sustainability

MDPI

Article

Simulating Physiological Potentials of Daylight Variables in Lighting Design

Mimi Ravn, Gabriela Mach, Ellen Kathrine Hansen and Georgios Triantafyllidis *

Department of Architecture, Design and Media Technology, Aalborg University, 1436 Copenhagen, Denmark; mira@create.aau.dk (M.R.); mach.gabriela96@gmail.com (G.M.); ekh@create.aau.dk (E.K.H.)
* Correspondence: gt@create.aau.dk

Abstract: A holistic approach to daylight dynamics in our built environment can have beneficial outcomes for both physiological and visual effects on humans. Simulations of how daylight variables affect light levels on the horizontal work plane are compared to their physiological effects, measured as melanopic EDI (Melanopic Equivalent Daylight Illuminance) on a vertical plane. The melanopic EDI levels were calculated in a simulated office space in ALFA software (Adaptive Lighting for Alertness) employing the daylight variables of orientation, time of day, season, sky conditions and spatial orientation. Results were analyzed for how daylight design can contribute to the physiological effects of dynamic light in office buildings. Daylight is shown to be a sufficient light source in the majority of cases to meet the recommended values of EDI and provide the suggested horizontal lx level according to the Danish Standards. A mapping of daylight conditions, focusing on the specific factors presented here, can provide guidelines in the design process and future smart building systems. The complex interrelationship between these parameters is important to acknowledge when working with daylight dynamics as a sustainable element in architecture and lighting design.

Keywords: daylight design; daylight variables; simulation melanopic EDI; lighting design; dynamic daylight design; physiological needs for lighting

Citation: Ravn, M.; Mach, G.; Hansen, E.K.; Triantafyllidis, G. Simulating Physiological Potentials of Daylight Variables in Lighting Design. *Sustainability* **2022**, *14*, 881. https://doi.org/10.3390/su14020881

Academic Editor: Lambros T. Doulos

Received: 23 November 2021
Accepted: 9 January 2022
Published: 13 January 2022

1. Introduction

Daylight is the planet's primary energy source [1]. While in the built environment there has been a focus on energy-optimizing and designing energy-efficient daylight solutions for thermal and visual needs, the physiological effects of light are increasingly studied and discussed as a parameter in lighting designs, becoming the new criteria for how and to what extent we qualify daylight and electrical light in buildings [2].

Commission Internationale de l'Eclairage (CIE) specifies "melanopic EDI to provide guidance on how to manipulate the human lighting environment for non-visual responses in people with a regular, day-active schedule [3]". By understanding light as something that both has a visual and physiological effect upon humans, we must rethink how we implement light in our everyday environments and thereby our approaches to lighting design; how do we quantify and measure these different qualities of light? Today the physiological effects are often validated in electrical light, but in practice, these effects are results of both daylight and/or electrical light exposure [4].

To seek the full potential of natural daylight dynamics at a given time, orientation and space, with both visual, physiological and sustainable benefits in mind, this article investigates the physiological effects of dynamic daylight by simulating the melanopic EDI and comparing this to the horizontal illuminance on a work plane within the same daylight variations. The aim is to investigate ways that architects and lighting designers can implement integrative dynamic lighting in the early design phase through simulations of both visual and physiological effects of dynamic light.

An understanding for how to implement daylight dynamics as a design parameter works toward ensuring adequate light in our built environments to meet human physical needs [4]. The growing awareness of the physiological effects of light can be seen as a new opportunity to discuss how we may optimize the sustainable considerations of daylight design by balancing the exposure of natural daylight and electric lighting [5,6]. While electrical light enables us to expand the length of daytime regardless of the presence of daylight, it also contributes to increased energy consumption. Through spending most of our time indoors, we are increasingly exposed to electrical lighting that affects us quite differently from the natural dynamics of daylight and natural light/darkness cycles [7].

The focus within the lighting industry has over the past years moved towards the biological potency of light, where adjustments in intensity and spectrum of electrical light are designed to mimic dynamic daylight changes and to support the human circadian rhythm [8]. This tendency has led to concerns being expressed by leading neuroscientists who experience the industry as being way ahead of the evidence-based research of the physiological effects of light [9,10]. In the article "Circadian Photoentrainment in Mice and Humans" [9], Foster and colleagues describe the current knowledge within the field as a "limited understanding of how the intensity and the duration of light exposure interact". In their view, we are still learning about the human circadian responses to light. Fundamental knowledge about the links between duration time, spectrum, intensity, age and light history is still to needed before we can work with the physiological effects of light as an actual design strategy [9,10]. As a way forward, Foster and colleagues suggest researching the duality between natural and electrical light by assessing their individual lighting parameters in relation to each other [9].

We investigate and discuss the effect of the daylight variations, expressed as melanopic EDI and horizontal illuminance. The vertical melanopic EDI calculations, in this case, represent the physiological effects of light, while horizontal illuminance represents today's standards for the visual effects of light on a work plane. The results of the calculations are compared to the recommendations of 250 melanopic EDI during the day [11] and the Danish Standards recommendation for 500 horizontal lx [12].

1.1. Balancing the Visual and Physiological Effects of Light

The physiological effects of lights are mediated by the photoreceptors in the retina: rod, cones and the Intrinsically Retinal Ganglion Cells (ipRGCs) [9,10]. The ipRGCs contain the photopigment melanopsin that sends direct signals to the brain's circadian clock, the suprachiasmatic nucleus (SCN). When the melanopsin photopigment is activated by light, it signals the brain to suppress the production of the melatonin hormone, also known as the hormone that prepares us for sleep [13].

The melanopsin photopigment is sensitive to high intensity, short wavelength light; adjustments in intensity and wavelength affects the production of melatonin [13]. When studying daylight dynamics, this wavelength sensitivity aligns with the natural day-night cycle. The daylight spectrum at noon and dusk respectively show a variation in both intensity and the presence of blue wavelengths, where the level of blue wavelengths falls as day turns into dusk [14]. Daylight is further characterized by the balance of direct and diffuse light—warm sunlight and cool skylight. The interplay between these two is a key element in daylight [15] and what differentiates daylight from today's static and uniform office lighting [16].

