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CircaLight, a new circadian light assessment tool for Grasshopper environment: Development and reliability testing

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ABSTRACT

Natural light exposure both in flux and spectrum is essential to human health due to its direct relationship with circadian rhythms. Given that light affects visual performance and circadian rhythms differently, metrics need to assess them independently. The aim of this research is to present a new parametric workflow to integrate metrics quantifying the effect of light on circadian rhythm. CircaLight is a new open-source tool for Rhino environment developed as a plugin for Grasshopper. This software enables the calculation of different metrics that quantify the effect of light, both natural and electric, on circadian rhythms, considering the influence of the spectral reflectance of inner surfaces. The CircaLight components can be integrated into Grasshopper plugins such as Solemma or Ladybug tools providing information about the Circadian Stimulus, the Equivalent Melanopic Lux and the Melanopic Photopic ratio, all of which provide current metrics related with circadian rhythms. This research evaluates the reliability of the software presented, quantifying its accuracy by means of other validated software. The results show the accuracy of this new parametric tool with an error under ±10% even in the most unfavorable scenarios.

Glossary

LRC	Lighting Research Center
ipRGCs	Intrinsically photosensitive ganglion cells
SCN	Suprachiasmatic nucleus
SPD	Spectral Power Distribution
CCT	Correlated Color Temperature (K)
CS	Circadian Stimulus
CSA	Circadian Stimulus Autonomy
CL_A	Circadian Light
EML	Equivalent Melanopic Lux
M/P	Melanopic/Photopic ratio

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1. Introduction

1.1. Background

Light, which has a major influence both on visual tasks and human health, is one of the main elements to be considered in the design of spaces. Circadian rhythm acts as a biological clock for humans, a set of physical and physiological changes occurring in 24-h cycles [1]. Although this cycle is endogenous, it has been shown that it can be affected by external factors known as Zeitgebers [2], the most important of which is light [3,4]. Insufficient exposure to light can cause the disruption of circadian rhythm, leading to the possible appearance of different diseases [5–8]. Although numerous studies focus on the relationship between circadian rhythms and these pathologies, these have focused mainly on workers subjected to changing shifts or night work, especially nurses and hospital staff [9]. Workers who engage in shift or night work are usually at a higher risk of suffering from different types of cancer [10], other pathologies such as cardiovascular diseases [11], atherosclerosis, diabetes [6], cognitive deficits, anxiety and depression [10], and even autoimmune diseases such as multiple sclerosis [12]. Chronodisruption has also been linked to delirium [13], bipolar disorders [14], and impaired mental activity [15]. Therefore, proper regulation of circadian rhythms has a beneficial effect on sleep cycles and human health overall [16].

Daylight is the light source that usually provides the right amount and spectrum for a suitable regulation of circadian rhythms. However, as people spend most of their time inside buildings, their exposure to natural light is limited. For this reason, an adequate design of lighting conditions, both natural and electric, is essential in architectural conception. This design must include an accurate analysis that guarantees a suitable illuminance level and spatial recognition, as well as guaranteeing a good circadian rhythm regulation.

Certain metrics are devoted to the quantification of the visual perception of light, as is the case of illuminance, Daylight Factor and Daylight Autonomy among others [17]. However, metrics that quantify the impact of light on circadian system do not replicate these parameters or match them linearly as they rely on different foundations whose use is not currently widespread. This difference in the metrics to be considered is a response to the different levels of sensitivity to light of visual and circadian systems, given that both systems engage different photoreceptors in the human eye. Rod and cone photoreceptors engage in vision while different receptors in addition with these, ipRGCs, operate in the circadian system. The metrics related to the circadian system are based on the behavior of the different photoreceptors that act on phototransduction, a process in which light received by the eye is converted into electrical signals that cause the secretion of different hormones. Currently, there are two main different hypotheses regarding which photoreceptors influence this process, depending on whether melatonin regulation is affected by rods and cones apart from iprGCs. These two theories in turn lead to the two current mathematical models of phototransduction and, thus, the identification of two main different metrics to assess light influence on circadian rhythms. The first model, developed by the Lighting Research Center (LRC) [18,19], takes into account the influence of rods, cones and ipRGCs photoreceptors in order to quantify the suppression of melatonin, the hormone responsible for sleep cycles. It assesses the influence of light on circadian rhythms through the Circadian Stimulus metric (CS) which expresses the melatonin suppression caused by light (from 0% to 70%). A recent update of this metric, Circadian Stimulus 2.0., is available [20]. The other mathematical model, developed by Lucas et al. [21,22], only considers the ipRGCs photoreceptors and is based on its photopigment's spectral sensitivity function, melanopsin. The Equivalent Melanopic Lux metric (EML) is derived from this model [22] and has been adopted by the Well Building Standard to assess circadian light. Additionally, the M/P ratio compares the melanopic (ipRGCs photopigment) potential to the light source's ability to produce light for daytime detail (photopic) vision. However, there is no consensus on how to calculate this metric and its current application is not straightforward as there are four different procedures to calculate this ratio [23]. Moreover, an M/P ratio is modified by considering also the photoreceptors that act in scotopic vision, as well as the ipRGCs photoreceptors [24], taking into account rods in the calculation process. This trend also brings about the appearance of the concept of circadian stimulus autonomy (CSA), which determines the percentage of days throughout the year when a suitable threshold of circadian stimulus is met by daylight [25,26].

