS. The study is only based on intermediate and overcast sky as it focuses on tropical climate, particularly in Malaysia. Besides the aspect of daylight performance efficiency, the others, such as solar heat gain and thermal comfort are not considered in this study. ADS will be used as the daylighting strategy for deep-plan and the design of the system will be tested to determine the daylighting performance. The design elements include the collector, duct size and aperture. Materials used for the ADS and the design of the collector will be studied by referring to previous researchers and will not be further developed in terms of design as it is more of an engineering design.

Deep-plan architecture has a long and deep open space, which is the current study. Occupants at different depths of space perform different tasks at the same time. Therefore, lighting in the workstation is important to have a comfortable setting. The potential of the daylighting system approaches in the deep plan of the workshop would help in lighting energy savings and provide sufficient illuminance. The relationship between the design variables and performance of daylighting illuminance will be explored and analyzed by using a professional lighting simulation tool, namely the VELUX Daylighting Visualizer.

1.6 Significance of Research

The purpose of this research is to introduce the importance of natural daylighting in deep-plan buildings. In tropical climate countries such as Malaysia, the heat radiant and glare are crucial to be avoided in architectural design. In other words, architectural design has to reduce the use of openings but still be able to achieve the requirements of rules and by-laws. The introduction of ADS which is a promising daylighting system which is able to provide sufficient illuminance in deep-plan promotes users' visual comfort that is needed for a particular space. This study is essential to determine the correct configuration to improve the efficiency of ADS for deep-plan particularly in tropical climates such as Malaysia.

1.7 Research Methodology

The research uses mixed research methods, which are qualitative data collection and quantitative approaches. The qualitative method is based on literature reviews, which are to collect secondary data and information on daylighting design strategies based on the topic. Besides, literature reviews are used to explore the information and corresponding relationship between ADS configuration and daylight performance as well. Meanwhile, quantitative data used the daylighting simulation tool of computer software, namely VELUX Daylight Visualizer 3.0 to determine the daylighting performance of different design variables and configurations of ADS in deep-plan.

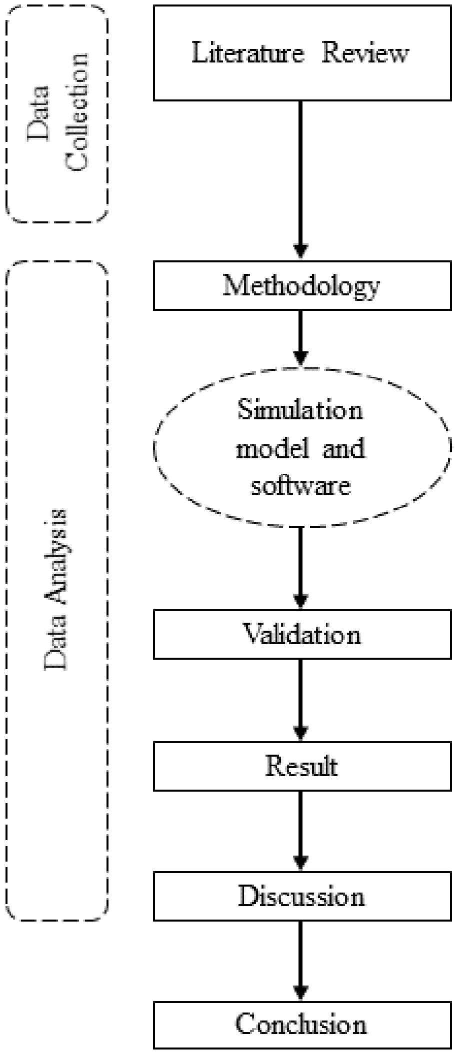


Figure 1.1 Flow Chart of Study (Author, 2022)

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The research will be discussed on benefits and positive impacts of daylighting in human well-being and building are studied. Besides, daylighting and the sky condition in tropical countries, as in Malaysia, daylight and sky condition availability are discussed. Architectural deep-plan spaces are being studied to understand the characteristics and the demerits of it with daylighting. Furthermore, the innovative daylighting systems are discussed and they rely on the daylighting availability in different geography and interior spaces. Then, Anidolic daylighting system (ADS) is being studied, including the design attributes and configuration of the system. Lastly, case studies of buildings with the installation of ADS were carried out. This chapter helps in determining the design parameters for ADS in tropical climates.