1.2. The Dynamic Daylight as Design Parameter

Optimization of daylight intake as a sustainable light source is well documented [17,18]. Knoop et al. describe how daylight characteristics surpass electric light when it comes to fulfilling human needs for light [17]. Another argument for optimizing the use of daylight is to focus on the qualities of the dynamic character of natural light—the changes in intensities and shadows as clouds pass in front of the sun; the contrast between cool skylight and warm sunbeams; sudden changes from clear to overcast skies. Dynamic daylight can change the atmosphere of our surroundings and bring materials and colors to life [19]. Architecturally, we invite these dynamic changes into our buildings through windows, glass facades and skylights, which also create a connection to the naturally dynamic environment outside [20]. Nevertheless, there are challenges in justifying dynamic daylight as a reliable contributor to indoor environments, where visual and physiological needs are met by electrical light with little or no response to the dynamics of daylight [4].

"*It seems intuitive that daylight should be preferred wherever possible over artificial light, yet we have little data to support this claim*" [21]. Research into the physiological effects of light is at a stage where it is still studied through controlled laboratory tests [10]. These laboratory tests are often focused on extreme parameters, such as very bright light for long durations [9]. The dynamic daylight is simply too complex to incorporate as a reliable factor and is therefore seldom an integrated parameter in these tests [4]. In the built environment, daylight is, however, an essential contributor to the total lit environment and since it is our natural light source, it should be considered as the main contributor to both physiological and visual stimuli [8].

Daylight dynamics are complex and dependent on many factors. For this experiment, four dynamic daylight variables have been defined: season, window orientation, sky conditions and time of day. The changes of seasons affect humans significantly, especially in northern latitudes such as Scandinavia. A study conducted in Sweden showed that, during the wintertime, 53.2% of participants experienced seasonal variation in mood and energy, and for almost 20% of participants, these changes influenced their daily life [22]. Throughout the seasons, daylight varies significantly in terms of intensity and distribution due to the number of daylight hours, the weather, the height of the sun over the horizon, etc. [17].

During a clear or partly cloudy-sky condition, each space with different window orientation gives a distinctive character and color tone of light. The directionality and illuminance levels of the light vary significantly as well [19]. For North and South facing spaces, the distinction can be especially noticeable with more diffuse and dim light for North facing spaces and direct sunlight with high illuminance values, as well as heat gain, if there is no daylight control, for South window orientation [23].

With a clear sky, there is a peak sky radiance distribution around the sun, which weakens with distance. With an overcast sky, the clouds cause a homogenous radiance [24]. Sky conditions, among other factors, have a remarkable influence on the biological effects of light [25,26].

1.3. Connectedness through Natural Lighting Qualities

In her book 'Connectedness: An Incomplete Encyclopedia of the Anthropocene', Marianne Krogh states how: "*We look at nature as something that is detached from ourselves*" [27]. The physiological effects of light are yet another piece of evidence for the inevitable connection that we have to nature and our surroundings [28]. The more we study the effects of light, the more we understand that the dynamic changes that daylight naturally holds have a connection to our experience of our surroundings, but also to our biological clock and our general physical and mental well-being [2,29,30]. To reconnect man and nature, it is therefore relevant to investigate how we can use daylights' dynamic changes strategically in lighting design solutions to enhance both visual and physiological effects [4].

As mentioned, the physiological effects of light have mainly been studied through controlled laboratory tests with electrical light [10]. However, we are beginning to see multidimensional technological tools that can simulate, calculate and measure the complex variables of daylight where we can begin to integrate these variations in the lighting design process. We need to see daylight as something more than just an overcast sky for calculating Daylight Factor. With a focus on the divergent qualities of daylight, we may find answers to the next chapter in lighting design, Integrative Lighting [3], where visual and physiological effects of light are equally acknowledged and considered in architecture and lighting design solutions [10].

Because of the scope of this article, the experiment is set in an office environment, but the overall idea of bringing daylight dynamics into the early design phase can later be studied for residential lighting, industrial setting, museum lighting, etc.

2. Experiment

2.1. Methodology

To study the impact and the relation of daylight dynamics to melanopic EDI levels, as well as their relation to horizontal illuminance levels, two experiments have been conducted with the ALFA simulation tool [31]. First, we examine how simulations of daylight dynamics with the variables of time of day, season, orientation and sky type meet 250 melanopic EDI, the minimum recommendation during daytime to support alertness, the circadian rhythm and a good night's sleep [11]. Secondly, we examine how calculations of dynamic daylight, using the same variables, meet Danish standards for 500 horizontal lx [12].

- Regarding the seasonal changes, simulations were conducted on the 21st of December, June and March/September respectively to obtain results from the summer and winter solstice as well as the spring/fall equinox.
- The daylight inflow is influenced by seasonal changes and orientation due to the sun's path and is studied throughout the day with calculations times at either 9 AM, 12 PM or 3 PM.
- Regarding sky conditions, clear sky, partly cloudy and overcast were used for the simulations.
- Regarding orientation, the window orientations of north, east, west, south were used.

The results of the experiments are presented through graphs and tables, where the individual results are assessed concerning how they meet the relevant recommendations. A green circle indicates that the calculations meet the recommendation, while the red circles indicate calculations that do not meet the recommendation.

2.2. ALFA Lighting Simulation Program

ALFA (Adaptive Lighting for Alertness) uses an extended Radiance lighting engine to render in high resolution with 81-colour spectra [31]. This approach allows an estimation of the amount of light absorbed by an observer's physiological photoreceptors, while at the same time considering the observer's location and direction of view. Measuring the light that is absorbed by the melanopsin photopigment in the ipRGCs, the quantity is referred to as equivalent melanopic lx, which easily translates to the CIE recognized melanopic EDI [32]. The ALFA lighting simulation program is used in this experiment to calculate the equivalent melanopic lx and horizontal lx within the different variables.

The Melanopic Equivalent Daylight Illuminance (EDI) is measured vertically, 1.2 m above floor level, to measure the retinal irradiance that reaches the eyes when sitting at a desk [32]. The amount of light measured vertically depends on the way the light is "present" in the space and will be a combination of direct light, reflected light from the surface and daylight coming from the windows.

