# M4.4 Report on modeling procedures for non-visual comfort

WP4. Modeling, T4.4

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# 1 Introduction

This report covers the investigations within FACEcamp ITAT1039 in the field of non-visual comfort modelling for modern facades. Within work package 4, different modelling procedures including energy and daylight simulations (visual and non-visual) are analyzed and combined in a FACEcamp modelling toolchain, which provides a bundle on tools for an integrative evaluation of complex façade systems. To address the aspect of non-visual effects of daylight, two available software tools, LARK and ALFA, have been analyzed and integrated into the toolchain.

This report gives an overview on the state of research and knowledge of non-visual effects of daylight as well as the established models and methods to quantify them. These results will contribute to the development of standardized methods and design tools as well as an interchangeable data structure between those tools. The outcomes are also catalyzer for further investigations in deriving a generally accepted and standardized characterization scheme for complex façade systems, which will be integrated in the consulting portfolio of the façade competence center.

The following steps were implemented towards a non-visual characterization of daylighting systems and will be described in detail within this report:

- State of Research and Fundamentals in non-visual effects of daylight
- State of research regarding modeling approaches
- Evaluation of existing international regulations and standards
- Evaluation of existing software tools: screening and comparison
- Integration into the FACEcamp toolchain
- Summary and outlook for further research

# 2 Aspects of non-visual effects of daylight

## 2.1 Daylight and health[1]

Since human-beings are diurnal creatures, they have always been dependent on the presence of daylight and have developed physiological signaling pathways (e.g. the circadian system) for adapting their body functions to their living environment, especially the time of day.

Light entering our eyes does not only provide visual information, but also delivers important non-visual information regulating the activity of several body systems. We are therefore differentiating the physiological effects of light from visual effects, also called image-forming effects of light, and non-visual effects of light, also called non-image forming effects of light.

While visual perception is induced by rods and cones only, non-visual perception is supposed to be mediated by rods, cones and the ipRGCs (intrinsic photosensitive ganglia cells). The character and amount of physiological reaction caused by light via non-visual pathways depends on several influencing factors, either concerning lighting conditions (e.g. amount of light, spectral composition of light) or the individuum itself (e.g. circadian phase during light exposure, amount of sleep, homeostatic sleep drive). Furthermore, other zeitgeber (social interaction, eating...) are important as well as individual chronotype, genetic profile, age and the overall health condition. Finally, light history (light exposure in the last several hours) plays an important role in modifying non-visual light effects as well as time and duration of light exposition, especially regarding the individual circadian phase.

Non-visual effects of light are affecting numerous body systems (e.g., cardiovascular, endocrine, and metabolic system). Besides an immediate regulation of physiological reactions such as the pupillary reflex, light modulates the autonomous nervous system and the secretion of several hormones including melatonin (the so-called sleep hormone), via complex neurological pathways (see figure 1). We are now gaining increasing knowledge about how light can acutely regulate alertness, and in the long run alter mood and modify circadian rhythm parameters including sleep and wakefulness.

## 2.2 Melanopsin and the circadian rhythm

Since the discovery of the photopigment melanopsin in the human retina, which reacts photo-chemically to a maximum of short-wavelength radiation around 490nm, intensive global research has begun to elucidate non-visual effects of light in humans. Since then, experts from a wide range of research areas (e.g. endocrinology, chronobiology, physiology, oncology, epidemiology, neurology, psychiatry, occupational medicine, psychology, lighting engineering, ergonomics, physics) have been intensively trying to determine acute and long-term effects of light on neurophysiological, endocrine, cognitive and mood-related parameters.

The circadian rhythm, colloquially also called day / night rhythm, describes a biological mechanism in humans that allows to anticipate certain events, e.g. sunrise, mealtimes, sleep times etc., and start biological processes in advance that are tailored to these events. As such, the circadian system largely controls the sleep-wake rhythm and physical activity in general. Since the circadian system has a period length of roundabout 24 hours (in order to be able to adapt more easily to changing environmental conditions), this system requires daily environmental (timer) stimuli (so-called Zeitgeber) that constantly adjusts the internal physiological system to the environment. The most important Zeitgeber for humans is light (since earth's rotation speed was constant over millions of years and thus acted as a reliable environmental time marker). In Fig. 1, the physiological pathways of phototransduction to calibrate the circadian rhythm (located in the suprachiasmatic nuclei, short SCN) and trigger alerting and reducing sleepiness effects (mainly responsible for these effects are a thalamic nucleus, the ventrolateral pre-optic nucleus, shortly VLPO, a brainstem nucleus, the locus

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[1] Lighting Europe (2015). Quantified benefits of Human Centric Lighting. https://www.lightingeurope.org/presentations/180-quantified-benefits-of-human-centric-lighting-april-2015

coeruleus, shortly LC, and the pineal gland which excretes melatonin during the typical sleeping period) are shown.

It is known that the human circadian system can be disturbed by too little light during the day or too much light exposure during the typical sleep phase. Typically, this mistimed light exposure occurs, in shift workers with strongly changing sleep/wake times, or in blue-collar workers during winter months due to lack of daylight.

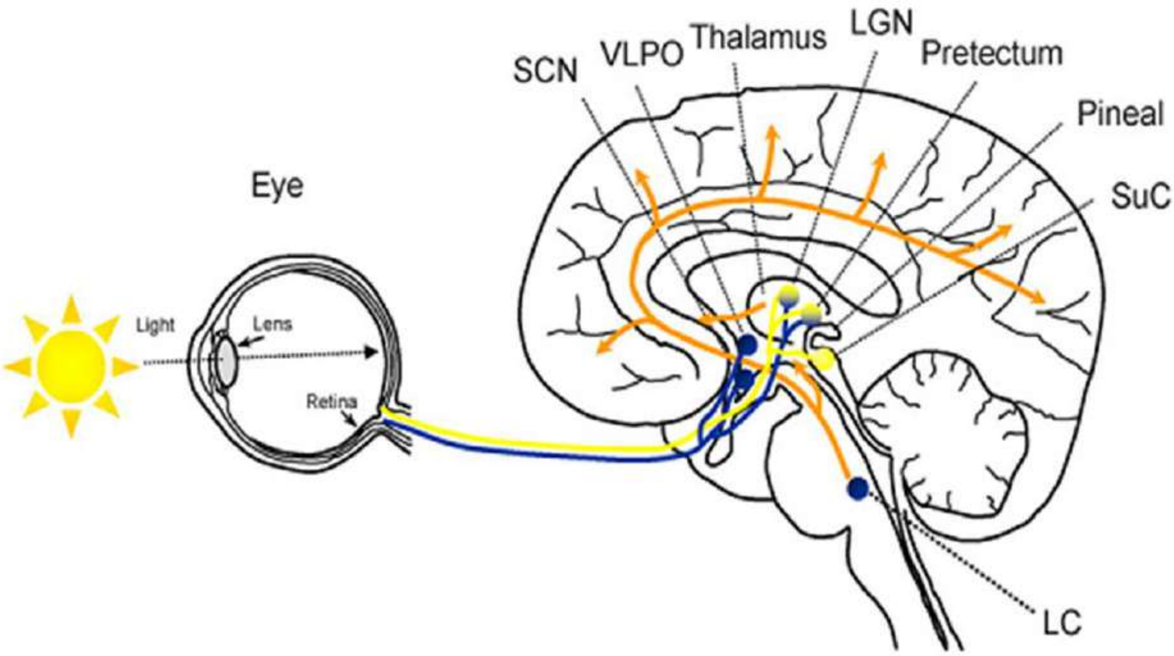



***Figure 1: Light-induced activation of areas of the brain associated with specific non-visual effects***

## 2.3 Quantifying non-visual light effects concerning human health

In contrast to visual perception as an immediate reaction of absorbing photons, non-visual effects of light are far more complex - resulting from an interaction of numerous neuronal pathways and nuclei. They are depending on up- and downregulations of many body systems. Predominantly, non-visual effects can be measured within seconds, to minutes and days after light exposure started and last even after light exposure ended. So, how can non-visual light effects be measured or quantified?

The last decade, mainly acute night-time light effects on suppression of melatonin excretion were utilized to quantify non-visual effects of light in human beings. However, acute non-visual night-time light effects may not be extrapolated to non-visual daytime light.

