

Review

# A Review on Effective Use of Daylight Harvesting Using Intelligent Lighting Control Systems for Sustainable Office Buildings in India

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**Abstract:** Lighting is a fundamental requirement of our daily life. A lot of research and development is carried out in the field of daylight harvesting, which is the need of the hour. One of the most desirable attributes of daylight harvesting is that daylight is available universally and it is a very clean and cost-efficient form of energy. By using the various methods of daylight harvesting, it is possible to attain the global Sustainable Development Goals. Daylight harvesting in the most fundamental sense is the lighting strategy control of the artificial light in an interior space where daylight is also present so that the required illumination level is achieved. This way, a lot of energy can be saved. Recently, in addition to energy efficiency, other factors such as cost-efficiency, user requirements such as uniform illuminance, and different levels of illuminance at different points are being considered. To simulate the actual daylight contribution for an office building in urban Chennai, India before construction, ECO TECH software is used by providing the inputs such as building orientation, and reflectance's values of the ceiling, wall, and floor to analyze the overall percentage of daylight penetration available versus the percentage prescribed in the Indian Green Building Council to obtain the credit points. Thus, the impact of architectural design on daylight harvesting and daylight predictive technology has experimented with office building in Chennai, India. This article will give an insight into the current trends in daylight harvesting technology and intends to provide a deeper understanding and spark a research interest in this widely potential field.

**Keywords:** daylight harvesting; sustainable building; smart lighting



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## 1. Introduction

Energy is central to almost every significant challenge and opportunity that the world faces today. As the world's population continues to rise, so will the energy consumption. Nevertheless, a fossil-fuel-based economy prevails as a prime driver of climate change. Achieving affordable and clean energy is expected to galvanize efforts to reach the Paris climate change agreement and also to expedite the progress in Sustainable Development Goals [1]. Augmenting the clean energy penetration is utmost for which research on investigating the potential renewable energy resource in a country [2–5], policy assessment [6] and developing an optimized scenario with various hybrid clean energy technologies is

pivotal [7]. A study suggests that the lack of energy efficient infrastructure and resiliency to climate change as the major weakness in progressing towards sustainability [8]. Thus, efficient use of energy as well as minimizing the energy consumption is desideratum.

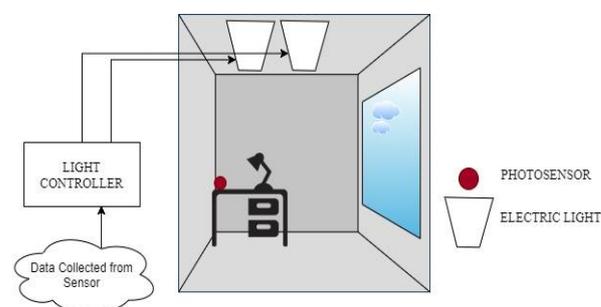
The annual electricity consumed in commercial buildings and households is about 20% to 40% per year [9]. The Lighting energy makes up a major portion of the total energy consumed. However, the amount of daylight available within a building can vary throughout the day since the motion of the sun from sunrise to sunset is also based on dynamic weather conditions. This energy can be saved by using different potential solutions. The costs and energy consumed to provide lighting for building occupants can be reduced phenomenally by implementing suitable daylight harvesting techniques. Since daylight is available in every part of the world and the energy produced by daylight harvesting is very clean and affordable, it is destined to be a promising solution by 2030. Cities predominantly require a cost-efficient energy system as the energy consumption is very high in cities. Daylight harvesting systems serves as a beneficial solution for the environment, to promote energy efficiency and to attain technological progress by 2030.

In [10], several lighting control methods and algorithms used in daylight harvesting are discussed. In recent decades, lighting controls have been broadly contemplated considering different variables such as light fixture design, framework topology, and occupancy satisfaction [10].

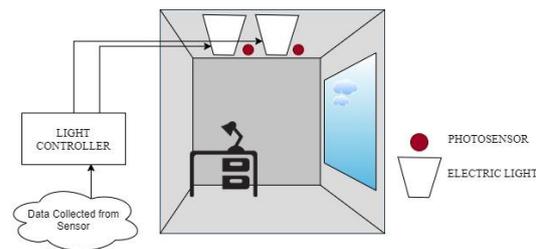
Lighting control systems are usually used to set the optimum brightness, select target sensors, and control light fixtures to be ON or OFF. However, in recent years a very significant feature in lighting systems automatically sets the light fixtures in accordance with the daylight lighting so that the total brightness in an area is consistent with the uniform distribution of light [11].

The general idea is that a daylight harvesting system includes a daylight sensor that distinguishes the natural and artificial illuminance in a workspace. Identifying the differences in illuminance allows the values of the contributions to be combined in several ways so that the desired total illuminance can be obtained [9]. Recently, lighting control techniques dependent on inhabitation and daylight illuminance have been reliably used to reduce electric energy consumption. The adoption of LEDs and the combination of data and communication technologies empower lighting control systems to be smarter [10].

For Closed-loop controllers, a light sensor is used to calculate the internal illuminance so that the controller will control the artificial light fixtures in accordance with the available daylight illuminance. Usually, these sensors are present closer to the occupant so that the controller can alter the lighting to increase the visual comfort of the occupant. Figure 1 shows a photosensor present on the desk [12]. Figure 2 shows a ceiling-mounted photosensor present in a workspace.



**Figure 1.** Photosensor on Desk.



**Figure 2.** Ceiling-Mounted Photosensor in Workspace.

Apart from the controller design, various control algorithms are used in daylight harvesting [12]. Daylight harvesting is an age-old concept and its effect can still be seen embedded in the architecture of ancient civilizations. The daylight harvesting systems include daylight prediction systems due to dynamic sky conditions. The estimation of the daylight metrics aids in increasing the efficiency of daylight harvesting. Various prediction models developed using time series prediction, nntool, nftool, and neural networks are discussed. Apart from controllers and algorithms, daylight harvesting can also be used using building geometrics. Furthermore, this paper discusses the various metrics used to obtain uniform and desired interior illumination using parameters such as Window-to-floor ratio, daylight factor, daylight autonomy, etc., by using building simulators.

The integration of daylight in buildings has significant potential to reduce energy use. However, the luminous environment can result in issues such as glare, headaches, eye strain if daylight designs are not well constructed. This thesis presents results from a broad-scale analysis involving data analysis and survey of three large commercial buildings using multiple shading methods such as automatic blinds, electrochromic glazing and roller shades. Physical data were obtained in order to assess the glare and sunshine conditions and a survey was sent to employees who were working with the same company to evaluate standard of visual ease and comfort in the workplace. The following are the key outcomes from [13],

- Employees who were more comfortable with their proximity to sunshine were more likely to have higher perceived efficiency levels and higher happiness levels.
- In buildings 1 and 2, the satisfaction of the occupants with their office ranged substantially depending on their distance to the doors, and those nearest to the perimeter of the facility were more comfortable than those who sat farther away from the walls.

Daylighting design is a complex topic, and an integrated design process is necessary for a well-lit space to be designed carefully [13].

Section 2 discusses about the concepts of daylight harvesting using controllers and algorithms. Section 3 discusses in detail about techniques for daylight prediction. Section 4 further elaborates about the influence of building geometrics in daylight harvesting techniques. Section 5 discusses a case study of where ECO TECH software is used to analyze the overall percentage of daylight penetration available versus the percentage prescribed in the Indian Green Building Council to obtain the credit points. Thus, the impact of architectural design on daylight harvesting and daylight predictive technology has experimented. Section 6 discusses the conclusions and future scope of work for daylight saving concepts.

## 2. Algorithms and Control Systems for Daylight Harvesting

The growing interest in energy and cost-efficient systems without compromising on user comfort has led to a boom in the research and development of daylight harvesting systems. Over the years, a lot of algorithms and control mechanism for the regulation of artificial lighting based on the availability of daylight is developed. One such approach is the use of a genetic algorithm as an optimizing tool for controlling the artificial illuminance. This approach is based on the fundamental principle of daylight harvesting, i.e., the required artificial illuminance equals the total illuminance required minus the available

daylight illuminance. In this approach [14–16], the illuminance of the required lighting systems is represented by (1),

$$E_R = E_D - DF_m \cdot E_O \quad (1)$$

(1) can be further written as (2)

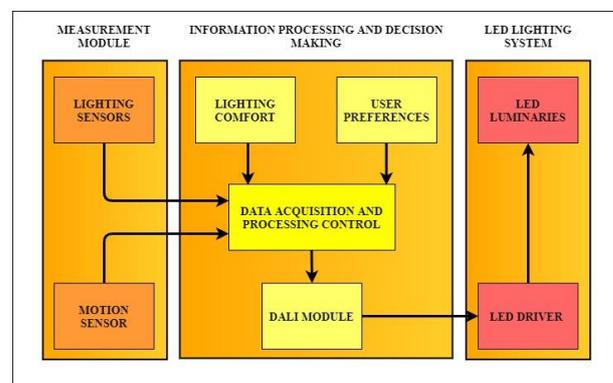
$$E_R = B \cdot Y = E_D - DF \cdot E_O \quad (2)$$

The minimization of  $Z$  is done using the Genetic Algorithm, which is used as a tool to develop an operation schedule for the light fixtures which are further controlled by dimming and ON/OFF control of lighting strategy. This system is used in public premises to minimize the usage of lighting energy and maximize the use of natural light [14,15].

Another important factor that is widely considered in daylight harvesting systems is providing desired illumination levels at the user-defined points. A self-tuning multivariable controller is being used for this purpose. It is a closed-loop controller that guarantees the stability of the LED lighting system [16].

The use of Fuzzy logic controllers has also increased over the years. This is because they are considered to be the most appropriate controllers for lighting systems owing to their generalization of lighting levels settings, simplicity, and auto-control [17]. Based on the presence of the users, daylighting levels, and comfort to the user, a controller using fuzzy logic is designed to vary the lighting. This way the lighting energy which contributes to a significant portion of building energy is also saved and user comfort is also not compromised.

The DALI protocol is used as a communication medium between the LED luminaires and controllers. The DALI protocol is used, as it is an intelligent protocol that is developed especially for lighting. Moreover, every LED light fixture is fitted with a constant-current DALI driver that obtains signals and controls the light output [18]. Figure 3 represents the working of a smart LED lighting system with a fuzzy logic controller.



**Figure 3.** Block Diagram of Smart Lighting System.

Adding on, it is found that a non-adaptive fuzzy controller, when tuned successfully, fails to achieve uniform illuminance when an ON/OFF failure of the bulb occurs. This problem is overcome by the use of a fully adaptive controller technique. This adaptive fuzzy control logic is also known as FMRLC [19].

