E3S Web of Conferences **436**, 01012 (2023) https://doi.org/10.1051/e3sconf/202343601012
*ICED2023*

# Methodology for the optimization of artificial lighting considering both visual and non-visual effects

*Evangelos-Nikolaos* Madias[1,2*], *Athanasios* Kotsenos[1], *Aris* Tsangrassoulis[3], and *Lambros* Doulos[2]

[1]Lighting Laboratory, School of Electrical & Computer Engineering, National Technical University of Athens, Iroon Polytechneiou 9, Zografou Campus, 15780, Athens, Greece
[2]School of Applied Arts and Sustainable Design, Hellenic Open University, Parodos Aristotelous 18, Patras, 26335, Greece
[3]Department of Architecture, University of Thessaly, Greece

**Abstract.** The effect of light on human physiology as well as its non-image forming effects have been known for several years. An important milestone in understanding the non-visual effects of light was the discovery of a new type of photoreceptor namely the intrinsically photosensitive retinal ganglion cells, or ipRGCs which play a vital role in the human circadian system. The non-visual effects of light are the following: regulation of melatonin secretion, circadian entrainment and modification of body temperature. With the advent of solid-state lighting, it is possible to precisely regulate the spectral power distribution of artificial lighting, so as to favour the human circadian rhythm. The scope of this paper is to present a conceptual methodology for the evaluation of artificial lighting systems with regards to visual, circadian effects and their energy consumption. In other words, this paper aims to outline an assessment process for lighting designers by elaborating not only on the visual aspects of each lighting system but also the melanopic effects and its energy efficiency.

## 1 Introduction

During the course of a day and for a wide variety of human activities, sufficient levels of natural and artificial lighting are required [1-10] sufficient levels for recreational spaces, schools, offices etc. Lighting contributes to both the visual and to non-visual effects on humans [11-13]. The visual effects of light contribute to the perception of space and to the overall appearance of the lighting. Artificial lighting should be able to deliver adequate lighting levels, without over-illuminating the surrounding areas. The combination of an adjustable direct lighting of task areas with indirect or diffused lighting of lower intensity in the areas surrounding the task area, allows for easier visual adjustment of the user, increasing his or her visual acuity and providing at the same time an appropriate background lighting. However, in addition to achieving visual comfort (visual effect), lighting design must also include the non-visual effect on humans, such as the synchronization of daily biological rhythms, alertness during the day and relaxation during the evening hours. The eye communicates with the brain through two pathways, the visual pathway and the non-visual pathway. An important milestone in understanding the non-visual effects of light was the discovery of a new type of photoreceptor in the human retina. This new photoreceptor, called the intrinsically photosensitive retinal ganglion cell, or ipRGC for short, is not located in the same layer of the retina as the already known rod and cone photoreceptors used by the human visual system. As its name suggests, it is a special form of ganglion cell. The photochromic substance contained in an ipRGC cell is melanopsin which has a maximum absorption at a wavelength of 480 nm [11,13].

All living organisms on earth have circadian rhythms. These rhythms are biological cycles that repeat themselves daily and are regulated by environmental stimuli. The most important cycle involves the alternation of day and night. This alternation of light and darkness that is transmitted through the non-visual pathway is converted into nerve signals to synchronise the biological clock of the brain with the body's local time. During the course of a day (circadian rhythm), the following basic hormones are produced: a) dopamine for pleasure, alertness and muscle coordination, (b) serotonin, a natural mood stabiliser, (c) cortisol for stress response; and (d) melatonin for relaxation and creating the right conditions for sleep. Disruption of the circadian rhythm may lead to long-term complications in physiological function, neurological performance and sleep, thus running a higher risk of cardiovascular disease, diabetes, etc. The description and requirements concerning biological effects in humans are given by technical guidelines (CEN/TR 16791) [14] and technical specifications of EU Member States (DIN SPEC 67600 [15] and DIN SPEC 5031-100 [16]).

The non-visual effects of lighting also include the feelings we get in a space from the atmosphere created. A pleasant, safe and familiar atmosphere (e.g., low uniform light levels) is relaxing, whereas a lighting atmosphere

* Corresponding author: madias@mail.ntua.gr

with sharp contrasts of light and abrupt changes between bright and dark areas makes us feel tense. Artificial lighting with a CCT lower than 3,300 K, emphasizing particular areas, causes significantly more pleasant feelings as it is associated with increased perception, comfort and reduced tension.

