SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Simulation Tools for Low Carbon, High Comfort Integrated Lighting

T70.C.4.1 – A Technical Report of Subtask C



IEA SHC TASK 70 | EBC Annex 90: LOW CARBON, HIGH COMFORT INTEGRATED LIGHTING

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PREFACE

Lighting accounts for 15% of the global electrical energy consumption and 5% of global CO_2 emissions. Thus, widening the rating perspective of lighting solutions to a more holistic view of its impact on CO_2 emissions, encompassing the whole life cycle chain also in the context of regional energy markets aspects, interaction with other building trades, etc. is urgently deemed necessary. This goes far beyond the pure LED lamp-driven energy efficiency gains.

The aim of IEA SHC Task 70 / EBC Annex 90 “Low Carbon, high comfort integrated lighting” is to identify and support implementing the potentials of lighting (electric, façade: daylighting and passive solar) in the decarbonization on a global perspective while aligning the new integrative understanding of humans’ light needs with digitized lighting on a building and a building related urban scale. This includes the following activities:

- Actively support broadening the view on lighting solutions as a whole in the context of decarbonization. Help bridge the gap between a component view (manufacturer’s focus) and design-oriented system approaches. Support the transition from a rather pure energy focused view so far to a life cycle assessment (LCA) perspective. On this basis, identify key impact factors, and develop the most effective strategies and roadmaps while including regional specifics.
- Contextualize this with the fast-developing digitization of buildings/lighting installations on the technology, design and operational side. Add to selected open points in the digital chain like better design processes.
- Align this with the still growing understanding of user needs; here specially build upon results from earlier IEA projects (e.g., IEA SHC Task 61 / EBC Annex 77).
- Integrate competencies: Bring the different involved players (electric lighting, façade, industry, controls) so far not connected on low carbon solutions together in workshops and specific projects. Create added value also by transferring into standardization, regulations and building certificates.
- Foster the broad implementation of low carbon solutions, also and especially in developing countries, by promoting tailored “Low Tech – High Impact Solutions” through demonstration, design guidelines, and workshops.

To accomplish these objectives, the work plan of IEA SHC Task 70 / EBC Annex 90 is organized according to the following four main subtasks.

Subtask A: Low Carbon Lighting and Passive Solar: Scenarios, Strategies, Roadmaps.

Subtask B: Visual and non-visual User Requirements.

Subtask C: Digitalized Lighting Solutions (Technology & Design Tools / Process).

Subtask D: Application and Case Studies.

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Executive Summary

Lighting is a central part of low-carbon, high-comfort building design. It affects energy use, visual performance, architectural quality, user satisfaction, health, and well-being. At the same time, lighting design is becoming more complex because daylight, electric lighting, controls, visual comfort, non-visual effects, spectral characteristics, and life cycle impacts increasingly need to be considered together. Simulation tools are therefore important for supporting decisions from early concept design to detailed planning and as-built performance evaluations.

This report provides a structured, systematic overview of current lighting simulation tools and related digital methods for integrated, integrative lighting design to help users identify suitable tools for specific tasks and project phases. It focuses on software used for daylighting, electric lighting, lighting visualization, control evaluation, and spectral and non-visual assessments, the softwares' links to whole building performance simulations and life cycle assessments, and examines the potential of Virtual Reality for lighting design. The report is intended for researchers, lighting designers, architects, engineers, software developers, educators, and other professionals interested in advanced lighting simulation methods. It is not intended to rank the tools or provide a full validation of all software; instead, it summarizes available information, capabilities, and application areas, and provides example outputs to help users identify features and capabilities of interest that match their unique analysis objectives.

A key contribution of the report is a comparison framework for the evaluation of lighting simulation tools consisting of three elements: (1) a table summarizing tool features, (2) short descriptions of each tool, and (3) two reference simulation models for comparing usability, capabilities, and outputs. In addition to being up-to-date, this work is distinguished from prior lighting software comparisons by its inclusion of non-visual effects and features for LCA, BIM and IFC interoperability, and VR tools. The two reference case studies – a side-lit office room and a prototypical top-lit factory hall – were used to present example simulation results across all tools. In addition, the simulation models and workflow for the reference cases are provided, enabling users to learn by example or to conduct cross comparisons of any tool with simulations using Radiance Version 6.0 with its most recent hyperspectral rendering engine.

The categories for the evaluation of the various software tools include intended users, design phase, algorithms and engines, electric lighting, daylighting, control systems, visual and non-visual effects, and life-cycle assessment support. In total, experts evaluated 26 software tools used for lighting simulation, visualization, or related building performance analysis. The tools range from specialized lighting calculation software to broader building performance and visualization platforms.

The review shows that many technical capabilities needed for low-carbon, high-comfort lighting design already exist. Current tools can answer practical questions related to daylight availability, electric lighting performance, glare, energy demand, lighting and shading controls, visualization, and, in selected cases, spectral or non-visual performance. Example outputs include daylight factor, spatial daylight autonomy, annual sunlight exposure, useful daylight illuminance, glare indicators, melanopic equivalent daylight illuminance, electric lighting energy use, and HVAC-related energy results. The majority of tools' outputs are or can be aligned with normative standards and recommendations for energy efficiency, comfort, IEQ, and health and well-being. All of the tools rely on ray tracing as the underlying model (with options of photon mapping or radiosity for some tools), most are based on the Radiance kernel (which has been extensively validated), and about half of the tools enable computationally efficient, parametric analysis by leveraging matrix modeling methods (which have also been validated).

However, the software landscape remains fragmented. No single tool covers all design phases, metrics, modelling requirements, and user needs equally well. Some tools are strong in daylight or electric lighting calculations (i.e., ease of use, comprehensive product and materials data, rapid turnaround), while others are stronger in visualization, energy analysis, or advanced spectral workflows. Several limitations were identified: some tools cannot support spectral simulations, daylight glare probability calculations, BSDF import, or the inputs needed for melanopic EDI calculations. In other cases, shading, glazing, or electric lighting assumptions had to be simplified or handled outside the intended workflow. Most tools support practitioners in the early design phase when concepts are rapidly changing and key decisions are being locked in. Tools suitable for detailed design and engineering or R&D typically have more advanced features and modeling options, such as user-defined controls, whole building/ HVAC co-simulations, and are IFC compliant and BIM enabled. Segueing from conceptual design

to commissioning of systems in the operations phase however remains largely a manual task, although there has been some progress with the BIM workflow to automate the communication and realization of design intent across phases and stakeholders (designers, owner/ facility managers). For this reason, tool selection should be based on the design question and on a clear understanding of each tool's assumptions and limitations.

The report also examines the potential of Virtual Reality in lighting design. VR can support immersive visualization, communication, user-perspective assessment, and perception-oriented evaluation. However, VR is still emerging as a professional lighting design tool. Platforms such as Unreal Engine and Unity were not originally developed as lighting simulation software, and their workflows are not always oriented toward lighting professionals. VR should therefore be used as a complement to conventional lighting simulation, especially for communication, design review, client engagement, and perception-oriented evaluation; it should not replace validated simulation workflows when quantitative metrics are required.

Overall, the report concludes that simulation tools already support many practical lighting design problems, but their capabilities are distributed across a scattered tool landscape. The software overview should be used as a decision-support resource, not as a ranking. Practitioners should first define the design task, such as daylight access, glare, controls, energy use, spectral effects, non-visual effects, life-cycle assessment input, or visualization, and then select tools accordingly. Note that the software tool landscape is constantly evolving and improving along with the underlying science, metrics, and regulatory environment: users are at liberty to use the comparison framework to further evaluate tool options. Future work by software developers should focus on interoperability, validation, usability, and better integration between daylighting, electric lighting, controls, building performance, non-visual effects, life-cycle assessment, and VR workflows.

1 Introduction

Lighting is a key element in the design of low-carbon and high-comfort buildings. It influences energy use, visual performance, architectural quality, user satisfaction, health, and well-being. At the same time, lighting design is becoming increasingly complex. Daylight and electric lighting must be considered together, lighting control systems need to respond to changing environmental and user conditions, and design objectives increasingly include not only visual comfort and energy efficiency, but also non-visual effects, spectral characteristics, and life-cycle impacts. Simulation tools are therefore essential to support informed decisions throughout the design process, from early concept development to detailed planning and performance evaluation.

The purpose of this report is to provide an overview of current lighting simulation tools and related digital methods that can support integrated lighting design. The report focuses on software used for daylighting, electric lighting, lighting visualization, control evaluation, spectral and non-visual assessment, links to building performance simulation, and selected aspects of life-cycle assessment. In addition, it discusses the potential role of Virtual Reality (VR) technologies in lighting design practice.

The report is intended for researchers, lighting designers, architects, engineers, software developers, educators, and other professionals interested in simulation methods for advanced lighting design. It does not aim to provide a full validation or ranking of all tools. Instead, it documents available information, summarizes capabilities and application areas, and provides examples that can help users identify tools suitable for specific design tasks, project phases, or performance questions.

A wide range of lighting simulation programs is available today, from commercial to free and open-source options. To help architects and planners choose appropriate tools for specific applications, experts within the IEA SHC Task 70 / EBC Annex 90 developed a framework for comparing simulation software. The framework includes three elements:

(1) a table summarizing each tool's features across key areas (intended users, design phase, algorithms/engines, electric lighting, daylighting, control systems, visual and non-visual effects, and LCA support);
(2) a short description of each tool; and
(3) two reference simulation models that allow tools to be compared in terms of usability, capabilities, and output.

Section 2 shortly introduces the example simulation projects suggested as common reference cases. Two reference models were defined: an office room in the UIBK office building in Innsbruck, Austria, and a prototypical top-lit factory hall based on CEN/TR 15193-2, located in the climate context of Stuttgart, Germany. These case studies represent different building types, lighting conditions, and modelling challenges. The office case represents a side-lit room in a renovated European office building and is linked to an existing Living Lab research environment. The factory hall represents a larger industrial space with roof daylight openings and standardized characteristics. Both models were prepared for spectral lighting simulations, including spectral reflectance data, glazing transmission data, and luminaire spectral power distributions. The reference model data and two software implementations were made publicly accessible. The detailed description of the two reference simulation models (element (3)) has been published in parallel with this report both in a data journal[1] and as separate report, which is available on the Task's website, i.e., Report T70.C.4.2[2].

Section 3 provides an overview of 26 simulation tools evaluated by experts participating in IEA SHC Task 70 / EBC Annex 90. The tools cover a broad range of applications, from specialized lighting calculation software to wider building performance and visualization platforms. Their features are summarized in a comparative table according to several domains, including target user group, design phase, electric lighting simulation, daylight simulation, control systems, visual and non-visual effects, life-cycle assessment, algorithms or calculation engines, and extended scope. For each domain, relevant sub-areas were assessed and classified as "yes", "partly", or "no", depending on how applicable they were to the respective software. The findings reflect features

[1] Geisler-Moroder, D., Maskarenj, M., Ward, G., Wang, T., Lee, E. S., & Altomonte, S. (2026). Dataset describing two reference models for full-spectral lighting and daylight simulations together with implementations for two software systems. Data in Brief, 67, Article 112922. https://doi.org/10.1016/j.dib.2026.112922
[2] International Energy Agency Solar Heating and Cooling Programme. Low carbon, high comfort integrated lighting (IEA SHC Task 70/EBC Annex 90). https://task70.iea-shc.org/

available during the period of the review (years 2024–2025) and consist of subjective evaluations by different users. Section 3 provides a compact overview of the current software landscape in a tabular format that helps readers compare software characteristics and thus supports the identification of tools relevant for different applications.

Section 4 contains structured descriptions of software tool listed in Section 3. Each tool overview follows, where possible, a common structure: (i) the General Information subsection summarizes basic facts such as developer, licensing model, website, and background information; (ii) the Description of the Software subsection outlines the main purpose, target users, underlying calculation methods or simulation engines, and primary application areas. Where available, information on validation, standards, and documentation is included; (iii) the Example Simulation Project Results subsection illustrates representative outputs generated by the tools, such as renderings, daylight metrics, illuminance distributions, energy-related results, or other performance indicators; and finally, (iv) the References subsection lists relevant publications, technical documents, and web resources.

Section 5 addresses the potential of Virtual Reality technologies in daylighting and lighting design. Although VR has been investigated in academic research as a promising medium for immersive visualization and evaluation, its use in professional lighting design practice remains less clearly documented. This section summarizes the motivation for investigating VR in the context of integrative lighting design, including opportunities and challenges related to the representation of lighting in immersive environments. It also presents the background and structure of an international online survey conducted among professionals using VR in lighting design and related fields, such as architecture, interior design, landscape design, urbanism, real estate, and research. The survey investigated general VR use, practical applications, complexity of VR experiences, and the integration of lighting in VR environments. A comprehensive analysis of the scientific literature on the topic of VR for lighting design, as well as the detailed documentation and complete evaluation of the international survey, were published in a scientific journal[3].

Section 6 summarizes the current capabilities of lighting simulation software describing the main findings from the evaluation of the twenty-six different tools. It further concludes on the current use and potential of Virtual Reality in lighting design. Finally, recommendations for practical applications of the results described in this report are given, and topics for future software developments to meet the simulation needs associated with low carbon, high comfort lighting are presented.

The appendices provide supporting material. Appendix A reports example results for selected software systems applied to the reference models introduced in Section 2. Appendix B contains the complete VR questionnaire used in the international survey described in Section 5.

Overall, this report provides a structured overview of current digital methods for simulating and evaluating integrated lighting solutions, supporting better-informed tool selection and the development of low-carbon, high-comfort lighting design workflows.

[3] M. Scorpio, A. Bladowski, D. Geisler-Moroder, J. Martyniuk-Pęczek, S. Sibilio, R. Pfluger, N. Sokół, Virtual reality in lighting design: Insights from academia and an international survey among professionals, Journal of Building Engineering 102 (2025) 112036. https://doi.org/10.1016/J.JOBE.2025.112036.

2 Reference Rooms for Lighting Simulations

Two case studies were defined then modeled with most of the investigated simulation tools. The case studies were defined to provide a tangible link between the four subtasks within IEA SHC Task 70 / EBC Annex 90, facilitating discussion between experts within the different subtasks on method and outcomes of analysis given common ground.

- In the first case, the UIBK office building was modeled in the moderate cold, alpine climate, Innsbruck, Austria, 47°N latitude. The office building is representative of typical new construction in the EU (completely renovated in 2014), side-lit with windows. It is monitored at the whole building level, and is currently the site of a Living Laboratory research study on healthy lighting (UIBK Room 518). This Room 518 with its west-facing façade was modeled, and interior furnishings were characterized using a handheld spectrometer.
- The second case is a reference or prototypical representation of a top-lit factory hall, defined in Annex J.1.1 of the Technical Report CEN/TR 15193-2 [1]. EN 15193 was developed to provide a standardized method for calculating and assessing the energy performance of lighting systems in buildings across Europe, supporting the implementation of the Energy Performance of Buildings Directive (EPBD) by enabling consistent evaluation and comparison of lighting energy use in building energy assessments. The prototype factory hall is modeled in the temperate Central European climate Stuttgart, Germany, 49°N latitude.