Compared to the human light sensitivity curve V( λ) (see figure 2), which allows to quantify visual perception based effects of light on integrated receptor sensitivity (i.e. middle- and long wavelength cones), night-time melatonin suppression is highly individual, dependent on internal (health) and external (environmental) conditions and has no linear additive effects.

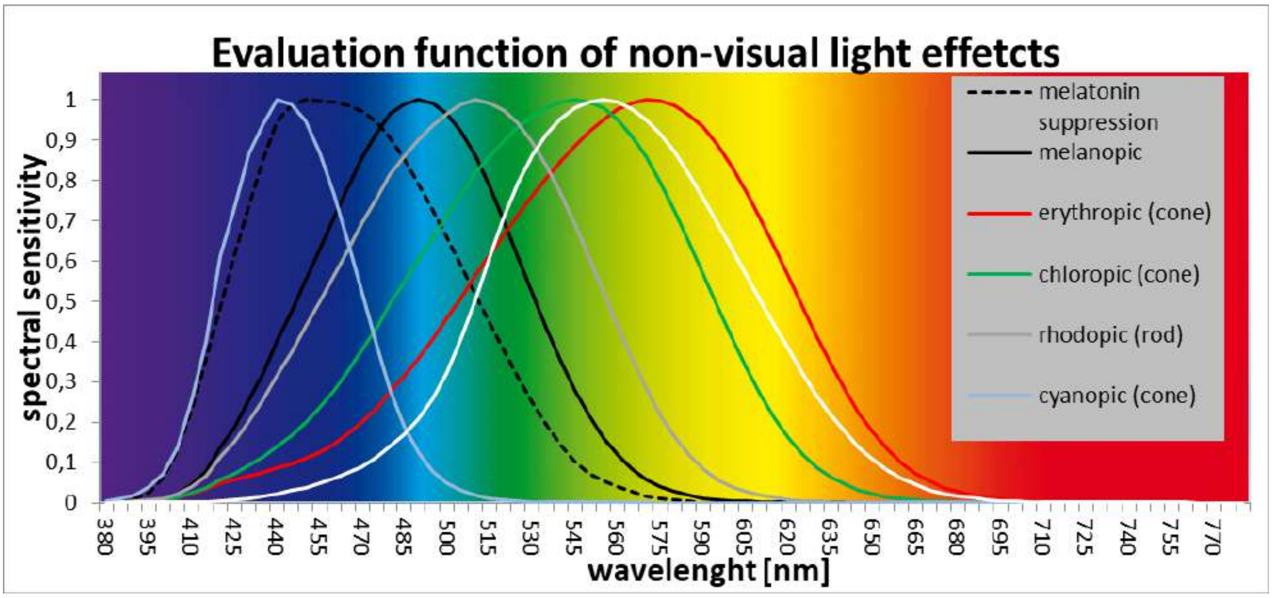



***Figure 2: Absorption spectra of the human cones and rods; additionally the action spectra of acute nighttime melatonin suppression and the photopigment melanopsin and the human light sensitivity curve (V(λ)) are shown. Source: DIN 5031-100 (2009)***

In the last years, a paradigm shift occurred in quantifying non-visual light effects. Today, the spectral sensitivity of the photopigment melanopsin, with a maximum at 479nm, is utilized to measure the potency of light to trigger non-visual effects.

Thus, currently photometry of visual as well as of non-visual effects is based on human receptor sensitivities. Still, our knowledge is limited today to assess light-related alterations of different complex and multifactorial body functions. Although state of the art photometry is quite helpful in predicting and measuring light effects on the visual system, state of the art modelling approaches in non-visual light effects are in their infancy.

# 3 Circadian daylight models and metrics

Until nowadays, standards and interior lighting design practices are based on visual needs (i.e. to perform visual tasks) but included no recommendations for lighting designs to trigger non-visual effects on human beings. In the last century, scientific research increased efforts to explore non-visual effects of light. As a matter of fact, it was proven that circadian entrainment is influenced by the timing, intensity, duration and wavelength of light exposure and depends on the light exposure history.

Through a growing body of research, it was shown that classical human photoreceptors (i.e., cones and rods) act in dual manner both enable visual perception and synchronize the internal circadian body clock (Lockley,2009). A technical memorandum has been prepared by the Illuminating Engineering Society (IES) to provide a comprehensive overview of non-visual impacts within architectural lighting that include circadian, neuroendocrine, and neurobehavioral responses in building occupants (Figueiro et al, 2008). Many aspects of human’s daily living (such as sleep/wake cycles, alertness, core body temperature fluctuations, and production of melatonin and cortisol) are influenced by the circadian system. Although some mechanisms of non-visual responses to light are partially well investigated and consolidated, several (quantitative) models on non-visual light effects have been proposed to date.

Based on these investigations, three approaches can be differentiated:

1) Models based on **acute night melatonin suppression** (outdated approach)

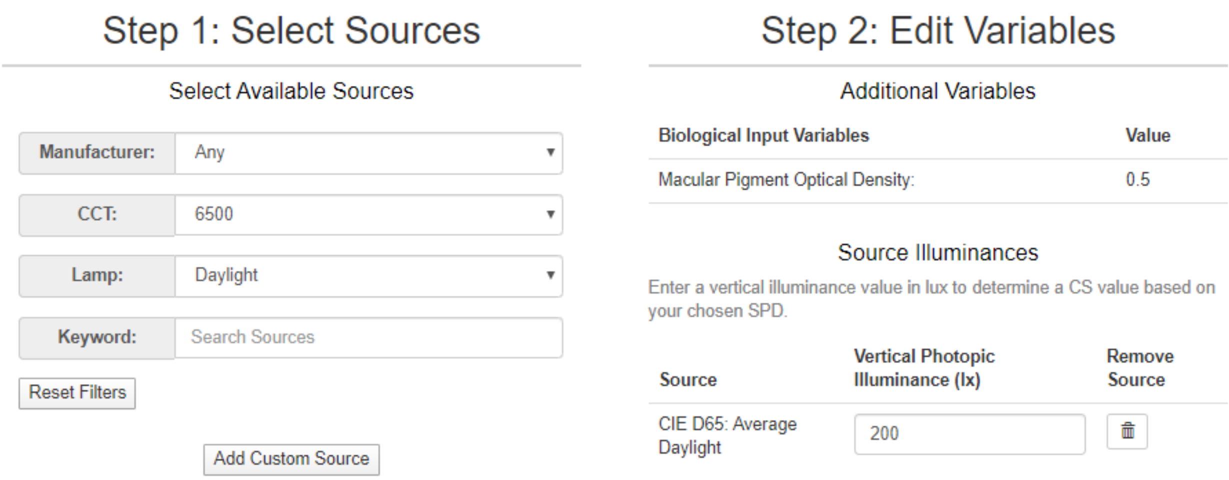
2) Models based the **spectral power distribution** (SPD) and weighted by the **melanopsin sensitivity curve** (state of the art according to CIE) – nevertheless, this approach does not consider the intensity of the radiation at all

3) **Dose model** for stabilizing the circadian system (Increasing the amplitude of circadian rhythms, reducing the sensitivity to adverse light exposure at night)

## 3.1 Circadian stimulus

Several efforts have been taken in the last 20 years to establish a consolidated model for estimating circadian light effects. Rea et al (2012) proposed one model based on the spectral sensitivity of the circadian system (i.e. melanopsin), rods and short-wavelength cones, which can be used to relate different spectral power distributions (SPDs) from various light sources and intensities at eye level to a stimulus effect (e.g. acute nocturnal melatonin suppression). By means of this model a circadian stimulus effect from 0 to 0.7 (i.e. 0% to 70% nighttime melatonin suppression) can be derived from a given SPD and intensity at eye level, which characterizes the relative effectiveness of a light scenario in nighttime melatonin suppression during 1-hour light exposure. For this purpose, an online circadian stimulus calculator is provided (https://www.lrc.rpi.edu/cscalculator/) (see Fig. 3) to derive the circadian stimulus (CS). For instance, daylight (D65) with 200 lux at eye level generates a circadian stimulus of 0.32 (32% nighttime melatonin suppression after 1-hour light exposure).

The Recommended Practice and Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People (UL RP 24480,), applies thresholds based on CS (see chapter 4.3).