Another method that is used to reduce the electrical energy requirement of the LED luminaires is Safety Extra Low Voltage wiring systems which can also be used to control them. This is achieved by using a Low-Latency communication Network, centralized 48 Volt DC to control LED luminaires, which is capable of gathering real-time data. DC power and control systems are also implemented using sophisticated monitoring methods that are capable of providing daylight harvesting from sole luminaires, delicate dimming, temperature sensing, and occupancy control. The dimming of the LEDs is controlled by PWM controllers which deliver a variable current ranging from 0 to an acceptable current

value of the light fixture. The LEDs are turned ON and OFF at high values of frequency which creates a square wave signal and the brightness of the LED is determined by the duty cycle of this signal [20].

A Neural network-based control strategy is also being used frequently these days. It is because it enables the design of a lighting control system where the user controls the lighting system without having any knowledge of the system parameters [21]. On the other hand, daylight as a disturbance involves using a controller whose main intent is enhancing the efficiency of lighting energy via feedback control of artificial illumination devices. The lighting control algorithm is specified as a MIMO system where power loaded to the luminaires is considered to be the input and the light level at the target points is the derived output [22]. Another approach commonly used for NZEB is to model a luminance system via ANN and to use it for controller design using the IMC principle [23].

Photodetectors are often used to continuously calculate daylight illumination and use it for the neural network as a bias value. It is ensured by this method that each region receives the desired level of power consumption, uniform lighting, and the required level of lighting [24]. An open-loop control system based on sensed values of daylight and information for adjustment obtains the fading rates of the lighting fixture for adjusting daylight and occupancy shift. Besides, the efficiency of the daylight sensing lighting control system is found to be more robust as compared to the photodetector-based system in the presence of changes of reflectivity in the environment. Figures 4 and 5 represent photodetector-based and daylight sensing LED-based lighting systems, respectively [25].

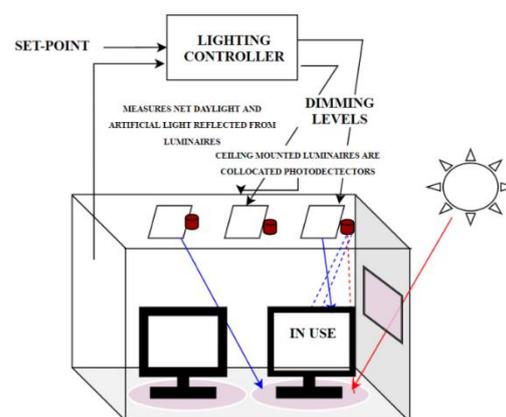


Figure 4. Photodetector-Based Lighting System.

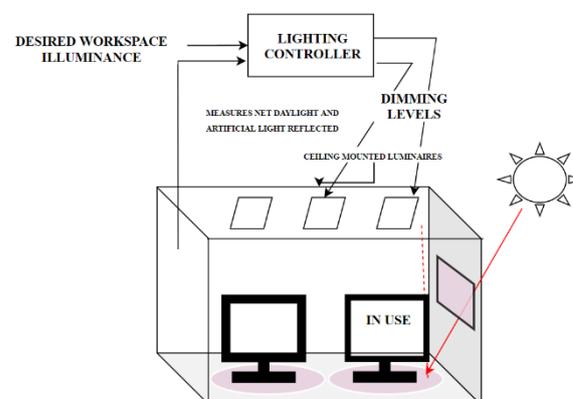
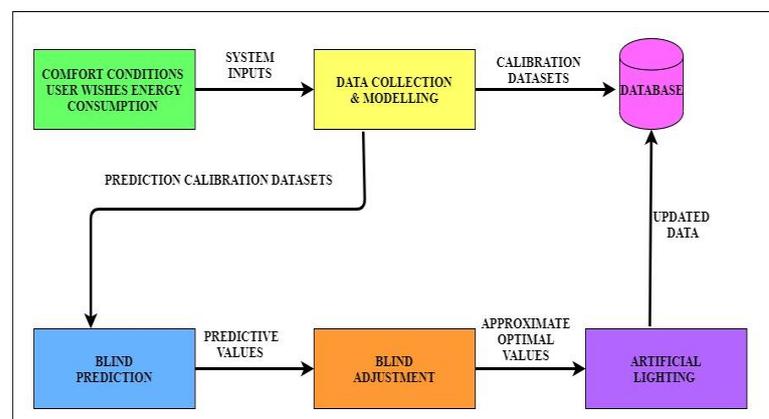


Figure 5. Daylight Sensing LED Lighting System.

Daylight harvesting systems are developed based on various methods. One of the most common methods of lighting control is by calculating the sum of illumination by daylight and artificial lighting and to evaluate the extent of fading of the light. One technique that is used is the dimming theory of PWM with partial- feedback loop control

for light fixtures that further analyzes and inputs the illuminance provided by artificial light. The main objective of this controller is to determine the illuminance level of daylight and determine the fading duty cycle founded on the idea of partial feedback and also to sustain even lighting for a series of control cycles using both daylight and artificial light. The illuminance control scheme comprises three steps namely: the measurement, estimation, and generation of the output control signal for the light fixture. For each control process, cycle, the measurement along with the calculations are done during the OFF Time and these functions are performed which consists of ON time and OFF Time, in each control output signal [26].

A more generic approach that is used to monitor lighting in any structure without any personalized programming can be accomplished by self-calibration and self-learning of the system. The resulting system controls blinds to use daylight harvesting efficiently and also resorts to artificial lighting in the absence of daylight. This system works in any location without any preprogramming involved. A WSN is used for control of lighting, which turns ON/OFF static lights and also controls the tilt angle in the windows' roller blinds. This lighting control contains three main stages-blind predictions, regulation, and control stage. For proper control of blinds, the blinds are initially calibrated for different illumination conditions. The obtained data is then used as input to the blind control mechanism. Blind prediction for the current situation is done using the calibrated data. Blind Prediction data is further forwarded to the blind control stage which adjusts the blinds in real time. Artificial light control mechanisms will illuminate the surrounding when there is no sufficient daylight or when light is not evenly distributed. Figure 6 reflects the System Control Window [27].



**Figure 6.** Lighting Control System.

Smart imaging sensors are used to control artificial lighting that controls numerous zones in the same room by independently regulating every one of the lighting fixtures [28]. The imaging sensor is placed on the ceiling and configured to evaluate the photometric quantities of the entire control area. Software is developed that consolidates the creation of DALI control signals for each lighting fixture, the control algorithm, and the photometric configuration of the imaging sensor. Initially, the device evaluates the illuminance levels of every work location and compares them with the respective set values of that location, calculates the ideal value and sends the suitable control signals to each luminaire. The DALI is generally used for controlling individual luminaires. The benefit of using it is that each luminaire is controlled individually by dimming it up or down, switching it ON or OFF. A program is customized to translate the control algorithm into DALI commands. An optimization algorithm is developed which determines the fading level of every one of the independent luminaires to achieve the desired levels and consistency. Daylight harvesting is employed as an innovative approach to providing energy efficiency through the development of a control system by regulating the lighting conditions for plant growth. The device regulates the fading of the LEDs based on the light luminosity data given by

the red and blue channels sensed by the light detecting sensors present on the testbed, bearing in mind the optimal red-blue mixing ratio of light essential for the growth of plants as shown in Figure 7 [29].

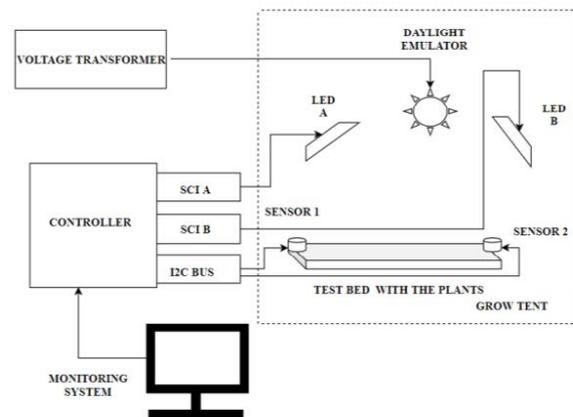


Figure 7. Test Bed of Lighting System.

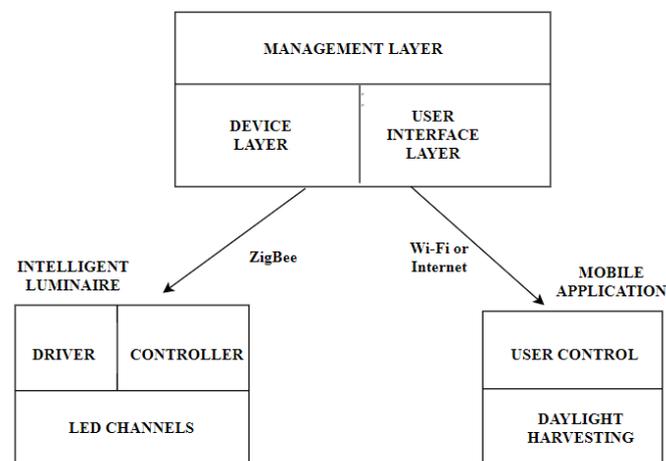
Similarly, a multi-input and multi-output control system integrated with daylight harvesting control are used to develop an energy-efficient greenhouse lighting. The main motive of this controller is to vary the intensity of dimmable LED fixtures for achieving the desired illumination level. The proposed control device is tested in a grow-tent containing fading lamps, LED fixtures and photosensors. Fading commands given to the light fixtures are taken as control inputs and the light irradiance levels at target locations are the output variables of the MIMO control system. This system is further used in the green tent to confirm the effect of higher illuminance of daylight in plants. The results indicate that the system achieved desired DLI for specific plants and was able to maintain perfect red and blue ratios [30].

A new and upcoming method is the use of smartphones to control home lighting systems. The growth in smartphones has tremendously contributed to the development of a smart home lighting system with daylight harvesting capabilities. This device comprises a luminaire with RGB channels which is powered by an Arduino, an Android app in the users' smartphone, and a Raspberry Pi processor. The mobile application serves as a user interface to monitor the lighting device and to receive data from the light sensor in terms of lux values on the mobiles so that the closed-loop lighting input is either dimmed or brightened continuously to preserve the required amount of illumination [31]. The luminaire includes RGB.