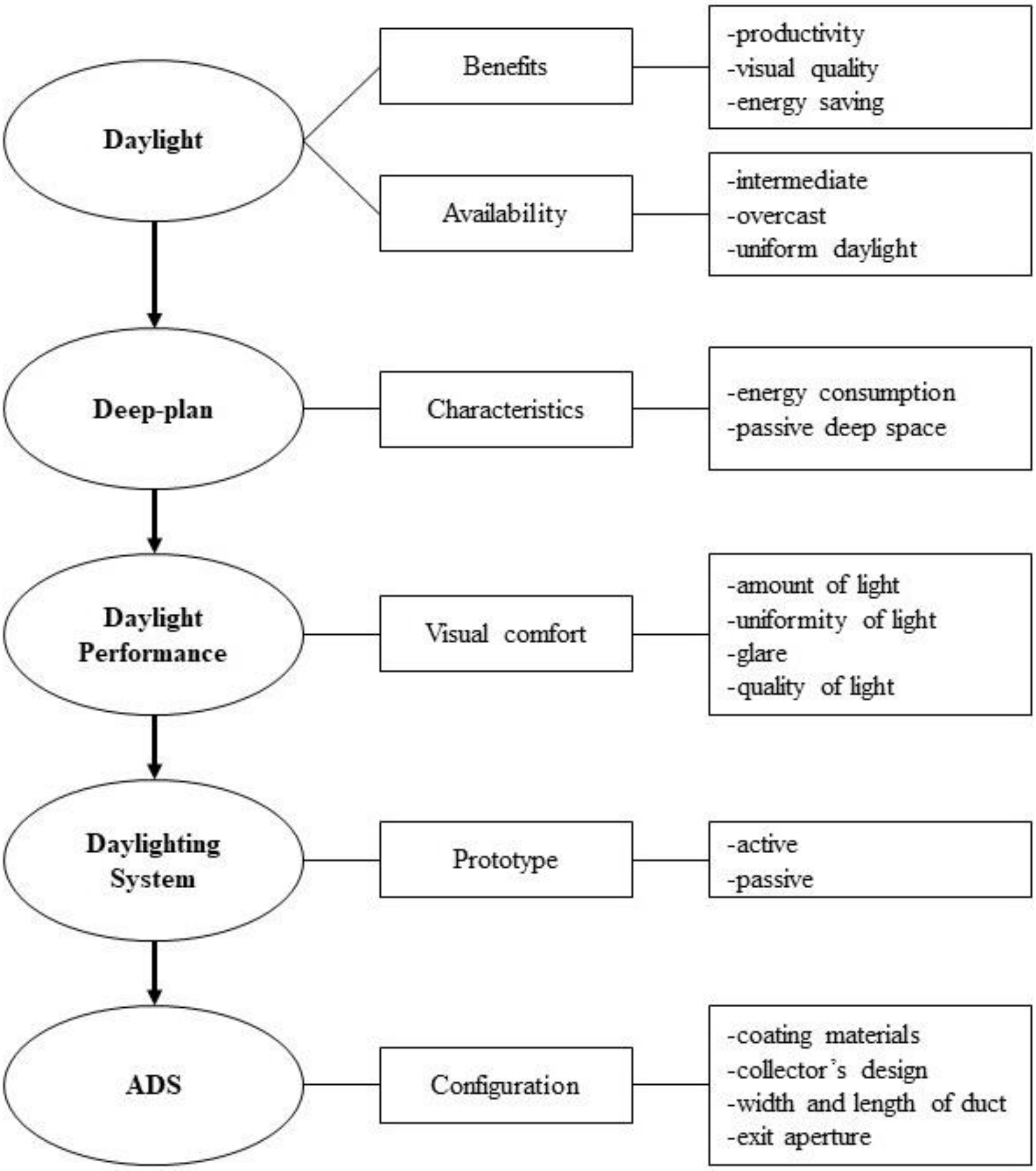


Figure 2.1 Summary of Literature Review (Author, 2022)

2.2 Daylighting

Daylight is the primary source of light, which is natural, sustainable, and free but limited to daytime. A combination of direct and indirect sunlight is considered daylight. The use of natural daylight in buildings is beneficial to humans but it also brings negative impacts when misuse. In general, daylighting brings benefits to humans, such as improving their health, performance, and comfort level. The majority of developments in artificial lighting happened in the 20th century, and it provides a high level of illuminance to a room (Fontoynont, M., 2002). Fontoynont, M. (2002) also stated that both daylight and artificial light do bring light into space and contribute to comfortable conditions for users of the space.