The melanopic EDI is the illuminance in radiation, compared to standard daylight (D65), with an equal a-opic irradiance [33]. The visual value of D65, for instance, 1000 lx, corresponds to 1000 lx of melanopic illuminance [8].

2.3. Experiment Setup

A model of an office was created in Rhinoceros 6, mimicking an office test space located in Copenhagen, Denmark (see Figures 1 and 2). The room dimensions were set to 6.2 × 4.3 × 2.6 m. The space consists of four workstations (four desks and chairs). Desks were created in Rhinoceros 6 with dimensions 1.2 × 0.76 m. The room was equipped with two side windows with a size of 1.35 × 0.85 m and 78% transmittance. Selected materials were presented in Appendices A.1 and A.2. The experiment setup does not consider outdoor parameters like reflections or obstacles, surrounding environments nor height. While these parameters are important local factors, this experiment focuses on the daylight variations described above; the influence of the surrounding environment is therefore considered as the next step in future work.

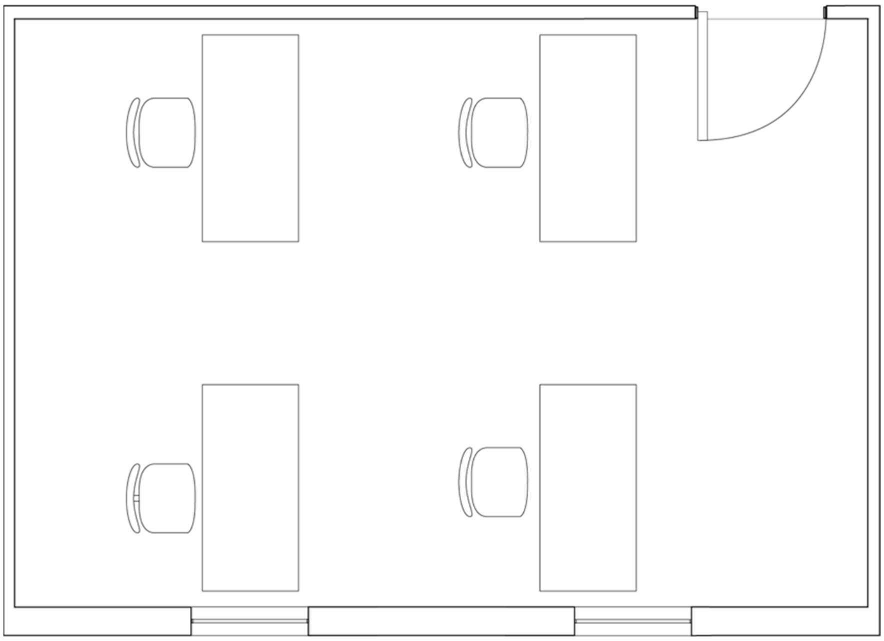


Figure 1. Plan of experiment simulation space in ALFA (Source: authors).

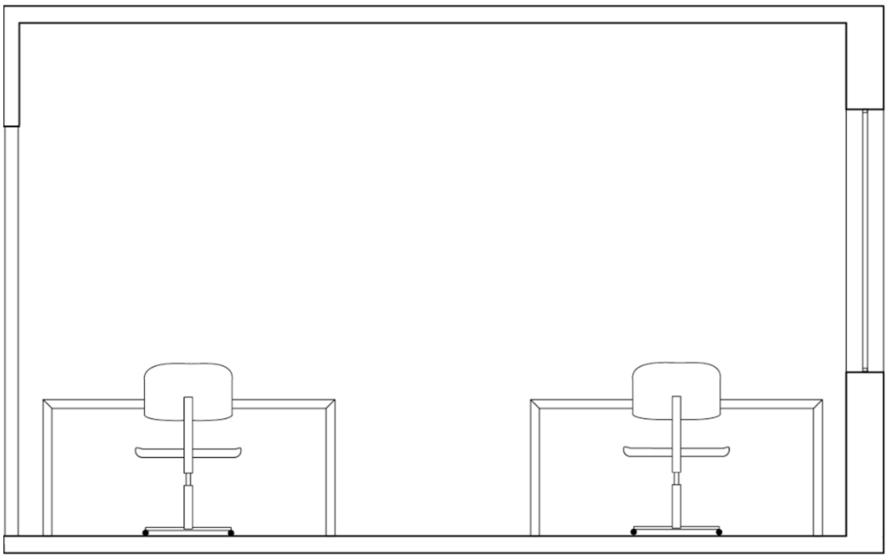


Figure 2. Section of experiment simulation space in ALFA (Source: authors).

To conduct a simulation in ALFA, the plane on which calculations were conducted had to be selected. To follow the CIE recommendations [11], four planes were applied to the model for each workstation. In Rhino, the "Plane" command was used to receive an accurate surface for calculation purposes. The four planes were installed with dimensions of 0.55 × 0.28 m.

The planes were placed at floor level for vertical calculations of equivalent melanopic lx at 1.2 m. The following results will be referring to the average values from four workstations in each case.

Only one view direction in the office was chosen in relation to the placement of the workstation.

The view direction was later rotated when the window orientation of the space was changed. The settings of the grid in ALFA were presented in Appendix A.3. The location in Copenhagen was applied with the following coordinates: 55.6509° N, 12.5419° E.

3. Results

The melanopic EDI calculations are analyzed according to a minimum recommendation of 250 melanopic EDI lx during the day [11]. The results can be seen in Figures 3 and 4. A similar analysis has been performed for the horizontal illuminance according to the recommendation of 500 lx [11], which can be seen in Figures 5 and 6.

The green circles in Figures 4 and 6 illustrate that in 78/108 of the daylight calculations the melanopic EDI level was sufficient, according to the minimum recommendations for light exposure during daytime [11], while the horizontal lx level was calculated as sufficient in 60/108 of the calculations according to the Danish standards [12].

When looking at seasonal changes, both Figures 5 and 6 illustrate large fluctuations. The summer and spring/autumn calculations result in high values despite different window orientations and changes in time of day. The melanopic EDI calculations all meet the recommended 250 melanopic EDI lx [11] in the summer and spring/fall calculations. In comparison, the winter calculations are, in most of the cases, and as expected, below the recommended minimum for both melanopic EDI and the horizontal lx.