Nowadays, there are different types of software that calculate the metrics described above independently. One of these types is the CS Calculator 2.0, used for the calculation of the Circadian Stimulus. This online tool was developed by the LRC and the first version of the Calculator is a spread sheet tool. The two variables that must be defined for CS calculation are the SPD of the lighting sources and illuminance values measured at a vertical point. It should be highlighted that this is a calculator, not software integrated into a simulation process, so the results obtained cannot be observed in the building context. In contrast, ALFA (Adaptive Lighting for Alertness) is the main program in terms of EML and M/P calculations [27]. This software for Rhinoceros uses the spectral raytracing method and unlike CS Calculator 2.0 is integrated into a simulation workflow.

Although these circadian light assessment tools allow the calculation of different metrics, they are separate from the rest of lighting simulation or energy performance programs, analyzing different metrics independently, and the integration of all these metrics into a single software program becomes essential. In contrast, major developments are being observed in the field of programs focused on metrics that quantify the influence of light on visual comfort. One of the main advances is the increase in lighting parametric tools. Parameterization allows multivariate complex analyses to be conducted taking into account a considerable number of parameters, allowing the incorporation of optimization procedures (non-linear).

Among parametric tools, Grasshopper is a visual programming language for generative algorithms and one of the main benchmark tools for parametric design [28]. Grasshopper has allowed the lighting parametric workflows from the incorporation of different calculation engines that enable complex and accurate calculation processes in a more efficient way. There are different lighting simulation plugins for Grasshopper such as Climate Studio, Diva, or Ladybug Tools but as all of these are focused on visual comfort and energy efficiency there is no parametric tool that quantifies the effect of light on human health.

1.2. *Aim and objectives*

The aim of this paper is the development and subsequent validation of a new parametric-integrated workflow and subsequent tool to provide an evaluation of the effect of natural and electric light on the melatonin response integrating the different current metrics related to the circadian system. The procedure is applied through a plugin for Grasshopper environment so that it can be integrated into other environmental or lighting parametric tools. This allows the development of a single parametric workflow starting at the room-building model and ending with numerical analysis and graphic representation of the results.

This new program brings novelties to the field of lighting and metrics related to circadian rhythms. Firstly, CircaLight carries out a parametric calculation of these metrics according to a 3D model, which is easier for the architectural designer. Secondly, this software integrates the calculation of the different metrics related with the circadian rhythm, including the new Circadian Stimulus 2.0 [20] and the different methods of M/P calculation, as well as the M/P modified by scotopic function [22,24]. Finally, it allows integration into other lighting simulation tools, contributing to the creation of a single workflow and obtaining lighting values and circadian metrics in a single simulation process.

2. Material and methods

CircaLight performs as a plugin for Grasshopper environment to evaluate the impact of light on circadian rhythms (Fig. 1). It enables the calculation of different metrics related to circadian rhythms such as Circadian Stimulus (CS), Equivalent Melanopic Lux (EML) or Melanopic/Photopic ratio (M/P) under natural and electric light scenarios. The light fixtures that have a direct relationship with circadian rhythms are the illuminance levels and the SPD and must therefore be defined. As the plugin described in this research is not a lighting simulation tool, illuminance levels must be measured using the Radiance engine. While this also occurs in other tools such as CS Calculator, the advantage of CircaLight is that components of lighting simulation tools such as Ladybug or Solemma tools can be integrated into the same workflow as CircaLight components. As for the SPD, the main novelty of the CS Calculator is that this new tool offers the possibility of combining natural and electric light SPD, while also considering the reflectance spectrum of environment surfaces. It has been developed with Visual Studio Software and uses the C# programming language. The validation of the software presented is carried out by comparison with other tools such as CS Calculator 2.0 or ALFA.

2.1. *Workflow*

Fig. 2 represents the proposed workflow for the new components of the CircaLight plugin and the integration of lighting simulation plugins.

Twenty-one components have been developed to support the workflow. These are divided into different groups depending on the workflow stage in which they act, as shown in Fig. 3 and Table 1.

2.1.1. *Model building*

The CircaLight plugin allows for model building in a parametric manner. This ensures a speedier calculation of circadian rhythm metrics as they are measured based on specific parameters which can be changed easily without the need to build a new model. In addition, the parametric model creation is part of a single workflow, unlike other software where the model is created separately and then imported. This means that it is possible to change any parameter in order to modify the values of the circadian metrics. The room

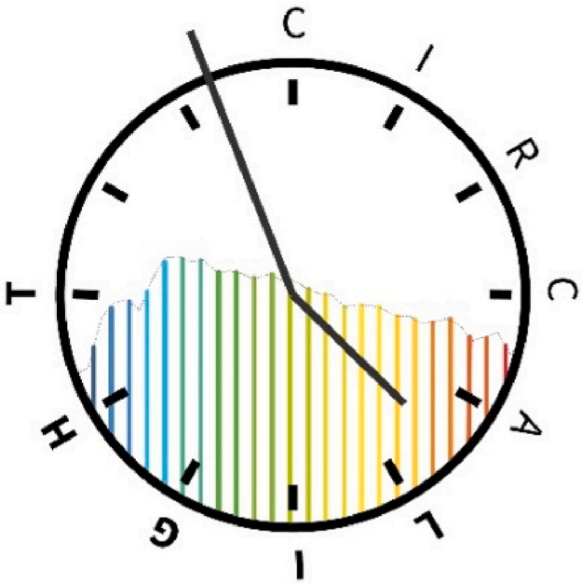

Fig. 1. CircaLight plugin logo for Grasshopper.