The sum of the aforementioned parameters included in the visual and non-visual effects of lighting constitute the concept of "Human Centric Lighting" (HCL). HCL is implemented by providing "the proper lighting at the proper time" [17], namely delivering the required amount of illumination and the appropriate wavelengths (i.e., the human eye perceives them as colour), for individual living and working needs, at any time of day. In overall, HCL must fulfil three primary goals, that correspond to visual, biological and emotional needs of the occupants (Fig.1). Visual needs entail the identification of tasks, minimization of glare and discomfort and the establishment of safety and security. Biological needs are connected to the circadian rhythm, namely the regulation of sleep-wake circle. Last but not least, HCL should address the emotional needs of occupants, namely their feelings that are aroused inside a lit space. As lighting has a range of effects on humans HCL must have a specific long-term positive effect on health, well-being and productivity of every human being through the adoption of a holistic design.

Therefore, this paper aims to provide a valuable tool for lighting designers and engineers in order to evaluate various lighting systems so as to provide sustainable lighting considering both photopic and circadian metrics and concurrently maximize energy efficiency.

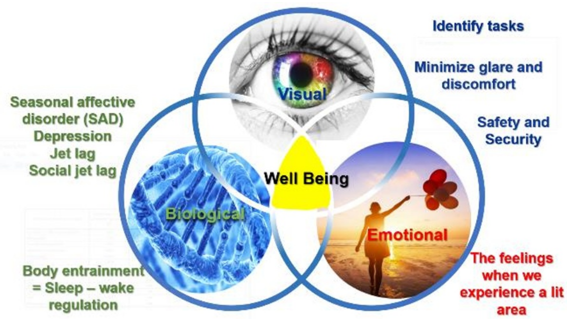


**Fig. 1.** Visual, biological and emotional needs of lighting.

## 2 Metric systems of HCL

Researchers have established three metric systems to measure the circadian impacts of light radiation: the equivalent melanopic illuminance, the melanopic daylight equivalent illuminance and the circadian stimulus.

### 2.1 Equivalent Melanopic Lux

Lucas et al [18] has introduced the equivalent melanopic illuminance (Equivalent Melanopic Lux, EML) in order to quantify the melanopic effects of light. The equivalent melanopic illuminance is calculated using the following formula:

$$EML = K_{melanopic,E} \times \int_{\lambda=380}^{780} SPD(\lambda) \times Smel(\lambda) \times d\lambda \qquad (1)$$

where $\boldsymbol{K_{melanopic,E}} = \mathbf{831.8} \frac{\boldsymbol{lm}}{\boldsymbol{melanopic_E}}$

The Equivalent Melanopic Lux can also be calculated by multiplying the photopic illuminance with the Melanopic Equal-Energy Efficacy Factor (MEER). Obviously, MEER depends on the spectral power distribution of the light source. The following Table provides representative values of MEER for typical light sources [19]. According to the WELL Standard [20] in workplaces, an equivalent melanopic illuminance of 150 EML in the vertical plane at a height of 1.2 m using only artificial lighting or 120 EML using both daylight and artificial lighting is suggested. A reduction in artificial lighting levels due to the daylight harvested is allowed, but the luminaires shall be capable of delivering the aforementioned EML levels regardless of daylight levels.

**Table 1.** Calculation of EML per 100 lx for various light sources [19].

| Type of light source | CCT | Photopic illuminance (lx) | Equivalent melanopic illuminance (EML) |
|---|---|---|---|
| Standard Illuminant P | 1,800 | 100 | 30 |
| Fluorescent | 2,700 | 100 | 38 |
| Standard Illuminant A | 2,856 | 100 | 55 |
| Halogen | 3,000 | 100 | 56 |
| Fluorescent | 3,000 | 100 | 45 |
| LED | 3,000 | 100 | 45 |
| Fluorescent | 4,000 | 100 | 58-62 |
| LED | 4,000 | 100 | 74-76 |
| LED | 5,400 | 100 | 87 |
| D55 | 5,500 | 100 | 100 |
| Standard Illuminant D65 | 6,500 | 100 | 110 |
| LED | 6,500 | 100 | 88 |
| Fluorescent | 8,000 | 100 | 106 |