A detailed description of each of the two buildings is given in the accompanying *Technical Report T70.C4.2*[4] of this IEA SHC Task 70 / EBC Annex 90. Both reference models are prepared for spectral lighting simulations, i.e., providing spectral reflectance data for all surfaces, transmission data for windows, and spectral power distributions for the implemented luminaires.

Both reference rooms were also implemented in two spectral lighting simulation software systems (Radiance and OWL). The model data (geometry, material definitions, spectral data, window specifications, shading and luminaire data, etc.) and the software implementations were made publicly available on Zenodo [2]. The overall dataset is described in detail in an article in Data in Brief [3].

In Appendix A, example simulation results for numerous software packages for both reference simulation models – office and factory hall – are reported.

References

[1] CEN. European Committee for Standardization. (2017). *CEN/TR 15193-2:2017: Energy performance of buildings – Energy requirements for lighting – Part 2: Explanation and justification of EN 15193-1, Module M9*.

[2] Geisler-Moroder, D., Maskarenj, M., Ward, G., Wang, T., Lee, E. S.& Altomonte, S. (2026). Reference Models for Spectral Lighting and Daylight Simulations. Data Set. Zenodo. https://doi.org/10.5281/zenodo.18836176

[3] Geisler-Moroder, D., Maskarenj, M., Ward, G., Wang, T., Lee, E. S., & Altomonte, S. (2026). Dataset describing two reference models for full-spectral lighting and daylight simulations together with implementations for two software systems. *Data in Brief, 67*, Article 112922. https://doi.org/10.1016/j.dib.2026.112922

[4] Geisler-Moroder, D. & Lee, E.S. (Eds.). Reference rooms for simulating low carbon, high comfort integrated lighting solutions. Technical Report T70.C4.2 of this IEA SHC Task 70 / EBC Annex 90. https://task70.iea-shc.org/publications

3 Overview of simulation tools

Experts of the IEA SHC Task 70 / EBC Annex 90 evaluated 26 different software tools used for lighting simulation, visualization, or related building performance analyses. They assessed functionality / features / application across multiple domains:

- User target group
- Design phase
- Suitability for electric lighting simulation
- Suitability for daylight simulation
- Control systems
- Visual and non-visual effects
- Life-cycle assessment
- Algorithms / engines
- Extended scope

For each domain, multiple sub-areas were investigated and scored with “yes” / “partly” / “no”. The results of the experts’ assessments are collected in Table 3.1.

A detailed description of the investigated categories and a high-level analysis of the coverage of features by specific software tools is provided in the book chapter “Simulation tools for integrative lighting design” in “Human visual and non-visual response to the built environment – recent achievements and their practical implementation”[5].

Table 3.1. Comparison of twenty-six software tools for integrative lighting. Applicable to software: ✓ = yes, o = partially, – = no.

	AftabRAD	ALFA	AGI32	A. Marsh Tools	ClimateStudio	DALEC	DesignBuilder	DIALux	DIAL+	DL-Light	Daylight Visualizer	ElumTools	frads	GB SWARE	Honeybee	IES VE	LARK	LightStanza	OpenStudio	OWL	PKPM	Radiance	RELUX	Sefaira	TRNSYS	Unreal Engine
SOFTWARE SUITED FOR																										
Lighting designers	✓	✓	✓	✓	✓	✓	o	✓	✓	✓	✓	✓	o	✓	✓	o	✓	✓	o	✓	–	✓	✓	✓	o	o
Architects	✓	✓	o	✓	✓	✓	✓	✓	✓	✓	✓	✓	o	✓	✓	o	✓	✓	✓	✓	✓	o	✓	✓	–	✓
Electric engineers	✓	o	✓	–	o	✓	o	✓	✓	–	–	✓	–	✓	✓	o	–	–	o	–	–	✓	✓	o	–	–
HVAC engineers	o	–	–	–	✓	✓	✓	–	✓	–	–	–	✓	✓	✓	✓	–	–	✓	–	✓	–	–	✓	✓	–
Building engineers/planners	✓	–	o	–	o	✓	✓	o	–	✓	✓	o	o	✓	✓	✓	✓	o	✓	✓	✓	–	–	✓	✓	o
Researchers	✓	✓	o	–	✓	✓	✓	o	–	✓	✓	o	✓	✓	✓	✓	✓	o	✓	✓	–	✓	✓	o	✓	✓
DESIGN PHASE																										
Suited for R&D	✓	✓	o	–	✓	–	✓	o	–	–	–	o	✓	o	✓	✓	✓	o	✓	–	–	✓	✓	o	✓	✓
Suited for early design	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	o	✓	✓	o	o	✓	✓	✓	✓	o	✓	✓	✓	✓
Suited for detailed design	✓	✓	✓	–	✓	–	✓	✓	–	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	o	✓	✓
ALGORITHMS / ENGINES																										
Ray tracing	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	o
Photon mapping	–	–	–	–	–	–	–	✓	–	✓	–	–	✓	–	–	–	–	✓	✓	–	–	✓	✓	✓	–	–
Radiosity	–	–	✓	–	–	–	–	✓	–	–	–	✓	–	–	–	–	–	o	o	–	–	–	✓	o	–	–
Radiance kernel	✓	✓	–	✓	✓	✓	✓	–	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	–	–
3 Phase Method	–	–	–	–	–	✓	✓	–	✓	✓	–	–	✓	✓	✓	–	–	✓	✓	–	–	✓	–	o	–	–

[5] Matusiak, B.S., & Khanie, M.S. (Eds.). Human visual and non-visual response to the built environment – recent achievements and their practical implementation. A Book of IEA SHC Task 70 / EBC Annex 90 “Low Carbon, high comfort integrated lighting”. Wiley.

	AftabRAD	ALFA	AGI32	A. Marsh Tools	ClimateStudio	DALEC	DesignBuilder	DIALux	DIAL+	DL-Light	Daylight Visualizer	ElumTools	frads	GB SWARE	Honeybee	IES VE	LARK	LightStanza	OpenStudio	OWL	PKPM	Radiance	RELUX	Sefaira	TRNSYS	Unreal Engine
5 Phase Method	–	–	–	–	–	–	–	–	–	–	–	–	✓	✓	✓	–	–	o	–	–	–	✓	–	o	–	–
Daylight Coefficient Method	–	–	–	–	–	–	✓	–	–	✓	–	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	–	–
ELECTRIC LIGHTING																										
Illuminance values	✓	✓	✓	–	✓	✓	✓	✓	✓	–	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓
Luminance values	✓	–	✓	–	–	–	–	✓	–	–	–	✓	✓	✓	✓	✓	✓	✓	o	✓	–	✓	✓	✓	–	✓
Calculation of connected wattage	o	o	✓	–	✓	✓	✓	✓	✓	–	–	✓	✓	–	–	✓	–	–	✓	✓	–	o	✓	✓	✓	–
Calculation of annual electricity consumption	o	–	–	–	✓	✓	✓	✓	✓	–	–	–	✓	–	✓	✓	–	–	✓	✓	–	o	✓	✓	✓	–
Import of luminaires (IES, Eulumdat, etc.).	✓	✓	✓	–	✓	o	–	✓	✓	–	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	–	✓
Database of luminaires	–	✓	✓	–	–	–	o	✓	✓	–	–	✓	–	✓	–	✓	o	o	–	o	–	–	✓	o	–	–
DAYLIGHTING																										
Point-in-time simulation	✓	✓	✓	✓	✓	–	✓	✓	o	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	–	✓
Climate-based annual simulation	✓	–	o	✓	✓	✓	✓	–	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	o	✓	–	✓	✓	–
Illuminance values	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	✓
Luminance values	✓	–	✓	–	✓	✓	–	✓	–	✓	✓	✓	✓	✓	✓	✓	–	✓	o	✓	–	✓	✓	✓	–	✓
Daylight factor values	✓	–	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	–
Daylight autonomy (DA, cDA, sDA)	✓	–	o	✓	✓	✓	✓	–	✓	✓	✓	–	✓	o	✓	✓	–	✓	✓	✓	o	o	–	✓	✓	–
CIE sky models	o	o	✓	✓	✓	–	✓	o	–	✓	✓	✓	✓	✓	✓	✓	o	✓	✓	✓	✓	✓	o	✓	✓	–
Perez sky model	o	–	✓	✓	✓	–	✓	–	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	–	✓	✓	–
Sensible to orientation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Consideration of daylight systems as geometry	o	–	✓	o	–	–	–	✓	✓	✓	✓	✓	✓	✓	✓	✓	o	✓	✓	✓	–	✓	✓	✓	✓	✓
Import of daylight systems as BSDF data	–	–	–	–	–	–	–	–	–	–	✓	–	✓	✓	✓	o	–	✓	✓	–	–	✓	–	✓	o	–
Database of daylight systems	–	–	–	–	o	✓	–	✓	✓	–	o	–	–	✓	–	o	–	o	–	–	–	–	o	o	–	–
Consideration of outdoor obstructions	✓	✓	✓	✓	✓	o	o	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	–	✓	o	✓
CONTROL SYSTEM																										
Preset control strategies for electric lighting	–	–	–	–	o	✓	✓	–	✓	–	–	–	✓	–	✓	✓	–	–	✓	✓	–	–	✓	o	o	–
Preset control strategies for daylight system	–	–	–	–	–	✓	✓	–	✓	–	–	–	✓	–	✓	✓	–	o	o	–	–	–	–	o	o	–
Preset integrated control strategies for electric and daylight systems	–	–	–	–	–	o	o	–	✓	–	–	–	✓	–	✓	✓	–	–	✓	o	–	–	–	o	–	–
User-defined control strategies for electric lighting	–	–	–	–	–	o	o	o	✓	–	–	–	✓	–	✓	✓	o	–	✓	✓	–	o	✓	–	o	o
User-defined control strategies for daylight systems	–	–	–	–	–	o	o	o	✓	–	–	–	✓	–	✓	✓	o	–	o	o	–	o	–	–	✓	o
User-defined integrated control strategies for electric and daylight systems	–	–	–	–	–	o	o	–	✓	–	–	–	✓	–	✓	✓	o	–	✓	o	–	o	–	–	o	o
Calculation of annual electricity consumption	–	–	–	–	✓	✓	✓	✓	✓	–	–	–	✓	–	✓	✓	–	–	✓	✓	–	–	–	✓	✓	–
EXTENDED SCOPE																										
Integration of lighting and thermal simulations	o	–	–	–	✓	✓	o	–	✓	–	–	–	✓	✓	✓	✓	–	–	✓	–	–	–	–	✓	✓	–

	AftabRAD	ALFA	AGI32	A. Marsh Tools	ClimateStudio	DALEC	DesignBuilder	DIALux	DIAL+	DL-Light	Daylight Visualizer	ElumTools	frads	GB SWARE	Honeybee	IES VE	LARK	LightStanza	OpenStudio	OWL	PKPM	Radiance	RELUX	Sefaira	TRNSYS	Unreal Engine
Interface with BIM software	✓	–	o	–	o	–	✓	✓	–	–	–	✓	–	✓	✓	✓	–	✓	o	–	✓	–	✓	✓	–	o
IFC import / export	–	–	–	–	–	–	–	✓	–	–	–	o	–	✓	✓	✓	–	–	o	–	✓	–	–	o	–	✓
VISUAL & NON-VISUAL EFFECTS																										
Reduced spectral simulations (3 channels)	–	–	✓	–	–	–	–	–	–	–	o	✓	✓	–	✓	–	✓	✓	✓	✓	–	✓	✓	✓	–	–
Reduced spectral simulations (4-10 channels)	–	✓	–	–	–	–	–	–	–	–	–	–	o	–	–	–	✓	o	o	o	–	✓	–	–	–	–
Full spectral simulations	–	✓	–	–	–	–	–	–	–	–	–	–	o	–	–	–	✓	–	–	✓	–	✓	–	–	–	–
Spectral models for electric lighting	–	✓	o	–	–	–	–	–	–	–	–	o	✓	–	–	–	✓	o	o	o	–	✓	–	–	–	–
Spectral sky models	–	✓	–	–	–	–	–	–	–	–	–	–	✓	–	–	–	✓	o	o	✓	–	✓	–	–	–	–
Evaluation of a-opic irradiance	–	✓	–	–	–	–	–	–	–	–	–	–	✓	–	–	–	✓	–	–	✓	–	✓	–	–	–	–
Evaluation of a-opic ELR	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	✓	–	–	✓	–	o	–	–	–	–
Evaluation of a-opic DER	–	✓	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	✓	–	o	–	–	–	–
Evaluation of a-opic EDI	–	✓	–	–	–	–	–	–	–	–	–	–	✓	–	–	–	✓	–	–	✓	–	✓	–	–	–	–
Calculation of circadian stimulus CS	–	o	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	✓	–	–	–	–	–	–
Electric lighting glare calculations (UGR, VCP, …)	✓	✓	✓	–	–	–	–	✓	–	–	–	✓	✓	o	✓	o	–	o	o	–	–	✓	–	o	–	–
Daylight glare calculations (DGP, DGI, …)	✓	–	–	–	✓	o	–	–	–	✓	–	–	✓	o	✓	✓	–	✓	✓	✓	✓	✓	–	✓	–	–
Calculation of light dose from electric lighting	–	–	–	–	–	o	–	–	–	–	–	–	–	–	–	–	–	–	–	o	–	o	–	–	–	–
Calculation of light dose from daylight	–	–	–	–	–	o	–	–	–	–	–	–	–	–	–	–	–	–	–	✓	–	o	–	–	–	–
Occupant modelling beyond standard schedules	–	–	–	–	–	–	o	–	–	–	–	–	✓	–	✓	o	–	–	✓	✓	–	o	o	o	✓	–
Evaluation of view out: access to view	–	–	–	–	✓	–	–	–	o	✓	–	–	✓	✓	✓	–	–	o	o	–	–	✓	–	o	–	✓
Evaluation of view out: content of the view	–	–	–	–	✓	–	–	–	–	✓	–	–	✓	–	o	–	–	–	–	–	–	✓	–	–	–	✓
Evaluation of view out: clarity of the view	–	–	–	–	–	–	–	–	–	–	–	–	✓	–	o	–	–	–	–	–	–	✓	–	–	–	✓
LIFE-CYCLE ASSESSMENT																										
LCA for electric lighting installation	–	–	–	–	–	–	o	–	–	–	–	–	–	–	–	✓	–	–	–	–	✓	–	–	–	–	–
LCA for daylighting / shading / facade systems	–	–	–	–	–	–	o	–	–	–	–	–	–	–	–	✓	–	–	–	–	✓	–	–	–	–	–
LCA for integrated lighting solution	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	✓	–	–	–	–	✓	–	–	–	–	–
Built-in LCA methodology	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	✓	–	–	–	–	✓	–	–	–	–	–
Import / export links to LCA software	–	–	–	–	–	–	o	–	–	–	–	–	–	–	–	✓	–	–	–	–	✓	–	–	–	–	–
LCA database included	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	✓	–	–	–	–	✓	–	–	–	–	–
Links to external LCA database	–	–	–	–	–	–	✓	–	–	–	–	–	–	–	–	✓	–	–	–	–	✓	–	–	–	–	–

4 Description of simulation tools

Experts of the IEA SHC Task 70 / EBC Annex 90 provided structured overviews for 25 of the 26 different software tools listed in Section 3. The overviews aim to give readers a concise understanding of each software package, its primary application areas, and its capabilities for simulating daylighting and electric lighting, evaluating visual and non-visual performance, and connecting to building performance simulation or life cycle analyses (LCA).