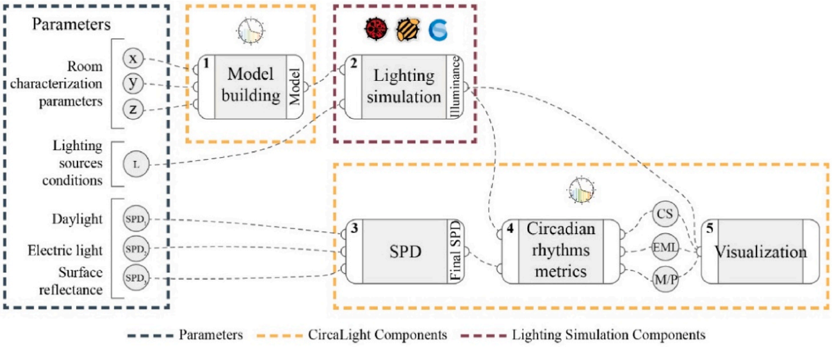

Fig. 2. Workflow.

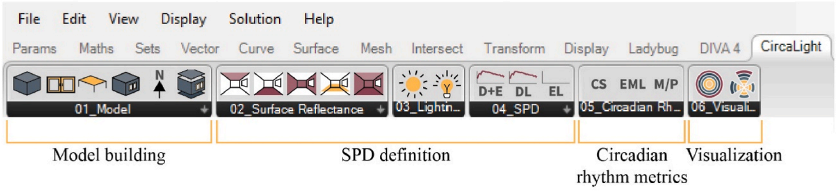

Fig. 3. CircaLight components.

Table 1
CircaLight components related to the general workflow.

Workflow part	Model building	SPD definition			Circadian rhythm metrics	Visualization
Group in the plugin	Model	Surface Reflectance	Lighting Sources	SPD	Circadian rhythm	Visualization
Components	Envelope	Ceiling reflectance	Daylight	Daylight final SPD	Circadian Stimulus	Vertical Results
	Window	Floor Reflectance	Electric light	Electric light final SPD	Equivalent Melanopic Lux	Horizontal results
	Furniture	Walls reflectance		Daylight and electric light final SPD	Melanopic/Photopic	
	Model	Workplane reflectance				
	Orientation	Resulting reflectance				
	Decomposition					

model includes all parameters related to the architectural geometry conception, as well to the capacity to define light properties –materials– for each surface in the model. Location and orientation are also considered in the model definition.

The basic parameters for room definition are physical dimensions, construction element thickness, and window positions and dimensions, including frame and glass characteristics (Fig. 4). The parameters below define the room model.

2.1.2. *Lighting simulation*

As CircaLight is a parametric tool, daylight and electric light simulations are required. The advantage of using a Grasshopper plugin is that any component of other plugins can be easily integrated into the workflow. The Ladybug components, already validated [29], are integrated into the workflow to define the calculation points (Fig. 5).

2.1.3. *SPD definition*

The spectrum of light that reaches the eye of a person is the combination of the spectrum of existing light sources—natural light, electric light, or both at the same time—as well as the influence of the reflectance of the different surrounding surfaces. In this case, the procedure for the resulting spectrum is.

1. Illuminance provided by electric and natural light sources is calculated with the components of lighting simulation plugin, measuring the light perceived in the vertical work plane, at the observer's eyes level.
2. The resulting SPD of electric and natural light sources is calculated considering the SPD of each light source and the spectral reflectance of the environment. These SPDs are combined based on the illuminance determined at each point.

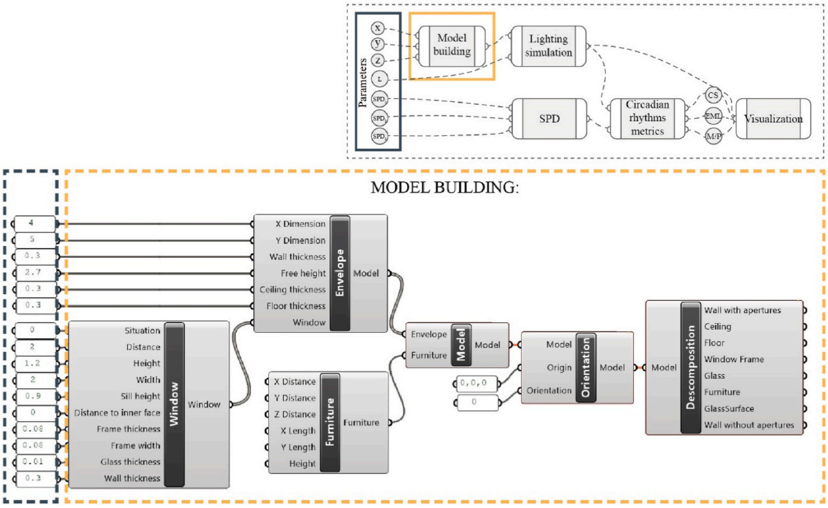

Fig. 4. Model building components and workflow in Grasshopper.