### 2.2 Melanopic Daylight Equivalent Illuminace

The International Commission on Illumination CIE has established a new index for determining the melanopic effects of light. The Melanopic Daylight Equivalent Illuminance (MDEI) is calculated by the following formula:

$$MDEI = \frac{\int_{\lambda=380}^{780} SPD(\lambda) \times Smel(\lambda) \times d\lambda}{K_{melanopic,D65}} \qquad (2)$$

where $K_{melanopic,D65} = 1.3262$ mW/lm

MDEI is the integral of the product of the spectral power distribution of the light source multiplied by the action spectrum of the melanopic response of the human eye divided by the constant K_(melanopic,D65). MDEI can also be calculated by multiplying the photopic illuminance by the melanopic daylight efficacy ratio (MDER). In a reference daylight spectrum, the MDER is 1. In general, artificial illumination has a less significant biological impact than daylight, with a MDER< 1.

### 2.3 Circadian Stimulus

The circadian stimulus (CS), developed by Rensselaer Polytechnic Institute's Lighting Research Center [21], is a nonlinear model of human nocturnal melatonin suppression which is based upon the levels of vertical illuminance on the eye as well as the spectral distribution of the source for 1 hour of exposure time. The model defines how light signals are converted by the retina into brain signals for the human non-visual system. First, the spectral distribution of the light source is used to determine circadian light (CLa). Circadian light is the radiation incident on the cornea, with the appropriate weighting function so as to approach the human circadian system's spectrum estimated from the acute suppression of melatonin secretion after one hour of exposure. After calculating the circadian light, the circadian stimulus CS is computed, which describes the efficiency of radiation, correctly weighted to approximate the spectral sensitivity of the cornea. The range of CS is between 0 and 0.7, with the latter being its saturation value. According to the guidelines of the Lighting Research Center, that have been established after experiments on different human subjects, a CS value of at least 0.3 for at least one hour early in the day is proposed, so as to stimulate the human circadian system and have a positive effect on the occupants' well-being. Furthermore, the recommended CS value for relaxation is 0.1, whereas for periods of work a CS value of 0.7 is suggested [22].

## 3 Methodology

In overall, lighting should comply with the following requirements for office installations: With regards to visual requirements, artificial lighting should deliver an average illuminance of 500 lx, with an overall uniformity of 0.6, whereas concerning biological requirements an EML of at least 150 EML is recommended and regarding emotional needs, a CCT of 4,000 K is proposed since according to relevant research the occupants prefer luminaires with a CCT of 4,100 K and exhibit now particular preference whether the light source is fluorescent or solid state lighting [23-24].

In order to quantify and compare the circadian effects of solid-state lighting the corresponding metrics of circadian lighting are utilized: the equivalent melanopic illuminance, the melanopic daylight equivalent illuminance and the circadian stimulus. The methodology that is followed for the implementation of this research is the following:

The final step of the proposed methodology is the derivation of conclusions regarding the optimization of lighting design taking into consideration the energy consumption as well as the photopic and melanopic effects of artificial lighting.

- First of all, an appropriate tunable white LED luminaire is selected.
- Secondly, appropriate measurements for the determination of the technical parameters of the selected luminaire are conducted, namely the photometric, electric and spectral parameters.
- The next step, is the utilization of a lighting simulation software (i.e. RELUX [25]) for the conduction of calculations at a typical office space.
- After the lighting simulations, the photopic and melanopic illuminance along with the HCL metrics are computed.
- The final step of the proposed methodology is the derivation of conclusions regarding the optimization of lighting design taking into consideration the energy consumption as well as the photopic and melanopic effects of artificial lighting.