However, artificial lighting consumes a high amount of electricity, which is not energy efficient. According to Ihm, P. et al. (2009), 25-40% of energy consumption in commercial buildings comes from the use of artificial lighting. But with the effective use of natural daylighting in buildings, it can save energy consumption for lighting significantly and also improve the interior comfort level (Oakley, G. et al., 2000). Alhagla, K. at al. (2019) further elaborate that artificial lighting and energy consumption can be minimized by increasing the effective use of natural daylight. Research has shown that the use of daylighting in the Asian regions can decrease energy consumption by about 20% (Zain-Ahmed, et. al., 2002). But in contrast, additional consumption of cooling demand might be needed although the utilization of daylighting in buildings helps in electricity consumption saving (Yassin, A. A. et al., 2017). Refer to the research from Zain-Ahmed et. al. (2002), besides from energy consumption, waste heat will be transmitted into building space that will affect the building cooling load when we consume artificial lighting.

2.3 Daylighting Availability in Malaysia

Daylighting is an important natural strategy to create a pleasant environment for users. But different geographical regions have very different daylight performance. In the tropics, as in Malaysia, it has more than 10 sun hours every day, with consistent temperature and great amount of sunshine (Munaaim, M. A. C., et al., 2016). Malaysia is located at the equatorial zone, which means zone of latitude within 10°. The sky condition is primarily overcast, and with hot and humid climate (Edmonds, I. R., & Greenup, P. J., 2002). According to Chirarattananon, S., et al. (2000), tropical climates have great potential for skylight due to the diffuse daylight light as the sky condition is luminous and overcast.

2.4 Deep-plan Space

A space is called as deep-plan when the ratio of internal floor area to external wall area is high, or when the space has a distance greater than 4m away from the external walls (Gorse, C. et al., 2012). High amount of artificial lighting is required to light up a deep-plan building which has a deeper space than daylight redirection distance (Heng, C. Y. S., et al., 2020). According to Baker, N., & Steemers, K. (2003), the passive zone of a building is the area of a building that has natural daylighting and ventilation, and the limit of it is twice of the ceiling height. Spaces exceeding the passive zone are considered as deep-plan.

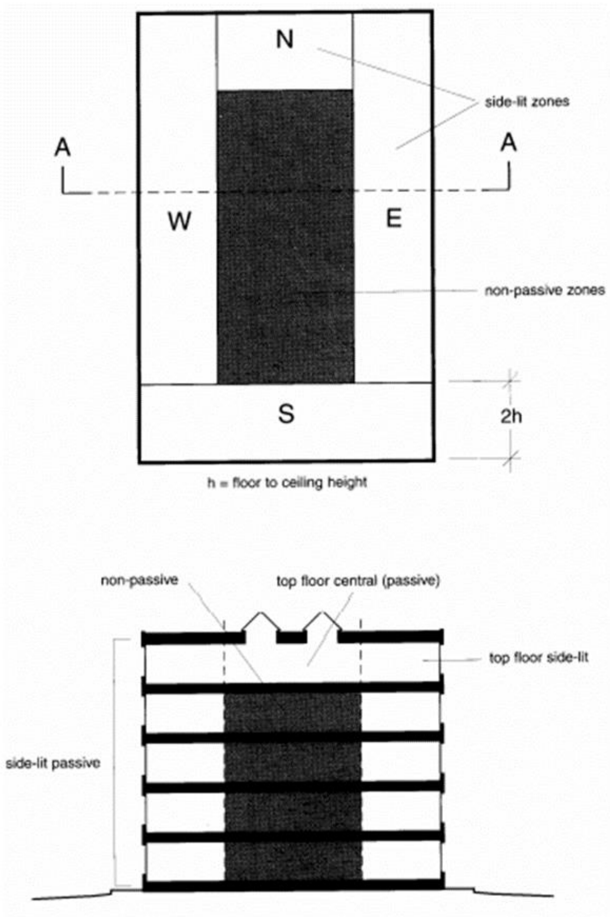


Figure 2.2 Passive Zone in Building (Baker, N., & Steemers, K., 2003)

Typical design normally causes unnecessary daylight around the passive zones and has large gloomy areas deep inside non-passive zones. (Wittkopf, S., 2015). Electric lighting is the common solution to light up the deep plan space, because the use of large and tall windows as natural lighting for deep-plan is inefficient because of the risk of non-uniformity daylight and also a problem with glare (Roshan, M., & Barau, A.S., 2016).