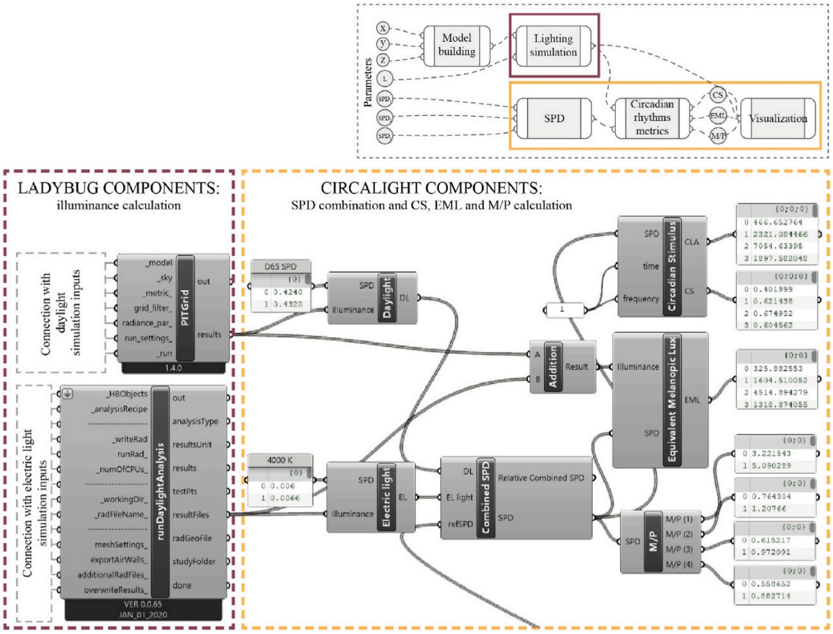

Fig. 5. Integration of Ladybug components with CircaLight components.

3. Once the illuminance value and perceived spectrum are known, the quantification of circadian metrics is conducted—Circadian Stimulus, Equivalent Melanopic Lux and Melanopic/Photopic relation.

This procedure, summarized in Eq. (1), is supported by previous research [26], where the resulting spectra perceived by the eye are determined following a similar protocol; the emitted spectra of the light sources by the average spectral reflectance of the inner surfaces are emitted according to a weighting factor defined by the designer.

$$\int_{380}^{730} SPD_{RES}d(x) = \frac{E_{DAY}}{E_T}\int_{380}^{730} SPD_{DAY}d(x)\cdot\int_{380}^{730} SPD_{REF}d(x) + \frac{E_{ELE}}{E_T}\int_{380}^{730} SPD_{ELE}d(x)\cdot\int_{380}^{730} SPD_{REF}d(x) \tag{1}$$

where SPD_{RES} represents the resulting SPD received by the observer's eye, E_{DAY} is the illuminance provided by a daylight source, E_{ELE} is the illuminance given by electric light, E_T is the total amount of perceived illuminance, SPD_{DAY} corresponds to the SPD of daylight conditions, SPD_{ELE} is the SPD selected for the electrical fixture, and SPD_{REF} is the average spectral reflectance of the environment. This procedure has already been used in other studies analyzing the effect on circadian rhythms of natural light in combination with electric light [30].

For this reason, it is necessary to first define the spectrum of every light source and the resulting reflectance spectrum of the inner surfaces.

- Daylight and electric light: the spectrum of the light source must be entered.
- Average spectral reflectance of the environment: to obtain this spectrum, the reflectance spectra of each inner surface of the room must first be defined: walls, floor, ceiling, and work plane. In addition, the percentage of influence of individual surfaces must be added. This research assumes that the resulting spectra received in the eye of the observer—resulting value, which serves to quantify the CS—, depend on the reflectance of the inner surfaces in accordance with the subtended angle of vision and their surface area, as in Bellia et al. [31]. The influence percentages estimated are: 30% for walls, 10% ceiling, 10% floor and 50% work plane.

2.1.4. Circadian rhythm metrics

This tool allows the calculation of different metrics that quantify the influence of light on circadian rhythms.

- Circadian Stimulus (CS): This is measured using Eq. (2) where CL_A is calculated using the mathematical model by Rea et al. [18,19], which depends on the illuminance measured in a vertical point and the Spectral Power Distribution SPD) of the light sources.

$$CS = 0.7 \cdot \left[1 - \frac{1}{1 + \left(\frac{t * f * CL_A}{355.7} \right)^{1.1026}} \right] \tag{2}$$

- Equivalent Melanopic Lux (EML): This is measured using Eq. (3), where Ev is the vertical illuminance measured at any point and M/P is the Melanopic/Photopic ratio.

$$EML = Ev \cdot M/P \tag{3}$$

- Melanopic/Photopic relation (M/P): there are four different methods to calculate M/P ratio [23]. Although any of these can be selected with the CircaLight method, the two most important ones are:

o Method 3 (Eq. (4)), which is used by the WELL Standard [32] and normalizes the distinct functions to a total area under each curve of 1 radiant watt when evaluating an equal energy spectrum.

$$\frac{M}{P}(3) = \frac{\int \left(SPD_{RES}(\lambda) * M(\lambda) / \int M(\lambda) \right)}{\int SPD_{RES}(\lambda) * V(\lambda) / \int V(\lambda)} \tag{4}$$

oMethod 4 (Eq. (5)), which is recommended by the CIE and is similar to method 3, except that it uses the standardized CIE daylight spectrum (D65) instead of using an equal-energy spectrum to calculate the area under each sensitivity curve. This is probably the most useful method as it quantifies relative to D65.