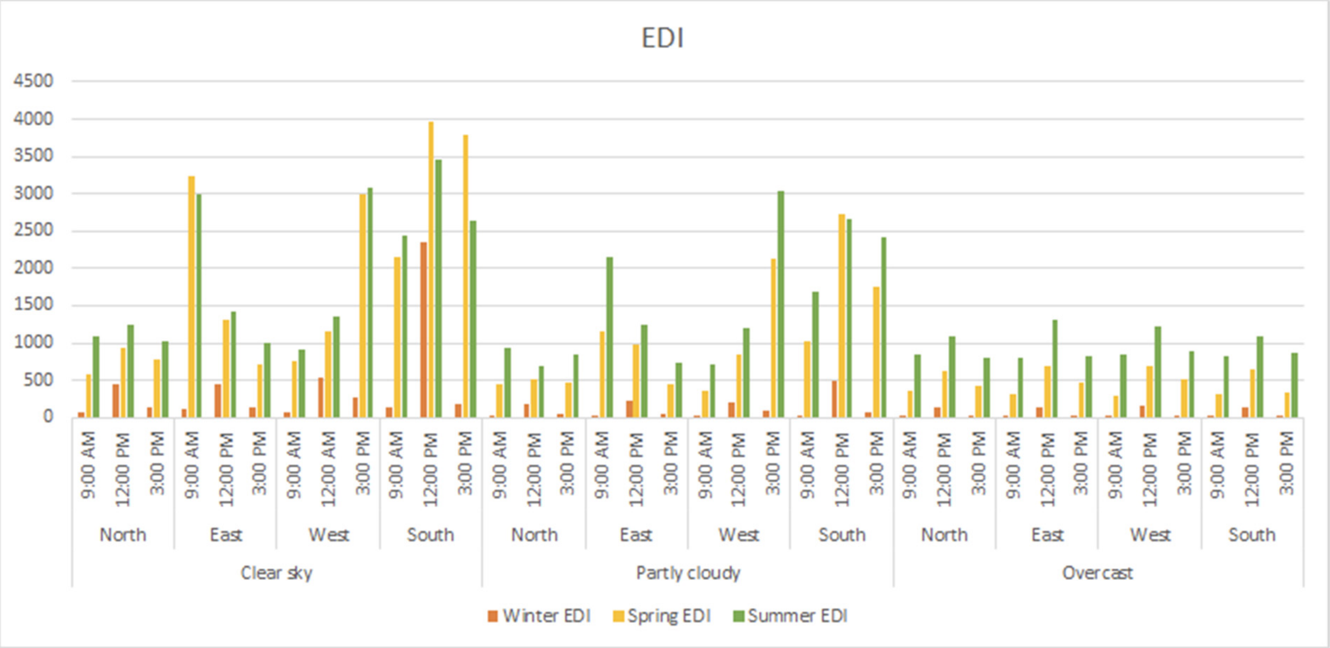
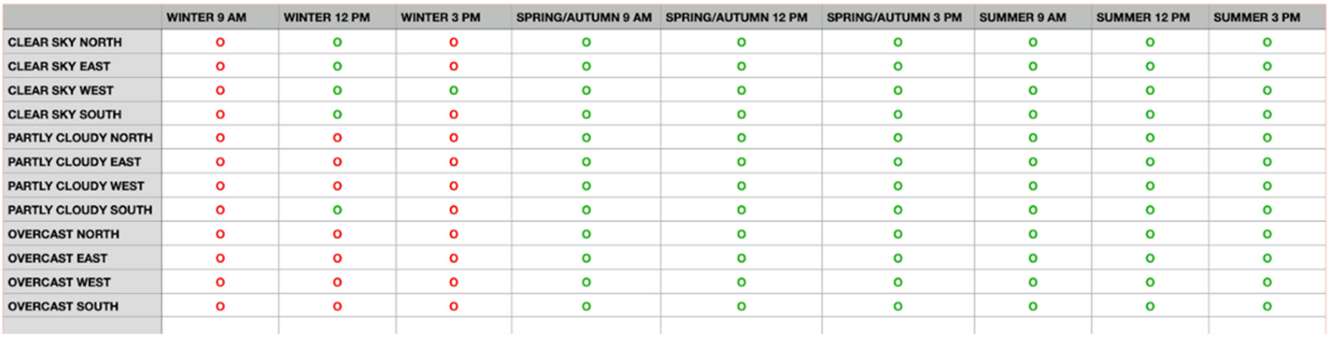


Figure 3. ALFA calculations of the vertical melanopic EDI level within the four daylight variations; orientation, time of day, season, and sky conditions (Source: authors).



	WINTER 9 AM	WINTER 12 PM	WINTER 3 PM	SPRING/AUTUMN 9 AM	SPRING/AUTUMN 12 PM	SPRING/AUTUMN 3 PM	SUMMER 9 AM	SUMMER 12 PM	SUMMER 3 PM
CLEAR SKY NORTH	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢
CLEAR SKY EAST	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢
CLEAR SKY WEST	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
CLEAR SKY SOUTH	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢
PARTLY CLOUDY NORTH	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢
PARTLY CLOUDY EAST	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢
PARTLY CLOUDY WEST	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢
PARTLY CLOUDY SOUTH	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢
OVERCAST NORTH	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢
OVERCAST EAST	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢
OVERCAST WEST	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢
OVERCAST SOUTH	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢

Figure 4. Validation of the melanopic EDI lx calculations according to the recommendations of 250 melanopic EDI lx from Brown et al. [11]. Green is above the recommended 250 melanopic lx, while red is below (Source: authors).