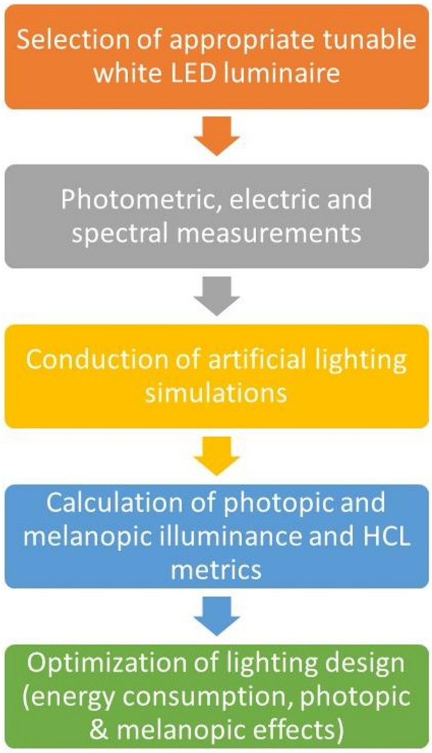


**Fig. 2.** Methodology of the research approach.

With regards to luminaire selection a linear luminaire for direct ceiling mounting. Inside the luminaire there are 6 LED modules that are also the light source. It is 1,700 mm long, 160 mm wide and 84 mm high. Externally it is equipped with a suitable diffuser which provides visual comfort with low UGR values. The luminaire is equipped with 6 LED modules which emit a spectral power combination in the visible range to provide a CCT in range from 2,700 K (warm-white) to 6,500 K (cool-white). The luminaire includes a dual wireless controller for continuous adjustment of a) luminous flux and b) color temperature using CASAMBI [26] technology. The luminous flux variates between 8,383 lm when emitting warm light (2,700 K) and 9,030 lm when emitting cool light (6,500 K). At intermediate CCT values the luminous flux takes intermediate values. The nominal power of the luminaire is 70W. The luminous efficacy has a maximum value of 150 lm/W in the use of cool-white light. The control is done wirelessly through the use of an application on a mobile phone or tablet. The lifetime of L80B10 is 80,000 hours. The color rendering index is greater than 80 and the color consistency is within a 3-step McAdam shortage. Figure 3 present the luminaire, Figure 4 depicts its luminous intensity distribution and Figure 5 shows the spectral power distribution of the tunable white LED luminaire for CCT 2,700, 4,000 and 6,500 K.