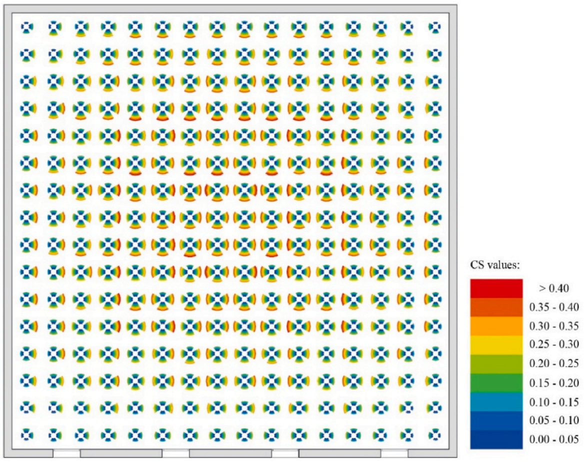

Fig. 6. An example of vertical illuminance values measured in four directions.

$$\frac{M}{P}(4) = \frac{\int (SPD_{RES}(\lambda) * M(\lambda)) * 4215}{\int SPD_{RES}(\lambda) * V(\lambda) * 4215} \tag{5}$$

o Moreover, Berman et al. [24] developed a ratio modified by also considering the photoreceptors that act in scotopic vision (Eq. (6)).

$$\frac{M}{P}(mod) = \frac{\int (SPD_{RES}(\lambda) * S(\lambda)) * 0.041212}{\int (SPD_{RES}(\lambda) * V(\lambda))} + \frac{\int (SPD_{RES}(\lambda) * S(\lambda)) * 0.45827}{\int (SPD_{RES}(\lambda) * V(\lambda))} - 0.07428 \tag{6}$$

2.1.5. *Visualization*

As regards visualization, there are two components that allow the results of horizontal metrics such as illuminance in the work plane or vertical metrics results like CS, EML or M/P to be visualized. This makes it possible to have spatial vision of the results obtained, as in Fig. 6.

2.2. *Validation*

A validation of its accuracy is developed to ensure the actual feasibility of the method with the different metrics assessed by the plugin. A prototypical case study is chosen.

2.2.1. *Case study*

A virtual room model is built with a dimension of 4 m × 5 m, a height of 2.70 m and a 1.2 m × 2 m window on the south façade, corresponding to a typical office. Inner surfaces have a reflection of 0.80 for the ceiling, 0.60 for walls, and 0.4 for the floor. There are twelve calculation points arranged in a 1 m × 1 m grid. The room model and calculation points are represented in Fig. 7.

The lighting source conditions are the following.

- Daylight conditions: a standardized CIE daylight spectrum (D65) is used in the simulation with the spectrum represented in Fig. 8. The illuminance and circadian rhythm metrics are calculated at 11.00 a.m. on June 21st. 11 a.m. was selected because the lowest levels of melatonin are achieved around this time, although melatonin suppression starts early in the morning.
- Electric light conditions: luminaries with a constant luminous flux of 4100 lm and a CCT of 4000 K are used as electric light source (no flux regulation). The spectrum is shown in Fig. 8.

2.2.2. *Circadian stimulus*

To assess the accuracy in CS calculation, results achieved are compared with those derived from the CS Calculator 2.0 developed by the LRC. It should be noted that as CS Calculator 2.0 does not consider the influence of the inner surface reflectance, it is also excluded from this calculation with CircaLight for the comparison. Fig. 9 shows the CS on the left vertical axis while relative error is reflected on the right vertical axis. CS is measured in the four directions in every calculation point, placed on the horizontal axis, so that each direction value is represented with different lines.

CircaLight CS values are close to those of CS Calculator 2.0 since the average relative error is 2.35%, while the maximum error is 4.33%. The difference can be attributed to slight differences in the spectral functions of the photoreceptors introduced in the CS equation, depending on the wavelength range used.

The calculation speed compared to the one typical of CS Calculator, where the illuminance value of each calculation point must be entered manually, should also be highlighted. In CircaLight all calculation points are calculated simultaneously by connecting the component with the illuminance results component, avoiding manual entries, and thus further reducing the risk of unintentional errors. The procedure allows the calculation not only of different points at the same time but also at separate times of day and on different dates, so that it is possible to calculate all the hours of an entire year at the same time, and CircaLight thus becomes an effort multiplier tool.

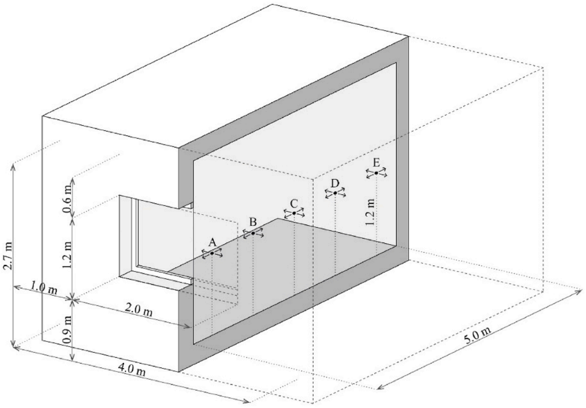

Fig. 7. Room model and calculation points.

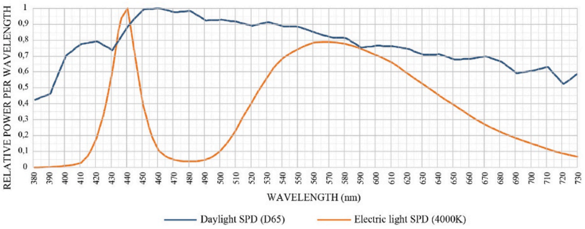

Fig. 8. Spectral Power Distribution of the different light sources.