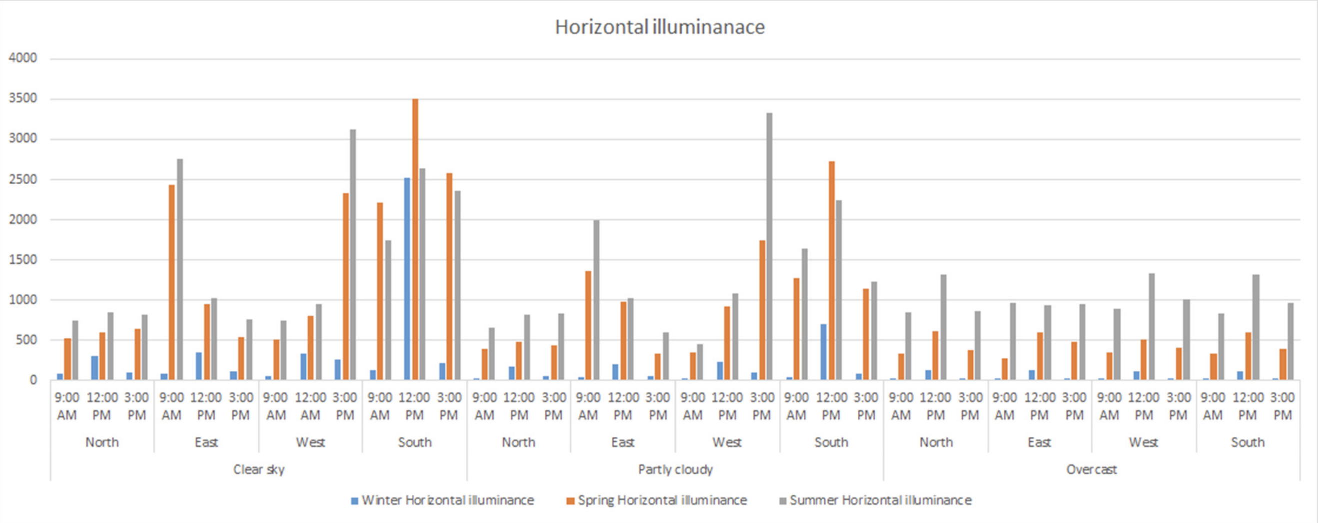
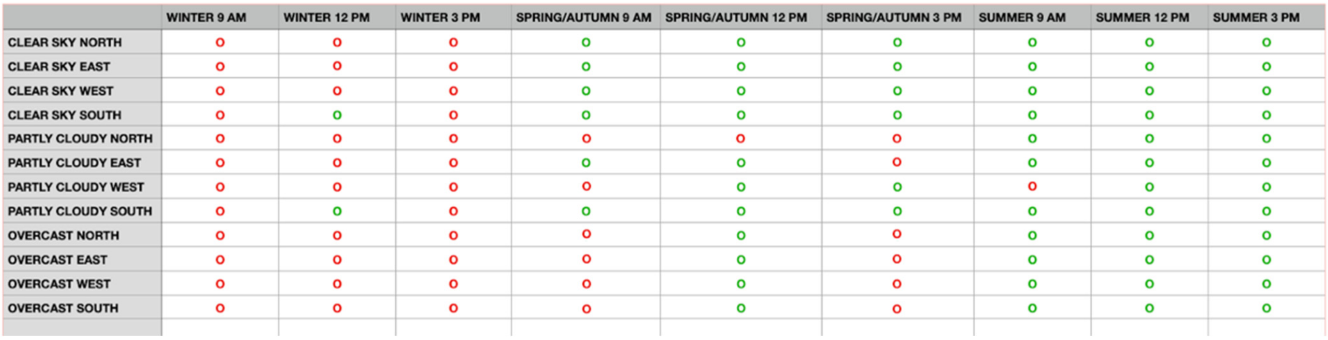


Figure 5. ALFA calculations of the horizontal lx level within the four daylight variations; orientation, time of day, season, and sky conditions (Source: authors).



	WINTER 9 AM	WINTER 12 PM	WINTER 3 PM	SPRING/AUTUMN 9 AM	SPRING/AUTUMN 12 PM	SPRING/AUTUMN 3 PM	SUMMER 9 AM	SUMMER 12 PM	SUMMER 3 PM
CLEAR SKY NORTH	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢
CLEAR SKY EAST	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢
CLEAR SKY WEST	🔴	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟢
CLEAR SKY SOUTH	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢
PARTLY CLOUDY NORTH	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🟢	🟢
PARTLY CLOUDY EAST	🔴	🔴	🔴	🟢	🟢	🔴	🟢	🟢	🟢
PARTLY CLOUDY WEST	🔴	🔴	🔴	🔴	🟢	🟢	🔴	🟢	🟢
PARTLY CLOUDY SOUTH	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢
OVERCAST NORTH	🔴	🔴	🔴	🔴	🟢	🔴	🟢	🟢	🟢
OVERCAST EAST	🔴	🔴	🔴	🔴	🟢	🔴	🟢	🟢	🟢
OVERCAST WEST	🔴	🔴	🔴	🔴	🟢	🔴	🟢	🟢	🟢
OVERCAST SOUTH	🔴	🔴	🔴	🔴	🟢	🔴	🟢	🟢	🟢

Figure 6. Validation of the horizontal lx calculation according to the Danish Building Standard [12]. Green is above 500 horizontal lx while red is below (Source: authors).

The aspect of "time of the day" seems to impact the result most during the winter due to short winter days at this Nordic latitude. The calculations at 9 AM visualize a clear pattern of low values, while the winter calculations at 12 PM visualize how weather changes between clear sky or overcast conditions impact the calculations in either a positive or negative direction.

In general, changes between clear and overcast skies seem to influence the results most for the horizontal lx level, where the spring calculations at both 9 AM and 3 PM resulted in inefficient levels, according to the Danish standards [12]. This may indicate that though the daylight level is low due to overcast conditions, there may still be a high enough daylight level to fulfill the physiological need for light.

Figures 5 and 6 visualize how window orientation is most relevant under clear sky or partly cloudy conditions since the direct sunlight inflow affects these calculations. Under these weather conditions, window orientation and time of day impact each other, because of the changing position of the sun. The calculations during overcast conditions are similar despite the change in window orientation.