Most software descriptions follow the same basic structure:

- The **General Information** section summarizes key facts such as the developer or company behind the software, licensing and pricing model, website, and other relevant background information.
- The **Description of the Software** section outlines the main purpose and target user group of the tool, identifies the underlying simulation methods or calculation engines (e.g., ray tracing or radiosity; usage of open rendering engine such as Radiance or proprietary approaches), and discusses its primary areas of application. Where available, information regarding validation studies or compliance with recognized standards is also included.
- To illustrate the practical output of each tool, the **Example Simulation Project Results** section presents representative simulation results and visualizations. These examples are intended to provide an impression of the types of analyses that can be performed and the manner in which results are generated and communicated.
- Finally, the **References** section lists relevant scientific publications, technical documentation, and web resources that were consulted during the review and that may serve as sources for further information.

4.1 AftabRad

Irina Silistraru & Georgios Triantafyllidis (Aalborg University Copenhagen)

4.1.1 General Information

- Current Version: 3.0.0 (as of late 2025)
- Official Website: https://aftabsoft.net/aftab-rad.php
- Download Source: Binaries and installation instructions are available via the official website.
- License Information: Trial-to-purchase licensing model – Free educational license.

AftabRad is an add-in for Autodesk Revit (versions 2018 through 2025) that enables lighting simulations by exporting the BIM model to Radiance/Daysim and bringing the calculated daylighting results back into Revit. It is developed and distributed by AftabSoft (Sweden). The official website for AftabRad (aftabsoft.net) provides the download link and documentation for installation and use.

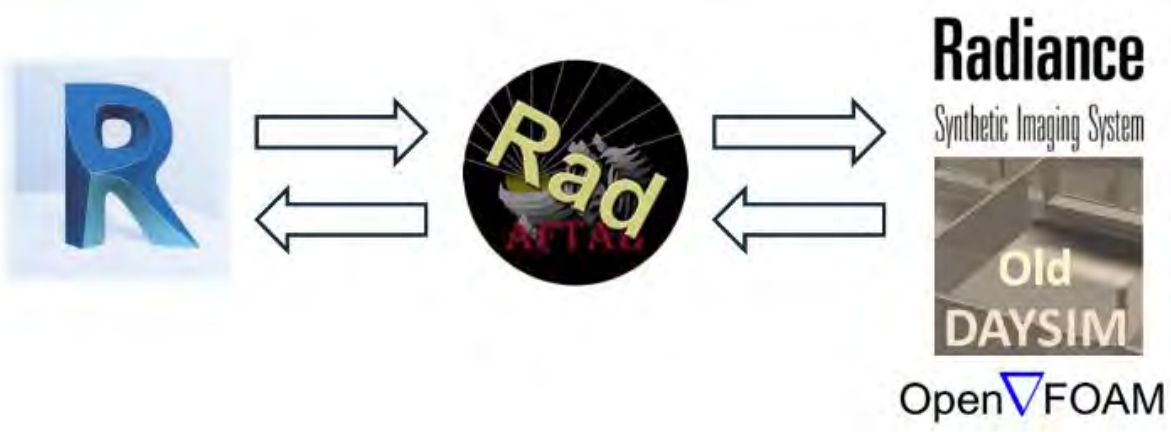


Figure 1: AftabRad Revit Add-in

To function correctly, AftabRad requires several simulation engines and auxiliary tools to be installed and configured:

- **Radiance** – serves as the core daylight rendering and calculation engine, predicting the distribution of visible light in 3D environments.
- **Linux-based Radiance** – for users running large or batch simulations, this enables faster computation and parallel processing.
- **Daysim 3.1e** – generates annual daylight metrics, such as Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI), using Revit geometry and material data exported to Radiance.
- **OpenFOAM** – an open-source computational fluid dynamics toolbox, enabling airflow, temperature, and ventilation analyses for thermal comfort assessments.
- **Accelerad** – accelerates Radiance simulations using GPU processing, significantly reducing computation time for daylight and glare analyses.
- **OpenStudio** – connects Revit models to EnergyPlus, allowing energy modeling, including heating, cooling, and electricity consumption analysis over time.

AftabRad is a proprietary software. The developer offers a fully functional trial version (approximately 6 weeks), after the trial period, users who find it useful are expected to acquire a license for continued use. In parallel, a separate educational license is offered to students. This license is also fully functional but is structured to be renewed annually, aligning with academic calendars.

4.1.2 Description of the Software

4.1.2.1 General

AftabRad serves as a bridge between Building Information Modeling (BIM) and advanced daylight simulation. It is written in C# and IronPython (with some components in C++ and Python) and runs entirely inside Autodesk Revit's

interface. The add-in exports all necessary geometric and non-geometric information from the Revit model to Radiance – including building geometry, materials, location and orientation – and then executes Radiance/Daysim simulations for various daylight metrics. After computation, it imports the results back into Revit for visualization and analysis, eliminating the need for manual file transfers or third-party tools. This tight integration means architects and engineers can perform iterative daylight analysis directly on their BIM model throughout the design process.

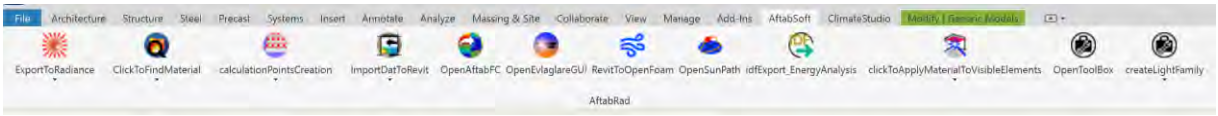


Figure 2: AftabRad tab within the Revit toolbar

4.1.2.2 Features

AftabRad supports a suite of analyses for evaluating electric lighting and daylighting performance. These capabilities are generally categorized as either point-based, which involve calculations on a grid of sensors, or view-based, which involve the generation and analysis of rendered images.

The software facilitates the calculation of foundational static daylighting metrics. This includes the Daylight Factor (DF), which is calculated under the standard CIE overcast sky condition and remains a common metric in many building codes. It also performs Sunlight Hours or Shadow Range studies. Notably, for sunlight hours calculations, the add-in employs a proprietary algorithm that pre-computes and saves sun positions for the selected period into sky files. This optimization can significantly accelerate simulation times compared to brute-force methods, which is particularly beneficial for urban-scale massing studies.

AftabRad's primary strength lies in its implementation of modern, climate-based dynamic daylighting metrics. It can conduct annual simulations based on typical meteorological weather files (EPW). This enables the calculation of metrics that are central to contemporary green building standards and occupant-centric design, such as Daylight Autonomy (DA), Continuous Daylight Autonomy (cDA), Useful Daylight Illuminance (UDI), and Annual Sunlight Exposure (ASE). These metrics provide a much more nuanced understanding of a building's daylighting performance throughout the year compared to static metrics.

The assessment of visual comfort, specifically glare, is another robust feature area. For point-in-time analysis, a user can render any Revit view to generate a High Dynamic Range (HDR) image. This image can then be processed using integrated interfaces for Radiance's evalglare and findglare utilities to calculate a wide range of glare indices, including Daylight Glare Probability (DGP), Daylight Glare Index (DGI), and Unified Glare Rating (UGR). More advanced studies are supported through its ability to perform *annual* glare simulations. Using either Daysim or the dcGlare method, the software can calculate metrics like annual DGPs (simplified Daylight Glare Probability) for a grid of points over an entire year, providing insight into the frequency and severity of glare events.

The tool also demonstrates an alignment with current European standards by providing dedicated workflows for analyses prescribed by EN 17037. This includes specific calculations for "Exposure to sunlight" and "View Analysis," the latter of which assesses the quality of view out based on horizontal sight angle, distance to outside view, and the number of visible layers (e.g., ground, landscape, sky). This capability moves beyond simple light quantity to address the qualitative aspects of the occupant's visual connection to the outdoors.

To address the computationally intensive nature of many of these simulations, AftabRad offers the option to utilize Accelerad. Accelerad is a port of the Radiance engine that leverages Graphics Processing Units (GPUs) for raytracing, which can result in significant speedups (between 3 and 24 times faster in tested scenes) compared to traditional CPU-based calculations. This feature is critical for enabling iterative design exploration and the analysis of large, complex models within practical project timelines.

Traditionally, daylight and lighting analyses for BIM models require exporting geometry to tools like IES-VE, IDA ICE, Diva, Ladybug, Ecotect, DIALux Evo, or Relux via formats such as GBXML, IFC, DWG, or OBJ. This often causes loss of BIM data (materials, room functions, geolocation), with most software only supporting simplified zone-based models. As a result, users must remodel or simplify geometry, making the process time-consuming and error-prone. AftabRad overcomes these issues by performing analyses directly in Revit, preserving model fidelity and material data.

AftabRad is suitable for early design (providing orientation, daylight, and shading feedback), detailed design (fine grid simulations, view analysis, material settings), and R&D (due to its scripting and extensibility).

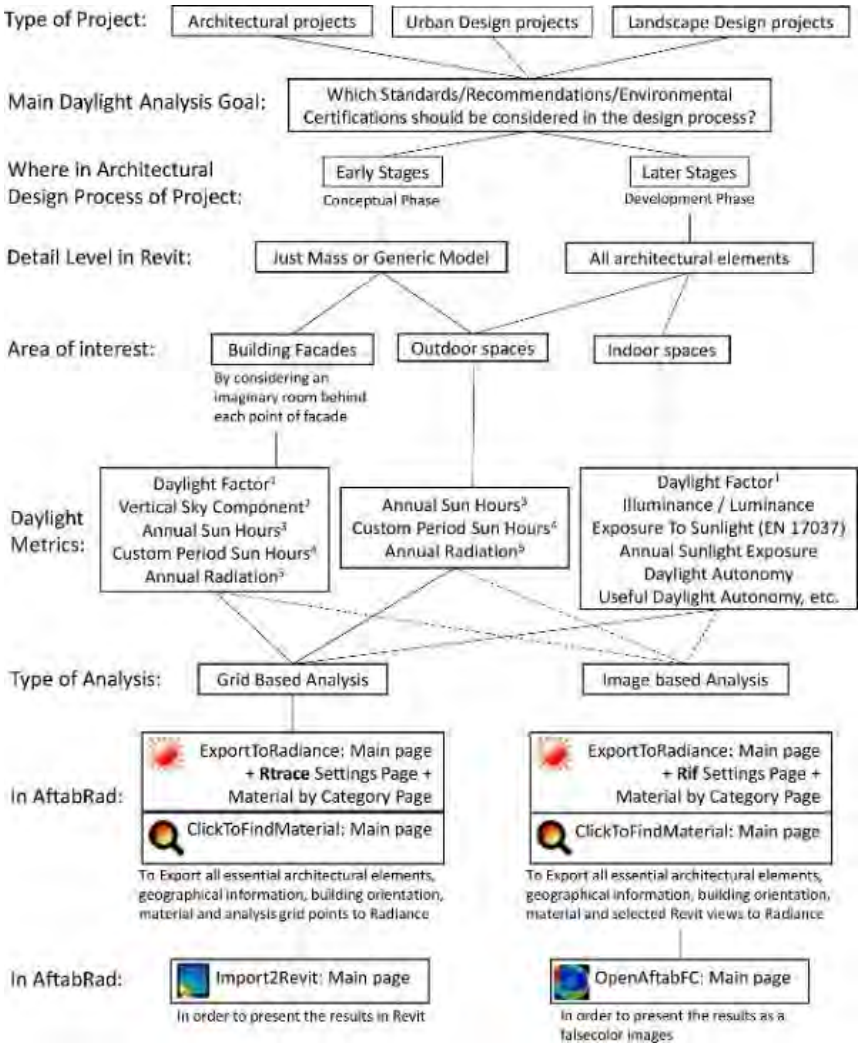


Figure 3: Flowchart (source: https://www.aftabsoft.net/AftabRad/images/flowchart.jpg)

Briefly, AftabRad core features include:

- Automated export of Revit geometry, materials, and family instances.
- Management of simulation parameters for both Radiance and Daysim.
- Execution of annual, time-based daylighting simulations.
- Calculation of key daylighting and visual comfort metrics.
- Re-importation and visualization of simulation results as false-color grids and data points within Revit views.

4.1.2.3 Target user groups

The tool is designed for both daylight simulation experts and typical design professionals with basic simulation knowledge. For advanced users, AftabRad can speed up model preparation – it generates the Radiance scene files (geometry .rad, materials .mat, sky definitions .sky, sensor points .pts, etc.) automatically, allowing experts to then customize or extend the analysis with their own Radiance commands or scripts if needed. They essentially get a ready-to-run Radiance model extracted from Revit, which they can use for custom calculations beyond the add-in's built-in features. For ordinary users (architects or engineers who are not Radiance specialists), AftabRad provides a user-friendly interface to compute the most common metrics that are required by building standards and green building certifications. The add-in's toolbar in Revit presents a guided workflow so that even non-experts can set up simulations by choosing the metric of interest, defining analysis grids, and running the calculation.

4.1.2.4 Explanation on categories relevant for AftabRad according to overview matrix

AftabRad builds on Radiance and integrates with Daysim, enabling ray-based and cumulative daylight simulations. It includes electric lighting calculations and supports daylighting, glare, solar exposure, and sky model generation, allowing for comprehensive visual comfort analysis. As a Revit add-in, it provides direct BIM integration and can export models to blueCFD/OpenFOAM for external wind analysis, although thermal coupling with lighting is not supported. Non-visual or circadian metrics are not included in its current scope, and there is no integration with LCA tools or embodied carbon assessments. Overall, AftabRad focuses strongly on lighting and visual comfort while offering limited support for thermal, non-visual, or sustainability analyses.