Combined Source Value Metrics

| Measurement | Value |
|---|---|
| CS: | 0.320 |
| $CL_A$: | 304.44 |
| Illuminance (lx): | 200 |
| Irradiance ($W \cdot m^{-2}$): | 8.8995e-1 |
| Photon Flux ($Photons \cdot m^{-2} \cdot s^{-1}$): | 2.4521e+19 |
| CCT: | 6501 |
| $D_{uv}$: | 0.003 |
| CRI: | 100.0 |
| GAI: | 97.5 |
| Color Coordinates (x,y): | 0.31, 0.33 |
| Relative Spectral Power Distribution: | (SPD) |
| Absolute Spectral Power Distribution: | (SPD) |

***Figure 3: Interface of the circadian stimulus calculator***

## 3.2 Spectral efficiency function (Equivalent melanopic lux / Equivalent daylight illum.)

Alternatively, Lucas et al. (2014) proposed a metric based solely on the melanopic spectral efficiency function following the concept of melanopic illuminance introduced by (Enezi et al. 2011; i.e. they relativize photopic and melanopic illuminance levels with the spectrum of equal energy [CCT of 5455 Kelvin]; consequently, 1000 (photopic) lux with this spectrum equals 1000 melanopic lux). Also, for this approach, a publicly available calculator can be downloaded under:

http://lucasgroup.lab.manchester.ac.uk/measuringmelanopicilluminance/.

By applying the model equivalent melanopic illuminance levels (EML) of various light sources can be calculated. However, by applying this model and calculating melanopic illuminance levels no specific non-visual light effects, such as night-time melatonin suppression, can be estimated but the general potency of the light stimulus to generate non-visual light effects can be determined. The Recommendations made in the Well-Being Building Certification applies thresholds based on EML (see chapter 4.2).

Similarly, the recently introduced metric melanopic EDI (Equivalent Daylight Illuminance) by the CIE S 026/E:2018 bases on the same approach using a spectral efficiency function (see chapter 4.4).

## 3.3 Bartenbach-model (2019)

The research team of Bartenbach recently established an alternative light-dose model to quantify non-visual light effects based on the actual state of knowledge regarding light therapy. This model primarily targets the stabilization of the circadian system which is thought to be an important factor of human health.

The model distinguishes between daytime and night-time light exposure settings.

**Daytime light exposure (typically between awakening in the morning till 2-3 hours before habitual sleeping onset):**

- Light colour (of the light source): 4000-5700Kelvin

- optimal daily light dose: 5000 lux-hours (equivalent to the recommended light dose in light therapy)
- max. illuminance at eye level during the day 1000 lux (to avoid visual impairment)

**Nighttime light exposure (2-3 hours before habitual sleep onset – evening - till morning awakening):**

- residential environment (evening/night): Ev, eye ≤ 50 lx / ≤ 10 lx at CCT(Eye)=2100 – 2400K
- working environment (during the night): Ev, eye ≤ 150 lx at CCT(Luminant) ≤3000K

In Fig. 4, achieved equivalent daylight illuminances are shown in correlation to the vertical illuminance at eye level and different spectral distributions (blue, cyan, D65) and colour temperatures.

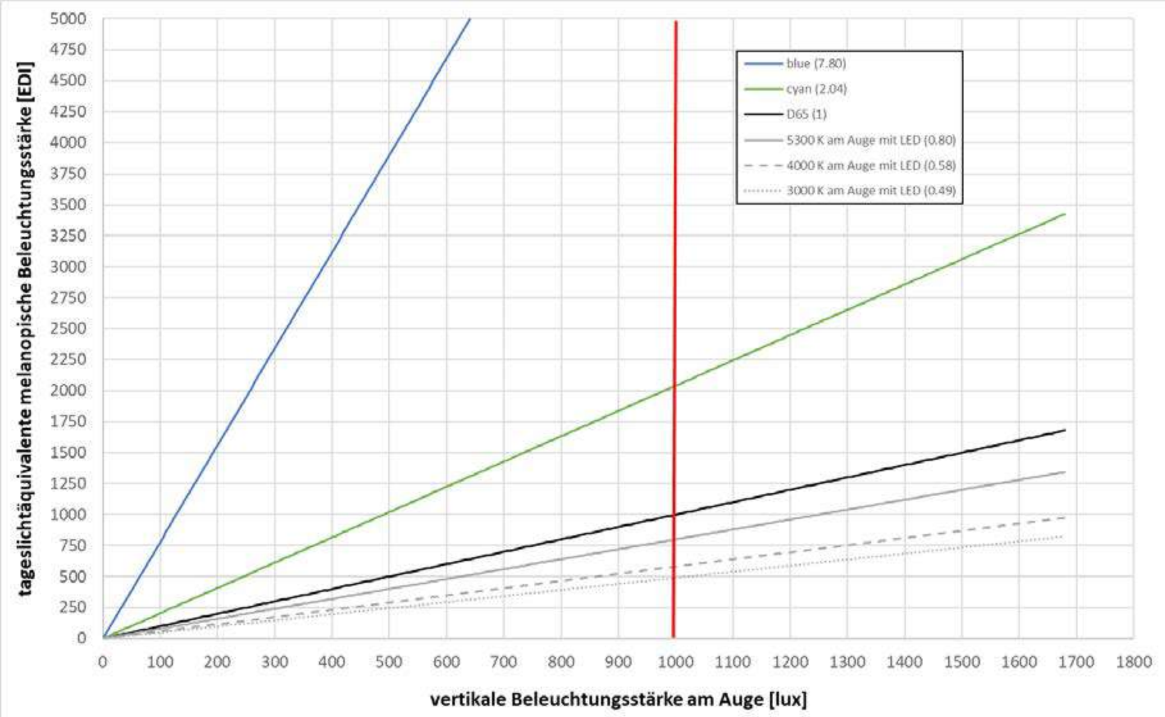



***Figure 4: Vertical illuminances on eye level required to reach certain EDI-values for different spectral distributions and CCTs***

Compared to international specifications (e.g. UL-Recommendations) for vertical illuminances (250 - 500 lux for 2 Hrs), the recommendations of Bartenbach are clearly higher in absolute values (600 – 700 lux for the whole day) and less restrictive in day times.

## 3.4 Alternative approaches

Furthermore, researchers tried to propose new approaches presenting a more holistic assessment on a given lighting condition. The research group of Andersen at EPFL developed such unified framework to evaluate non-visual spectral effectiveness of light, which also incorporates a lens transmittance model to account for the relative loss in retinal exposure due to the age of the observer. (Amundadottir et al. 2016).

The developed framework compares the non-visual spectral effectiveness of various light spectra in terms of melatonin suppression, melatonin phase shift and perceived alertness.

# 4 Development of Design guidelines

Although several models and metrics are developed and standards published in recent years, there is no scientifically based consensus for the appropriate minimum light exposure threshold to effective circadian lighting or for how long the exposure duration must be. The knowledge on biological effects of light are based on limited data, mainly from studies conducted during the night under highly controlled laboratory conditions and in disciplines of neuroscience and photobiology. Translating results from these studies into useful metrics and figures for lighting designers is not possible today. Nevertheless, there exists a growing interest to provide guidance by developing applicable guidelines for circadian lighting design.

Since the discovery of the ipRGC receptors, several recommendations have been published to quantify non-visual light effects. The following figure depicts in chronological order the introduction of new benchmarks for circadian lighting designs established by the DIN (SEPC 5031-100) and the CIE (TR 16791).