The gateway communication between the controller and the smartphone was protected using PKI as suggested by the IEEE Standards Association and the communication between the key controller and light fixtures is protected using the AES. Moreover, to ensure that the daylight harvesting process does not interfere with the usage of the phone, an algorithm is developed using the accelerometer of the smartphone. Therefore, this system is tested and proven to give high accuracy while enabling users to perform daylight harvesting using their smartphones without compromising their desired lighting color. Figure 8 shows a block diagram of the smart lighting system [31].

For minimizing energy consumption and to find the best suitable daylight harvesting system, a typical Greek high school classroom was used in [32]. This paper evaluates a variety of illumination methods along with two devices for daylight harvesting. To estimate light adequacy and energy savings, the first system uses a stand-alone photo sensor per luminaire, while the second system uses a photo sensor per control field. This process was illustrated using the dimming curves of the LEDs calculated along with the installed photo sensor power. The results indicate that the actual  $90.5 \text{ kWhp/m}^2$  of annual primary energy consumption for lighting can be reduced to  $0.55 \text{ kWhp/m}^2$ . When it comes to the selection of the photosensor control system, comparing system 1 and system 2, the results show that

more energy can be saved while using a central photosensor. Ref. [33] ADHS is a derivative of the traditional daylight harvesting methods. In this paper, the active daylight harvesting method is extensively studied with solar concentration, collimation, and beam orientation. A 0.1 m diameter light pipe can emit an average of 30,000 lumens of daylight over 8 h each day. The ADHS system uses a high-pass mirror to filter out unwanted infrared radiation, which acts as the heating load for HVAC. Also, slope error effects, tracking error, incident angle and solar divergence angle are monitored by ray tracking in ADHS system. The biggest drawback to ADHS systems is that the effective lighting time for ADHS is more than double that of the non-tracking typical lighting system but this is compensated by an increase in transmitted light by 100 times than other systems. Other advantages of ADHS include continuity of beam patterns across solar elevations and efficiency of light extraction and control [34].



**Figure 8.** Architecture of Smart Home Lighting System.

The implementation of DLCs ensures major advantages such as maximizing both energy savings and visual comfort for occupants. This paper aims at conforming this by performing daylight illuminance measurements at a workplace and the ceiling in a side-lit office building during summer and winter. The model building was planned with two windows. Measurements, orientation and functioning of the system in closed-loop were modeled to observe results at both the seasons. The results showed that the DLCs have better efficiency for analyzed situations [35].

This method comprises the use of millions of micro mirrors that can guide and control the light which in turn reduces the power consumption and improves the lifetime. The concept of Optical MEMS is used and the micromirrors are electrostatically actuated and miniaturized, hence they are not visible as individual mirror elements at distance more than 20 cm. The main advantage of this method includes:

- Long lifetime despite using mechanical components.
- Lower power consumption compared to other active systems. Light is almost completely reflected inside or outside the room.
- Does not change the spectrum of sunlight.
- Works even at low temperatures [36].

A smart way to conserve energy is to combine LED lighting systems with a high-resolution sensor system and a localized light sensor. The localized light sensor mounted on each fixture is capable of improving local spatial conditions and gaining an additional 35 percent savings relative to a single photo sensor monitoring all the luminaries. Moreover, an increased number of occupancy sensors are also used because of which the detection of the occupants is more reliable and hence the lifetime of LEDs is improved as they are not affected by the increased switching frequency. Savings amounting to 79% was achieved when a combination of daylight harvesting and local occupancy data was used. Moreover,

the average energy savings of approximately 28% can be attributed to daylight harvesting depending on the season, window, location, window size, etc. The automated daylight harvesting was carried out by first calculating the readings of the photosensors co-located for each LED luminaire. At each phase of the system, the readings of the photosensor was analyzed and the quantity caused by electrical illumination was subtracted from it. The quantity remaining is due to daylight from which daylights contribution to the desktop level in that zone was estimated. The amount of electrical lighting needed to sustain the required illumination can be determined by subtracting this value from the target desktop illumination value [37].

Daylight lighting control systems were expected to be in higher demand given the widespread awareness of the advantages of daylight in an indoor environment and the energy-saving benefits. However, this did not happen since their functioning cannot be effectively determined while designing and that the difficulties in calculating energy and economy benefits from the daylight system. Hence a new methodology is needed to overcome these obstacles. The advantages of the new performance parameters (Daylight Integration Adequacy, Percentage Light Deficit, Percentage Light Waste, Percentage Intrinsic Light Excess) should be understood [38].

In the more recently developed buildings, a special emphasis is being given to energy savings and the quality of lighting in the building. A special case of the lighting quality and savings for the Construction, Design and Building Environment of the Beirut Arab University is taken and parameters such as Window Size, Obstruction Angle, Glazing Visible Transmittance are taken. Firstly, an analysis was done for understanding the existing lighting in the area using the Dial DIALux software, the existing situation relating to daylight was done using the Autocad Ecotect software and the information regarding the user behavior was analyzed using Hobo loggers. Based on all these data daylight designs which are based on hollow prismatic light guides were proposed which provided solutions regarding the environmental, technological, energy savings and green buildings technology needed. The proposed designs were used to obtain high intensity illumination levels and steady lighting in the facility [39].

The concept of the ASF as a scalable, effective, and versatile type of smart facades could be a potential solution for a comfortable environment through accurate integration with the parametric architecture. A study is therefore intended to analyze the production phase of ASF focused on parametric modeling techniques with an emphasis on its comfort parameters via a tractable shading framework. To optimize the advantage of daylight for individuals, the indoor architecture for daylight harvesting must ensure the visual comfort of the occupants. Daylight decreases the use of electricity, and visual convenience is usually preferred by consumers over energy quality issues for heating and cooling. Therefore, the system will adjust the shading equipment depending on the occupant's sensation of visual comfort. In this regard, the building fenestrations are responsible for incorporating daylight in indoor rooms. An origami-based hexagonal adaptive solar skin was fabricated using a single office workspace as a test bed for this study. A pragmatic strategy was systematically used in which three-time curves were developed as test methods for the study of point-in-time illumination and glare probability. The geometric characteristics of all timings were obtained from field measurements and used in simulations to increase glare change quality. The results reveal that the use of spaces with a high degree of transparency has a favorable impact on the illumination, but also a negative effect on the glare only in selected fields of indoor view. Eventually, it can be altered by choosing a proper time-based skin configuration for glare-free daylight. The findings also indicated that incorporating the proposed timing patterns over the receptive skin could enhance incoming daylight and shading opportunities [40].

The need for environmentally conscious buildings has risen over the past few years. The electric power demand of luminaries can be greatly decreased by integrating daylight harvesting, but the solar heat gain is increased. The need to analyze the solar heat gain and the natural lighting of façades using different external sun shading is required. The

LCEM constructs a simulation model that tests the use of electric power by integrating Radiance's measurement results with NewHASP using the BIMs model and a heat gain calculation [41].

In [42] an embedded photometric device to combine high-resolution sky lighting tracking based on HDR imagery with quasi-real-time on-board daylight computing, consisting of a low-cost image sensor and an FPGA microprocessor is proposed. The intentional calibration of the entire imaging system with regard to its spectral response, vignetting effect and signal response was formulated and confirmed experimentally. The instrument was designed to measure a large spectrum of luminance, including direct solar disk, sky vault, and landscape at the same time. Finally, experiments were carried out under prevailing clear and overcast sky conditions to assess its efficiency, both qualitatively and quantitatively. The built-in photometric device has demonstrated its benefits in real time daylight simulation, response time, simulation efficiency and adaptability. In the context of building automation, the device can potentially be used to control shading, illumination or electro-chrome glazing to control daylight penetration. Its ability to monitor solar luminance and location monitoring makes it suitable for producing solar photovoltaic power or changing the angle of profile of the modules [42].

Fenestrations are the reason for a substantial amount of energy consumption in the urban environment and have a significant impact on daylight and occupant's visual comfort. The equilibrium between energy usage and occupant well-being can be accomplished by automatic dynamic indoor shading systems. In this analysis, full-scale experimental evaluation of two types of roller shades using two different control systems was carried out in three separate orientations under different sky conditions. Each orientation used a typical room with no shading or lighting control, and a second similar room with embedded shading and lighting control. Two different types of glazing were also used to assess the performance of roller shades when used along with different types of glazing. Using dynamic roller shades and lighting control, relative to the baseline case of no shading system or lighting controls, an overall lighting energy saving of 52 percent was achieved. This energy conservation in lighting was remarkably robust across all test cases due to the configuration of the control strategies used, regardless of adjustments in glazing, orientation, and shading equipment [43].

Day-light-quality strategies take effective advantage of natural daylight supply and operate only a minimal amount of artificial illumination to meet the necessary level of lighting. The two primary techniques for regulating illumination in daytime areas are daylight switching and daylight dimming. Gradual lighting regulation will save 30–40 percent of electricity. The saving can be even more so with the on/off light control [44].

Daylight distribution and solar energy harvesting are two important construction strategies for mitigating energy usage in buildings. Effective daylight increases the amount of usable natural light in a room and compensates for the need for electrical lighting. This text mentions the architecture and the experimental demonstration of the LFPL method. Daylight redirection is accomplished by the geometry of the prismatic louver and accurate orientation, while energy harvesting is accomplished inside the prisms through IR absorption from the liquid (e.g., water). Daylighting efficiency was assessed at key space locations by illuminance measurements. The experiments show that in two separate systems, effective redirection can be accomplished. First, with all prismatic louver components in a fixed orientation, distributed light redirection is performed. In this case, at the prismatic louver orientation of 20°, daylight redirection efficiency toward the ceiling is increased 8 times. Second, by allowing various rotations of the individual prismatic louver modules, a selective dynamic redirection of the incoming solar radiation is achieved, leading to a rise of 100 to 200 times of the concentrated daylight redirection on a single ceiling area relative to the situation where no LFPL is used [45].

An LFPL that can harness daylight and heat energy with the ability to give improved degrees of natural lighting to office spaces. Daylight harvesting is one major energy con-

servation technique. For the purpose of providing natural illumination and to potentially balance electrical lighting, daylighting is the regulated entry of natural light into a building. This paper focuses on the daylight benefits of the LFPL facade approach and shows that not only can we obtain significant daylight penetration of solar radiation deeper into the office space with a reasonable range of prism louver orientation, but also lighting uniformity and potentially mitigate glare effects [46].