Table 1. AftabRad simulation capabilities according to overview matrix

Category	***Simulation Capabilities***
Algorithms / Engines	Utilizes Radiance kernel; compatible with raytracing, daylight coefficient, and 3-phase/5-phase daylight simulation methods.
Electric Lighting	Supports IES and EULUMDAT luminaire import; calculates illuminance and luminance values.
Daylighting	Enables point-in-time and climate-based annual simulations; calculates daylight factors, DA, sDA, and illuminance maps; supports CIE and Perez sky models; sensitive to orientation and external obstructions.
Control Systems	Allows definition of lighting control strategies and daylight-linked dimming for annual energy estimation.
Extended Scope	Interfaces directly with BIM (Revit); allows coupling with OpenStudio and OpenFOAM for thermal analysis; supports IFC-based workflows.
Visual and Non-Visual Effects	While not a spectral simulation tool, Radiance-based engines enable analysis of glare indices (DGP, DGI) and light exposure; useful for visual comfort evaluations.
Life-Cycle Assessment	No built-in LCA features.

4.1.2.5 Low Carbon, High Comfort Evaluations

AftabRad's Contribution to IEA SHC Task 70 Goals (Low Carbon, High Comfort) is focused on the integrated performance metrics and simulations

- Climate-based daylighting: Computes DA, UDI, ASE directly from BIM, linking daylight availability to energy savings and visual comfort.
- BIM-integrated workflows: Enables early evaluation of façades, glazing, and shading in Revit, supporting low-carbon and comfort targets.
- High-fidelity daylight & comfort analysis: Uses validated Radiance/Daysim engines for accurate daylight and glare predictions.
- Radiance-based accuracy: Builds on Radiance's well-documented validation record for illuminance and luminance predictions.
- Reliable data flow: Direct BIM extraction minimizes errors and ensures strong model-to-analysis fidelity.
- Standards compliance: Outputs align with EN 17037 and LEED daylight metrics, supporting validation and benchmarking against measurements.
- All-in-one tool: Runs static and annual daylight simulations, view quality, and glare analyses in a single Revit interface, reducing complexity.
- Design feedback: Visualizes results as false-color maps and grids in Revit, enabling quick interpretation and iterative design for comfort.

4.1.3 Validation

At present, there is limited published validation specifically for AftabRad. However, the reliability of its underlying simulation engines — Radiance, Daysim, OpenFOAM, and OpenStudio — is well-established and documented extensively in scientific literature.

The accuracy of AftabRad's simulations is fundamentally reliant on Radiance, has been validated through multiple international studies as a highly accurate lighting simulation tool for daylight and electric lighting analyses. Radiance is a well-established, physics-based lighting simulation program that has been extensively validated by the lighting research community over the past 30+ years. Studies have compared Radiance's predictions against real-world measurements for various building types, sky conditions, and shading devices, and found good agreement. For example, Mardaljevic (1995) demonstrated Radiance's ability to predict interior illuminance under real sky conditions with high accuracy, and Reinhart & Walkenhorst (2001) validated Radiance's daylight coefficient method for a test office with blinds. Since AftabRad uses Radiance as the calculation core, its results inherit this validated accuracy so long as the input data from the BIM model is correctly translated.

The developers stress that all critical inputs – material properties, sky definitions, sensor locations, etc. – must be set up properly, and they have designed the add-in to extract most of this information from the Revit model automatically. The tool provides interfaces to adjust or review these inputs (for instance, assigning correct Radiance materials to Revit geometry, defining reflectances, etc., in case the default BIM data needs refinement). As Radiance is open-source and continually verified by its user community, AftabRad's reliance on it gives confidence in the physical correctness of the simulations.

In the publications introducing AftabRad, the authors did not report a bespoke validation study (e.g. comparing AftabRad outputs to measured data), but they did test the software on case-study projects and cross-checked results with known Radiance workflows. No significant deviations were found, implying that AftabRad's integration does not introduce error beyond Radiance's normal uncertainty.

In summary, AftabRad's validity is grounded in Radiance's proven accuracy and the thorough transfer of BIM data to the Radiance engine. With correct use, users can trust that the daylight factors, illuminance levels, and other metrics reported by AftabRad are as reliable as those from any Radiance-based analysis tool.

4.1.4 Simulation Results

4.1.4.1 Information about typical results from software

The outputs generated by AftabRad are both visual and quantitative, to satisfy the needs of design presentation as well as technical evaluation. Inside Revit, AftabRad can display results on the model itself – for instance, coloring surfaces according to illuminance or daylight factor values, or overlaying false-color maps on floors and walls. A designer might see a gradient map over a floor plan where blue areas indicate low daylight and red areas indicate high daylight, based on the calculation for a given sky or time. These visualizations make it easy to spot patterns, such as darker zones at the back of a deep room or excessively bright spots near a facade. For more detailed analysis, the tool can also produce numeric data outputs. After a simulation, AftabRad can generate summary tables (in PDF or Excel format) listing key performance indicators for each space – for example, the average and minimum illuminance on the workplane, the percentage of area meeting the design illuminance target, the daylight autonomy percentage for each sensor grid, etc. The ability to export results as reports or data files is built-in: users can save result summaries to PDF directly through the add-in, and even share interactive web links for clients or consultants to view the daylight analysis outcomes



Figure 4: Calculation Point based Analyses by AftabRad Revit Add-in (source: https://aftabsoft.net/aftab-rad.php)

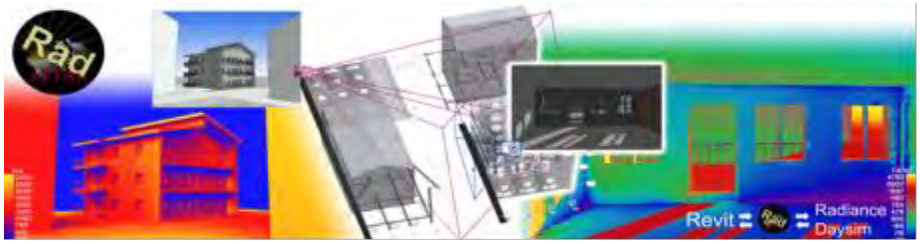


Figure 5: View based Analyses by AftabRad Revit Add-in (source: https://aftabsoft.net/aftab-rad.php)

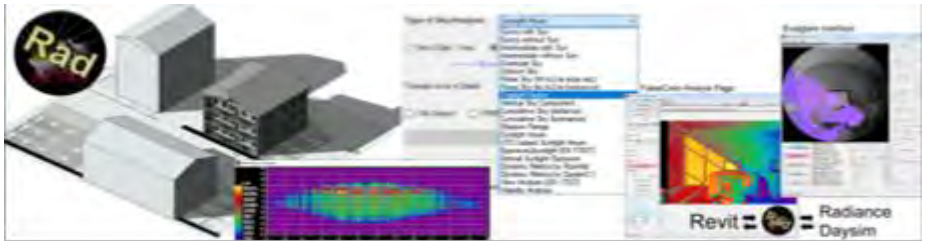
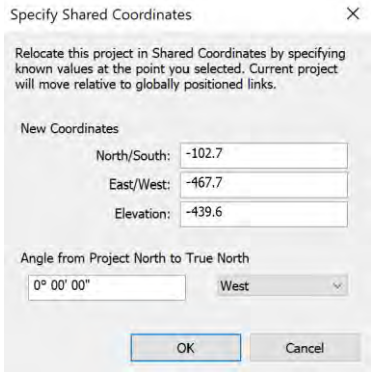


Figure 6: Different Types of Analyses and Tools by AftabRad Revit Add-in (source: https://aftabsoft.net/aftab-rad.php)

4.1.4.2 Example Simulation Project Results

- **Variant 1:**
  Context as defined in the Reference Rooms document.

- **Variant 2:**
  Reference space simulated in an alternative context:
  - Copenhagen, Denmark
  - Orientation:

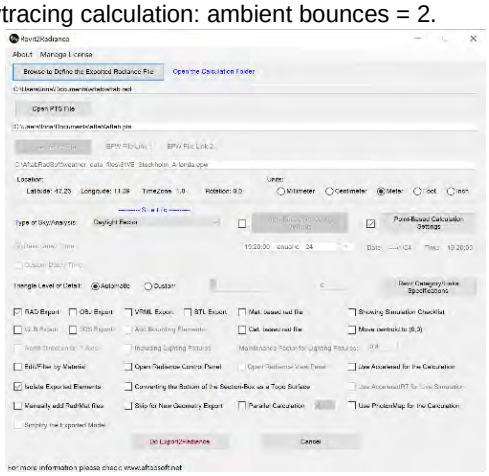


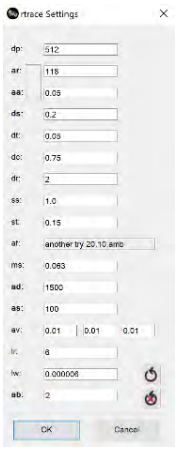
Variant 1:

- AftabRad add-in to Revit (2024), version 3.0.0
- Timestep calculations: Forwards raytracing.
  AftabRad performs **forward raytracing** to compute radiative heat transfer and irradiation distributions.
  Backward raytracing was used in rendering and optical analysis for these simulations (e.g.,Daylight Factor and in RADIANCE for daylighting)

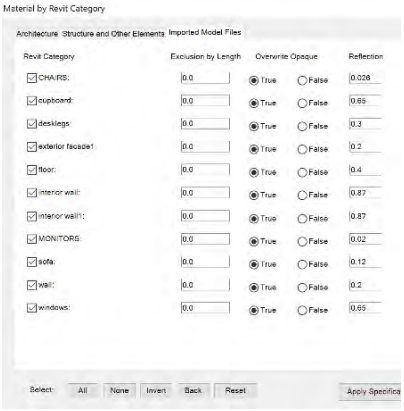
Simulation settings:

Settings for raytracing calculation: ambient bounces = 2.

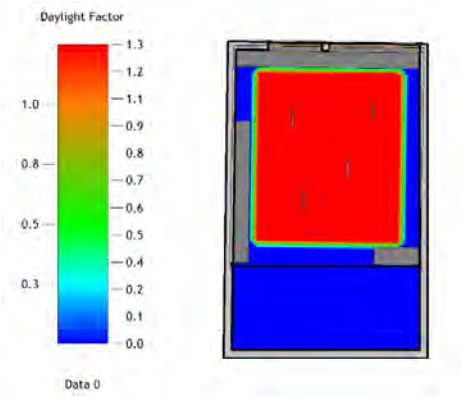


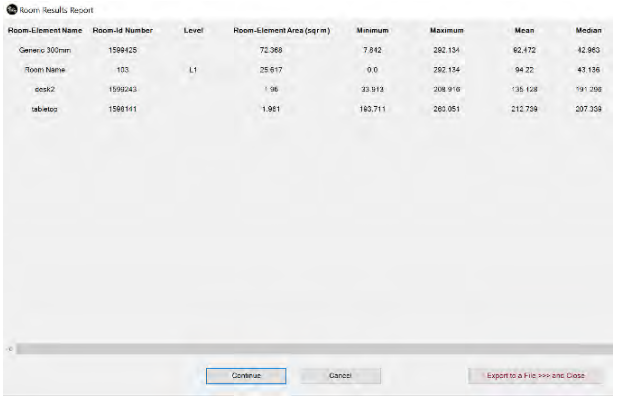


Settings for renderings:
Location, materials, orientation:



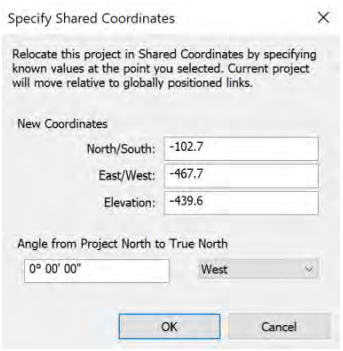
- Sky model: Daylight Factor Analysis

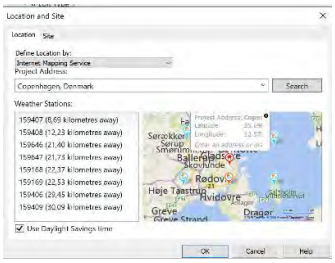


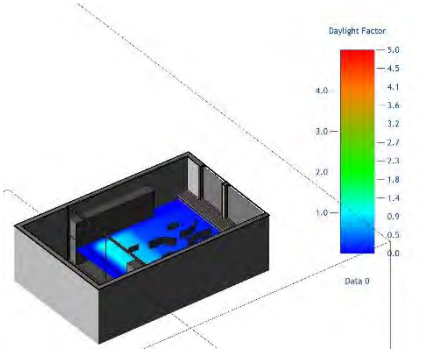


- Total run time (raytracing time only) for simulation, general hardware description: 3 min, on ASUS ROG Zephyrus G14| RTX4070| Ryzen 9| 16 GB" 1TB

Variant 2:







Results for reference case “office”:

	Metric	Reference case	Context CPH
Daylight Factor (CIE overcast sky)	DF min	0.78 %	0. 8%
	DF mx	29.2%	10.1%
	DF avg	4.3%	3.1%

4.1.5 AftabRad References

[1] Miri, M. & Ashtari, E. (2019). Daylight Study from Early to the End of Architectural/Urban Design Process by Developing an Add-in for Revit. Proceedings of the 16th IBPSA Conference (Building Simulation 2019), Rome, Italy.

[2] Miri, M. & Ashtari, E. (2022). Implementing a Digital Solution for Architectural Daylight Analysis in BIM Based Projects by developing a new plugin. IOP Conference Series: Earth and Environmental Science, 1099(1), 012013.

[3] Mardaljevic, J. (1995). Validation of a lighting simulation program under real sky conditions. Lighting Research & Technology, 27(4), 181–188.

[4] Reinhart, C. F., & Walkenhorst, O. (2001). Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. Energy and Buildings, 33(7), 683–697.

4.2 AGi32

Taoning Wang, LBNL (Lawrence Berkeley National Laboratory)

4.2.1 General Information

- Current Version: AGi32 v24
- Official Website: https://lightinganalysts.com/agi32/
- Developer: Lighting Analysts, Inc.
- License: Commercial
- Platform: Windows
- Annual Simulation: Requires Licaso add-on software

AGi32 is a lighting calculation software that implements radiosity and direct illuminance methods for interior and exterior lighting design. The software is developed by Lighting Analysts, Inc.

4.2.2 Description of the Software

AGi32 provides photometric calculations using multiple computational approaches. The software supports 3D modeling and imports CAD geometry.