4. Discussion

The results are based on parameters, in this specific simulation, of latitude, spatial and material qualities. The experiment aims to understand how changes in season, weather, time of day and orientation affect the daylight conditions in our buildings, focusing exclusively on the daylight intake's ability to meet either the melanopic EDI lx recommendations or the Danish horizontal lx standards for office spaces [11,12]. Knowing that a high daylight intake can also have negative impacts, such as glare or overheated spaces [34], this illustration of the visual and physiological qualities from the direct sunlight intake can give rise to a more nuanced discussion of when to block direct sunlight and how we design shading devices [35,36]. For example, the design of sunscreens that filter the daylight intake instead of blocking; or allowing direct sunlight to enter in directions where it will not cause any glare. With a general sustainability focus in architecture, including the interplay between visual, physiological and energy-efficient aspects of daylight, there is a need to work more diversely with the given daylight conditions. By increasing our understanding of the diverse aspects of daylight and the importance of the dynamics of light in our everyday environments, we can eventually begin to integrate this knowledge into the design process.

The winter calculations for morning and overcast conditions resulted in low values for both the horizontal lx and melanopic EDI lx. During these periods, additional electrical lighting will be needed to meet the recommendations.

Daylight must thus also be an element in “Integrative Lighting” where daylight is sufficient for both visual and physiological needs [3,37]. In this regard, the study of specific daylight variations can be used to get a better understanding of planning for when the daylight is sufficient, as well as when and to what extent additional electrical light is needed. The results also show that there may be times where the daylight is efficient enough to fulfill the recommendation for melanopic EDI lx, but not the horizontal lx. By differentiating the two approaches throughout the design process, it is possible to investigate solutions for specific needs, ensuring the sustainable aspects of electrical light by providing it only when and where it is needed according to visual and physiological needs. A mapping of daylight variations according to both visual and physiological light needs can therefore be seen as the first step towards a more holistic approach to light, as something that not only provides visual comfort but also perceived qualities, physiological effect and energy efficient solutions. These can be conflicting criteria, but if we unfold the potential within each criterion by studying how daylight variations can meet the specific needs, it may inspire new approaches for working with the complex interplay between daylight and electrical light.

Research projects, such as the Double Dynamic Lighting research (DDL), have already been studying the spatial distribution of light through lighting hierarchies and combined CCT, inspired by the natural dynamics of daylight changes between cool skylight and warm direct sunlight. Through layers of electrical light, combining diffuse cold and direct warm electrical light, the DDL project studied how the spatial distribution of light becomes more balanced through a combination of different lighting qualities that respond to the dynamic changes of the daylight intake [16,38].

In this article, we investigate more daylight variables than in the DDL research calculating both horizontal lx and melanopic EDI lx. Since the criteria and calculation methods are different, the results are not to be compared as such. However, the juxtaposition of these two measuring methods gives an opportunity to discuss how we quantify light. Horizontal lx measurements may not be the most relevant method in modern office environments since our workflows and tasks have changed. Today, we mainly work with screens, which set new demands for our need for light [39]. In the article, “*The ambient lighting manifesto*”, the four gurus within lighting research, Boyce, Cuttle, Kelly and Raynham, call for a paradigm shift in lighting practice, changing the perspective of lighting standards from even horizontal (desktop) illuminance, towards a focus on the spatial presence of light [39]. If we begin to quantify our visual needs for light through the vertical measuring method as well, we get an understanding of the light that reaches our eyes, which is more dependent on the spatial distribution of light through a combination of electrical light, reflected light from the surface and daylight coming from the windows.

In this experiment, we investigated the possibility of integrating daylight variations in the early design phase. The results illustrate the complexity of involving daylight dynamics into the design, but also indicate how a mapping of specific variations can provide a guideline for the additional electrical light needed to complement daylight and is relevant when seeking answers for how to work with Integrative Lighting [3,39].

5. Conclusions

Daylight performance in the early design phase is often reduced to simplified metrics such as Daylight Factor measured under overcast conditions. Today's approach to daylight design does not allow for the nuances in daylight dynamics, the relationship between these shifts in conditions, dynamic shading devices, nor electrical light.

The overall aim of this article is to investigate selected daylight variations, using the simulation tool ALFA. Through calculations of melanopic EDI lx and horizontal illuminance, the results were validated and discussed according to the recommendation of 250 melanopic EDI lx during the day [11] and the Danish Standards recommendation for 500 horizontal lx [12]. With the rise of multidimensional simulation tools such as ALFA, we can work with more complex light variables than previously. This article is a step in the direction towards how to implement daylight variations in the early lighting design process, to create more sustainable and energy-efficient lighting solutions in our built environment.

The results of the experiment can be divided into categories of time, weather conditions, architectural design choices and lighting conditions, as guidelines for understanding daylight qualities and the need for additional electrical light. Apart from seasonal changes, time of day is connected to window orientation, the only parameter controlled and designed by the architect and lighting designer. The weather conditions have an overall impact depending on seasonal changes, and since sky conditions can change several times during the day, it is the most acute and dynamic of the four factors.

The complex interrelationship between these parameters is important to acknowledge when working with daylight dynamics as a sustainable element in architecture. A mapping of daylight conditions, focusing on specific factors as presented here, can visualize the potential benefits and obstacles as guidelines in the design process and future smart building systems.

The results illustrate the potential of daylight variations as an integrated part of lighting design solutions for offices, since the calculated daylight is shown to provide a sufficient light source in the majority of cases to meet the recommended values of melanopic EDI (78/108 calculations) and horizontal lx level (60/108 calculations) [11,12]. The discussion argues for a more holistic approach to the daylight performance indicators—visual needs, physiological needs and energy aspects, where a common evaluation framework throughout the design process, will result in a more nuanced interpretation of daylight's diverse qualities. Understanding daylight as a diverse source to both visually pleasant light through a focus on flow, directionality and hierarchies of light (the DDL approach) [16,38], provides a guideline for the supplement of electrical lighting (DDL and CIE's Integrative Lighting) [3,16,37,38] and as a way for optimizing indoor climate and energy efficiency, through a more optimal intake of daylight. Further the focus on both visual and physiological effects through two different measuring methods, can be seen as an opportunity to rethink how we quantify light in accordance with actual needs, by focusing on light that reaches the eyes for both visual and physiological needs.

6. Future Work

Future work will develop strategies for how to ensure daylight-enhanced buildings through tests in larger, outdoor contexts with more parameters, such as reflections, surrounding environments and buildings, as well spatial volumetrics [40,41].