2.5 Visual Comfort and Daylighting Performance

Visual comfort is one of the criteria that has the key to enhancing the effective reduction of energy consumed in space (Mohamed, M. A. S. et al., 2020). Carlucci, S.

et al. (2015) stated that the available amount of light, light uniformity, light quality, and the risk of glare are the characteristics of visual comfort between human needs and light environment through assessment. Visual comfort is defined as "a subjective condition of visual well-being induced by the visual environment" by European standard EN 12665. Visual quality can be accessed through the performance of lighting in buildings in several different aspects, followed by the scope of indices.

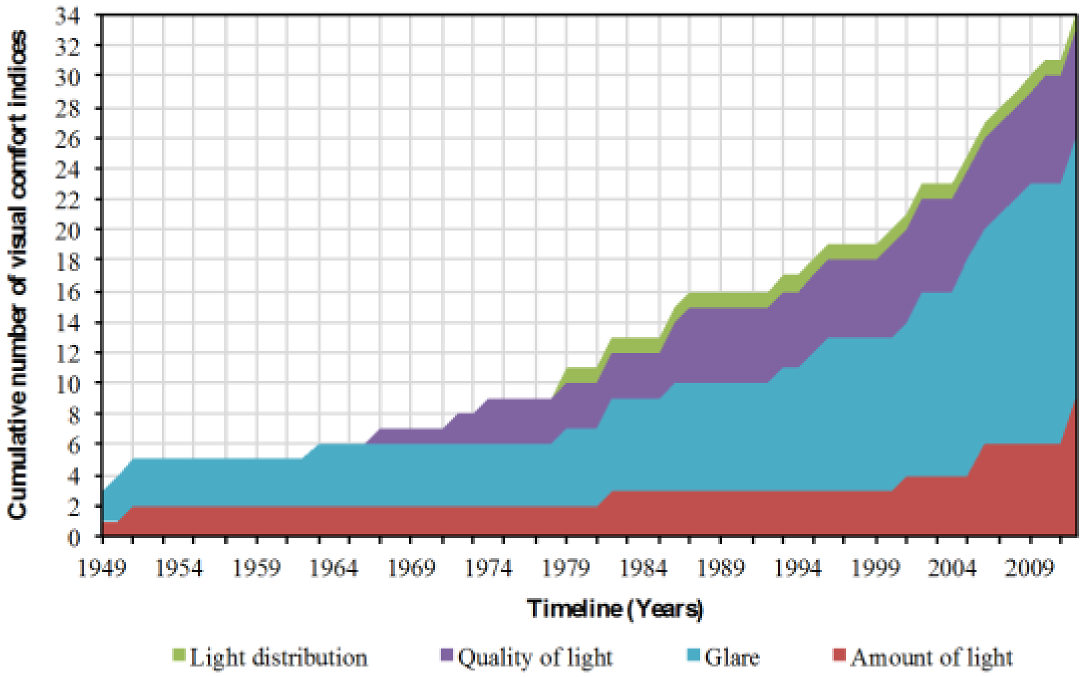


Figure 2.3 The Cumulative Number of Visual Comfort Indices Proposed Over Time (Carlucci, S., et al., 2015)

Regarding the graph, the change of proposed indices over the years has indicated that there is no summary for overall visual comfort in a single value.

2.5.1 Amount of Light

Good visibility is when an adequate amount of light is present and occupants are able to conduct their work. An excessive or insufficient level of light in a space can cause discomfort for the user, which will affect their mood and performance. The amount of light is measured by illuminance level (lux), for which different workplaces are recommended with different standard lux values. As in Malaysia, the Department of Standards Malaysia, 2007 (MS 1525:2007) and the Department of Occupational Safety and Health (DOSH) have designed guidelines to assess the indicators of lux value for different workspaces.

2.5.2 Uniformity of Light

The uniformity of light is the degree to which light is dispersed uniformly over an area. Carlucci, S. et al. (2015) claim that visual comfort from light uniformity is the minimalization of visual stress as a result of the regular eye adaption from over-lit to under-lit areas. Uniform of daylight can be measured and evaluate through formula of ratio between E_{min} / E_{max} that the value more than 0.5 is acceptable, and more than 0.7 is preferable, where E_{min} is minimum illuminance; E_{max} is maximum illuminance of the space.