Computational Methods:

- Full Radiosity: Iterative calculation of inter-reflections between surfaces
- Direct-Only: Point-by-point illuminance from sources without inter-reflection
- Ray Tracing: Optional rendering technique for visualization

Calculation Capabilities:

- Illuminance (horizontal, vertical, and custom planes)
- Luminance (average and point values)
- Unified Glare Rating (UGR)
- Daylight factor (CIE overcast sky)
- Roadway luminance
- Connected lighting load

Electric Lighting:

- IES and EULUMDAT photometric file formats
- Manufacturer luminaire databases
- Custom source definition

Daylighting:

- Point-in-time simulation at specified date/time
- CIE sky models (overcast, clear, intermediate)
- Perez all-weather sky model using weather station data
- Daylight factor under standard conditions
- Obstruction and shadow calculations
- Daylight Study command for batch calculations at multiple times

Annual Climate-Based Daylighting:

AGi32 can prepare models for annual daylight simulation, but calculations require the Licaso add-on software. Licaso is climate-based annual daylight simulation software that works with AGi32 models.

With Licaso integration, the following annual metrics can be calculated:

- Spatial Daylight Autonomy (sDA)
- Annual Sunlight Exposure (ASE)
- Daylight Autonomy (DA) - minimum, maximum, basic, continuous
- Useful Daylight Illuminance (UDI)

- Annual Daylight Exposure
- Annual average, maximum, and minimum illuminance

Note: Licaso uses radiosity methods (not Radiance-based), making it the first non-Radiance climate-based annual simulation tool.

Geometry:

- Built-in 3D modeling tools
- CAD import (DWG, DXF, SketchUp)
- Material property definition

Target Users:

Lighting designers, electrical engineers, architectural lighting consultants.

Validation:

Calculation methods validated through comparison with measured data. Used for IESNA compliance calculations. Developer reports ±2% illuminance and ±3% luminance accuracy under test conditions.

LEED Compliance:

- LEED v4 Option 2: Point-in-time calculations (9 AM and 3 PM on equinox) - native AGi32
- LEED v4 Option 1: Annual metrics (sDA, ASE) - requires Licaso add-on

Limitations:

- Annual climate-based metrics require separate Licaso software
- No thermal/energy simulation integration
- Control system modeling not included
- Spectral calculations not available

4.2.3 AGi32 References

[1] Lighting Analysts, Inc., https://lightinganalysts.com/agi32/

[2] AGi32 Documentation, https://docs.agi32.com/AGi32/Content/daylighting/

[3] Lighting Analysts, "CBDM," https://www.agi32.co.uk/index.php/cbdm

4.3 ALFA

Gabriele Zocchi, Georgios Triantafyllidis (Aalborg University Copenhagen, Denmark)

4.3.1 General Information

- Current Version: 2.2 - in process of integrating ALFA functionalities within ClimateStudio
- Official Website: https://www.solemma.com/alfa
- Download Source: Binaries and installation instructions are available via the official website.
- License Information: Commercial (paid) and educational licenses; trial available via contact.

ALFA—an acronym for Adaptive Lighting for Alertness [1]—is a software plugin developed by Solemma [2] for the architectural and product design platform Rhinoceros 3D. It is designed to support architects and lighting designers in evaluating both visual comfort and non-visual effects of light in interior environments.

Light does not only influence vision; it also plays a non-visual physiological role, regulating circadian rhythms and affecting the secretion of key hormones such as cortisol and melatonin. ALFA builds on this scientific foundation, using models of the human internal clock to assess and optimize lighting conditions that support human health and well-being. ALFA employs Radiance as its core lighting simulation engine. For its specific purposes, Radiance has been extended to use 81 spectral channels, enabling high-resolution spectral calculations. This allows the software to simulate and analyse the non-visual effects of light, including the response of various photoreceptors and their influence on hormonal regulation. A key metric used by ALFA is Equivalent Melanopic Lux (EML) [3], which is referenced by the WELL Building Standard. As the field has evolved, this metric has been aligned with the CIE-recognized melanopic Equivalent Daylight Illuminance (mEDI) [4]. The two are directly convertible using the following relationship [5]: mEDI = 1.103 x EML

4.3.2 Description of the software

ALFA (Adaptive Lighting for Alertness) is a Rhino plugin developed by Solemma that allows users to simulate, visualize, and evaluate both visual and non-visual lighting effects within interior spaces. Once the 3D model is prepared in Rhinoceros, the software is launched by typing ALFA in the Rhino command line. From this point, the workflow follows a series of structured steps to set up the simulation environment and obtain scientifically meaningful lighting metrics.

1. Location Setup

Upon launching ALFA, the first window that appears is the “Location” tab. Here, users can:

- Select a predefined location from a global database of cities and climate files.
- Manually input coordinates by entering the latitude, longitude, and elevation (altitude above ground).
- Model surrounding buildings in the 3D environment. These external obstructions are crucial for accurate daylight and light distribution simulations.

2. Defining Simulation Parameters

Before running any calculations, ALFA requires several essential parameters:

- Time: Select the date, month, and time of day. This determines the sun’s position (elevation and azimuth) and therefore the angle and intensity of incoming daylight.. Simulations at late hours (when no daylight is present) will yield no results unless artificial light sources are included.
- Sky Condition: ALFA allows the simulation of different sky types:
- Clear sky
- Partly cloudy (hazy)
- Overcast
- Heavy rain

Each condition has a distinct influence on how daylight enters the space.

- Ground Spectra
- Users can choose surrounding ground surface types (e.g., concrete, forest, grass, snow, water).
- Each surface has different reflective properties, influencing how much light is redirected into the building.

3. Material Assignment

After setting location and environmental parameters, users proceed to “Choosing Materials”:

- ALFA includes a predefined material library without textures but with optical properties already calculated.
- Each material includes:
- Photopic reflectance (visual light response)
- Melanopic reflectance (non-visual light response)
- Melanopic/Photopic ratio (M/P)

Materials are categorized as:

- Opaque Materials
- Glazing Materials

They are further subdivided into typical interior finishes (e.g., ceiling, floor, furniture). It is recommended to assign each 3D element in Rhino to a material layer before entering ALFA, ensuring a faster and more organized material assignment. Once finished, click “Finished with Materials” to move on to luminaire setup.

4. Luminaire Setup

In the “Create Luminaires” tab, users can:

- Select from a built-in library of luminaires with associated IES files, categorized by lumen output.
- Choose or upload a custom IES file to match specific luminaire specifications.
- Define the source spectrum by specifying the M/P ratio.
- View the SPD graph, showing the contributions to photopic and melanopic response.
- Insert the luminaire into the Rhino model and position it precisely in the 3D space.

5. Sensor Grid and View Planes

To capture and evaluate lighting performance, a calculation grid must be created:

- Go to “Choose View Position Planes” and place surfaces where sensor points should be located.
- The Grid Setup tool allows users to control:
- Spacing: density of calculation points
- Direction: number of sensor orientations per plane
- Rotation: orientation of sensor arrays
- Radius: visual size of sensor markers

Offsets

- View plane offset: defines the height at which melanopic response is evaluated — typically 1.20 m above the floor on a vertical plane, corresponding to seated eye level [6].
- Work plane offset: defines the horizontal plane height for photopic measurements.

6. Running the Simulation

After all parameters are set, pressing the PLAY button starts the simulation. Results appear after a short processing time and can be visualized in the “Grid” tab using different metrics:

- Alertness (melanopic/EML evaluation)
- Visual comfort
- Work plane illuminance

Results are displayed through color-coded view sensors:

- Light blue → Alerting light (M/P > 0.9)
- Orange → Calming light (M/P < 0.35)
- Intermediate values indicate a neutral effect.

7. Visualizing and Interpreting Results

- Render View: Clicking on a sensor activates a camera icon that opens a render view of that point in time.
- Exposure and gamma settings can be adjusted to enhance visibility.

- Melanopic Lux & Photopic Lux:
- Visualize results with false color plots and custom color scales.
- Switch between melanopic and photopic illuminance as needed.
- Clear Results: Clicking the X icon resets the simulation, allowing new parameter settings and reruns.

Conclusion

ALFA provides an intuitive workflow to model, simulate, and evaluate both visual and non-visual lighting performance in architectural spaces. By integrating location-based environmental data, material properties, spectral lighting characteristics, and sensor grid analysis, it offers lighting designers and researchers a powerful tool for creating environments that support comfort, performance, and human well-being.

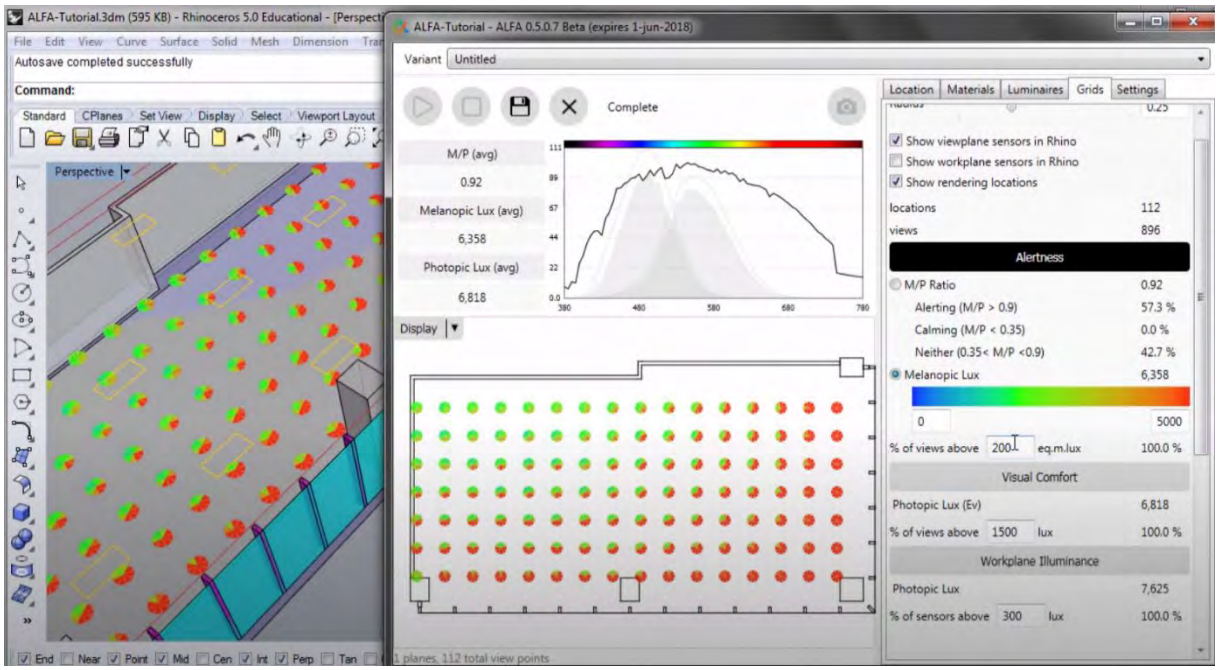


Figure 1: User interface of ALFA after simulation (www.solemma.com/alfa)

4.3.3 Explanation on categories relevant for ALFA according to overview matrix

Algorithms / Engines: ALFA relies on the Radiance lighting simulation engine, extended with 81 spectral channels to support high-resolution spectral rendering. This allows accurate modeling of both photopic and melanopic light components, enabling biologically informed lighting simulations.

Electric Lighting: The software integrates electric lighting through imported or predefined IES files, allowing users to assign luminaires with specific spectral power distributions and melanopic/photopic (M/P) ratios. Luminaires can be positioned within the 3D model for hybrid daylight–electric light scenarios.

Daylighting: ALFA supports climate-based daylight modeling by linking the 3D geometry to location-specific weather files (EPW) and sky models (clear, overcast, hazy, heavy rain). It accurately computes daylight availability based on solar position, sky condition, and ground reflectance.

Control Systems: While ALFA does not simulate dynamic control systems explicitly, it enables scenario-based simulations that can represent different control states (e.g., switching between daylight and electric lighting or modifying spectral composition), supporting manual or time-based lighting control strategies.

Extended Scope: The software is designed primarily for indoor lighting analysis, but its high spectral resolution and flexible environment setup make it applicable to a wide range of building typologies, including offices, classrooms, and healthcare settings.

Visual and Non-Visual Effects: A core feature of ALFA is its ability to calculate both photopic illuminance and melanopic Equivalent Daylight Illuminance (mEDI). This dual-domain approach allows designers to evaluate visual comfort and circadian-effective lighting simultaneously, supporting WELL and CIE S 026 guidelines.

Life-Cycle Assessment: ALFA does not natively include environmental or energy life-cycle assessment modules. However, its outputs (e.g., illuminance levels, daylight availability, electric lighting demand scenarios) can be exported to external tools to support energy and environmental impact analyses.

4.3.4 Validation

To investigate ALFA's reliability, a pilot study was conducted [7], involving both field mEDI measurements and ALFA simulations. For the field experiment, 1600 mEDI measurements were collected over 10 days in a typical Copenhagen office, using a GL SPECTIS 1.0 Touch + Flicker spectrometer. Concurrently, 1600 calculations were performed using ALFA with an accurate 3D office model. ALFA, which utilizes Radiance, was extended with 81-color spectra channels for non-visual light effect simulations, converting EML to mEDI. Luminaire IES files, location, time, and sky conditions were incorporated. Material reflective values, including melanopic reflectivity, were obtained via manual measurements with a Voltcraft MS-200LED SE lux meter. The full dataset is publicly available at https://github.com/Gazo93/mEDI_RE_SIM. The comparison between ALFA and measurements was twofold: a) on the predictive accuracy of the recommendation in meeting the 250 lux mEDI threshold [6] and b) on predictive accuracy of the numerical mEDI values

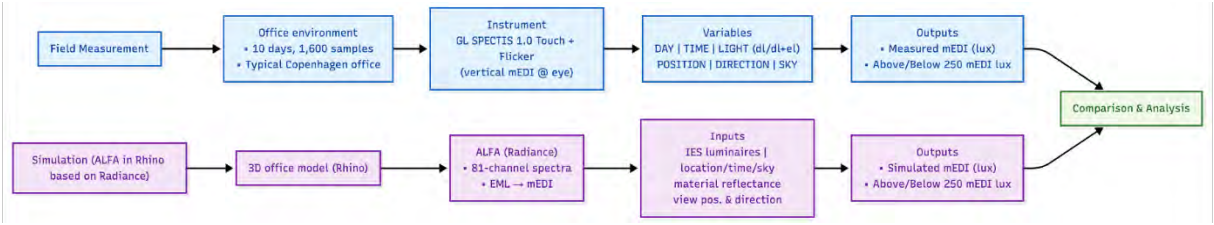


Figure 2: Validation methodology

a) Predictive Accuracy of the Recommendation (meeting the 250 lux mEDI threshold)

Confusion matrix	Simulation: Above	Simulation: Below
Measured: Above	TP (True Positive): 882	FN (False Negative): 77
Measured: Below	FP (False Positive): 95	TN (True Negative): 546

Metric	Formula	Result	Interpretation
Accuracy	(TP+TN) / Total	89.3%	High overall accuracy indicates the simulation is generally reliable at identifying whether the threshold is met or not.
Precision (above)	TP / (TP+FP)	90.3%	Reliability of “above” predictions. When the simulation says it’s “above,” it usually is.
Recall (above)	TP / (TP+FN)	91.9%	Ability to catch actual “above” cases. High recall means the model rarely misses real above-threshold cases.
Precision (below)	TN / (TP+FP)	87.6%	Reliability of “below” predictions. When the simulation says it’s “below,” it usually is.