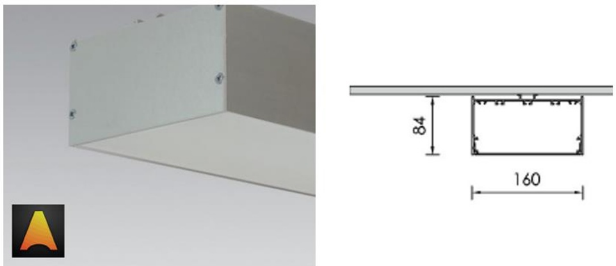


**Fig. 3.** Linear luminaire with tunable white LED sources.

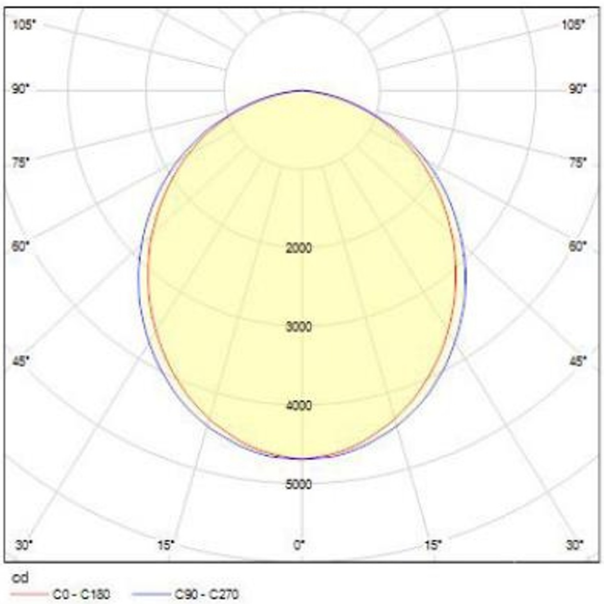


**Fig. 4.** Luminous intensity distribution of the linear LED luminare.

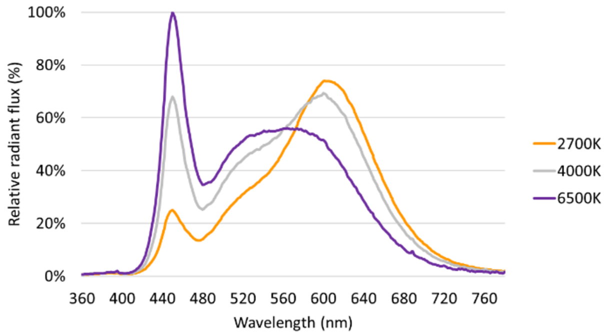


**Fig. 5.** Spectral power distribution.

## 4 Results and discussion

In order to quantify the melanopic effects of tunable white LED luminaires a simulation was conducted in an indoor space with dimensions 4 x 7 x 3 m, as shown in the Figure 6. The interior space in our simulation is illuminated by 2 tunable white LED luminaires. In order to fulfill the visual and emotional requirements we propose a reference scenario of an average illuminance 500 lx and a CCT setting of 4,000 K, which as we stated previously is the most preferred hue for office users [23-24]. The corresponding power consumption of the LED lighting system for the reference scenario is 7 W/m$^2$. Additionally, in order to address the biological requirements as well, namely achieve a melanopic illuminance of at least 150 EML, the average horizontal illuminance should be increased to 604 lx and the power consumption should be increased to 8.4 W/m$^2$ which equals an energy waste rate of 20% compared to the reference scenario. The results of the research will provide all relevant measurements along with the calculations of lighting simulations and the calculations of the circadian lighting metrics. All circadian metrics have been calculated at the vertical plane at a height of 1.2 m from the ground, namely a typical office sitting position. Figures 7 and 8 show the relationship between power consumption (W/m$^2$) and EML and between illuminance and power consumption (W/m$^2$). Observing Figure 7, it is evident that for a given illuminance level 500 lx, as the CCT increases, the values of EML also increase whereas the energy consumption decreases. This means, that there exists an inversely proportional relationship between the equivalent melanopic illuminance and the power consumption. Figure 8 illustrates the relationship between the photopic horizontal illuminance and the power consumption for a given value of 150 EML. It is evident, that as CCT increases, both the power consumption as well as the photopic illuminance decrease. The main conclusion from our analysis, is that if a lighting designer prefers to design a lighting installation using warm white LED luminaires, e.g. with a CCT of 2,700 K, a common trend in office lighting design, the final result is a significant increase in power consumption, namely 14.7W/m$^2$ which equals to an energy waste of 209%. More luminaires are required so as to accomplish the required melanopic limit. Therefore, designing artificial lighting with warm white LED luminaires while attempting to achieve the biological threshold of 150 EML, causes an excess of energy consumption and impacts negatively the environmental footprint of the building.