Parametric architecture can be used to improve construction quality by integrating and arranging design elements. In this research, daylight within the building has been improved by creating a kinetic shading system with different units that react parametrically to sunlight by 3D rotation (around the center of the units) and 2D motion (around the surface of the shading system). Various patterns have been determined to construct a basic model of system to enable the designer to make a wide range of choices. Their rotation was parametrically governed by the direction of the sun and the weather to provide constant, balanced sunlight inside the house. A simulated room and the geometry of the shading method have been built in the parametric modeling environment. Various parameters such as length, width and height of the room, the height of the upper window and the top of the window, and the dimensions of the shader units were used to calculate the effects depending on the position of the sun and the pattern of the units. Models for daylight simulation were provided on the basis of the parametric design of the shading system. A daylight simulation engine measured the UDI. In terms of the changes in UDI, the experiment was reviewed, and important improvements were found. The suggested shading scheme has shown many benefits, including the potential to maximize visibility within the room and enhance the efficiency and uniformity of daylight. The environment (diffused) light was maximized in this system and the probability of glare was minimized [47].

In this paper, light sensors and temperature sensors with solar energy harvesting and wireless connectivity capabilities have been developed. The Hybrid sensors are designed by combining printed sensing elements with EnOcean technology that delivers solar power harvesting and remote monitoring functions. The Light sensing and temperature sensing components have been printed on lightweight PET films using organic photosensitive materials and particle-filled polymer inks. The resulting hybrid sensors have been tested and shown to meet the design requirements. Light sensors have been mounted in a full-scale office test bed to show effective light management [48].

The study was conducted on the first zero energy building in Southeast Asia. It was redesigned from an existing building and comprised of passive and active construction techniques for sunny tropical weather. It was found that efficient lighting and air conditioning systems were the most successful among the active strategies. Controls were found to be most efficient among the passive technique of lighting pies and lighting. Passive tactics were considered to have a happier life and payback. It was concluded that active and passive techniques must be integrated into the architecture of buildings for increased energy efficiency. Specifically, passive architecture must be integrated as they have substantial energy enhancements [49].

The lighting of a setting has a significant impact on the working of the office workers, but the psychological variables relevant to the office setting in the process of lighting commissioning is lacking. The research examined how many workers employed in a recently renovated building felt that they could monitor the current lighting system and their perceived efficiency levels and an affective organizational contribution to explore the association between the variables and the level of satisfaction with the lighting commission process. The satisfaction with the commissioning process did not correspond with the perceived efficiency, controllability, affective organizational engagement, or the number of working hours on average after the refurbishment. Perceived efficiency strongly correlated with controllability and affective organizational commitment, both of which were associated with the perceived number of productive hours of work. The findings have also demonstrated that lighting controllability plays an important role in enhancing workers' perceived efficiency and job satisfaction [50].

More and more effort is being made to minimize building energy and increase occupant comfort daylight. The downside to this is that daylight can also cause thermal and visual discomfort. Hence, The Vertical Greening Device can be used on the outside of the building exterior and can be used to monitor the amount of light inside buildings. Plant surfaces can reflect and diffuse direct light. To verify the three typically used VGS vines were selected and their effect on the quantity and efficiency of daylight was investigated. Lighting parameters, such as illumination, refraction, discomfort, and light color temperature, were calculated and analyzed. The results showed that the glare of discomfort was reduced with the aid of the vines and also depends on the location of the sun, such as the altitude and azimuth angles, at various climatic conditions [51].

Most office lighting systems are fitted with occupancy sensors to reduce energy consumption. Since these sensors have limited reliability in the presence of detectors, very conservative strategies are typically used. In this paper, we suggest a novel lighting control method for an office that considers the performance of the sensor to be a noisy observation of the actual occupancy status. Instead of either flipping the light on or turning the light off the device dims the light in the office according to the likelihood of occupancy earned. According to this occupancy likelihood, the device optimizes the degree of lighting in the office to minimize energy consumption. Simulation results show that it saves more energy compared to the traditional "on/off" approach [52].

A sustainable lighting system in a building can easily be accomplished by feeding lighting loads to any renewable energy generation system, but the reduction of the full payback period depends in the performance of the lighting system. The goal is to decrease the lighting load to such a small amount that the payback period is limited and the building can use free of charge lighting. This research paper documents a range of initiatives that can minimize the demand for lighting in a university building and describe the implementation of these measures on the building site. In conclusion, the payback time of the planned efficient lighting system implementation is estimated to explain the need for an energy-efficient lighting system in buildings [53].

Smart room lighting is achieved using external fenestration and central and dispersed light sensors. The proposed dispersed light illumination system had an improved efficiency of 28% relative to the proposed central light illumination system. The level of illumination of the indoor atmosphere is calculated using light sensors and this electrical input from the sensors is translated to information on illumination. This light information can be calculated using a centrally placed sensor or several sensors in a dispersed fashion. This value is compared to the ideal reference value of the illumination and thus the illumination degree of the LED luminaires can be increased or decreased to obtain the desired illumination value [54].

The key purpose of the paper is to explore the effects of various design options on electric lighting energy needs and to determine the impact of energy demand for electric lighting on global energy efficiency. A simulation is conducted to explain how the supply of sunshine and the consequent energy requirement for illumination, heating and cooling differ as the design features of the building/room vary. As a case study, a single room was used and research was done by modifying its location, orientation, etc. The architecture approach for daylight optimization has proven to have a major effect on the global demand for electricity in a vacuum. Increasing the amount of daylight results in a decrease in global demand for primary energy, especially in the presence of a sensitive dimming device for daylight [16].

Daylight can be added to lighting systems in buildings to minimize energy consumption. The goal of this research is to study the effect of daylight illumination on each cycle. The illumination is measured with the daylight function of the DIALux software. The fluorescent T5 tube lamp is used for simulation. The case study room without daylight is contrasted with the case study room with the daylight of each time span. The outcome of the simulation showed that the daylight could increase the average illumination of the work plane, but uniformity is difficult to maintain. To improve uniformity, the artificial

light dimming capability must be implemented to monitor the illumination of the work plane at the desired value [55].

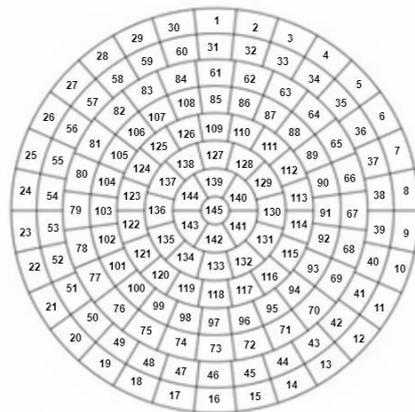
The purpose of [56] is to determine the amount of POF required to achieve optimum indoor illumination by light transport and to explore the benefit of two-dimensional solar tracking and light concentration in indoor light enhancement. A dual-axis solar tracker-based microcontroller was developed to measure sunlight at the POF collector node every 10 s. The purpose of this paper is to decide the amount of optical fiber needed for daylight transport in order to achieve comfortable indoor lighting. The optimum amount of POF necessary for the sample space was determined by the size of the room, the location and area of the current window, the height of the ceiling and the glazing material at the window. The payback time was calculated for the study room and was judged to be within a promising range of 5.07 years. This promising technology, for further growth it is important to address the basic challenge of reducing the price of low-grade POF using dedicated supply and large-scale development because the cost of the available POF is the major part of the investment in these daylight retrofits.

### 3. Daylight Prediction

Daylight prediction is the process of estimating daylight metrics well advanced in times that these parameters can be used by lighting controllers to use maximum daylight illuminance and in turn reduce energy consumption. Daylight prediction data is used to control shading devices, lighting control systems which provide the user to experience an even illuminance. Daylight Harvesting is made less complex and effective by using daylight prediction techniques. Since daylight is non-linear, various prediction models are used such as time series prediction, nntool, nftool, and neural networks to achieve the most efficient and perfect prediction method to perform daylight harvesting and to obtain ideal visual comfort [57–61]. To add upon it, prominent energy forecasting models especially used for predicting solar radiation can be extended for forecasting the daylight availability. A detailed review on the available various energy forecasting models using big data and deep learning models is presented in [62].

Dynamic daylight simulations are frequently used to aid daylight prediction models. It is very difficult to predict daylight metrics at a particular time corresponding to weather conditions and occupancy levels at a target location. For this purpose, dynamic daylight metrics and dynamic daylight simulations are used in [59].

Another popular simulation method for predicting daylight is APPSM [60]. APPSM is used to predict sensor signals for controlling the lighting fixture under dynamic daylight conditions. In [60] along with the theoretical foundation of APPSM, validation of results from APPSM was also performed to validate the accuracy of the prediction results. Prediction results from APPSM were validated using PDENS program results. APPSM algorithm works by the principle of daylight coefficient principle and hence it assumes the illumination from sun and illumination from the sky as separate light sources. APPSM algorithm uses daylight coefficient values of 145 sky patches for evaluating the illuminance contributions from patches to the target including interreflections. The 145 sky patches structure is shown in Figure 9 [60]. The association between the luminance of the sky patch and the intensity at the target point is called the daylight coefficient. To gain better precision when calculating daylight, daylight illumination is subdivided into direct component and reflected component. Rtrace—a radiance tool is used to compute direct illumination from the sun. The reflected illuminance component is calculated using the daylight coefficient data that has been predicted using 145 sky patches which were used to calculate illuminance contribution from the sky [60]. Radiance and Energy Plus software is the most efficient and reliable software used in daylight simulations to predict daylighting and energy usage. A simulation-based lighting model is proposed in [61], which uses prediction methods to speedup computation.



**Figure 9.** 145 Sky Patches Structure.

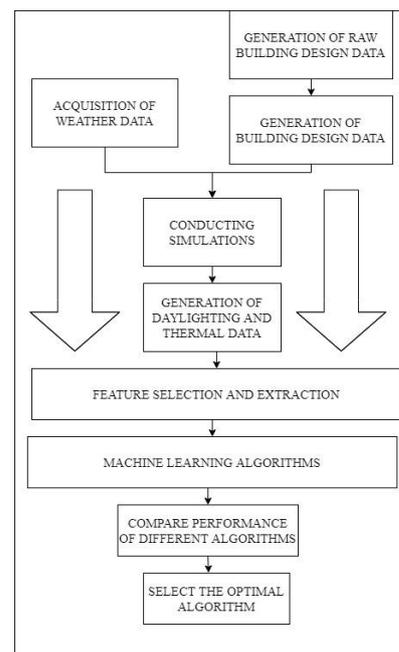
The three-phase method from Radiance software was used for daylighting simulations since it employs BSDF algorithms to avoid complexity and hence it speeds up simulation time. These predicted values are then fed to respective control systems for the desired use of daylight [61].