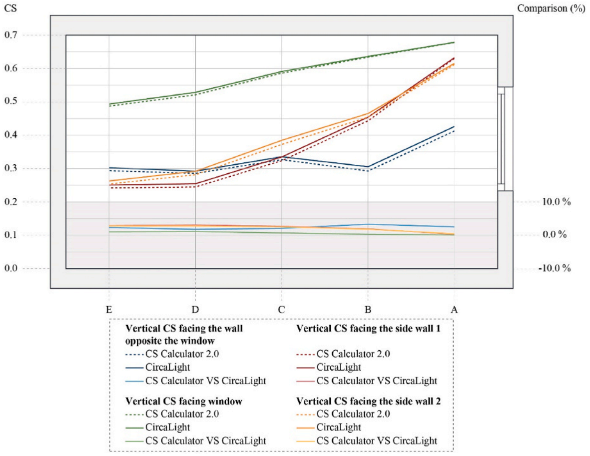

Fig. 9. Assessment of the CS obtained by the CS Calculator and CircaLight.

2.2.3. *Equivalent Melanopic Lux*

To evaluate the accuracy in EML calculation, results are compared with those achieved using ALFA. Fig. 10 shows the EML on the left vertical axis while relative error with respect to the validated software ALFA is symbolized on the right vertical axis. As with CS results, EML is measured in the four directions in every calculation point, placed on the horizontal axis, so that each direction value is represented with different lines.

As represented, EML values achieved by CircaLight closely match those resulting from ALFA with an average relative error of 6% and a maximum of 9.95%. This difference is due in part to the measured illuminance values. Due to the specific ALFA calculation method where not only EML is calculated but also vertical and horizontal illuminance, illuminance levels are also measured separately. CircaLight uses lighting simulation plugins such us Ladybug or Solemma tools – already validated – integrated into the same workflow. Due to the different processes followed, some variation in the results can be expected.

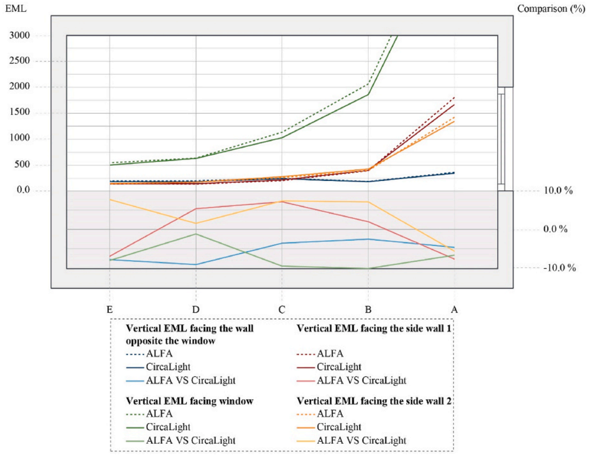

Fig. 10. Assessment of the EML obtained using ALFA and CircaLight.

2.2.4. Melanopic/photopic ratio

M/P is validated using ALFA software. As was the case with EML, ALFA only calculates M/P using method 3, as used by the WELL Standard. This means that M/P method 4—defined by the CIE—and the modified M/P cannot be compared with other procedures, given the lack of previous software to contrast the results obtained with the metrics mentioned and only an analytical approach can be applied. Fig. 11 shows the M/P on the left vertical axis, while relative error with respect to the validated software ALFA is symbolized on the right vertical axis. As seen previously, M/P is measured in the four directions at every calculation point, placed on the horizontal axis, so that each direction value is represented with different lines.

The average relative error is again 6% while the maximum is 9.86%. As can be seen, the accuracy of CircaLight in M/P replicates that of EML calculation since the EML depends on M/P results.

3. Results

A real case study was developed to show its applicability. This case study is based on an ICU at Virgen del Rocio Hospital in Seville due to the specific characteristics of shift work for caregivers and typical chronoregulation disorders associated with this kind of unit [9]. The space consists of two different areas: a box area where the patients are located and another central control area where the care personnel are located (Fig. 12).

The aim of this application is to evaluate the influence of lighting on circadian rhythms by calculating one of the circadian metrics, the Circadian Stimulus (Cs), as an indicator. Analysis is developed both with natural light alone and with daylight in combination with electric light. The lighting source conditions are as follows.

- Daylight conditions: a clear sky (CIE 12) is used in the simulation. The illuminance and circadian rhythm metrics are calculated at 11.00 a.m. on June 21st. 11 a.m. was selected since the lowest levels of melatonin are achieved around this time although melatonin suppression starts early in the morning [33].
- Electric light conditions: luminaries with a constant luminous flux of 4100 lm and a CCT of 4000 K are used as electric light source.

As the ICU space consists of several different areas a set of calculation positions have been defined to measure illuminance and Cs values.

- Boxes area: two groups of calculation points were established according to the possible positions of the patients:

o Patient completely lying on the stretcher: horizontal illuminance values are measured at a height of 0.90 m (Position 1 in Fig. 13).
o Patient partially sitting on the stretcher: illuminance values are measured at 1.40 m and at 45° above the horizontal (Position 2 in Fig. 13).