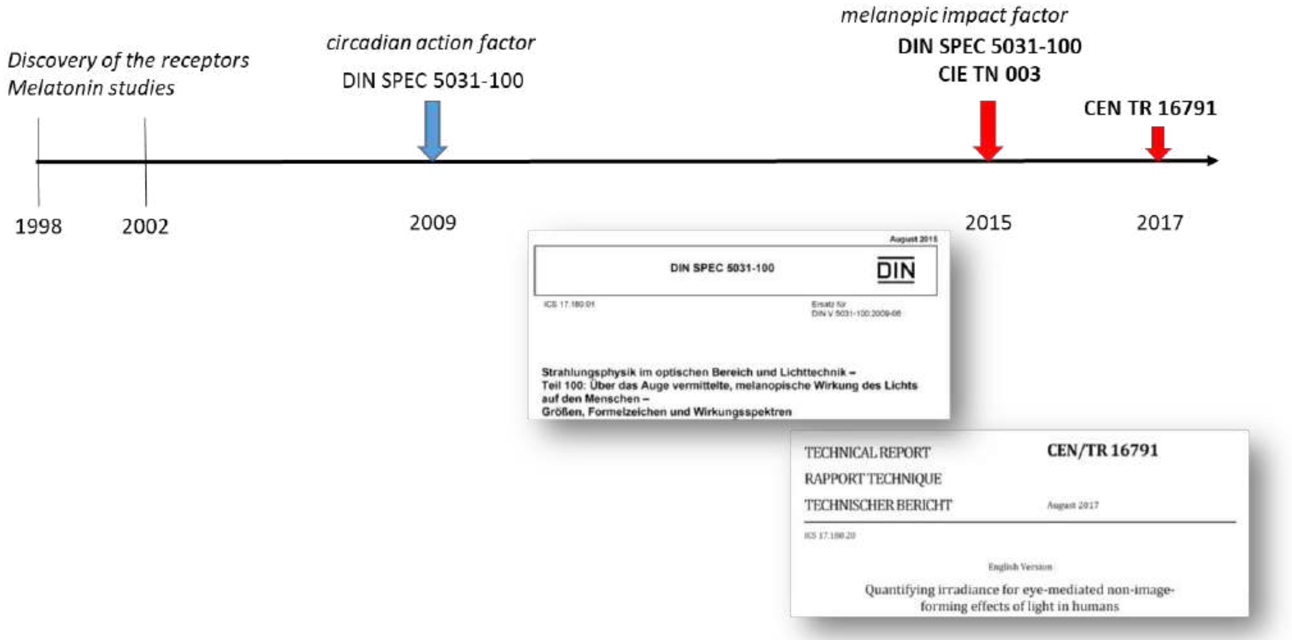



***Figure 5: Benchmarks to evaluate non-visual light effects***

In general, non-visual lighting design should always integrate available natural daylight, which is an attractive alternative to electrical lighting maintaining human circadian entrainment due to its intensity (at least when staying nearby windows) and spectrum. Therefore, design recommendations should be based on following main criteria:

- Melanopic – daylight equivalent illuminance levels
- Daytime of light exposure
- Duration of light exposure

Enabling designs that ensure the delivery of an appropriate light spectrum, timing, light intensity and duration of light exposure to maintain circadian entrainment requires a new set of performance objectives. Based on the above-mentioned benchmarks, different design recommendations have been developed, which are shown in their chronological timeline of publication in Fig. 5.

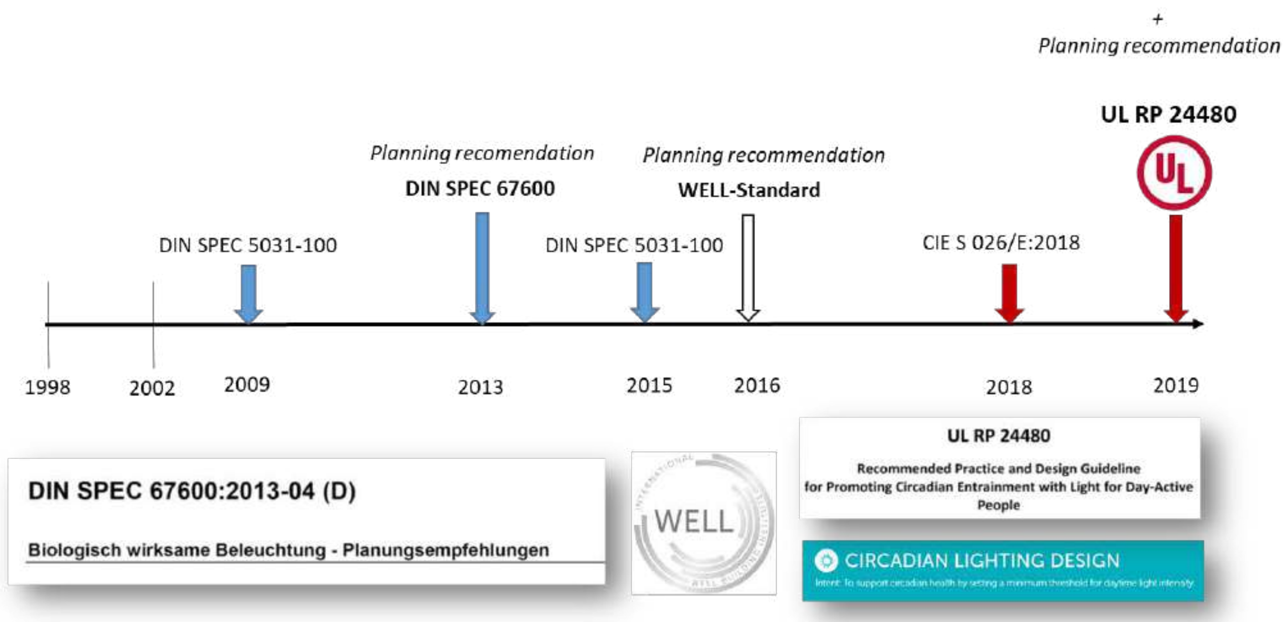



***Figure 6: Overview on published planning recommendations within the last years***

## 4.1 DIN SPEC 67600

In 2013, a first recommendation was provided in Europe by the **DIN SPEC 67600** as a guideline for melanopic lighting, which utilized measures and terminology of DIN SPEC 5031-100 (2009). It defines minimum 250lx at 8000K during day and 200lx at 3000K during night as specific values for vertical illuminance levels to create for activating and calming situations.

## 4.2 WellBeing Building Certification

Three years later, in 2016, the **WellBeing Institute**[2] published a guideline, including a Circadian Lighting Design precondition based on the equivalent melanopic illuminance (EML) measure. It promotes specific lighting designs for work places and refers to the workplace area: for workspaces with daylight contribution, 75% of the workplaces should reach 200EML at least in the hours between 9 a.m to 1 p.m. each day; for workplaces illuminated with electric lighting only 150 EML during the whole day should be reached.

**Melanopic Ratio by Light Source**

| CCT (K) | Light Source | Ratio |
|---|---|---|
| 2700 | LED | 0.45 |
| 3000 | Fluorescent | 0.45 |
| 2800 | Incandescent | 0.54 |
| 4000 | Fluorescent | 0.58 |
| 4000 | LED | 0.76 |
| 5450 | CIE E (Equal Energy) | 1.00 |
| 6500 | Fluorescent | 1.02 |
| 6500 | Daylight | 1.10 |
| 7500 | Fluorescent | 1.11 |

** Source: WELL Building Standard v1*

$$E_{mel} = E_{phot} * Ratio_{mel}$$

[2] WELL (2019). The WELL Building Standard v2 with Q1 2019 Addenda. New York, NY: WELL Building Institute.

Although, the guideline does not fix specific times, when an effective circadian stimulus must be presented, it is a first important step to transfer scientific knowledge into performance requirements, so that buildings might better support occupants' well-being and circadian health.

## 4.3 UL RP 24480

Almost in parallel, the **Underwriters Laboratory[3] (UL)** institute in US published a new design guideline RP 24480, which bases their evaluation on the Circadian stimulus metric (CS). Like the DIN SPEC, the RP 24480 gives recommendations for CS values for the following daytime periods:

- 7am – 4pm (day) CS ≥ 0,3 (for at least 2 hours)
- 5pm – 7pm (evening) CS ≤ 0,2
- 8pm – (night) CS ≤ 0,1

The guideline addresses explicitly commercial rooms, schools and industry halls without night working times. It should stabilize the circadian rhythm and reduce the sleepiness of people during working/while staying in those environments. The CS-value represents acute melatonin suppression caused by 1 hour of light exposure during the night (0 ≤ CS ≤ 0,75).

The international public review of the publication of the UL design guideline has recently ended. Several open points were raised by means of this review process by international experts[4][5]:

- Daylight integration: so far only benchmarks for artificial lighting are mentioned
- User interaction: is their influence included in the evaluation?
- Lighting control: seasonal influences are not considered (fixed day times throughout the year)
- Calculations are based on the emitted spectrum of the light source but not on the light spectrum entering the eyes
- Gaze directions of the user are not considered but varying gaze directions significantly influence the amount and spectrum of light received by the retina

## 4.4 CIE S 026/E:2018

Meanwhile, the CIE published the new standard **CIE S 026/E:2018[6]** (Metrology of optical radiation for ipRGC-influences responses to light) which substitutes the DIN SPEC 67600 and introduces the new melanopic metric - the EDI (Equivalent Daylight Illuminance). Within this standard spectral sensitivity functions, quantities and metrics are described. By means of the standard radiation for its ability to

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[3] UL. (2019). UL RP 24480, Recommended Practice and Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People. (In public review.) Northbrook, IL: Underwriters Laboratories Inc.