Three machine learning algorithms are evaluated in [63], which are PCA, ANN and SVM. The Overall structure of prediction followed by the algorithms is shown in Figure 10. Input needed by machine learning algorithms such as weather data, building design data, and window configurations is given by the data generation programs such as Python and MATLAB. The algorithm then predicts the hourly daylight levels at several sensor points and also estimates the hourly energy consumption. UDI is used as a daylighting metric in [63]. The algorithm classifies the daylighting level values into different UDI values and also estimates the energy consumption. When prediction results from PCA, ANN, and SVM are compared with real-time data, it can be observed that the prediction data generated by PCA has the highest accuracy when compared with others. An algorithm cannot be run using all of the parameters because it will slow down the algorithm's performance and make it difficult to visualize so many features in any graph. As a result, the number of parameters provided to the algorithm as input must be limited. It is difficult, frustrating, and time-consuming to manually find correlation in thousands of parameters. This is something PCA excels at. All of the Principal Components are independent of one another after applying the PCA. There is no link among them. With limited parameters, the training time of the algorithms is greatly reduced. Values predicted by PCA can be further used by lighting control, blind controls to obtain the desired illumination [63].

Similarly, Ref. [64] employs ANN for daylight prediction. In prediction models, to estimate interior illumination due to daylight, the illuminance of daylight incident on the exterior of the window must be estimated. Ref. [65] proposes an efficient daylight prediction model that combines the Perez Model to estimate exterior illuminance and uses the ANN model to predict interior illumination. This prediction model with ANN provides fast, accurate, and reliable values of illuminance.

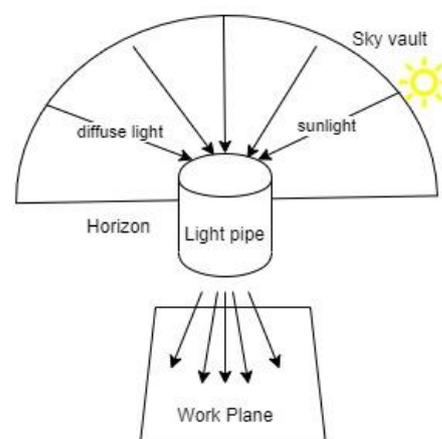
The Kriging method is frequently used for various prediction and interpolation problems [66] uses the kriging method coupled with energy simulation tools to predict daylight conditions. This system when combined with an energy simulator can plot hourly indoor light illuminance.

BSDFs are used in modeling and predicting daylight scattering by considering building window parameters, but BSDFs are very expensive and are not often reliable. Hence ref. [66] proposes an analytical BSDF model that predicts daylight design metrics based on climatic change. This system is efficient and accurate which is based on the empirical BRDF. The devised BSDF model is inexpensive and can model common fenestration devices such as shades and blinds. They are very effective while predicting daylight metrics at the design stage. This analytical model can be easily integrated into ray-tracing programs such as Radiance which can further be used to predict daylight due to direct radiation [66].



**Figure 10.** Prediction Algorithm.

The problem and the only practical way to gain deep insight into complex shifts of the cloud is by computational simulation [67]. Hence ref. [67] developed a model using the UniSky simulator and HOLIGILM tool, which provides accurate predictions of fundamental variations of light guide behavior under homogeneous and non-homogeneous cloud conditions. Natural light can be delivered into a light guide system. One such light guide system is a light pipe since it does not require any additional energy sources and does not have a negative effect on the natural environment. The structure of a light pipe is shown in Figure 11. Though several daylight prediction methods are invented, it is very challenging to accurately predict the performance of lighting control under dynamic meteorological conditions since existing methods do not account for random configurations of clouds and its high changing frequency [67] treats the light field below the tubular light pipe theoretically and numerically by taking nonhomogeneous sky patterns into account. This numerical assumption is used as input in UniSky and HOLIGILM to predict daylight conditions in the building which has light guide systems [67].



**Figure 11.** Structure of Light Pipe.

Light transported through internal reflections via the guidance mechanism is deliberately or accidentally spread in both directions, depending on the optical properties of

the output unit. Ideally, increasing the flux density if the luminous energy that escapes the base of the light tube results in the best possible indoor illumination [68].

The lack of data to represent the energy consumption of buildings in underdeveloped countries makes it hard to decide on the intervention methodology for the existing building stock. This difficulty was tried to overcome using a 6-step process to examine and identify a methodology for the energy-saving ability of the existing building architecture. The six steps include a process to define a reference building, dynamic archetype model simulations, a baseline estimation of the energy consumption, selection of measures for the energy retrofit, an analysis of the optimal cost, development of scenarios for energy saving and the estimation of the building stock energy-saving potential. The energy-saving scenario projection demonstrated the urgency of dealing with the high-rise offices at present and that policymakers should be more observant of new buildings to reduce energy consumption [69].

An HDR image processing algorithm is employed in [70] for capturing and predicting real-time sky conditions for controlling input signals to a building's AF system, DH, and HVAC system.

The performance of three non-linear prediction models as performed in [59] are examined in [71]. NLARX, TDNN, and ANFIS are the three non-linear models that are used in daylight prediction that are evaluated in [71]. These three models use online interior and exterior measurements to predict daylight illumination. They are evaluated using the RLS adaptive algorithm, which identifies the error between the actual system parameters and results from the predictive algorithm. Initial values of interior and exterior illumination are fed into the system as input and then the models predict the illumination values  $p$  steps ahead. The exterior and interior illuminance are expressed as  $E_{ext}$  and  $E_{int}$  respectively. (3) and (4) are used to predict illuminance values ' $p$ ' steps ahead [71].

$$E(k + p) = f_0(E(k)) \quad (3)$$

$$E(k + p) = f_0[E(k), E(k - \tau), E(k - \tau), E(k - 2\tau), \dots, E(k - (d - 1)\tau)] \quad (4)$$

The results from predictive algorithms are then verified using RLS to check which one has the least error [71].

Most of the daylight prediction models use photometric sensors to predict daylight metrics, but ref. [72] introduces a daylight prediction system through theoretical discussion followed by empirical analysis, which is a sensor-less model that employs mathematical equations to predict daylight illumination. This is done by using an exponential distribution that uses lux reading from a weather station to predict the daylight at a given target location in a building. This model allows us to estimate the dimming level required to achieve the desired illumination that uses both daylight and artificial light. For a sensor-less daylighting system, a smart lighting control system, lighting simulation software, numerical evaluation software, and a rooftop weather station to predict daylight conditions are required. To effectively maintain the lighting levels the lighting parameters are divided into external and internal variables. External variables are the daylight metric that will be predicted by the weather station and the internal variables concern the target environment design and hence they are considered to be constant. The ratio of internal lux intensity to external lux intensity is known as the DF [72].

$$DF = (\text{Internal Illuminance}/\text{external illuminance}) \times 100\% \quad (5)$$

The variables affecting daylight penetration into the building are unattended which brings complexity while using DF. Hence a relationship between external illuminance and internal illuminance at a particular target point is used as a scalar factor which depends on decaying luminance intensity known as SF is used and this varies with varying distance from the window [72].

$$SF = (\text{External LUX Value}/\text{Internal LUX Value}) \quad (6)$$

Presently, hot desert countries are adopting policies that ignore their climate change dependent on fully glazed constructions. This results in low productivity and identity crises in construction. Any effort, therefore, seeks to minimize excess sun exposure and make available effective sunlight. The results from the observations and studies suggest that Passive bio-climatic vernacular architecture approaches and daylight strategies by incorporating smart materials can achieve clean energy, thermal/visual comfort, and daylight design objectives [73].

Daylight simulation for a real space using TMY data and active local weather data with a one-minute interval was performed in [74]. In this research TMY data was used to foresee the quality of daylight, develop a daylight-responsive closed-loop lighting control system, to select calibration hours, and to predict the efficiency of the control system. Whereas, the active local weather data was used to determine daylight quality. The purpose of this analysis was to investigate whether the traditional weather data (i.e., the TMY data) allowed reliable daylight quality and daylight-responsive performance control system predictions. A real space model equipped with four different types of fenestration systems such as clear glazing, 0 degree and + and -45 degree venetian blinds and three different daylight simulation methods such as daylight coefficient, three-phase and five-phase methods were used for comparison in this research. It was observed that the expected energy saving based on the TMY data was accurate when the calibration was carried out in environmental conditions close to those defined based on the TMY data. Conversely, calibration under inappropriate environmental conditions has been shown to result in lower energy savings.

#### 4. Influence of Building Geometric in Daylight Harvesting

In recent years, the advantages of using daylight and the plans of many buildings taking daylight into account have increased exponentially. The architectural influence makes daylight a vital aspect of the construction process. The incorporation of daylight in architecture, by using design methods, results in better daylight and thus reduces visual discomfort. The key goal is to replace electric light fixtures with natural daylight and to reduce the expense of electric charge. Hence apart from lighting control modules, building design can also be used to achieve the desired illumination using daylight [75,76].

The architecture and orientation of model buildings for the different climatic zones of India is analyzed in [75]. The target building is modeled using the Ecotect daylighting tool and simulated with the help of Radiance Beta V2.0. [75] focuses on the study of interior lighting due to daylight availability in traditional low-rise buildings under various climatic conditions. Daylight availability analysis aids in perfect designing and will also help to minimize artificial lighting sources.

As the model building is considered to be in India, climate variables such as solar radiation, ambient air temperature, air humidity, wind speed, forecast, etc. have been taken from the Bureau of Indian Standards. To evaluate different climatic conditions, the model building is simulated to be in different cities with varying climatic zones.

Equinox is a phenomenon in which the earth's equator crosses through the center of the sky, making day and night more or less the same with respect to length. Equinox takes place every year in India on 21st March and 21st September, daylight analysis on equinox days is performed for the cities considered. The area with daylight illumination and the area illuminated artificially differ from dusk to dawn, so equinox is used because it has equal periods of day and night so that we can achieve the average value of the illumination effects. The area covered by the selected level of luminous intensity is separated from the simulation and therefore the average area of illumination is estimated. Results from [75] show that the area illuminated by daylight of the model building is maximum when the building is located in a temperate and least in a composite climate environment [75]. VELUX is also like the Radiance Building Simulator used to design building models so that they can be validated for obtaining maximum daylight illumination. This is used to test construction models for estimating daylight metrics such as daylight impact and

light distribution. The daylight factor is known as the ratio of indoor lighting and outdoor lighting and is typically written in percentage form [76].