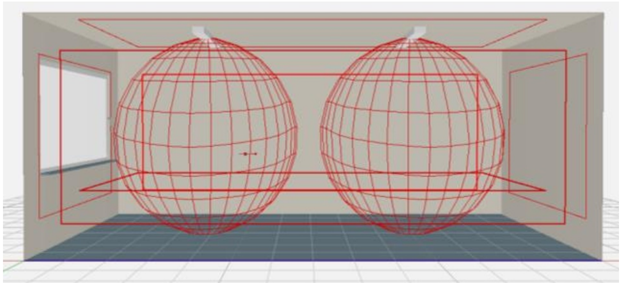

**Fig. 6.** Artificial lighting simulation of an interior space in RELUX [25] software.

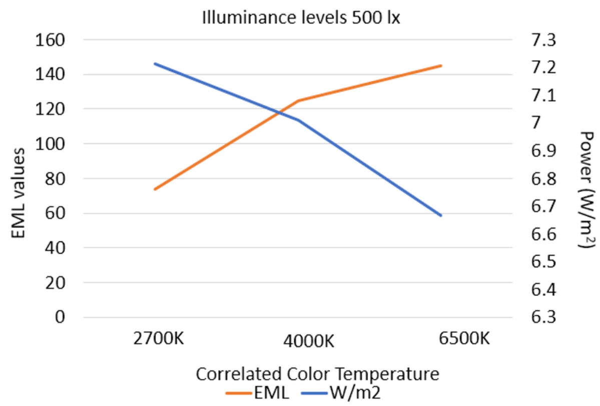


**Fig. 7.** Relationship between power consumption (W/m$^2$) and EML.

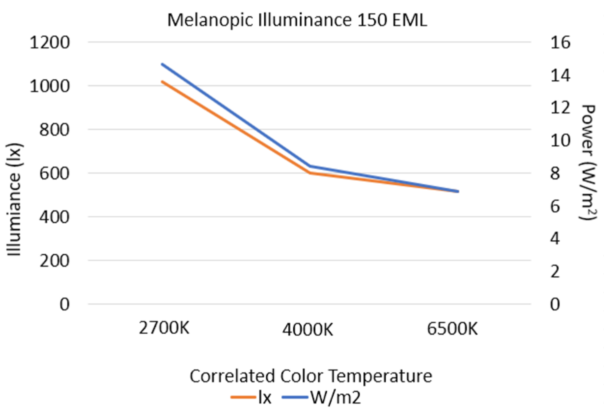


**Fig. 8.** Relationship between illuminance and power consumption (W/m$^2$).

## 5 Conclusions

The effects of lighting design must consider not only the visual but the non-visual effect on humans as well, and especially the supporting the circadian rhythm. The concept of "Human Centric Lighting" encompasses three primary goals, that correspond to visual, biological and emotional needs of the occupants. Visual needs concern the identification of tasks, control of glare and the establishment of safety. Biological needs are determined by the human circadian rhythm and the emotional needs depend on their psychology inside a lit space. Extensive literature review has concluded that three metric systems have been prevalent for quantifying the non-visual effects of light, namely melanopic equivalent luminance, melanopic equivalent daylight luminance and circadian stimulus. The proliferation of solid-state lighting has facilitated lighting professionals to implement human centric lighting providing "the right light at the right time", through the use of tunable white LED luminaires. Our approach proposed a methodology for the assessment of artificial lighting, considering all the aforementioned parameters, visual, biological and emotional and the important factor of energy efficiency. The main conclusions from our analysis are the following: For a given level of photopic illuminance an increase of the CCT results in an increase of EML whereas the energy consumption decreases. Thus, an inversely proportional relationship exists between the equivalent melanopic illuminance and the power consumption. Furthermore, for a given level of equivalent melanopic illuminance i.e. 150 EML, both the power consumption as well as the photopic illuminance decrease. Designing lighting with luminaires that emit light with warm-white hue results in the installation of more luminaires in order to achieve the same melanopic effects on the occupants, as compared to luminaires with cool-white hue. Therefore, an excess of energy consumption is caused which influences negatively the environmental impact of artificial lighting in buildings. Another useful conclusion is that lighting designers should consider not only the visual aspects of artificial lighting but the non-visual, i.e. melanopic effects of light to the occupants in order to favor their circadian rhythm. Artificial lighting should not be perceived in one-dimension, i.e. as a means to provide visual comfort and safety for the occupant but also as means to boost work performance and improve the well-being of the occupants. However, the energy efficiency of tunable white LED luminaires should be considered as well, especially in an era where lighting stakeholders maximize their efforts towards sustainable lighting equipment. Lighting professionals are advised to achieve a balance between three axes, namely visual, non-visual effects and energy consumption. This paper aspires to serve as a valuable tool for lighting designers and engineers in order to evaluate various lighting systems and provide sustainable lighting considering both photopic and circadian metrics and concurrently maximize energy efficiency.

Authors would like to thank Bright Special Lighting S. A. and, specifically, Mr. Vassiliou Georgios (owner) and Mr. Angelidakis Dimitrios (test engineer) for their support in the luminaire equipment.