[4] The Society of Light and Lighting (2019). Position Statement, Circadian Lighting April 2019 https://www.ies.org/about-outreach/position-statements/ps-12-19-ies-position-on-ul-rp-24480-regarding-light-and-circadian-entrainment/

[5] ES (2019). PS-12-19: IES Position on UL RP24480Regarding Light and Circadian Entrainment Issued May 20, 2019

https://www.ies.org/about-outreach/position-statements/ps-12-19-ies-position-on-ul-rp-24480-regarding-light-and-circadian-entrainment/

[6] CIE S 026/E:2018: CIE system for metrology of optical radiation for ipRGC-influenced responses to light. Published on January 12, 2018.

stimulate each of the five photoreceptor types and contributing to the melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs) are described.

In the following, three central new ideas of this standard are described:

- definition of nine new LED reference spectra (CIE TC 1-85): LED-B1, B2, B3, B4, B5, BH1, RGB1, V1 und V2
- Age correction: action spectrum for standard observer with an age of 32 years; age-related correction of light transmission through lens should be applied when needed in specific applications (e.g., lighting in senior homes)
- Recommendation to calculate retinal illuminance instead of corneal illuminance in environments with varying luminance or use a lens tube to restrict measurement field

# 5 Approaches for simultaneous evaluation on non-visual effects

Climate-based daylight modelling metrics have been developed with the primary goal to provide a benchmark for an area-based evaluation of lighting quality under dynamic daylight environments. Annual metrics like continuous daylight autonomy (cDA) or spatial daylight autonomy (sDA) quantifies the fraction of occupied hours, where a given evaluation area receives sufficient daylight to reduce artificial lighting  As those benchmarks are developed for horizontal illuminance levels, it is problematic to adapt them for light exposure at the vertical plane on eye-level including the timing of the day and the spectral response of the circadian system.

For simulating circadian lighting effects, two general approaches can be distinguished:

- (1) Multi-spectral simulations (using Radiance)
- (2) Annual analysis to calculate standard photopic illuminances and weight them by a coefficient to estimate the potential for circadian stimulus

The first approach allows to consider the spectral influence of different materials. On the other hand, only point-in-time evaluations are realistic which doesn’t consider the daily and seasonal variation of daylight. The second approach instead neglects the full spectral interaction of light sources and surface materials of the walls, ceiling, floor and furniture.

Designers need analysis tools, that enables them to evaluate a project’s circadian daylight performance including the seasonal variations of daylight in terms of intensity and spectrum. and compare different design solutions by summarizing benchmarks. Within the next chapter, two available tools enabling multi-spectral simulations for evaluating the above-mentioned aspects are analysed in their capabilities and compared.

# 6 Comparison of existing software tools

Simulation of non-visual/circadian lighting designs has been carried out by means of two software tools:

**LARK**, a plugin for Grasshopper developed by the University of Washington in collaboration with ZGF Architects LLP, and **ALFA** (Adaptive Lighting for Alertness) developed by Solemma.

ALFA LARK

As a test case for a prototypical circadian lighting design, the PASSYS outdoor test cell from Innsbruck University was chosen. It represents an office situation and consists of a south facing façade. Beside integration into the toolchain model comparison, it might also give the possibility to use monitoring data in future. The following features fully specify the implemented design:

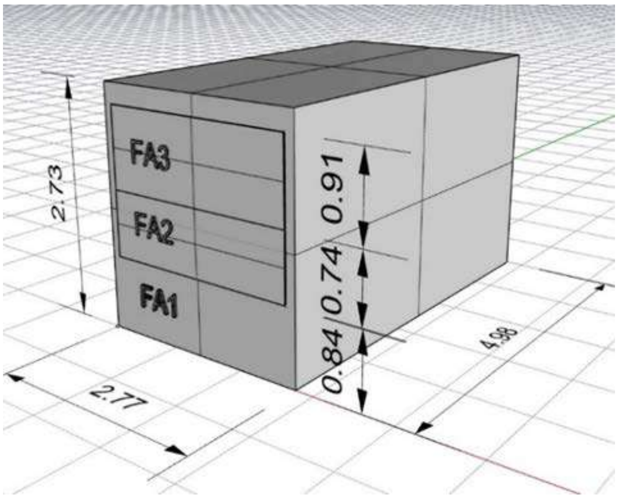



*Figure 7: Sketch of the PASSYS test cell model in Rhinoceros*

| | |
|---|---|
| Geometry | Rhino 3D-model |
| Date | 21st of March, 9am |
| Site | Innsbruck |
| Sky condition | Clear sky |
| Ground surface | RGB reflectance = 0.5 |
| Inner surface properties | 0.76/0.585/0.132 (RGB) |
| Spectral glazing | Single glazing system, (Tvis=0.342/0.448/0.473) |

## 6.1 ALFA

ALFA tool has a User interface that is embedded into Rhinoceros 3d CAD (Fig. 6). The tool creators offer a tutorial available on the official site: http://www.solemma.net/Alfa.html.

ALFA tool can "predict the amount of light absorbed by an observer's non-visual photoreceptors, given her location and direction of view. Since these receptors absorb light using the photopigment melanopsin, the quantity is referred to as equivalent melanopic lux, or EML. Using ALFA, one can quickly predict EML for an array of view positions in any lighting environment, which allows easily to calculate WELL Circadian Lighting credits. ALFA furthermore provides an extended Radiance lighting engine for spectral raytracing using 81 spectral channels (i.e., 5 nanometers bandwidth of light spectra). For modelling spectral skies, *libRadtran* (www.libratran.org) is implemented to model physically-accurate clear, hazy, or overcast skies. Beside an integrated library for luminaires, it also allows a direct integration of the IGDB (International glazing database), which allows to select between thousands of spectrally measured glazing products.

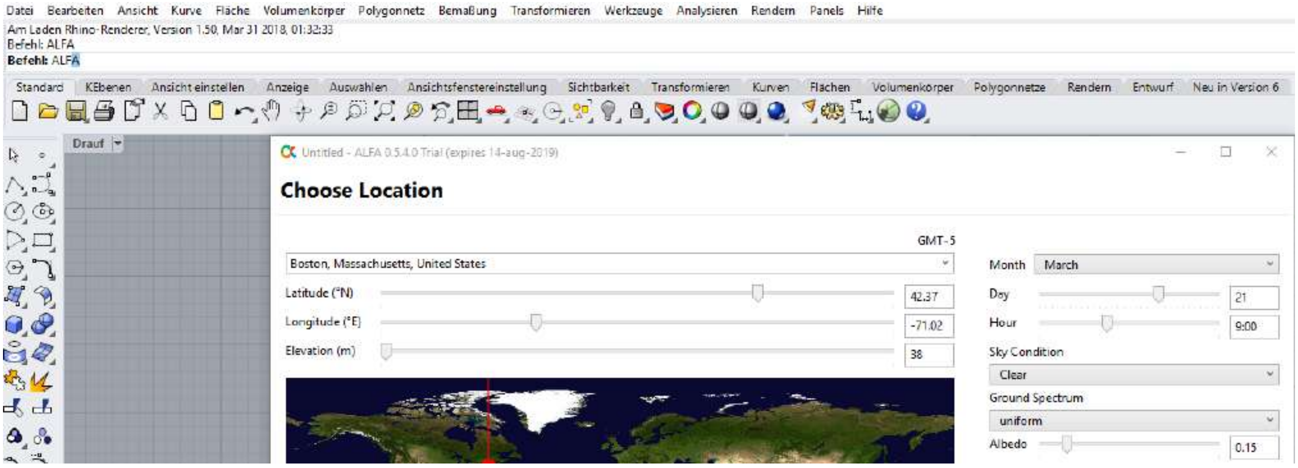



*Figure 8: ALFA user interface*

### 6.1.1 Simulation workflow

**The simulation workflow is as follows:**

1. Build a 3D model in Rhinoceros, being careful to split the different building components (walls, roof, floor, etc.) in different layers.
2. After that, it is possible to start the ALFA from the Rhinoceros command line, it allows to select the site location (or separately latitude, longitude and elevation), the date, sky condition, ground spectrum.
3. Define the opaque and transparent components by selecting a suitable material (Fig. 7). The tool has a default library that incorporates data from http://spectraldb.com/.