In [76] daylight impact and light distribution relating to various space conditions and window settings were examined. Daylight can be used well because it falls on the windows every day. Several criteria are weighed such as construction, the height of the door, sky views, reflectance from the ground, and interior design, to achieve viability for each portion of a room. Usually, credits for daylighting are given in various iterations of the LEED (Leadership in Energy and Environmental Design) rating systems and are given in correspondence to room architecture. This credit system determines the criteria and their application to satisfy basic specifications. A building architecture strategy should improve the ability to achieve the required credit criteria. For example, windows placed at or over 30 inches above the floor level should satisfy the following requirements [76]:

$$0.150 < VLT * WFR < 0.180 \quad (7)$$

From Simulation performed using VELUX in [76], it is obvious that the configuration of the window influences the distribution of daylight in the house. The daylight factor increases when window size increases. Simulations were also performed for analyzing the perfect window type among punched, strip, and full windows. The tests performed show that the penetration range of daylight is greater in the case of strip windows relative to the punched ones. It is also noted that strip windows achieve uniform daylight in the room [76].

A parametric study of the impact of independent variables on dependent variables with the help of computer simulations using RELUX software is performed in [77]. This scientific study analyzes the impact of various architectural elements such as reflectivity of surface materials, the geometry of space, internal layouts, dimension, and position of the windows as independent variables on the dependent variables such as uniformity rate, daylight factor. Several configurations were simulated using Relux software to understand the role and influence of architectural elements in a study space for a better and more balanced distribution of natural light. The results have been summarized as follows:

- Windows with a maximum height to width ratio of 35 to 45% with the preferable ratio of 40% can decrease the electrical energy consumption by 32% with horizontal and vertical divisions. It also improves visual comfort by 7.5%.
- The optimal length to width and height ratios are 6.5 and 5.2 respectively, which reduces the electrical consumption by 34%.
- In terms of inner surface layout, using horizontal and vertical surfaces with two front windows along the length of the building provides a better uniformity rate in lighting [77].

A similar study was performed in [78] using DIVA software to research the impacts of various rooms and window geometrics on daylight harvesting. Two classrooms were simulated, a square and a rectangular classroom of the same total space and they have a square and a rectangular window with 8% and 12% WFR, respectively. The rooms have two separate dimmable lighting schemes, fluorescent and LED dimmable lights, to measure energy savings. The measurement of daylight is carried out by the assessment of Daylight factor (DF) and Daylight autonomy (DA). The results from the DIVA simulator have been summarized as follows:

- At constant WFR, a rectangular room achieves better energy performance with a rectangular window. Similarly, for a square room, the best performance are provided when equipped with a square window.
- DA ratios do not show any noticeable differences once the orientation and WFRs are fixed.
- The best energy result is obtained when a combination of a rectangular room with a rectangular south-oriented window, with 12% WFR [78].

To find an easy and objective way of daylight harvesting, performed a daylight simulation to acquire basic data about factors affecting daylight harvesting. A simple simulation model has been developed and was assumed to be in Tokyo with the following dimensions: 39.8 m wide, 15 m depth, and 2.8 m high, and it was assumed that the modeled layout office was fitted with daylight harvesting systems using ceiling sensors. Different combinations of Window-to-wall ratio, window orientation, no of windows, Venetian blind position, and depth of space were used to study for daylighting simulation. The simulation was performed in Radiance using the ideal annual daylight data, which combined annual solar light and skylight distribution per 1 h in the Tokyo metropolitan area. It is evident from the simulation findings that there is a strong link between window-to-floor ratio and annual energy consumption of artificial lighting and it is independent of space form and window orientation.

Approximately 10% of electricity can be reduced when the window-to-floor ratio is 10% and consumption can be reduced by 20% when the aperture ratio is 20%. It was also observed that the conservation benefits of daylight harvesting improved by a factor of 2 when automated monitoring of the Venetian blind system was used. Hence it is clear that the Window-to-Floor ratio is one of the easy and objective ways to assess the energy-saving effect of daylight harvesting [79].

The Atrium is an important and efficient architecture used for using maximum daylight. Daylight use using an Atrium is one among the easiest ways to boost energy quality and indoor atmosphere.

The design of an atrium can be defined using a parameter known as the plant aspect ratio (PAR). PAR is the ratio of the width and the length of the atrium [80], which determines the elongation of the atrium as expressed in (8).

$$\text{PAR} = (\text{Width}/\text{Length}) \quad (8)$$

To figure out the correct configuration of the atrium's PAR, various models of atrium width and length were studied in [80]. The models were simulated using Radiance and values of Average Daylight Factor (ADF) were also estimated for each model. The study indicates that the expansion of the atrium's length would allow for more sunshine in offline spaces with the optimum mode of PAR as 1/3. The findings further show that the increased height of clerestory windows will increase the amount of ADF in the atrium and adjacent spaces [80].

Numerous studies established that students' and a teacher's capability to teach, learn and their general health are heavily dependent on the standard and quantity of daylight and indoor thermal conditions. The main purpose of using daylight in schools is to minimize energy usage and costs, but also to enhance student efficiency. An appropriate window configuration increases comfort by reducing glare, spreading light, and regulating the solar energy gain. This investigation's focal point is on the effect of various transparency ratios and window designs in two vital directions (west and east) on the comfort of the occupants and the energy requirements of the classroom. A structure was chosen for an investigation at the design stage. One classroom facing the east direction and another facing the west direction have been studied. The two classrooms were simulated using the lighting and energy simulation programs DIALuxEvo 6.0, DesignBuilder 5.5 and EnergyPlus 8.9. The study aimed on the stage of architectural design and is therefore dependent completely on simulating a model virtually and other required calculations. The main goal was creating a design in which daylight would complement artificial light when it was not enough. A total of three different models, based on different transparency ratios, are developed to describe the effect on the indoor conditions of classrooms. Based on the study of comparable buildings, the window height was fixed at 1.70 m and the sill height was set at 0.90 m in both versions. A 50% glazing ratio was found to minimize the need for artificial lighting by at least 15 per cent and provide more comfortable conditions [81].

The effect of the extended metal mesh on the building of energy consumption and natural daylight is also discussed. Parameters including WWR, perforation rate, and

window glass glazing were examined and the daylight standard of the LEED rating system was used for evaluating. In this analysis, three variables were widely used in building facade design to address the effect of lighting and air conditioning on energy consumption. From the lighting simulations, it can be concluded that only three scenarios were compatible with the LEED daylight standard and S16, consisting of 50 per cent WWR, laminated transparent glass and extended metal mesh at 21% perforation, showed the highest energy efficiency. It has been found that WWR plays a key role in affecting the quantity of daylight entering the house. As a result, higher the WWR, more is the energy-saving capacity of extended metal mesh and glazing [82].

The adjustable window awning shelf contains a canopy connected on both sides of the window to a support. The supports are attached to vertical drive screws allowing for the capability of pushing the canopy up and down. Each drive screw is connected to a standard driveshaft. During the time of the year during which cooling is required, the canopy is spread out above the window, shielding the window from the light. During the time of the year when heating is required, the canopy is placed at the bottom of the windows by rotating the supports with the canopy down. The canopy angle relatively increases with the window angles. When in the lower position, the awning reflects the sunlight falling on the window and increases the quantity of sunlight and solar heat entering the building through the window [83].

This research investigated the nature and daylight efficiency of a new Louver screen for office buildings. A Louver device capable of providing sunshine and thermal control efficiency as a part of an environmental façade strategy for office buildings was aimed to designed. The Louver screen was assessed for three distinct material finishes such as conventional materials commonly used in louvers and two other types of materials with ceramic finishes with an effort to decrease the system's environmental impact. Annual efficiency simulations for the full-scale room, using Daysim software lighting tools, were performed to gauge the impact of the three material systems on indoor daylight levels and distributions using both the standard daylight factor and Daysim climate-based daylight metrics. The key purpose was to examine the possible lighting efficiency of the louver device by investigating the various geometrics in the louver profile. This paper states that daylighting systems can be classified based on three main features:

- Daylighting function—light distribution performance, visual comfort, and solar gains control.
- Building integration—interior, exterior, envelope of the building.
- Type of operation—passive or active.

Each type has various features that need to be taken into account while constructing the louver scheme. According to observation, a louver with a specular surface has been shown to be a daylighting device capable of achieving optimum daylight efficiency, particularly under a radiant sky with sunlight. The results indicate that louver with traditional material can provide an acceptable degree of daylight and visual needs inside the room, whereas ceramics tend to be a viable substitute medium to be used in the development of advanced daylight technologies [84]. The need to use natural and green energy sources to power buildings has brought growing attention to daylighting issues over the last few decades. The daylighting architecture in ancient Romania was examined for this purpose. The work was split into two sections: a typological study of Roman houses, aimed at explaining the relation between the parameters for ancient architecture and daylight harvesting and a dynamic simulation of the daylight conditions. Ancient architects were very concerned with daylighting, experimenting with design methods, mostly very basic, but successful in providing useful light conditions for everyday indoor activities. The appearance of the building form and facades was strictly related to both the outside environment and the activities carried out inside. This correlation between the building environment and the atmosphere helped to determine a particular culture of architecture and therefore a prudent use of daylight. To explain simulation results such as the CDI, the corresponding minimum CDImin, and sCDI, a new set of performance metrics was created. The CDI at

the point is the maximum task illuminance of the collection for which a daylight autonomy equal to at least 50 percent is measured, provided a point and set of task illuminance values (e.g., those suggested by the standards). Then, given a CDI, the proportion of the floor area characterized by this very CDI value is the corresponding sCDI. For example, in a room where sCDI 300 lx is equal to 50 percent and sCDI 500 lx is equal to 50 percent for 50 percent of the year, the daylight guarantees an illuminance value equal to 500 lx in half of the room alone, while a 300 lx illuminance is guaranteed in the remaining part of the room. Lastly, the minimum CDI is the minimum CDI value observed in the area, i.e., the value for which an autonomy of at least 50 per cent of daylight is observed in the entire room. The results seem to indicate that there was a strong relationship between the levels of indoor sunlight and the operation of the rooms. The more sunlight a room earned, the more impressive its function was [85].

Lighting strategies can be applied to create environments which are friendlier to the occupants and reduce the interventions in lighting conditions. An IVR environment can be used to test the design system quick and easy. The rated contrast on the window wall as well as the negative lighting interventions in an IVR office room with different window-to-exterior-wall ratios can be increased by increasing the illuminance of the areas around the window and the electric wall-washing system. In relation to other lighting conditions, the greater lighting contrast between the window and the surroundings was found to be 15 percent WEWR. The suggested low-power electric wall-washing device will decrease the possibility of the consumer interfering in a room with different size windows with the lighting conditions [86].