Recall (below)	TN / (TP+FN)	85.2%	Ability to catch actual “below” cases. High recall means the model rarely misses real below-threshold cases.

Findings:

- Overall accuracy of nearly 90% supports the practical use of ALFA simulations in early design and compliance checks
- High precision and recall for above-threshold → reliable for ensuring lighting designs meet recommended levels.
- Slightly lower performance for below-threshold → caution when diagnosing underlit conditions.
- The confusion matrix shows more false positives than false negatives. This means ALFA tends to slightly overpredict in borderline conditions (e.g., between 220–280 lux).

b) Predictive Accuracy of the mEDI values (Numerical Prediction)

Metric	Total Dataset	Above 250 lux	Below 250 lux	What it means	Interpretation (Above vs. Below)
Correlation (r)	0.619	0.560	0.894	Indicates how well the simulation values follow the same trend as the measured values. A higher r means a stronger linear relationship.	Much higher correlation for below 250 lux shows the model follows low-light measurements more consistently than high-light ones.
Mean Absolute Error (MAE)	286.97 lx	456.51 lx	33.32 lx	Average of the absolute differences between simulated and measured mEDI values. Lower MAE means smaller prediction errors.	Simulations are very accurate in low-light conditions, but errors are larger for above-threshold cases, likely due to higher variability in daylight and reflections.
Root Mean Square Error (RMSE)	1117.43 lx	1442.72 lx	52.19 lx	Gives more weight to larger errors compared to MAE. A high RMSE indicates the presence of big deviations between simulation and measurement in some cases.	Errors in bright conditions are much larger, confirming that overestimation or underestimation peaks mostly occur above 250 lux.
R^2 (Coefficient of Determination)	0.36	0.28	0.63	Explains how much of the variability in measured values is explained by the simulation. Higher R^2 indicates a better model fit.	R^2 is more than twice as high below 250 lux, meaning the model explains low-light variability much better than high-light variability.

Findings:

- General
- Correlation of 0.619 reflects an overall moderate linear agreement.

- Below 250 lux
- Very strong correlation (r = 0.894) and low error values (MAE ≈ 33 lx, RMSE ≈ 52 lx).

- The simulation model performs very consistently in low-light conditions, likely because these scenarios are less affected by complex daylight dynamics.

- Above 250 lux
- Moderate correlation (r = 0.56) and significantly larger errors (MAE ≈ 457 lx, RMSE ≈ 1443 lx).
- The increased error is mainly due to the higher variability of daylight, especially under sunny or mixed sky conditions, reflections, and occupant view direction.

4.3.5 ALFA References

[1] Solemma. (n.d.). ALFA — Adaptive Lighting for Alertness. Retrieved October 18, 2025, from https://www.solemma.com/alfa

[2] Solemma. (n.d.). About Solemma. Retrieved October 18, 2025, from https://www.solemma.com/about

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[4] Commission Internationale de l'Eclairage. (2018). System for metrology of optical radiation for ipRGC-influenced responses to light (CIE S 026/E:2018). Vienna, Austria: CIE.

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[6] Brown, T. M., Brainard, G. C., Cajochen, C., Czeisler, C. A., Hanifin, J. P., Lockley, S. W., Lucas, R. J., Münch, M., & Wright, K. P. (2022). Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults. PLOS Biology, 20(3), e3001571.

[7] Zocchi, G., & Triantafyllidis, G. (2025). Assessing the predictive accuracy of circadian lighting simulations in an office environment. Paper presented at the Sustainable Lighting International Conference (SLIC 2025), Aveiro, Portugal.

4.4 Andrew Marsh Web Apps

Natalia Sokol, Gdansk University of Technology

4.4.1 General Information

- Current version: Second iteration (released 15 October 2019)
- Website: Dr. Andrew Marsh – Web Apps (Dynamic Daylighting app available online: https://andrewmarsh.com)
- License: Free for educational and research use; browser-based, no installation required

Dynamic Daylighting is a web-based, interactive daylight analysis tool developed by Dr. Andrew Marsh. It models daylight distribution inside a simple rectangular room in real time, based on detailed CIE Standard General Sky luminance distributions. The application combines split-flux calculations (for internally reflected light) with raytracing methods (for direct sky and reflected components), enabling both speed and accuracy.

Users can load weather files from EnergyPlus (.epw) or DIVA/DAYSIM (.wea), and the application applies the Perez All-Weather Sky model to generate dynamic sky luminance distributions based on instantaneous direct and diffuse radiation and/or illuminance. From this, hourly illuminance values at each grid point across an entire year can be calculated and analysed to derive spatial dynamic daylight metrics. When viewing a dynamic sky, users can also interactively navigate through time of day and year, or watch animations of daylight conditions.

The software is intended primarily for students, educators, researchers, and designers who wish to explore daylight behaviour interactively, without the steep learning curve of full CAD or simulation environments. Target Groups: Architecture/lighting students, educators, early-stage researchers, and practitioners requiring simplified real-time analysis.

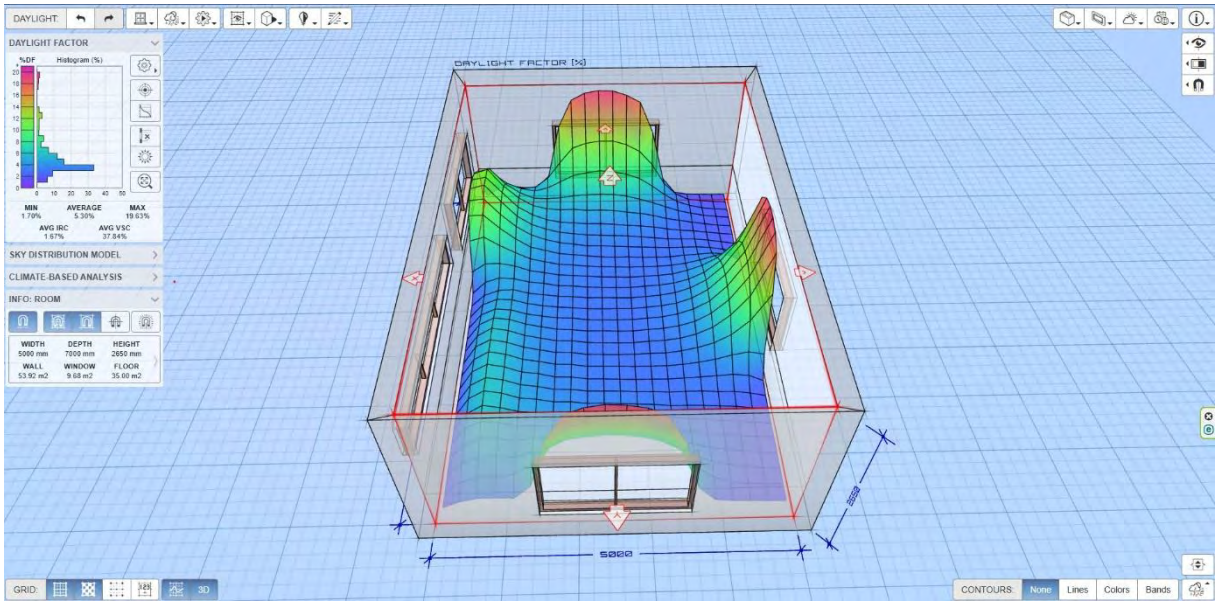


Figure 1: User interface of Andrew Marsh, Dynamic Daylight with a sample DF simulation (https://drajmarsh.bitbucket.io/daylight-box.html)

4.4.2 Description of the Software

The app allows the definition of basic optical properties for transparent and opaque elements. For glazing, users can adjust visible light transmittance (Tvis), while for interior and exterior surfaces, reflectance values can be assigned. These parameters determine how light enters and interacts within the simple shoebox geometry.

Users begin by creating a shoebox-style model, directly within the interface. The room's size can be modified by dragging bounding surfaces, and apertures or shading devices can be positioned interactively. External obstructions, horizontal and vertical shades, or linked combinations can be added, although their parametrisation

is limited to dimensions, offsets, and linkage rather than custom complex forms. Sensor grids are automatically applied across the workplane for evaluating daylight penetration and uniformity.

The app runs real-time calculations based on a split-flux method for internally reflected light, combined with raytracing for direct sky and externally reflected components. Users can select among the CIE Standard General Skies (16 types) or upload weather data files to dynamically generate hourly sky conditions. Results update interactively in near real-time, allowing immediate visualisation of the impact of design changes such as window size, orientation, or surface reflectances.

The application provides several quantitative outputs relevant to climate-based daylight modelling (CBDM). These include Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Daylight Saturation Percent (DSP), Annual Sunlight Exposure (ASE), Cumulative Daylight (lux·h), and even no-sky line analysis for regulatory compliance. Results are displayed as illuminance distribution maps, updated instantly with every design change. Interactive shading masks further visualise how external obstructions block parts of the sky dome.

While shading systems can be represented as simple planes (horizontal, vertical, or linked), their behaviour is not described through advanced optics such as BSDFs. This means that shading evaluation is limited to geometric obstruction rather than spectral or scattering performance. The app does not compute glare indices, but it enables users to explore luminance distributions, daylight sufficiency, and exposure to direct sunlight in a highly interactive manner. Its speed and visual feedback make it particularly suitable for early design exploration and educational use, where iterative testing of daylight strategies is valuable.

Basic Features

- Geometry input: Simple axially-aligned rectangular rooms with any number of rectangular windows and cuboid shading devices/obstructions; geometry edited through direct 3D manipulation or numeric input; INFO panel for grouped parameter editing.
- Daylight calculation method: Combination of split-flux method for internally reflected components and raytracing for direct sky and externally reflected components.
- Sky & climate models: 16 CIE Standard Skies (ISO 15469:2004(E) / CIE S 011/E:2003); Perez All-Weather Sky model with dynamic input from EPW/WEA weather files for Climate-Based Daylight Modelling (CBDM).
- Outputs: Colour maps, binned grids, contour plots, histograms, daylight factors, shading masks, sun-path diagrams, visible sky percentage, and target compliance overlays.
- Daylighting metrics available for simulation include:
- Daylight Autonomy (DA)
- Useful Daylight Illuminance (UDI)
- Daylight Saturation Percent (DSP)
- Annual Sunlight Exposure (ASE)
- Cumulative Daylight (Lux·hrs)
- Interaction: Real-time 3D manipulation (dragging/resizing), numeric editing of parameters, annual/hourly sky animations, snapshot comparisons, export to Radiance/DIVA for validation.
- Limitations: Current version restricted to simple rectangular rooms; CAD/BIM arbitrary geometry support is under development for future versions.

Key Features

- Interactive manipulation of room size, windows, surface reflectances, window transmittances, external shading devices, and obstructions.
- Real-time visual updates of daylight distribution on the working plane.
- Library of 16 CIE standard skies, with option to generate skies dynamically from weather data.
- Export functionality for validating models in Radiance and DIVA/DAYSIM.
- Entirely JavaScript-based, runs on desktop and mobile devices.

Low Carbon, High Comfort Evaluations

The app's main contribution to Task 70 goals lies in its ability to:

- Support rapid testing of daylight strategies (window placement, shading, reflectance) that influence visual comfort (glare, uniformity).

- Encourage daylight-centred design by allowing easy experimentation with aperture size, glazing transmittance, and external shading — key parameters for reducing reliance on electric lighting and lowering carbon emissions.
- Act as a teaching and early-design decision-support tool to raise awareness of daylight's environmental and health impacts, even though the software itself does not directly calculate non-visual metrics (e.g., melanopic EDI).

Validation

- Validation has been carried out by direct comparison with Radiance and DIVA/DAYSIM, showing close correlations for simple rectangular room models.
- External shading and obstruction handling have been tested using raytracing masks.
- Users can export their own models to Radiance/DAYSIM and re-import results for visual cross-checks.
- More complex geometry validation (non-rectangular spaces, BIM models) is under development.

4.4.3 Example Simulation Project Results

The simulation application is designed primarily for shoebox analysis of simple rectangular rooms. Models cannot be imported but must be constructed directly within the interface. Users can incorporate external obstructions as well as horizontal, vertical, or linked shading devices, though modifications are limited to adjusting their size, offset, and linkage rather than creating detailed custom geometries. The tool provides real-time daylight distribution results, visualised through illuminance maps across the working plane that update instantly with any design change. It illustrates the impact of window orientation, size, glazing transmittance, surface reflectances, shading elements, and obstructions on daylight penetration and uniformity. In addition to performance metrics such as Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Daylight Saturation Percent (DSP), Annual Sunlight Exposure (ASE), and Cumulative Daylight (Lux·hrs), the simulation of the no-sky line is also possible, enabling assessment of daylight provision according to building regulations and standards. Interactive shading masks further provide intuitive feedback by showing how obstructions block portions of the sky dome. According to the developer's description, although the application prioritises speed and interactivity, validation studies indicate that its results show a strong correlation with those obtained from Radiance and DIVA/DAYSIM.