The integrative lighting design approach [3,39] is relatively new; the process of developing tools and methods for integrating more criteria such as physiological effects is an ongoing process. The horizontal work plane lx and melanopic EDI lx are only two criteria in the complex process of designing with daylight and electrical light, where overheating, energy, the perceived qualities of the daylight and the view are other important factors. The tool presented for simulating melanopic EDI lux is relevant toward integrating the complex parameter physiological effects, however it is still a simulation. In future work, these different criteria must be integrated into digital design tools to support the process of designing with daylight and electrical light as a holistic and sustainable design element.

Author Contributions: Conceptualization, M.R., E.K.H. and G.M.; methodology, G.M.; software, G.M.; validation, E.K.H. and G.T.; formal analysis, M.R.; investigation, M.R., E.K.H.; data curation, G.T.; writing—original draft preparation, M.R.; writing—review and editing, M.R., G.M., E.K.H.; visualization, M.R., G.M.; supervision, E.K.H., G.T.; project administration, M.R., E.K.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this article are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1

	Name	**R (photopic)**	**R (melanopic)**	**Specularity**
Walls	White painted corridor walls	79.8%	75.8%	0.4%
Floor	Interior Flooring	38.1%	38.4%	1.1%
Ceiling	White painted room ceiling	82.2%	77.4%	0.4%
Window Frame	Aluminum white railing	78.2%	79.2%	1.7%
Table	Dupont Desaturated blue 119	21.6%	23.4%	0.0%
Chair	Munsell N 6.35	32.3%	32.7%	0.0%

Appendix A.2

	Name	**T (photopic)**	**T (melanopic)**
Windows	Double IGU Clear Tvis 78%	78.5%	77.7%

Appendix A.3

Spacing	**119.5**
Direction	1
Rotation	Depending on window orientation • 0—South • 90—East • 180—North • 270—West
Radius	23.2
Viewplane offset	120 cm
Workplane offset	76 cm

References

1. König, B.; Bochet, C.; Egli, T.; Kling, S.; Norton, B.; Wehrli, B. Uses of Daylight. In *Changing Perspectives on Daylight: Science, Technology and Culture*; The American Association for the Advancement of Science: Washington, DC, USA, 2017.
2. Boubekri, M.; Cheung, I.N.; Reid, K.J.; Wang, C.-H.; Zee, P.C. Impact of Windows and Daylight Exposure on Overall Health and Sleep Quality of Office Workers: A Case-Control Pilot Study. *J. Clin. Sleep Med.* **2014**, *10*, 603–611. [CrossRef] [PubMed]
3. Commission Internationale de l'Eclairage (CIE). *CIE Position Statement on Non-Visual Effects of Light: Recommending Proper Light and the Proper Time*, 2nd ed.; CIE: Vienna, Austria, 2019.
4. Münch, M.; Wirz-Justice, A.; Brown, S.A.; Kantermann, T.; Martiny, K.; Stefani, O.; Vetter, C.; Wright, J.K.P.; Wulff, K.; Skene, D.J. The Role of Daylight for Humans: Gaps in Current Knowledge. *Clocks Sleep* **2020**, *2*, 61–85. [CrossRef] [PubMed]
5. Global Market Insights. Human Centric Lighting. Available online: www.gminsights.com/toc/detail/human-centric-lighting-market (accessed on 26 September 2021).
6. Kearney, A.T.; Market Study. Human Centric Lighting Going beyond Energy Efficiency. Available online: https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjP362U1qj1AhUSat4KHY8HA2sQFnoECAwQAQ&url=https%3A%2F%2Fwww.lightingeurope.org%2Fimages%2Fpublications%2Fgeneral%2FMarket_Study-Human_Centric_Lighting._Final_July_2013.pdf&usg=AOvVaw08nd0mq2vb9aZ4jBdp5fBJ (accessed on 30 July 2013).
7. Amundadottir, M.L.; Rockcastle, S.; Khanie, M.S.; Andersen, M. A human-centric approach to assess daylight in buildings for non-visual health potential, visual interest and gaze behavior. *Build. Environ.* **2017**, *113*, 5–21. [CrossRef]
8. Houser, K.; Boyce, P.; Zeitzer, J.; Herf, M. Human-centric lighting: Myth, magic or metaphor? *Light. Res. Technol.* **2021**, *53*, 97–118. [CrossRef]
9. Foster, R.G.; Hughes, S.; Peirson, S.N. Circadian Photoentrainment in Mice and Humans. *Biology* **2020**, *9*, 180. [CrossRef]
10. Vetter, C.; Pattison, P.M.; Houser, K.; Herf, M.; Phillips, A.J.K.; Wright, K.P.; Skene, D.J.; Brainard, G.C.; Boivin, D.B.; Glickman, G. A Review of Human Physiological Responses to Light: Implications for the Development of Integrative Lighting Solutions. *Leukos* **2021**, 1–28. [CrossRef]
11. Brown, T.; Brainard, G.; Cajochen, C.; Czeisler, C.; Hanifin, J.; Lockley, S.; Lucas, R.; Munch, M.; O'Hagan, J.; Peirson, S.; et al. Recommendations for healthy daytime, evening, and night-time indoor light exposure. *Preprints* **2020**, 2020120037. [CrossRef]
12. BS EN 124643. *Light and Lighting—Lighting of Work Places—Part 1: Indoor Work Places*; BSI Standard Publication: London, UK, 2015.
13. Brainard, G.C.; Hanifin, J.P.; Warfield, B.; Stone, M.K.; James, M.E.; Ayers, M.; Kubey, A.; Byrne, B.; Rollag, M. *Short-Wavelength Enrichment of Polychromatic Light Enhances Human Melatonin Suppression Potency*; Thomas Jefferson University: Woodbury, NJ, USA, 2015; p. 82.
14. Blume, C.; Garbazza, C.; Spitschan, M. Effects of light on human circadian rhythms, sleep and mood. *Somnologie Schlafforschung Schlafmed.* **2019**, *23*, 147–156. [CrossRef] [PubMed]
15. Boyce, P. *Human Factors in Lighting*; CRC Press: Boca Raton, FL, USA, 2015.
16. Hansen, E.K.; Mathiasen, N. Dynamic lighting balancing diffuse and direct light. In Proceeding of ARCH19: Building for Better Health—Research and Innovation in Architecture and Urban Design for Care and Health, Trondheim, Norway, 12 June 2019.
17. Knoop, M.; Stefani, O.; Bueno, B.; Matusiak, B.; Hobday, R.; Wirz-Justice, A.; Martiny, K.; Kantermann, T.; Aarts, M.; Zemmouri, N.; et al. Daylight: What makes the difference? *Lighting Res. Technol.* **2019**, *52*, 423–442. [CrossRef]
18. Reinhart, C.F.; Mardaljevic, J.; Rogers, Z. Dynamic Daylight Performance Metrics for Sustainable Building Design. *LEUKOS* **2006**, *3*, 7–31. [CrossRef]
19. Tregenza, P.; Wilson, M. *Daylighting, Architecture and Lighting Design*; Routledge: New York, NY, USA, 2011.
20. Boyce, P.; Hunter, C.; Howlett, O. *The Benefits of Daylight through Windows*; Lighting Research Center, Rensselaer Polytechnic Institute: Troy, NY, USA, 2003.
21. Münch, M.; Brøndsted, A.E.; Brown, S.A.; Gjedde, A.; Kantermann, T.; Martiny, K.; Mersch, D.; Skene, D.J.; Wirz-Justice, A. *The Effect of Light on Humans—Changing Perspectives on Daylight: Science, Technology and Culture*; The American Association for the Advancement of Science: Washington, DC, USA, 2017; Chapter 3; pp. 16–24.
22. Rastad, C.; Sjöden, P.O.; Ulfberg, J. High prevalence of self-reported winter depression in a Swedish county. *Psychiatry Clin. Neurosci.* **2005**, *59*, 666–675. [CrossRef]
23. Day, J.; Theodorson, J.; Wymelenberg, K.V.D. Understanding Controls, Behaviors and Satisfaction in the Daylit Perimeter Office: A Daylight Design Case Study. *J. Inter. Des.* **2012**, *37*, 17–34. [CrossRef]
24. Lou, S.; Li, D.H.W.; Chen, W. A study of overcast, partly cloudy and clear skies by global illuminance and its variation features. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *556*, 012015. [CrossRef]
25. Bellia, L.; Pedace, A.; Barbato, G. Daylighting offices: A first step toward an analysis of photobiological effects for design practice purposes. *Build. Environ.* **2014**, *74*, 54–64. [CrossRef]
26. Bellia, L.; Pedace, A.; Barbato, G. Winter and summer analysis of daylight characteristics in offices. *Build. Environ.* **2014**, *81*, 150–161. [CrossRef]
27. Krogh, M. *Connectedness*; Strandberg Publishing: Copenhagen, Denmark, 2020.
28. Beute, F.; de Kort, Y. Let the sun shine! *Measuring explicit and implicit preference for environments differing in naturalness, weather type and brightness. J. Environ. Psychol.* **2013**, *36*, 162–178.
29. Heschong, L. *Visual Delight in Architecture—Daylight Vision and View*, 1st ed.; Routledge: London, UK, 2021. [CrossRef]