The human biological clock is mainly synchronized by the perceived light, specifically the short-wavelength daylight rays, also known as the circadian rhythm. Human health and well-being may be threatened by inadequate access to daylight or comparable electrical lighting. The results of circadian stimulus autonomy, i.e., the percentage of days during the year when CS is above the minimum threshold in conventional classroom designs, are seen in this study. It is quantified by circadian stimuli, facilitated either by natural or electrical illumination. Under three standard sky conditions, the location studied has a window of variable length, direction, and orientation, as well as different reflectance values of the classroom's inner surfaces. The goal of this study is a first approach to the determination of the appropriate window size for multi-purpose educational building classrooms, in order to promote the correct CS value for students and to provide a well-trained circadian system, as well as to evaluate the effect of electric lighting on their biological clock. Taking into account the different daylight SPDs and the variable luminance of the sky vault, measurements were made for three positions. The classroom studied had a variable window size with two primary orientations and a variable reflectance of the interior surfaces. The following results were obtained:

For different conditions and variables, such as the frame size, the reflectance of the inside surfaces and the observed working plane, as well as the color temperature of the ceiling luminaires, the CS may be quantified. In the case of a light blue work plane, cool LED lamps with a CCT of 6500 K allowed up to 5 percent more CS than warm luminaires, 19 percent more compared with the results for a white work desk and 81 percent more than the light wood environment scenario. Window orientation also affects this metric's measurements, but its impact and lintel height are not as important when the reflectance of the classroom's inner surfaces and the observed atmosphere is sufficiently high [87].

##### **5. Light Pipe Efficiency and Life Cycle Cost for Daylight Harvesting Systems**

The light pipe is studied elaborately to understand its efficiency and internal illuminance distribution. For the same objectives, extensive experiments are performed for a continuous eight months considering three cloud conditions, namely clear, cloudy, and intermediate [88]. It was found that the daylight penetration factor remained almost constant during cloudy days and varies significantly during clear days. A study suggested to avoid excessive aspect ratio and many bends to obtain effective daylighting devices

with light pipes. Also, larger diameter light pipe should be utilized whenever possible [89]. The prismatic diffusers are compared extensively with the radial diffusers for internal illuminance distribution parameter. It is observed that prismatic diffuser absorbs light with uniform light distribution just below the pipe, whereas the radial diffuser provides higher light under the pipe and absorbs light away from pipe for working plane that are placed 700 mm below the pipe [90]. The performance of top lighting and side lighting light pipes are studied in and it was observed that the side lightning light pipes had better illumination characteristics in morning while top lightning light pipes performs better in afternoon under sunny conditions of Beijing [91].

The cost of implementation of daylight harvesting scheme is another important aspect of daylight harvesting. Two different lighting schemes were compared wherein one scheme involves Fluorescent luminaires without daylight harvesting and other one involves LED fixtures with daylight harvesting combined with occupancy and daylight dimming sensors. A simple replacement of fluorescent lamps with LED light fixtures itself led to savings of about 22% in the Life Cycle Energy Cost. Moreover, LED fixtures have added advantages like higher lamp life and the ability to add features like occupancy control. Furthermore, when the LED fixture was combined with daylight harvesting and occupancy and daylight dimming sensors, the Life Cycle Energy Cost is reduced by 33% of what can be achieved by using only fluorescent luminaires [92]. In another study, the life cycle cost analysis for manual, interior and exterior automated lighting system was performed. It was found that the manual blinds cost the least and the exterior automated system was the most expensive one. This was probably due to the required equipment and the complexity of installation controls for the exterior system [93]. Hence, daylight harvesting systems have proven to be cheaper and more environmentally friendly in the long run.

## 6. Case Study of Daylight Harvesting in Urban India

To simulate the actual daylight contribution for any building before construction, ECO TECH software is used by providing the inputs such as building orientation, reflectance's values of the ceiling, wall, floor to analyze the overall percentage of daylight penetration available verses the percentage prescribed in the IGBC to obtain the credit points. To simulate the actual daylight contribution for any building before construction, ECO TECH software is used by providing the inputs such as building orientation, reflectance's values of the ceiling, wall, floor to analyze the overall percentage of daylight penetration available verses the percentage prescribed in the IGBC to obtain the credit points.

Hence if the overall percentage of daylight penetration is between 50 to 75% then the building is eligible for one credit point (total of one point), further, if the percentage is between 75 to 95% then it is eligible for additional one credit point (total of two points) and in some case if the percentage is more than 95% then it is eligible for an additional two credit points (total of three points). Refer below IGBC extracts related to daylight harvesting credit points.

In this paper, the Daylight Analysis is employed on a proposed multi-story office building in urban India. The specific objective of this study is to evaluate the daylight quality as per the requirement of IGBC Green NB: SA Credit 03—"Passive Architecture" & IEQ Credit 02—"Daylighting".

Requirement as per IGBC Green New Buildings (Version 3.0):

- SA Credit 03—Passive Architecture.
- Option 2: Prescriptive Approach-Daylighting: 50% of the regularly occupied spaces with daylight illuminance levels for a minimum of 110 Lux (and a maximum of 2200 Lux) in a clear sky condition on 21st September at noon, at working plane (through simulation or measurement approach).
- IEQ Credit 02—Daylighting.
- Option 1: Simulation Approach-75% of the regularly occupied spaces with daylight illuminance levels for a minimum of 110 Lux (and a maximum of 2200 Lux) in a clear sky condition on 21st September at noon, at working plane. With the given

information from architectural drawing and considering actual materials and clear sky conditions of Chennai, the modeling and simulations are carried out in the Design Builder software tool. Daylight analysis was performed for the IGBC recommended living/regularly occupied spaces.

With the given information from architectural drawing and considering actual materials and clear sky conditions of Chennai, the modeling and simulations are carried out in the Design Builder software tool. Daylight analysis was performed for the IGBC recommended living/regularly occupied spaces.

The following specifications are considered for the proposed building:

- Wall: Paints with surface reflectance of 50%.
- Floor: Floor tiles with surface reflectance of 20%.
- Ceiling: Paints with surface reflectance of 70%.
- Glazing specification are considered in Table 1.
- Figure 12 shows considered working plane height, sky conditions, and solar position for daylight simulation as per IGBC. Daylight is studied for the proposed blocks. Table 2 shows the daylight simulation result for Office Building.
- Figure 13 show considered minimum and maximum threshold limit of illuminance as per IGBC requirements.
- Figure 14 shows the LUX color indicators.

Calculation Options	
General	
Calculation Description	
Calculation Options	
Report type	1-Map
Detail template	6-High quality
Working plane height (m)	0.7500
Margin (m)	0.500
Sky	
Sky method	1-Standard sky
Sky model	2-CIE clear day
Solar position	
Month	Sep
Day	21
Hour	12
Grid	
Min Grid Size (m)	0.500
Max Grid Size (m)	1.000

Figure 12. Daylight Simulation Input Details.

Display Options	
General	
Report type	
Type	2-Grid (Radiance)
Margin	
Threshold	
Threshold type	2-Illuminance
Min illuminance (lux)	110.000
Max illuminance (lux)	2200.000

Figure 13. Illuminance Threshold Limit.

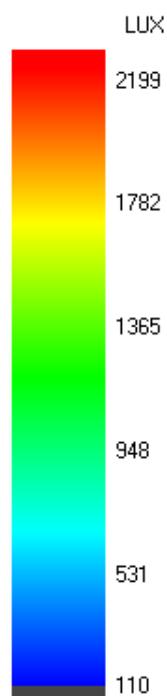


Figure 14. LUX Color Indicators.

Table 1. Glass Specifications of Business Center.

Space	Product	VLT (%)	SHGC	U Value (W/m <sup>2</sup> K)
Office Building	6 mm SKN 765 +12 mm air gap + 8 mm clear	38	0.24	1.5

Table 2. Daylight simulation results for Office building 1.

Floor Level	Regularly Occupied Area	Floor Area (m <sup>2</sup> )	Floor Area above Threshold (%)	Area with Illuminance between 110 to 2200 lux (m <sup>2</sup> )
Ground Floor	Lobby1	56.2	97.9	55.1
	Corridor1	100.5	29.0	29.2
	Entrance lobby1	169.3	100.0	169.3
	Corridor2	102.0	41.7	42.5
	Entrance lobby2	163.2	100.0	163.2
1st Floor	Office space	1536.3	100.0	1536.3
	Office space	3023.5	53.2	1608.8
	Lobby1	55.9	24.2	13.6
	Lobby2	55.8	50.0	27.9
2nd Floor	Office space	2993.2	64.4	1927.0
	Breakout area	83.4	100.0	83.4
	Corridor2	33.8	38.5	13.0
	Lobby2	55.8	100.0	55.8
	Lobby1	55.8	45.8	25.6
3rd Floor	Corridor1	31.6	25.0	7.9
	Office space	2993.2	67.5	2020.1
	Breakout area	83.4	100.0	83.4
	Corridor2	33.8	38.5	13.0
	Lobby2	55.8	100.0	55.8
4th Floor	Lobby1	55.8	47.9	26.7
	Corridor1	31.6	25.0	7.9
	Office space	2993.2	72.1	2158.1
	Breakout area	83.4	100.0	83.4
	Corridor2	33.8	38.5	13.0
4th Floor	Lobby2	55.8	100.0	55.8
	Lobby1	55.8	54.2	30.2
	Corridor1	31.6	29.2	9.2

Table 2. Cont.