- Control area:

o Nurse working in a seated position: vertical illuminance values are measured at 1.20 m (Position 3 in Fig. 13).
o Nurse working standing up: vertical illuminance values are measured at 1.55 m (Position 4 in Fig. 13)

The CS values obtained in the different positions for patients and nursing staff and in the different seasons of the year are represented in Fig. 14 and Fig. 15. Values are on the vertical axis and ICU depth is represented on the horizontal axis. In addition, the minimum CS threshold of 0.3 established by the LRC to achieve a suitable synchronization of circadian rhythms in hospital personnel has been represented with the red horizontal line [34]. This value of 0.3 is achieved with an approximate illuminance level of 200 lx with a D65 sky or 300 lx with a led luminaire with a neutral CCT of 4000 K. Therefore, reaching that value of 0.3 the general minimum illuminance conditions recommended for ICUs of 100 lx are also reached [35]. The results obtained with only natural light appear in Fig. 14 and those achieved through the combination of natural and electric light are found in Fig. 15.

In the boxes where the patients are located, the CS values exceed the threshold to synchronize the circadian rhythms only with natural light (Fig. 14), whether the patient is lying down or sitting up. Although circadian stimulus is reached in all situations, the values observed in the boxes with windows facing south are higher than in north-facing ones and in the lying position. In boxes with a south orientation, CS values are almost 0.1 higher than in north-facing ones in winter and spring/autumn but similar values are achieved in summer. Regarding the position of the patients, CS values are higher in the lying position during the entire year.

However, in the central control zone, daylight alone does not result in a suitable level of CS and the proper regulation of the circadian rhythms of the care staff at all points in space cannot be ensured. Thus, the participation of electric lighting is required. Fig. 15 shows that with a luminous flux of 3900 lm, an intensity of 70% and a CCT of 4000 K, the minimum CS value required to promote a good circadian rhythm is reached throughout the entire space. In both figures, it can also be seen that similar values are obtained in the two different positions of the nurses, sitting and standing. Although the 0.3 value is commonly accepted as a CS threshold, and was therefore adopted for the case study application, following some advances the option of increasing it to 0.4 for noticeable effect is currently being discussed. This in turn would result in the analysis being more limiting in terms of geometry so that a higher contribution of electric light will be required.

4. Conclusions

This work develops a comprehensive workflow for quantifying the influence of light on human health, allowing the different metrics involved in the assessment of circadian rhythms to be calculated. These metrics —Circadian Stimulus, Melanopic Photopic ratio and Equivalent Melanopic Lux— can be calculated in a unified procedure which requires an important effort —both on modelling

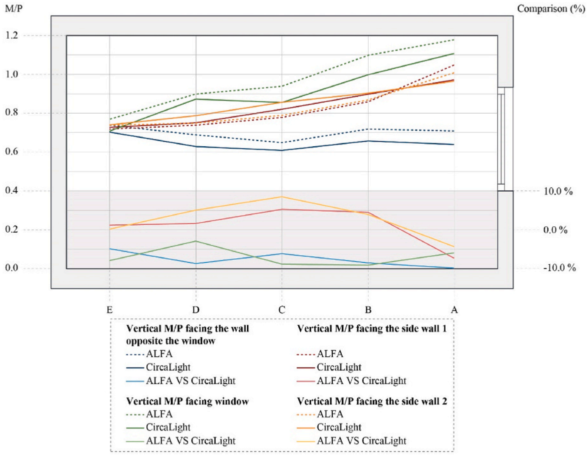

Fig. 11. Assessment of the EML obtained using ALFA and CircaLight.

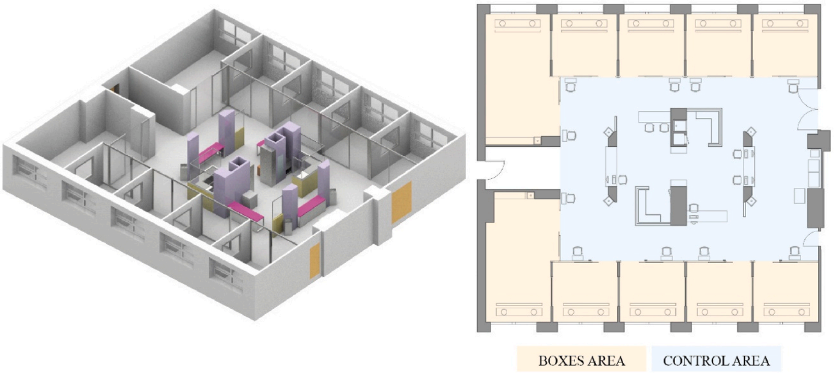

Fig. 12. Plan and model of the Traumatology intensive Care Unit.

Fig. 13. Positions of calculation points.

and computing work— and thus allows a more complete and affordable analysis of actual indoor spaces, under different operational conditions. The parametric tool allows a multicriteria analysis with the potential to integrate multiple variables into the assessment.

While this tool presents advantages compared to previous procedures there are also some limitations to be considered. In terms of CS calculation, CircaLight entails lower calculation times with the possibility of calculating multiple points with different directions, and this is repeated for every timestep throughout the year at the same time. As a comparison in the general CS Calculator method, every CS value is calculated independently, and illuminance values must be entered manually. In addition, reflectance of inner surfaces is taken into account in CS calculation as well as in the calculation of the rest of the metrics. However, this inner surface reflectance is introduced as a resulting average reflectance. This is a limitation compared to ALFA software for EML and M/P ratio calculation. Despite this, the relative error is within the range of ± 10% for both tools. A new step provided is the calculation of the different M/P ratios from the different models that currently exist. It should also be noted that the new plugin allows the model building in the same workflow whereas typical previous procedures need to be created separately.