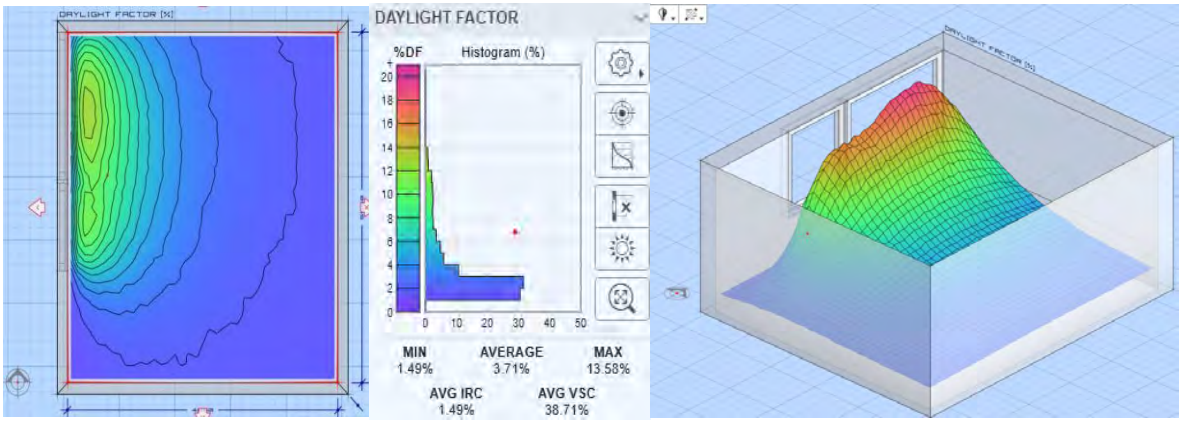


Figure 2: DF simulation for an office room using Andrew Marsh, Dynamic Daylight (https://drajmarsh.bitbucket.io/daylight-box.html)

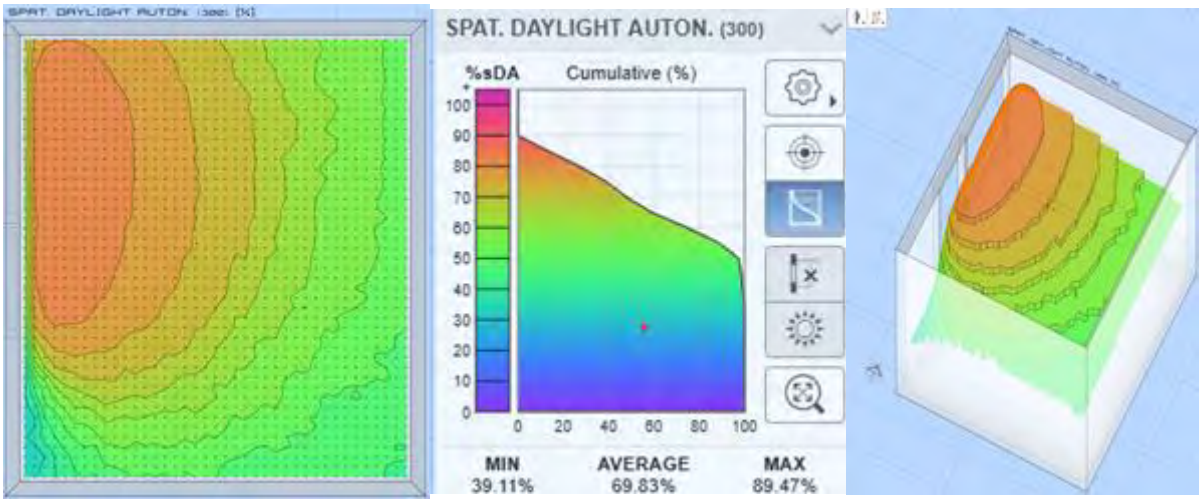


Figure 3: Spatial Daylight Autonomy 300/50 simulation for an office room using Andrew Marsh, Dynamic Daylight (https://drajmarsh.bitbucket.io/daylight-box.html)

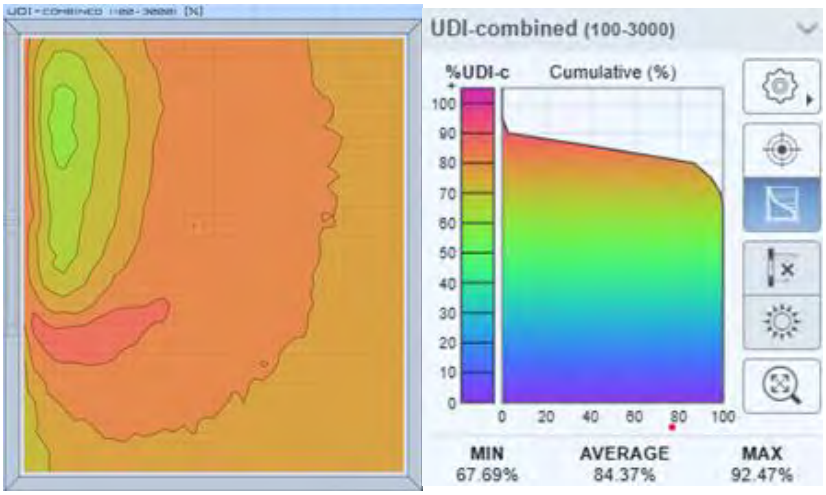


Figure 3: Useful Daylight Illuminance (100-3000 lx) simulation results for an office room using Andrew Marsh, Dynamic Daylight (https://drajmarsh.bitbucket.io/daylight-box.html)

4.4.4 Andrew Marsh App References

[1] ISO 15469:2004(E) / CIE S 011/E:2003. Spatial distribution of daylight – CIE Standard General Sky. International Commission on Illumination.

[2] Marsh A., Computer-Optimised Shading Design, Proceedings of Building Simulation, 11–14, 2003.

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[6] Roberts A., Marsh A., ECOTECT: Environmental Prediction in Architectural Education, Proceedings of ECAADE Conference, Cardiff University, 2001.

4.5 ClimateStudio

Valerio R.M. Lo Verso, Anna Pellegrino, and Alberto Gremo (Politecnico di Torino, Turin, Italy)

4.5.1 General Information

- Version 2.2, available online on Solemma website https://www.solemma.com/climatestudio

ClimateStudio is a fast and accurate simulation tool for lighting (both visual and non-visual) and thermal analyses in the frame of environmental performance in Architecture, Engineering, and Construction (AEC) field, allowing both energy and indoor environmental quality analyses. Its simulation processes support designers and consultants in fine-tuning buildings to enhance energy efficiency, daylight penetration, electric lighting performance, as well as visual and thermal comfort, among other factors impacting occupant well-being. Operating as a plugin for Rhinoceros 3D, ClimateStudio necessitates the utilization of the more recent versions 6, 7 or 8.

ClimateStudio is developed by Solemma, and the current version is ClimateStudio 2.2.9338.29724. It can be downloaded at: https://www.solemma.com/climatestudio (last access: October 14, 2025). Different types of licenses are available for professionals and scholars (professors, researchers), while free-of-charge licenses are offered for students over a period of specific courses.

4.5.2 Description of the Software

ClimateStudio runs lighting simulations (using a novel RADIANCE-based path tracing technology) and/or thermal simulations, using ENERGYPLUS. Simulations are fast and accurate, faster than cloud-based tools.

SPEED: as stated by the developers, ClimateStudio employs Radiance, a widely accepted physically-based engine developed and maintained by Lawrence Berkeley National Laboratory, to simulate light behavior. However, distinguishing itself from earlier versions, ClimateStudio utilizes Radiance in a progressive path tracing mode. Instead of tracing all potential light paths prior to computing a result, ClimateStudio traces a limited number of paths at once, updating the result incrementally. This progressive method allows ClimateStudio to generate initial estimations almost immediately, followed by a gradual refinement of the data as more light paths are traced. Although precision improves continuously with additional passes of paths, only a few passes are required for a reliable outcome to emerge. By merging progressive path tracing with its own, embedded hardware acceleration tool, ClimateStudio achieves accurate results swiftly. For instance, in a given scenario, ClimateStudio determines the Spatial Daylight Autonomy (sDA) of a side-lit office in approximately ten seconds. In contrast, Daysim and native Radiance typically take hours to arrive at the same result.

ACCURACY: the novel RADIANCE-based path tracing technology guarantees fast yet accurate simulations. This means that instead of tracing every potential light path before calculating a result, ClimateStudio tracks a small number of paths at once and plots the results, then continuously updating them as the simulation progresses. The developers report on the site a comparative analysis carried out for a sample office in Boston where they compare spatial daylight autonomy results obtained from ClimateStudio to those obtained using Radiance stand-alone and Daysim, both set to 'high fidelity simulation parameters. The results perfectly converge for the three tools. This is possible because the algorithm used by ClimateStudio eliminates the use of low-quality settings, thus achieving higher out-of-the-box fidelity than its predecessors. Daysim takes so long to produce an accurate result, legacy daylighting tools have tended to use low-fidelity settings out of the box, compromising accuracy to gain speed. DIVA-for-Rhino, for example, uses a default limit of two ambient light bounces, rather than seven.

Low Carbon, High Comfort and Energy Evaluations

ClimateStudio offers a wide range of analyses, in the lighting field, considering both visual and non-visual effects of light, and in the thermal field.

Lighting analyses

The following analyses can be carried out:

- *site analyses*: this part of the program reads information in the weather file of the site selected (over 30000 files are already contained in a library of the program), in terms of wind, radiation, temperature and relative humidity values; besides, a solar path is plotted and 3D qualitative overshadowing analyses

are generated for the model under consideration, showing the shadows cast by neighboring buildings or by shading systems (such as overhangs, fins, and so forth) for any time-step during a year

- *point-in-time illuminance*: this part of the program allows illuminance values to be determined on a wide numbers of user-defined calculation grids for any time-step during a year; for each time-step, it is possible to set the sky condition (choosing from: CIE clear sky, CIE intermediate sky, CIE overcast sky, Perez sky - calculated from the weather file of the site considered -, uniform sky, Utah colored sky), to add luminaires by selecting from a library or importing their photometric data as *.ies* format) or a tubular daylighting guidance devices (light-pipes), selecting among different typologies contained in the library of the program
- *daylight availability*: this part of the program allows static simulations and climate-based daylighting modeling CBDM to be performed on an annual basis. Static simulations are aimed at the calculation of the daylight factor, while CBDM simulations at the calculation of several metrics, such as daylight autonomy DA, spatial daylight autonomy sDA and annual sunlight exposure ASE (thus assessing the compliance with the daylighting credits contained in the LEED v4-1 protocol), useful daylight illuminance UDI. By default, UDI is provided in four categories: $UDI_{failing}$ <100 lx, $UDI_{supplemental}$ 100 lx-300 lx, $UDI_{autonomous}$ 300 lx-3000 lx and $UDI_{excessive}$ >3000 lx; however, users can customize the thresholds for different analysis, if needed. Annual analyses can also be performed to verify the compliance of daylighting conditions with respect to EN 17037:2018, “Daylight in buildings”.
  Annual results are displayed, but they can be read at each time-step during a year. Moreover, hourly data can be exported as *.csv* data and analysed through excel tools.
- *annual glare*: this part of the program allows annual simulations of glare to be performed, particularly by calculating the Daylight Glare Probability DGP over any user-defined grid (at eye-level); DGP values can be calculated for up to sixteen directions of observations at each point of the grid, thus providing a full glare analysis of the space under consideration within one simulation; moveable blinds are also considered during this analysis, plotting out an annual usage profile. Besides, it is possible to generate a render of the room for each view direction, setting date and time: the tool runs Evalglare to produce the render and to evaluate the vertical illuminance and view-dependent DGP at the same time. Glare results are provided on an annual basis, but they can also be read at each time-step during a year
- *Radiance rendering*: this part of the program calls Radiance for the generation of renderings based on *Rhinoceros* standard views, named views defined by the user or specific camera settings, for instance a fisheye at eye level.
- *view analysis*: this part specifically addresses the quantification of the view out from each point of user-defined grids. Results are provided in terms of compliance with the requirements of either the LEED 4.1 protocol or the standard EN 17037.
- *spectral point-in-time illuminance*: this part has been implemented in the latest software update. The workflow allows to calculate illuminance distributions for electric lighting and/or daylight at specific moments using hyperspectral Radiance simulations. The simulation kernel is based on a progressive path-tracing version of Radiance raytracer, dividing the visible spectrum into 20 channels. Output encompasses photopic and melanopic illuminances, as well as spectral irradiances in 380-780nm range, in 20nm bands. Results dashboard distinguishes photopic from melanopic lux, and automatically evaluates M/P ratio (melanopic to photopic ratio). The users can select either work plane or vertical eye illuminance to be simulated: in the former case, a sensor points grid is positioned typically at desk height, in the latter, sensors are placed at eye level of a sitting person, accounting for one or multiple view directions. Sky models can be selected among CIE clear, overcast or intermediate sky, Perez sky - calculated from the weather file of the site considered -, uniform sky, Preetham colored sky or libRadtran spectral sky.
- *Radiance rendering*: this part of the program relies on Radiance v6.0 for the generation of hyperspectral rendering (HSR pictures). Results cover the visible spectrum within the 380-780nm range, and unlike standard HDR file format, HSR contains information for melanopic illuminance evaluation.

Materials: ClimateStudio contains a huge library of real materials, both opaque and transparent, fully characterized in visual and thermal properties. However, it is possible for the users to add new materials as Radiance definition (as explained above).

Transparent materials: these are based on LBNL’s International Glazing Database (IGDB). The internal library encompasses both static and dynamic material properties, for instance representing the seasonal changes in leaf colour. Users can also choose to model electrochromic or diffusing glazings.

Blinds: The presence of blinds can be modeled, and their annual profile of use is shown among the output. Blinds can be selected from a library contained in the program: data of over one hundred existing blinds on the market are available, with a light transmittance in the range 0.0%-47.2%, sourced from LBNL’s Complex Glazing Database (CGDB). The blinds in the database are also classified based on five categories of glare control as a

function of the blinds openness factor (permeability): very little effect, little effect, moderate effect, good effect, very good effect. It is also possible to manually add a blind from other manufacturers, with a different light transmittance, or importing a *.xml* file representing the BSDF behavior of the chosen blind. To model how blinds can be operated during the year, they can be controlled either manually or automatedly; the blind control can be done either through the rule set by the IES LM-83 document (*whenever >2% of regularly occupied area is hit by DHI> 1000 lx, the blinds are closed; whenever closure condition is no longer met - assessed hourly -, blinds are re-opened*), or through a user-defined control logic.

Thermal analyses

- *radiation map*: this part allows irradiance values to be calculated on external surfaces of buildings, over an user-defined grid; irradiance data are read from the weather file of the site selected and computed for large areas to assess the impact of urban settings on the building surface, for instance to analyze the potential of a surface in terms of solar radiation for the installation of PV systems
- *thermal analyses*: this part of the program calls EnergyPlus to allow multizone energy modeling; for each zone, input parameters for HVAC and electric lighting systems can be specified for the calculation of the annual energy demand for cooling, heating, and lighting. Besides, ClimateStudio computes highly resolved annual spatial comfort maps to reveal local thermal comfort issues early in the design process and can simulate and visualize detailed energy and mass flow through a multi-zone model, using its advanced AirflowNetwork capabilities. Pressure Coefficients can be self-calculated or provided as an envelope mesh from CFD simulations. Finally, the performance of photovoltaics can also be simulated to offset energy demands or demonstrate net-zero feasibility.