Floor Level	Regularly Occupied Area	Floor Area (m <sup>2</sup> )	Floor Area above Threshold (%)	Area with Illuminance between 110 to 2200 lux (m <sup>2</sup> )
5th Floor	Office space	2993.2	76.4	2287.4
	Breakout area	83.4	100.0	83.4
	Corridor2	33.8	42.3	14.3
	Lobby2	55.8	100.0	55.8
	Lobby1	55.8	58.3	32.5
6th Floor	Corridor1	31.6	29.2	9.2
	Office space	2993.2	31.0	927.3
	Breakout area	83.4	100.0	83.4
	Corridor2	33.8	38.5	13.0
	Lobby2	55.8	100.0	55.8
7th Floor	Lobby1	55.8	58.3	32.5
	Corridor1	31.6	33.3	10.5
	Office space	2993.2	79.7	2386.8
	Breakout area	83.4	100.0	83.4
	Corridor2	33.8	46.2	15.6
8th Floor	Lobby2	55.8	100.0	55.8
	Lobby1	55.8	62.5	34.9
	Corridor1	31.6	33.3	10.5
	Office space	2993.2	81.0	2424.2
	Breakout area	83.4	100.0	83.4
9th Floor	Corridor2	33.8	50.0	16.9
	Lobby2	55.8	100.0	55.8
	Lobby1	55.8	66.7	37.2
	Corridor1	31.6	33.3	10.5
	Office space	2993.2	81.9	2451.2
10th Floor	Breakout area	83.4	100.0	83.4
	Corridor2	33.8	46.2	15.6
	Lobby2	55.8	100.0	55.8
	Lobby1	55.8	75.0	41.8
	Corridor1	31.6	33.3	10.5
11th Floor	Office space	2993.2	32.3	966.8
	Breakout area	83.4	100.0	83.4
	Corridor2	33.8	38.5	13.0
	Lobby2	55.8	100.0	55.8
	Lobby1	55.8	68.8	38.3
12th Floor	Corridor1	31.6	33.3	10.5
	Office space	2993.2	84.4	2526.9
	Breakout area	83.4	100.0	83.4
	Corridor2	33.8	50.0	16.9
	Lobby2	55.8	29.2	16.3
Total Regularly Occupied Area (m <sup>2</sup> )	Lobby1	55.8	79.2	44.2
	Corridor1	31.6	33.3	10.5
	Office space	2993.2	89.0	2664.0
	Breakout area	83.4	100.0	83.4
	Corridor2	33.8	65.4	22.1
% of Regularly occupied space achieved required daylight illuminance levels	Lobby2	55.8	33.3	18.6
	Lobby1	55.8	100.0	55.8
	Corridor1	31.6	41.7	13.2
Total Regularly Occupied Area (m <sup>2</sup> )		41,051.1	Total Area with lux between 110 to 2200 (m <sup>2</sup> )	28,515.9

Based on this, Figures 15–20 shows the daylight simulation results of proposed Office Building. In our case study, the building is simulated using ECO TECH software and from the analysis the overall percentage of day light penetration is around 69% which is between 50 and 75%. Hence this building is eligible for 1 credit point stipulated under IGBC.



Figure 15. Overall Achieved Day Light Levels (110 lux to 2200 lux) on (a) Ground Floor (b) 1st Floor.



Figure 16. Overall Achieved Day Light Levels (110 lux to 2200 lux) on (a) 2nd Floor (b) 3rd Floor.

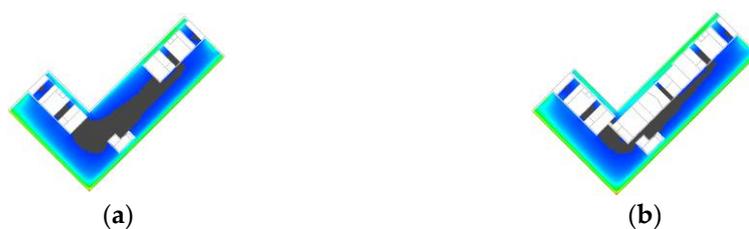


Figure 17. Overall Achieved Day Light Levels (110 lux to 2200 lux) on (a) 4th Floor (b) 5th Floor.

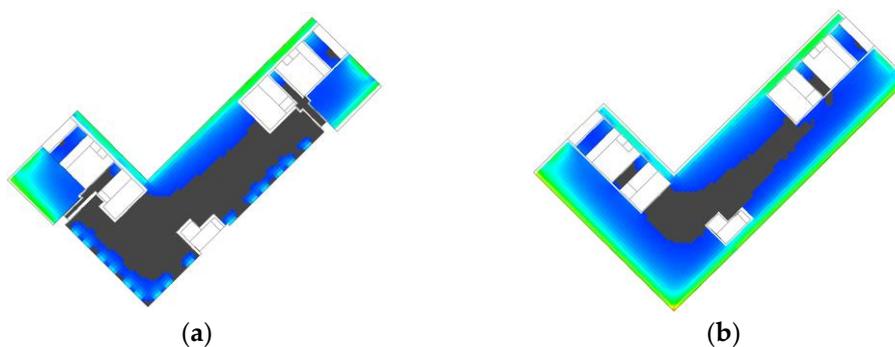
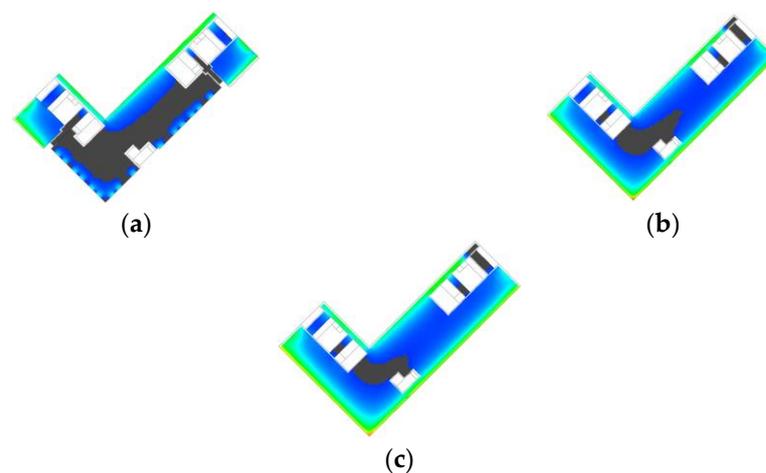


Figure 18. Overall Achieved Day Light Levels (110 lux to 2200 lux) on (a) 6th Floor (b) 7th Floor.



Figure 19. Overall Achieved Day Light Levels (110 lux to 2200 lux) on (a) 8th Floor (b) 9th Floor.



**Figure 20.** Overall Achieved Day Light Levels (110 lux to 2200 lux) on (a) 10th Floor (b) 11th Floor (c) 12th Floor.

## 7. Conclusions and Future Scope

This study presents a detailed review of all the recent technological advancements in the field of daylight harvesting. The concepts of daylight harvesting and its significance is well-established. Daylight harvesting systems and algorithms provide the next-generation solution to achieve clean energy and also facilitate tremendously in minimizing electrical consumption globally. Initially, algorithms employed for daylight harvesting such as Genetic Algorithm, Neural Network, Fuzzy logic, and PWM control for the dimming of LEDs were discussed. It was seen that user comfort and needs are also given prime importance during the process of designing these systems. It was also found that with the emergence of IoT and due to the possibility of the interconnection of daily life devices, smartphones can also be used to control the home lighting system. Various tools and methods that are recently discovered are discussed and the importance of daylight prediction is portrayed. Also, the various aspects of architecture that affect daylight harvesting are highlighted. It is found that architectural design makes a huge impact on the process of daylight harvesting. For instance, it was found that high glazing provided good lighting which could further provide good daylight harvesting. It is evident that the geometry of the window affects the daylight distribution and uniform daylighting can be achieved by using strip windows. It further talks about the impact of various architectural aspects such as WFRS, DF, PAR, and ADF, which are analyzed, and their impact on daylight harvesting was discussed. Furthermore, the daylight saving was employed on a multistoried building in urban Chennai, India and the results are very satisfactory. The results obtained comply with required daylight factor via simulation for the proposed buildings. Also, it is determined that the building achieves the IGBC Green NB recommended daylight level in more than 50% (i.e., 69%) of living spaces; hence the office building meets the criteria of sustainable architecture and design criteria Passive architecture credit: Daylighting. The building is eligible for 1 credit point stipulated under IGBC and also meets the sustainable architecture and design requirement. Using the proposed daylight harvesting scheme it is possible to realize self-sustainable buildings which is incorporated with suitable daylight energy storage features. This in turn aids in realizing sustainable smart cities for the benefit of the future generations.

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## Abbreviations

ANN	Artificial Neural Network
ADF	Average Daylight Factor
AES	Advanced Encryption Standard
AF	Automated Fenestration
ANFIS	Adaptive Neuro-Fuzzy Inference Schemes
APPSM	Annual Photosensor Performance Simulation
B	Matrix that represents the lighting offered by p luminaires in q working places
BRDF	Blinn-phong bidirectional Reflectance Distribution Function
$E_O$	Matrix represents the illumination level outside
BSDF	Bidirectional Scattering Distribution function
DA	Daylight Autonomy
DALI	Digital Addressable Lighting Interface
DF	Daylight Factor
DH	Daylight Harvesting
DLI	Daily Light Integral
DFm	Matrix represents the daylight coefficients
$E_D$	Matrix representing the desired illuminance
TMY	Typical Meteorological Year
$E_R$	Matrix represents the illuminance required from lighting systems
FMRLC	Fuzzy Model Reference Learning Controller
HDR	High Dynamic Image
HOLIGILM	Hollow Light Guide Interior Illumination Method
IGBC	Indian Green Building Council
IMC	Internal Model Control
LEED	Leadership in Energy and Environmental Design
MCU	MicroController Unit
MIMO	Multi-Input Multi-Output
NLARX	Non-Linear Autoregressive
NZEB	Net Zero Energy Buildings
PAR	Plant Aspect Ratio
PCA	Principal Component Analysis
PKI	Public Key Infrastructure
HDR	High Dynamic Range
LEED	Leadership in Energy and Environmental Design
FPGA	Field Programmable Gate Array
DLC	Daylight Linked Control Systems
ASF	Adaptive Solar Façade
FMRLC	Fuzzy Model Reference Learning Controller

LFPM	Liquid filled prismatic louver
UDI	Useful Daylight Illuminance
ASF	Adaptive Solar Façade
CDI	Characteristic Daylight Illuminance
CDI <sub>min</sub>	Minimum CDI
sCDI	Spatial CDI
PWM	Pulse Width Modulation
SELV	Safety Extra Low Voltage
SF	Scalar Factor
SVM	Support Vector Machine
TDNN	Time Delay Neural Network
UDI	Useful Daylight Illuminance
VLT	Visible Light Transmittance
WFR	Window-to-Floor Ratio
WSN	Wireless Sensor Network
IVR	Immersive Virtual Reality
WWR	Window to Wall Ratios
CS	Circadian Stimulus
POF	Plastic Optical Fiber
WF	Window to Floor Ratios
DF	Daylight Factor
DA	Daylight Autonomy
WEWR	Window-to-Exterior-Wall Ratio
Y	Product of the total lamps (p) and the total number of workspace (q)

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