2.5.3 Glare

The definition of glare is that the illuminance level of visual sensation available for observation is adequately higher than the illuminance level that the eyes can accept that would cause annoyance, discomfort, and reduction in visibility and performance (IESNA, 2020). In short, glare happens when there is difficulty seeing that caused by the light environment being bright. Most glare incident happens when there is direct light from light sources, for example, artificial lighting or daylight from a large opening.

2.5.4 Quality of Light

The characteristic of light that consumers like in various regions and settings is its quality. The degree of light intensity and its variation both have an impact on occupant preferences. Daylight is generally preferred due to the benefits it brings to users compared to artificial lighting, such as improving users' performance and mood, and reducing their consumption of electricity. Therefore, good quality of daylight availability often helps in ideal visual conditions in space that do not cause glare, and non-uniformity of light environment.

2.6 Daylighting System

Since a very long time ago, daylighting has been used in building, thus it is not a recent idea. A window is the only traditional method of daylight design that can bring enough light into a space (Beltran, L. O. et al. 1997). A daylighting system is a way to introduce daylight into a place for the benefit of the residents while also conserving electricity. An energy-saving daylighting system can reduce the demand for artificial illumination in some areas. Buildings can utilise a variety of daylighting system strategies, which must be considered based on the building's typology and intended usage of the areas.

Over the years, several daylighting system prototypes have been created to address and accommodate various requirements for daylight illumination. By bringing natural illumination from the outside into a specified interior space, a daylight transporter system can increase daylight performance and lower energy costs. There are two types of daylighting systems: passive and active. The passive system is a direct daylight transporter system with an installed collector that is stationary and provides daylight illumination. The active system, on the other hand, has a collector that is mobile and is controlled by sensors or other devices.

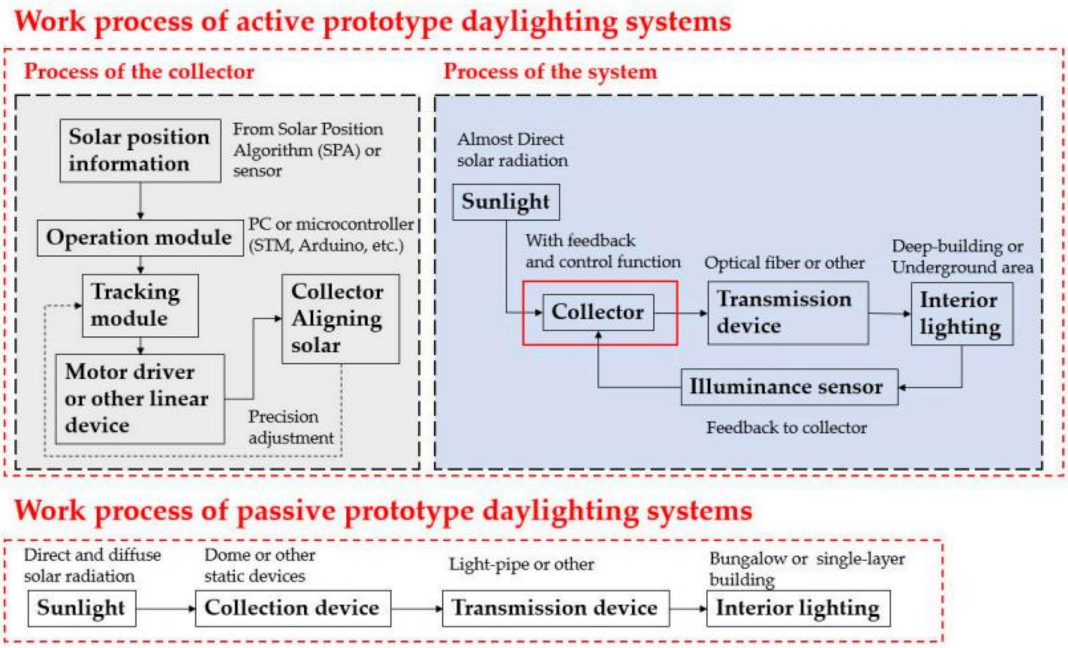


Figure 2.4 Daylighting System's Work Process (Yassin, A.A., et al., 2017)

In other words, an active prototype daylighting system requires energy to collect sunlight where it uses mechanical structures in the sunlight transmission; a passive prototype is a system that does not need energy for the progress of sunlight transmission (Whang, A. J. W et al., 2019).