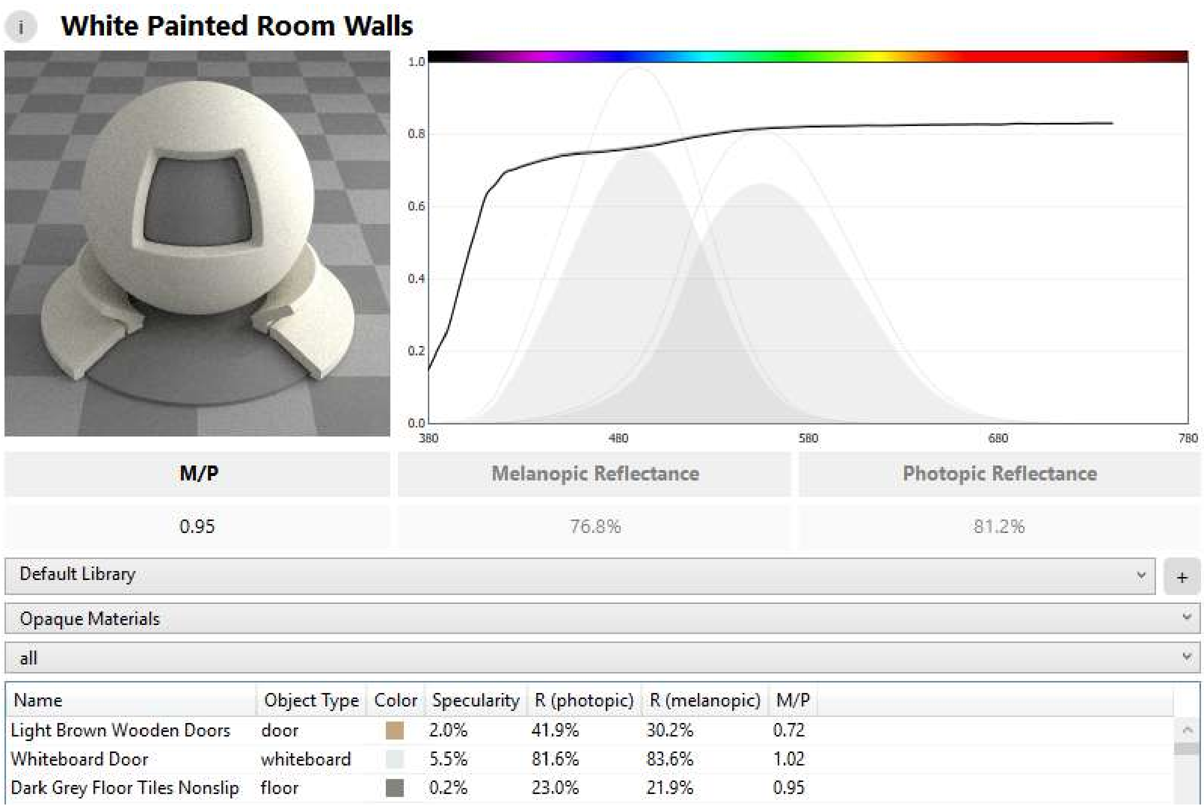



*Figure 9: Assign materials by layer*

4. Create the luminaires choosing from the IES library. ALFA has an implemented library from which it is possible to select the luminaires and the corresponding spectrum of the light source. The selected luminaire including the light distribution curve will be shown in the Rhino model in order to arrange it in the desired spatial position (Fig. 8).

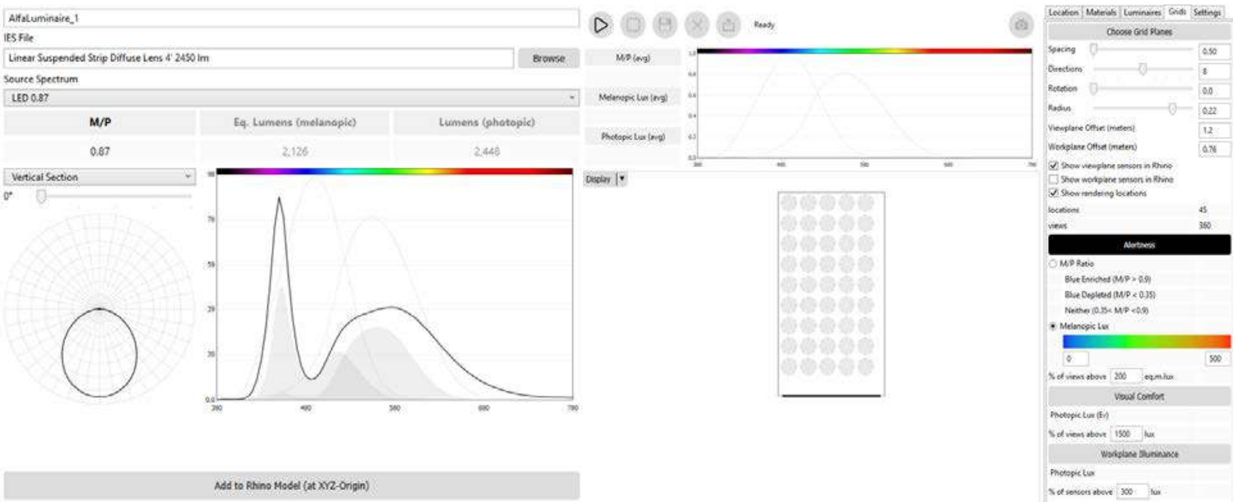



*Figure 10: Assign luminaries (left) and showing results (right)*

5. The reference plane and direction for the evaluation must be defined. On this plane it is possible to define an equidistant evaluation grid.
6. Different outputs are provided: *Alertness* (M/P ratio, Equivalent Melanopic Lux(EML)), *Visual Comfort* and *Workplace Illuminance* (Fig. 8).
7. Selecting one point of the grid, it is possible to create a rendered view. In this section a *Falsecolor* Display both for Photopic Luminance and Melanopic Luminance is available.

ALFA includes daylighting via the facade as well as artificial lighting, to evaluate the non-visual light effect received by both light sources. Nevertheless, it does not allow to specify the façade system (including a shading or light redirecting blind system). This limits the practical evaluation of non-visual effects including visual criteria like glare protection.

ALFA was used as a full trial version (available for 4 weeks) for the described circadian lighting design, afterwards the use of ALFA is commercial.

## 6.2 LARK

Inanici et al. (2015) developed a simulation routine to more accurately compute spectral lighting for the purpose of circadian lighting design based on indicators like EML and CS.

The Lark tool “Lark Spectral Lighting” is currently implemented as a plugin in Grasshopper and allows lighting designers and architects to analyze luminance renderings for different viewpoints and irradiance data from point-in-time calculations.

The workflow combines both, the 3-step and the 9-step multi-spectral channel computation, which is not that accurate compared to the 81-channels in the software tool ALFA. The circadian model adopted from the tool calculates circadian values with two methods based on:

1) the circadian spectral sensitivity curve published by Rea et al. (2005) and
2) the melanopsin spectral sensitivity curve published by Lucas et al. (2014).

LARK also shows for each view point the photopic luminance. A separate file provides the results for the 3-channel and 9-channel calculation.

In contrast to ALFA, the tool LARK is free available via following website: http://faculty.washington.edu/inanici/Lark. Through its implementation as an open-source Grasshopper component it allows also full inspection of the used algorithms as well as is high flexible in combining it with other powerful software tools in Grasshopper (e.g. Ladybug and Honeybee for energy and daylight simulations). In course of the project FACEcamp, Bartenbach has developed a workflow for evaluating non-visual light effects using the components of LARK.

In the following chapter, this workflow is described in more detail and applied to the reference model (PASSYS outdoor test cell at University of Innsbruck).