As this procedure is developed as a plugin for Grasshopper it presents the advantage of continuous evolution and can be improved with the creation of new components. Future research lines could allow a more adapted evolution of the software and reduce its limitations, such as the calculation of dynamic metrics like Circadian Stimulus Autonomy (CSA) according to the variation of the SPD, as well as the integration with electrical lighting control systems into the workflow. Moreover, in future research this tool will be used

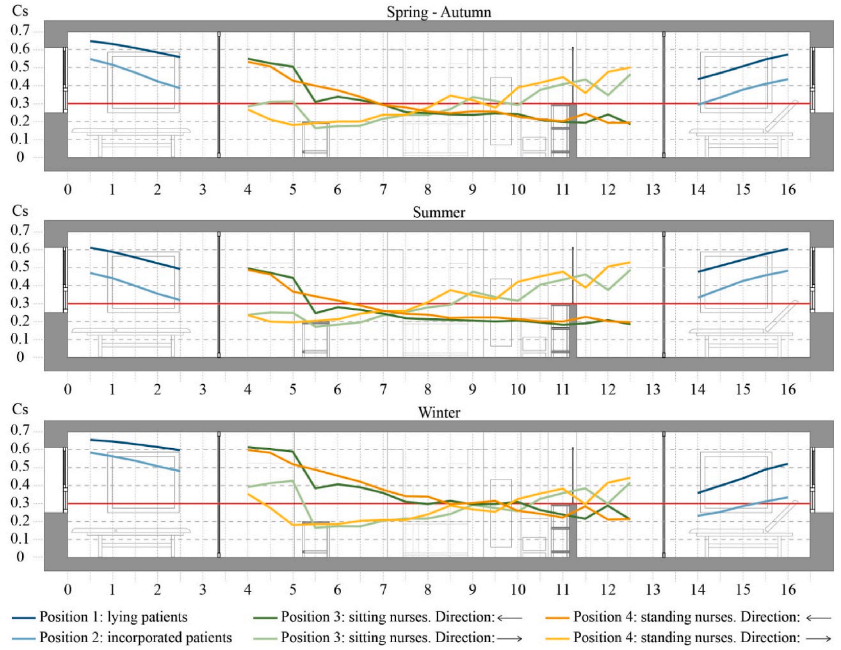

Fig. 14. Circadian stimulus promoted by natural light.

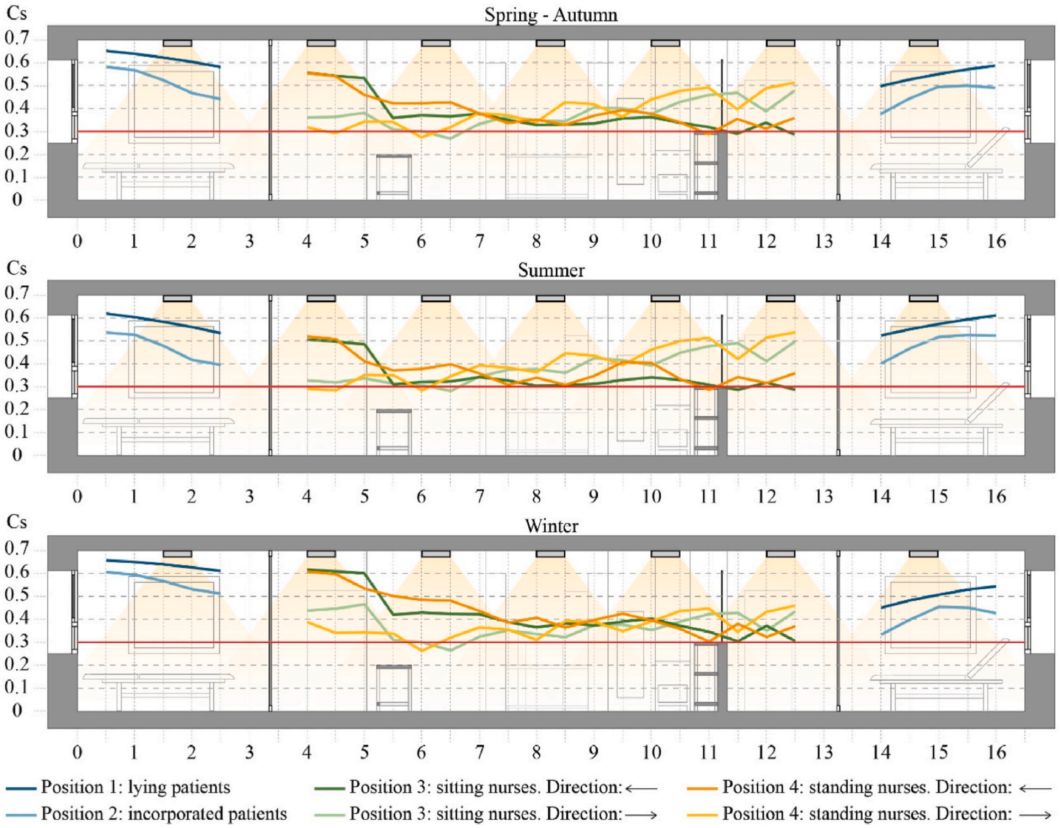

Fig. 15. Circadian stimulus promoted by the combination of natural and electric lighting.

in a practical way in real buildings for lighting design.

Credit author statement

María Teresa Aguilar-Carrasco: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing-Original Draft, Visualization. **Ignacio Acosta**: Supervision. **Samuel Domínguez-Amarillo**: Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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