2.6.1 Skylight

According to Kischkoweit-Lopin, M. (2002), skylights can illuminate the rooms while glare and overheating issues are avoided. The direct light guiding systems can diffuse sunlight, and they have similarities in their overall performance and the positions in the building (Hansen, V. G., 2006). The systems can be either active or passive depending on the needs of the climate conditions.

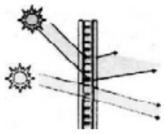
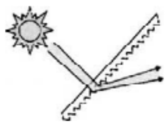
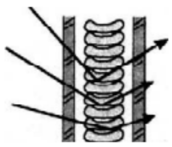
System	Climate	Attachment	Criteria for the choice of elements
Laser Cut Panel (LCP) 	All climates	Vertical windows, skylights	– View outside (D) – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available
Prismatic panels 	All climates	Vertical windows, skylights	– View outside (D) – Lightguiding into the depth of the room – Saving potential (artificial lighting) – Available
Holographic Optical Elements in the skylight 	All climates	Skylights	– View outside – Homogeneous illumination – (artificial lighting) (artificial lighting) – Available
Light guiding glass 	All climates	Vertical windows, skylights	– Glare protection – View outside – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available

Figure 2.5 Direct Light Guiding Systems (Kischkoweit-Lopin, M., 2002)

2.6.2 Transported Light

Light can be transported into deep plan over long distances without window openings. It can have horizontal or vertical light pipes, and an active daylight collecting system. It redirects light from the exterior through the system and diffuses the sunlight into useful daylight into a deep plan. Light transporter systems can also be different prototypes of daylighting systems, but they are mostly passive prototypes of daylighting systems.

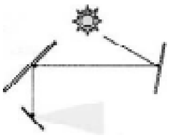
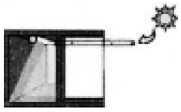
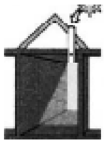
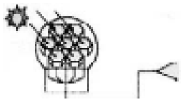
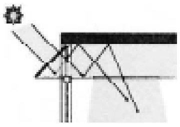
System		Climate	Attachment	Criteria for the choice of elements
Heliostat		All climates, sunny skies		– Lightguiding into the depth of the room – Saving potential (artificial lighting) – Need for tracking – Available
Light-Pipe		All climates, sunny skies		– Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available
Solar-Tube		All climates, sunny skies	Roof	– Lightguiding into the depth of the room – Saving potential (artificial lighting) – Available
Fibres		All climates, sunny skies		– Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Need for tracking – Available
Light guiding ceiling		Temperate climates, sunny skies		– Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Research and development

Figure 2.6 Light Transport Systems (Kischkoweit-Lopin, M., 2002)

2.7 Anidolic Daylighting System (ADS)

An anidolic daylighting system is a prototype passive daylighting system that uses an anidolic collector to passively transport sunlight into interior areas. The deep-plan interior area may receive sunshine from the outside through a horizontal light conduit. This technique, according to Whang, A. J. W et al. (2019), is capable of gathering and rerouting daylight to the interior of deep-plan or high-rise structures, which are unable to do so with a side opening. However, a few factors, such as the sky's condition, the angle of incidence, the material utilised, and the pipe's diameter, can influence how well the daylight transmission system works. A better daylighting system that can operate well in the daylight and lower construction costs will be provided through experiments.