30. Woo, M.; MacNaughton, P.; Lee, J.; Tinianov, B.; Satish, U.; Boubekri, M. Access to Daylight and Views Improves Physical and Emotional Wellbeing of Office Workers: A Crossover Study. *Front. Sustain. Cities* **2021**, *3*, 92. [CrossRef]
31. Solemma. ALFA—Solemma. 2021. Available online: https://www.solemma.com/alfa (accessed on 20 September 2021).
32. Commission Internationale de l'Eclairage (CIE). *System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light*; CIE S 026/E:2018; CIE: Vienna, Austria, 2018.
33. Lucas, R.J.; Peirson, S.N.; Berson, D.M.; Brown, T.M.; Cooper, H.M.; Czeisler, C.A.; Figueira, M.G.; Gamlin, P.D.; Lockley, S.W.; O'Hagan, J.B.; et al. Measuring and using light in the melanopsin age. *Trends Neurosci.* **2014**, *37*, 1–9. [CrossRef] [PubMed]
34. Pierson, C.; Wienold, J.; Bodart, M. Review of Factors Influencing Discomfort Glare Perception from Daylight. *Leukos* **2018**, *14*, 111–148. [CrossRef]
35. Borisuit, A.; Linhart, F.; Scartezzini, J.-L.; Munch, M. Effects of realistic office daylighting and electric lighting conditions on visual comfort, alertness and mood. *Light Res. Technol.* **2014**, *47*, 192–209. [CrossRef]
36. Kulve, M.T.; Schlangen, L.; Lichtenbelt, W.V.M. Interactions between the perception of light and temperature. *Indoor Air* **2018**, *28*, 881–891. [CrossRef] [PubMed]
37. International Standards Organization (ISO); Commission Internationale de l'Eclairage (CIE). Light and Lighting—Integrative Lighting—Non-Visual Effects. Under Development 2020. Report No. ISO/CIE TR 21783. Available online: https://www.iso.org/standard/71623.html (accessed on 10 October 2020).
38. Hansen, E.K.; Pajuste, M.; Xylakis, E. Flow of Light: Balancing Directionality and CCT in the Office Environment. *Leukos* **2020**, *18*, 30–51. [CrossRef]
39. Matrix Print Consultants Ltd. The Ambient Lighting Manifesto—Issuu. 2020. Available online: https://issuu.com/matrixprint/docs/3043_sll_light_lines_september_october_2020_issuu/s/10939717 (accessed on 20 September 2021).
40. Carli, R.; Dotoli, M. A Dynamic Programming Approach for the Decentralized Control of Energy Retrofit in Large-Scale Street Lighting Systems. *IEEE Trans. Autom. Sci. Eng.* **2020**, *17*, 1140–1157. [CrossRef]
41. Beccali, M.; Bonomolo, M.; Brano, V.L.; Ciulla, G.; Di Dio, V.; Massaro, F.; Favuzza, S. Energy saving and user satisfaction for a new advanced public lighting system. *Energy Convers. Manag.* **2019**, *195*, 943–957. [CrossRef]