### 6.2.1 Simulation workflow

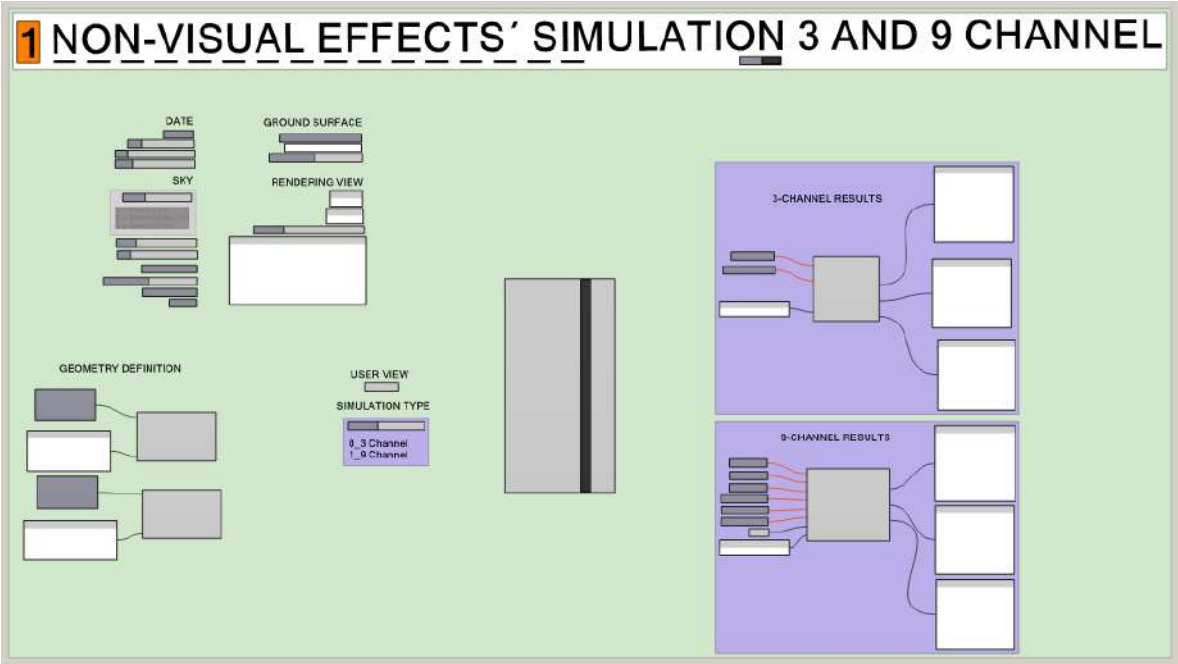



***Figure 11: Lark workflow - Overview***

**The simulation workflow is as follows:**

1. Build a 3D model in Rhinoceros; being careful to split the different building components (walls, roof, floor, etc.) in different layers and open the grasshopper file called “non-visual effects' simulation”.
2. Load the site location through the weather file and select the date; the simulation will run for that precise time.

The weather file has been taken from https://energyplus.net/weather. For our case it has been utilized the file AUT_Innsbruck.111200_IWEC.

3. Define the sky type among sunny, intermediate and overcast, then the quality of the output sky datum and bounces (Figure 6). Define the ground surface through HBsurface choosing the RGB components.
4. Define the Sky data file path (.exc). The referred file is an excel file that depends on time and on sky Type. The Lark team provide three files that stand for a quite good representation of three different sky model: Overcast sky, Intermediate sky, Clear sky (Figure 6).
5. Selected a view selector, the image size and the camera type it is possible to assign proprieties to the rendering view that the simulation produce.

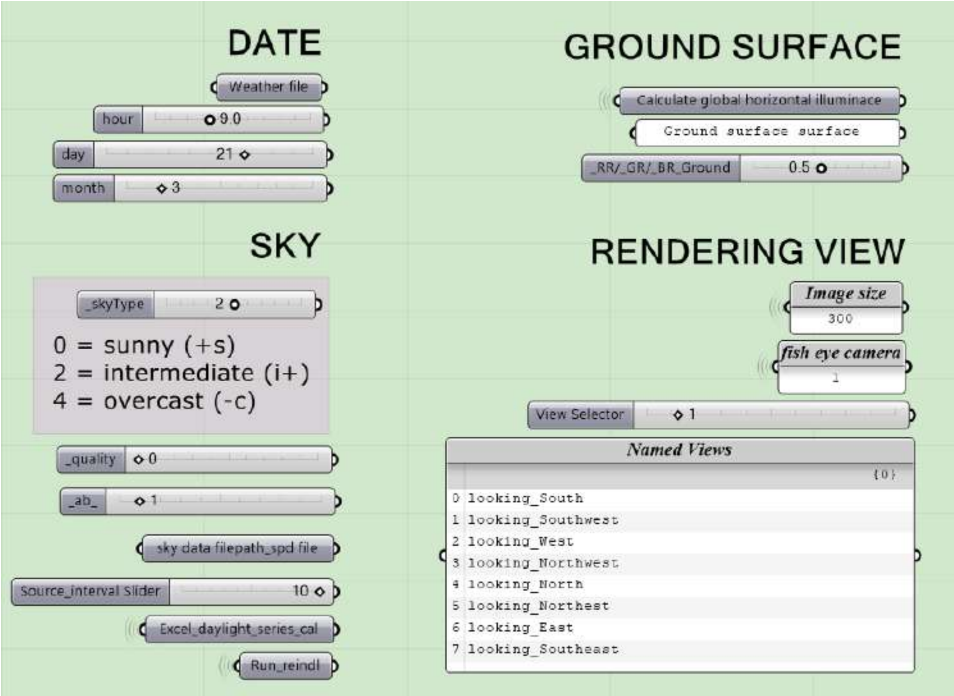



***Figure 12: LARK workflow inputs***

6. Define the occupant view by "Point position". From this point are generated by default, eight vector directions: South, Southwest, West, Northwest, North, Northeast, East, Southeast (figure 7).
7. Convert the geometry in RAD material through HBsurface: In the section "Geometry definition" should be define the layer and the corresponding proprieties. Possible Lighting materials for the simulation: http://spectraldb.com/.
8. In the Simulation type is possible to select if the simulation is going to run for 3-step or 9-step multichannel (Fig. 11).

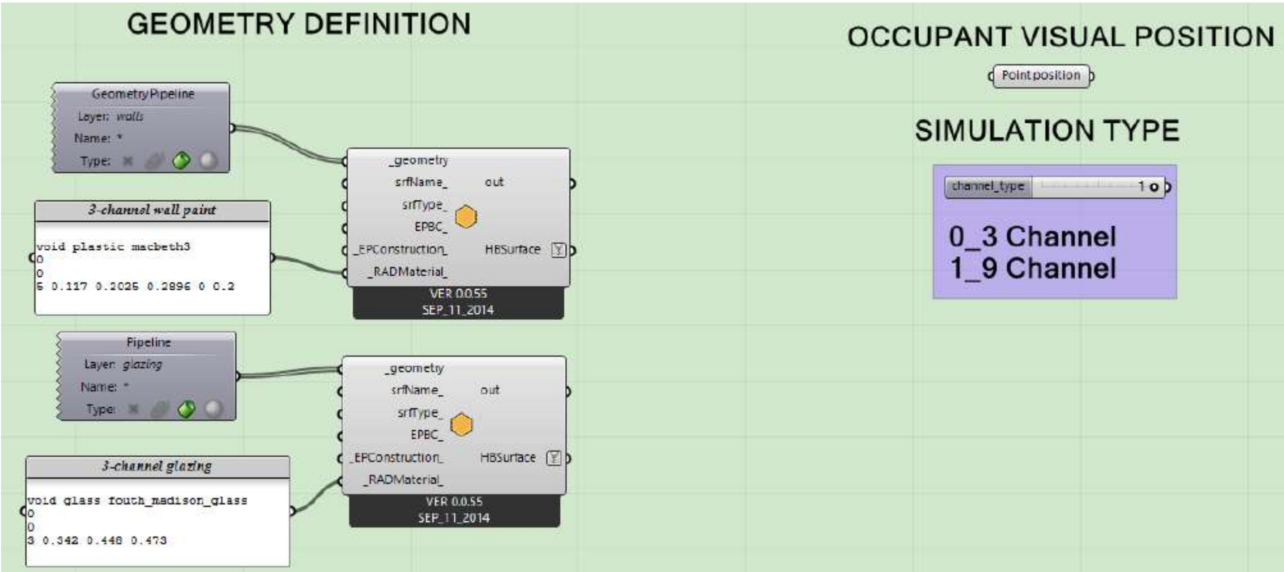



***Figure 13: Geometry definition and simulation type***

9. For run the simulation, double click on the sign *False.*
10. After running the simulation, the first results are grouped in three panels that represent in the following order Rea [lx], Lucas [lx] and Photopic [lx] (Fig. 12).