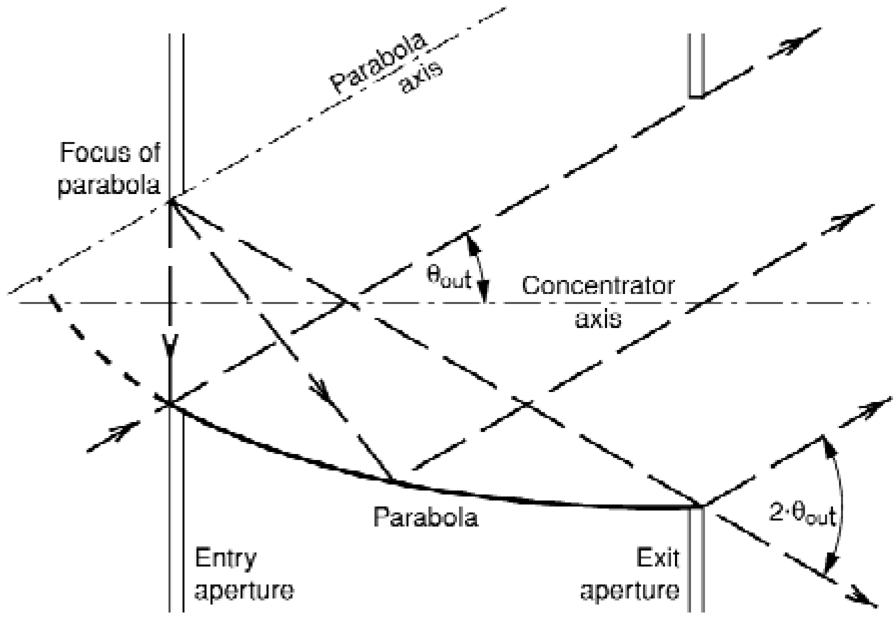


Figure 2.7 ADS's reflector profile (Scartezzini, J. L., & Courret, G., 2002)

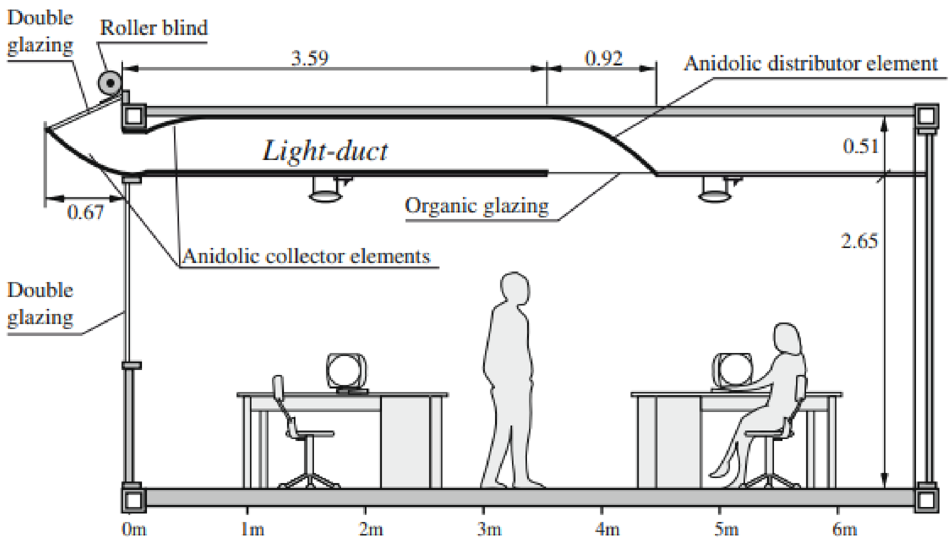


Figure 2.8 Typical section of ADS in office building (Linhart, F., et al., 2010)

2.8 ADS Configurations

ADS is structured into a few different parts, each with different configurations that will affect the performance of the light transport. This is because light rays bounce from the beginning of ADS to the end of the system. As in Figure 2.8, the parts of ADS are collectors, ducts, and distributors, as A, B, and C respectively.

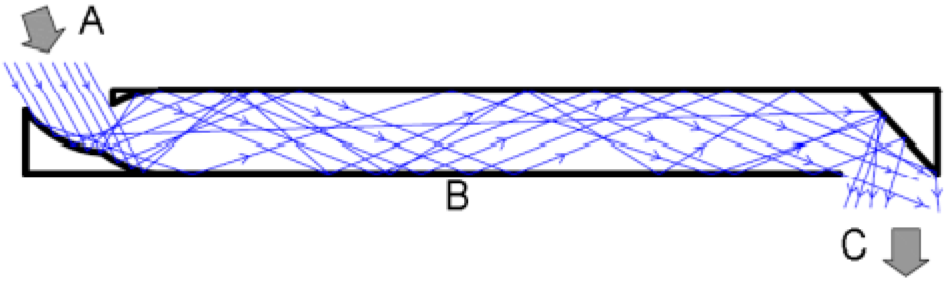


Figure 2.9 Ray paths in ADS (Roshan, M., 2014)

The modifications to the duct configurations of the collector's design, the width, length, and depth of the duct, and the orientation of collectors affect the efficiency of ADS. There is previous research and studies about the configuration of the ADS, which will be explained in sections below.