## References

1. E.-N. Madias, K. Christodoulou, V. P. Androvitsaneas, A. Skalkou, S. Sotiropoulou, E. Zervas, L.T. Doulos, J. Build. Eng., **76**, (2023)
2. A. Mesloub, M.M. Alnaim, G. Albaqawy, B. Alsolami, M.S. Mayhoub, A. Tsangrassoulis, L.T. Doulos, J. Build. Eng. **68**, (2023)

3. G. Labiris, E.K. Panagiotopoulou, S. Taliantzis, A. Perente, K. Delibasis, L.T. Doulos, Clinical Ophthalmology **15**, 4553-4564 (2021.
4. A.I. Samiou, L.T. Doulos, S. Zerefos, Energy Build., **258**, (2022)
5. A. Tsangrassoulis, L. Doulos, A. Mylonas, Energies **14**, (2021).
6. P. Pallis, K. Braimakis, T.C. Roumpedakis, E. Varvagiannis, S. Karellas, L. Doulos, M. Katsaros, P. Vourliotis, Build Environ., **206**, (2021).
7. L.T. Doulos, A. Tsangrassoulis, E.N. Madias, S. Niavis, A. Kontadakis, P.A. Kontaxis, V.T. Kontargyri, K. Skalkou, F. Topalis, E. Manolis, M. Sinou, S. Zerefos, Energies **13**, (2020).
8. E.N. Madias, L.T. Doulos, P.A. Kontaxis, F.V. Topalis, Int. J. Oper. Res., (2020).
9. Doulos L.T., A. Kontadakis, E.N.Madias, M. Sinou, A. Tsangrassoulis, Energy Build., **194**, 201-217, (2019).
10. E.N.D. Madias, L.T. Doulos, P.A. Kontaxis, F.V. Topalis, Int. J. Oper. Res., 1-20, (2019).
11. E.N. Madias, E. Patrikios, C. Grigoropoulos, L. Doulos, *Design and Development of a Sustainable Environmentally Friendly and Human Centric Luminaire*, in 3nd International Conference On Environmental Design 22-23 October 2022 Athens, Greece, IOP Conf. Ser.: Earth Environ. Sci., (2022).
12. I. Tservartsidis, C. Skandali, L.T. Doulos, *The environmental impact of the new version of the Interior Lighting European Norm in Lighting and Circadian Design*, in 3nd International Conference On Environmental Design 22-23 October 2022 Athens, Greece, 2022 IOP Conf. Ser.: Earth Environ. Sci., (2022).
13. A. Kotsenos, E.N. Madias, F. Topalis and L. Doulos, *Circadian stimulus calculators as environmental building design tools: Early results of a critical review*, in 3nd International Conference On Environmental Design 22-23 October 2022 Athens, Greece, IOP Conf. Ser.: Earth Environ. Sci., (2022).
14. European Committee for Standardization (CEN), CEN/TR 16791:2017, Quantifying irradiance for eye-mediated non-image forming effects of light in humans (2017).
15. German Institute for Standardization, DIN SPEC 67600:2013-04, Biologically effective illumination - Design guidelines, (2013).
16. German Institute for Standardization, DIN SPEC 5031-100:2015-08, Optical radiation physics and illuminating engineering - Part 100: Melanopic effects of ocular light on human beings - Quantities, symbols and action spectra, (2015).
17. International Commission on Illumination (CIE), Position statement on non-visual effects of light, Recommending proper light at the proper time, 2nd edition (2019).
18. R.J. Lucas, S.N. Peirson, D.M. Berson, T.M. Brown, H.M. Cooper, C.A. Czeisler, G.C. Brainard, Neurosci., **37**(1), 1–9 (2014).
19. Technical Chamber of Greece, Technical Directive 20701-7/2021, Artificial and Natural Lighting in Buildings, (2021).
20. International WELL Building Institute (IWBI), WELL Building Standard v2, (2020).
21. M.S. Rea, M.G. Figueiro, A. Bierman, R. Hamner, Lighting Res. Technol., **44**, 386–396 (2012).
22. M.G. Figueiro, K. Gonzales, D. Pedler, Designing with Circadian Stimulus, Illuminating Engineering Society (IES), LD+A, (2016).
23. J. Ma, J.K. Lee, S.H. Cha,. Build Environ. (2022)
24. J. Viitanen, J. Lehtovaara, E. Tetri, L. Halonen, Leukos, **9**(4), 261-290 (2013).
25. Relux Informatik AG, RELUX software, https://relux.com/en/.
26. Casambi Technologies Oy, CASAMBI, https://casambi.com/.