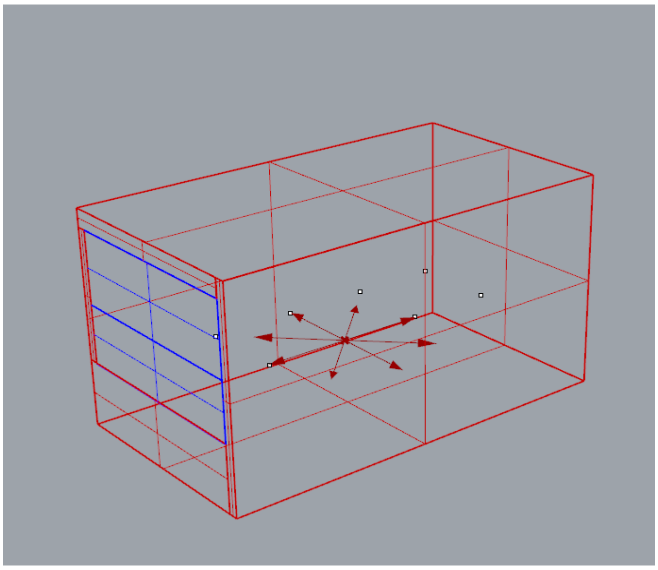


*Figure 14: Different view directions defined*

| 3 CHANNEL | | | | 9 CHANNEL | | | |
|---|---|---|---|---|---|---|---|
| | Lucas Lux | Rea Lux | Photopic Lux | | Lucas Lux | Rea Lux | Photopic Lux |
| 0 | 245.62 | 361.0 | 641.83 | 0 | 367.56 | 514.10 | 420.20 |
| 1 | 157.77 | 232.05 | 411.11 | 1 | 248.86 | 347.78 | 284.44 |
| 2 | 30.69 | 45.11 | 80.23 | 2 | 41.91 | 58.77 | 47.95 |
| 3 | 34.88 | 51.25 | 91.18 | 3 | 52.94 | 74.09 | 60.53 |
| 4 | 47.92 | 70.42 | 125.35 | 4 | 72.86 | 101.95 | 83.30 |
| 5 | 47.66 | 70.02 | 124.72 | 5 | 72.93 | 102.06 | 83.39 |
| 6 | 74.29 | 109.16 | 194.36 | 6 | 113.24 | 158.33 | 129.45 |
| 7 | 204.82 | 300.96 | 535.72 | 7 | 298.59 | 417.72 | 341.37 |

*Figure 15: Comparison of 3-channel and 9-channel results*

The results shown in Fig. 15 show a direct comparison of 3-channel and 9-channel calculation. The photopic lux has been created from the standard photopic spectral sensitivity curve (V(λ)), while the non-visual results for “Lucas Lux” are spectrally weighted by the response curve of Lucas et al. (2014) and “Rea Lux” spectrally weighted by the response curve of Rea et al. (2014). Therefore, significant differences can be figured out for several view directions, which should be investigated in further detail. Although the LARK tool allows a comprehensive evaluation of spectral results, an evaluation and summarized interpretation of a floor area is still not addressed adequately.

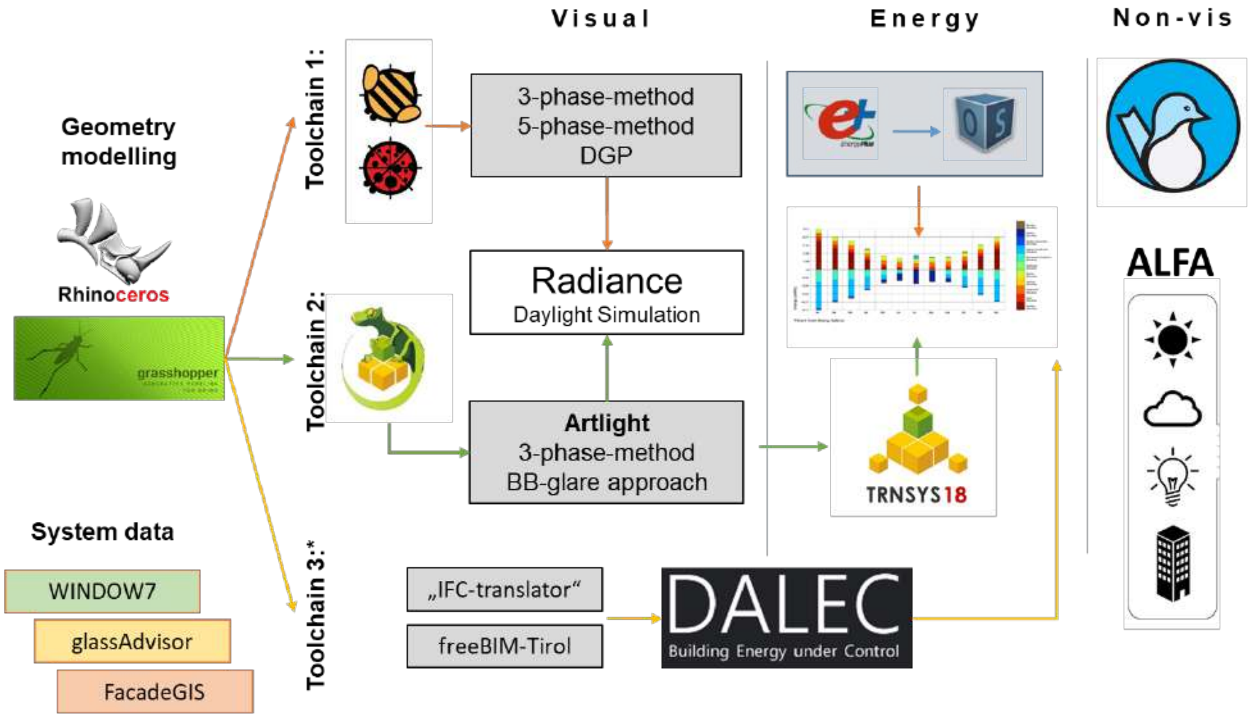
Therefore, (Konis 2016) addressed this need by developing a novel area-based circadian daylight metric for building design and evaluation. It allows to differentiate the performance of various daylighting strategies during the design phase of a building. This might be of great interest to combine this new evaluation metric with the created results.

# 7 Integration into FACEcamp simulation toolchain

Within workpackage 4 of the project FACEcamp, a toolchain was established to enable a multi-objective optimization of complex façade systems including energy and daylight simulations.

**Rhinoceros** including **Grasshopper** is defined as common platform for geometry generation and model setup. For thermal comfort and energy balancing, **EnergyPlus (via Ladybug/Honeybee) or TRNSYS (via TRNLizard)** is used. For daylight simulations **Radiance** is implemented either via **Honeybee or via TRNLizard** including the Artlight-coupling routine between TRNSYS and Radiance. For covering the non-visual comfort evaluation, **LARK** is implemented within the toolchain workflow, based on the method described in 6.2.1.

For an early stage design evaluation, **DALEC** is implemented within the FACEcamp toolchain, enabling a combined thermal and daylight evaluation of complex façade systems based on a single-zone model. Based on the evaluation of vertical illuminances on eye-level it might also provide the possibility to evaluate non-visual light effects. A first comparative evaluation of this toolchain is published in (Hauer et al. 2019).




2.

*Figure 16: FACEcamp simulation toolchain for complex facade systems*

# 8 Summary and further development

Within the project FACEcamp, it was the purpose to screen existing simulation- and modelling- tools for a non-visual/circadian lighting design (ref. chapter 6) as well as implement their integration into the FACEcamp toolchain approach (chapter 7). This method enables firstly a multi-objective optimization of complex façade systems and shows its potential in flexibility and capability by the used approach.

As ongoing activities, a comparison between the different modelling approaches and their evaluation benchmarks might be useful. Furthermore, an adaption of the methods toward the actual standards (ref. chapter 4, CIE S 026/E:2018) as well as to the new benchmarks (ref. EDI - Equivalent Daylight Illuminance) might be of great interest, to enable lighting designers and architects to improve their designs.

In course of workpackage 4 within FACEcamp, Bartenbach already implemented its light-dose model for evaluating the circadian effectiveness of a lighting design in an own Grasshopper component, which might be further developed towards the actual CIE standard.

# FACEcamp partners

| | | |
|---|---|---|
| eurac research | EURAC<br>Eurac Research, Institute for Renewable Energy | Coordinator |
| IDM Südtirol Alto Adige | IDM<br>IDM Suedtirol - Alto Adige | Partner |
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