2.8.1 Coating materials

The duct of ADS uses highly reflective materials to redirect and bounce light rays from the collectors into the long distance of the deep plan. According to Roshan, M. (2014), collectors of ADS requires reflective coatings as it has a major influence on daylight performance. The choice of coating materials is the main criteria where the material properties studied by Heng, C. Y. S., et al, (2020) and Roshan, M., & Barau, A. S. (2016) for the tropic climate are in Table 2.1.

Table 2.1 Material properties (Heng, C. Y. S., et al., 2020; Roshan, M., & Barau, A. S., 2016)

Element	Reflectance	Specularity	Roughness	Transmittance
Wall	0.70	0.03	0.03	-
Floor	0.20	0.03	0.20	-
Ceiling	0.80	0.03	0.03	-
Light pipe (inner surface)	0.99	0.05	0.03	-
Pipe reflector	-	-	-	0.75

2.8.2 Collector's Design

The collector in the ADS is where the light rays start to be redirected into the duct. Therefore, the collector is significant that the design should be able to redirect most of the light rays and avoid reflections inside the duct. Wittkopf, S., et al. (2010) have studied and researched collector's design in tropical climates. Several of the collector's designs in Figure 2.10 are investigated, and type 5 is selected as the optimum design for tropic climate regions because of the parabolic design of de-concentrators that have very little loss of light rays. Subsequently, the type 5 collector's design is being used for current research simulation.

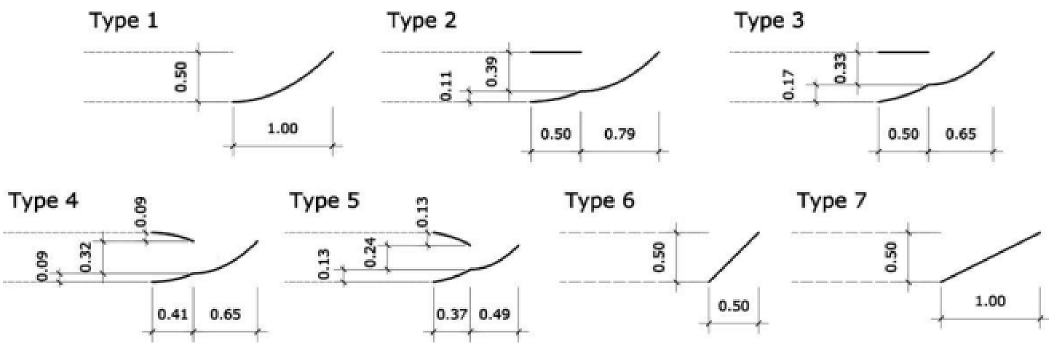


Figure 2.10 Relationship of ADS width and efficiency (Linhart, F., et al., 2010)

2.8.3 Width and Length of Duct

According to an experiment by Linhart, F., et al. (2010), the width of the duct has a direct relationship to the efficiency of daylight performance. The experiment was tested with a duct width of 5m to 1m and the result shows there is a decrease in ADS efficiency from 5m to 1m. The thinner the width of the duct is, the worse the performance of ADS. The width of the duct can be decided among designers based on the design of the building for aesthetic value and daylight performance. Meanwhile, the performance of ADS over the length of the duct depends on how deep the plan is over the distance and the other configurations such as width and exit apertures.

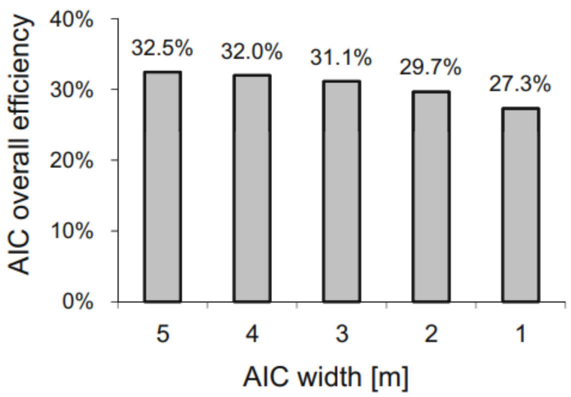


Figure 2.11 Relationship of ADS width and efficiency (Linhart, F., et al., 2010)

2.8.4 Exit Aperture of ADS

The exit aperture of ADS can be known as a distributor as it is where the end of redirection of light or the source of illuminance from ADS of deep-plan. As stated by Roshan, M. (2014), modification of distributors has no specific data as the performance of ADS mainly depends on locations and numbers of exit apertures. Therefore, the number of exit apertures will be identified in this study.

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