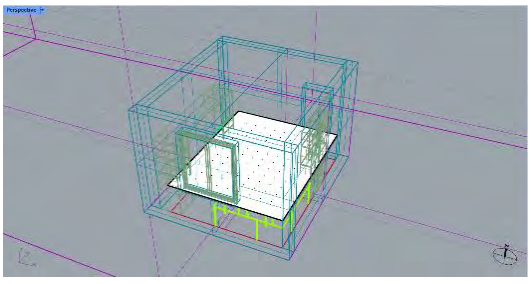
ClimateStudio for Grasshopper: it is worth pointing out that ClimateStudio allows fully parametric daylight and energy modeling via Grasshopper for optimizations and sensitivity analysis.

Combination with LCA

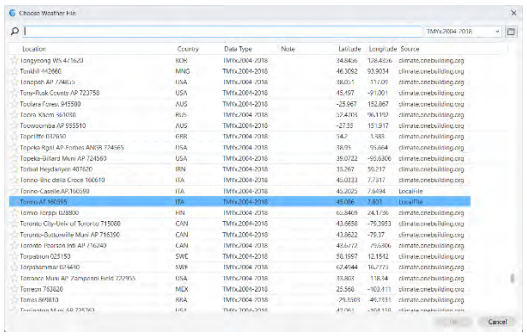
Oghazi et al. show an example how daylight simulations using ClimateStudio can be combined with whole life carbon simulations according to EN 15978 [4].

4.5.3 Example Simulation Project Results

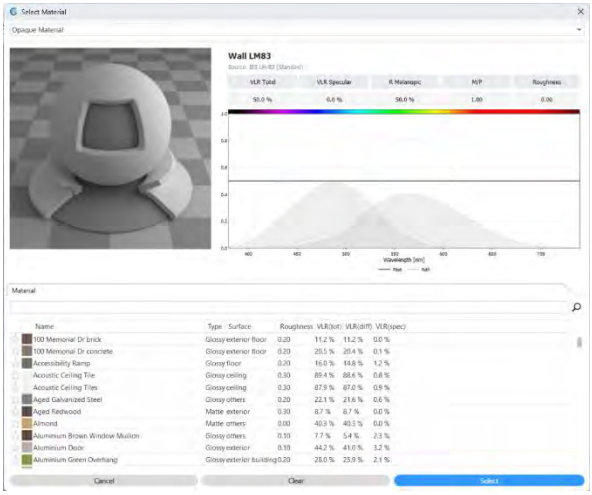
As an example, daylighting simulation results of a living room in a residential unit are shown.



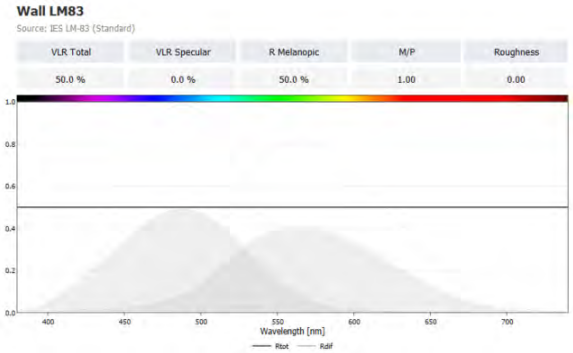
3D model in *Rhinoceros 8*



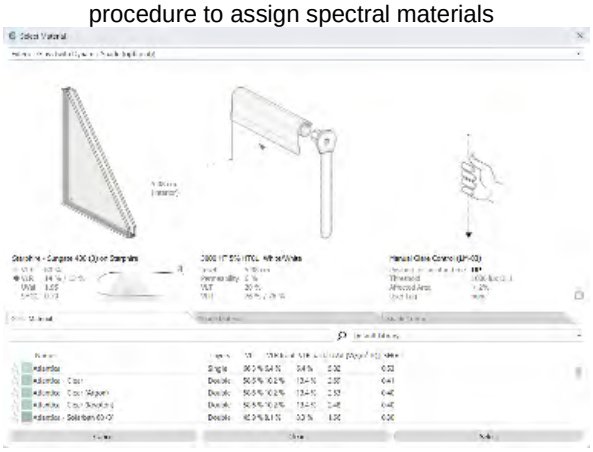
internal database of *.epw* files



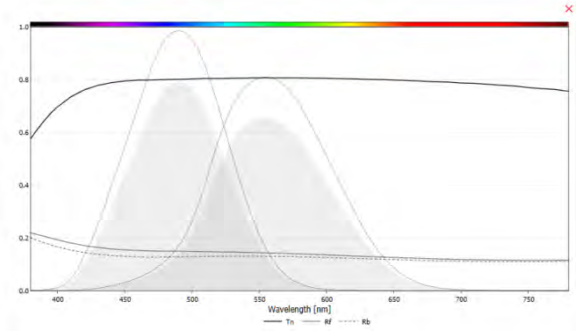
procedure to assign spectral materials



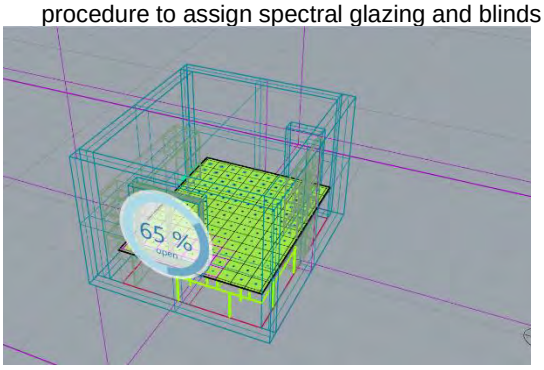
spectral properties for the material



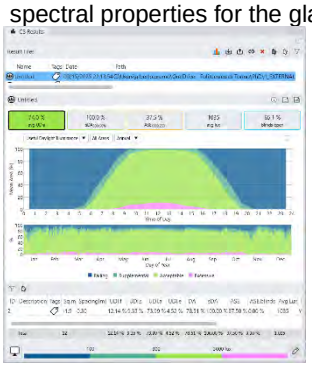
procedure to assign spectral glazing and blinds



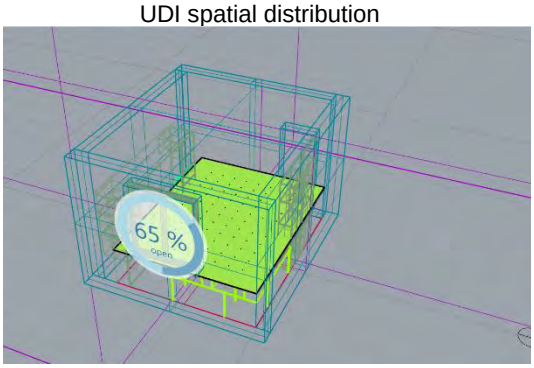
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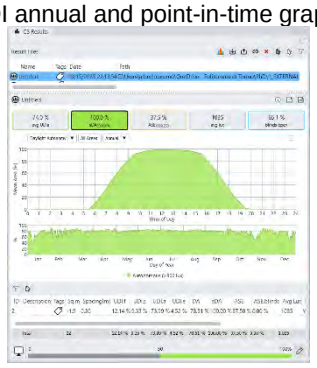
UDI spatial distribution



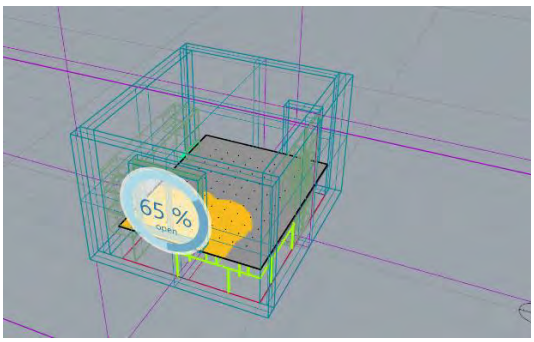
UDI annual and point-in-time graphs



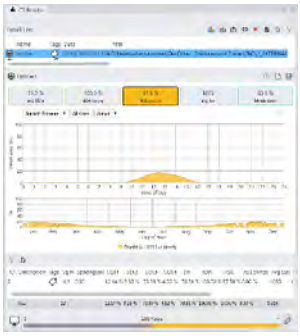
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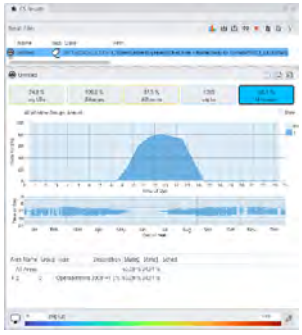
sDA annual and point-in-time graphs



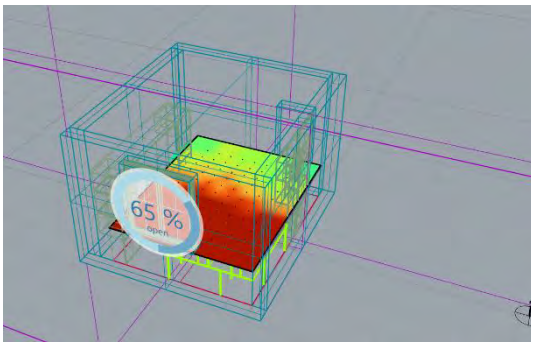
ASE spatial distribution



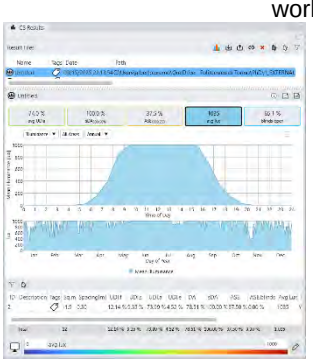
ASE annual and point-in-time graphs



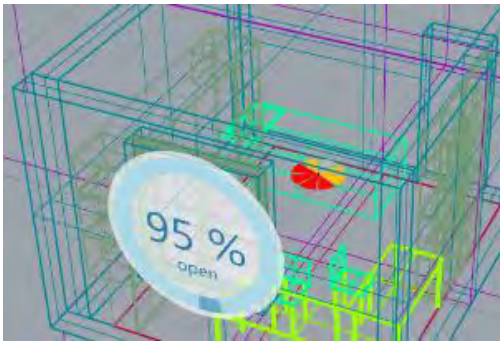
blinds annual usage profile for daylight availability workflow



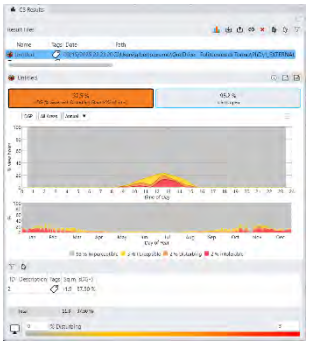
average illuminance spatial distribution



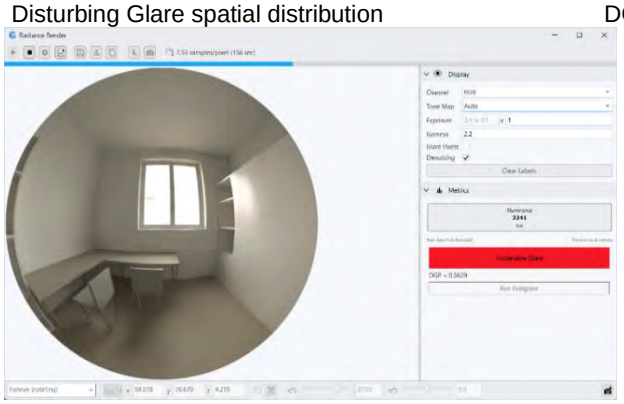
average illuminance annual and point-in-time graphs



Disturbing Glare spatial distribution



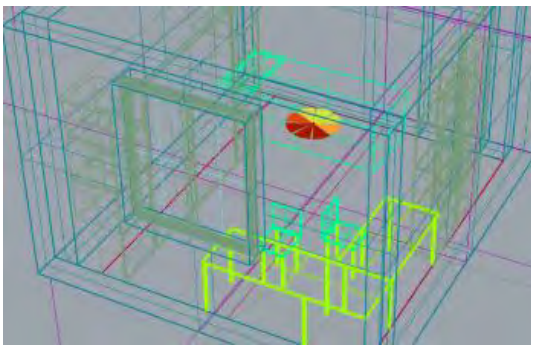
DGP annual and point-in-time graphs



Radiance rendering window, with preliminary Evalglare outputs



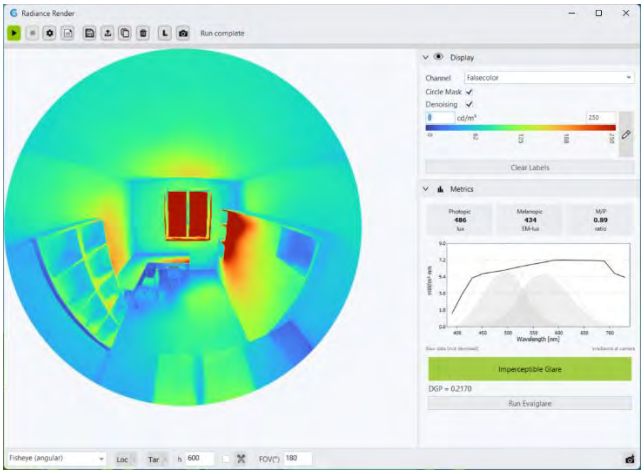
Render view completed, December 21, 12.30



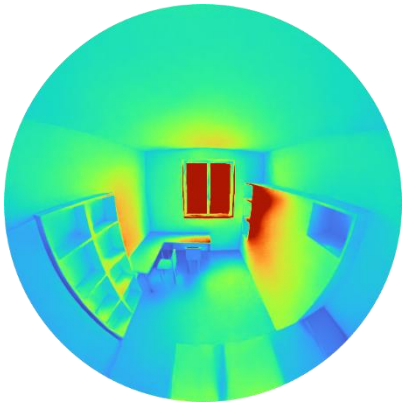
Spectral illuminance at eye level spatial distribution



Spectral illuminance point-in-time graphs June 21, 12.30



Spectral Radiance rendering window



Falsecolour render view completed December 21, 12.30

4.5.4 ClimateStudio References

[1] Aguilar-Carrasco MT, Díaz-Borrego J, Acosta I, Campano MA, Domínguez-Amarillo S. Validation of lighting parametric workflow tools of Ladybug and Solemma using CIE test cases. Journal of Building Engineering 64 (2023) 105608, https://doi.org/10.1016/j.jobe.2022.105608.

[2] Bartholdy MM. A first suggestion on how to make Climate-Based Daylight Modelling through Radiance simple and available to the Danish building industry and how to validate Climate-Based Daylight Modelling. Master Thesis, Indoor Environmental & Energy Engineering Aalborg University - BUILD Department October 12 2023.

[3] ClimateStudio User Guide - SOLEMMA: https://docs.solemma.com/, Online comprehensive user guide (accessed October 14 2025).

[4] Rezaei Oghazi, N., Jusselme, T., & Andersen, M. (2024). Daylight and carbon interactions: An explorative method to reconcile daylight performance and carbon budget constraints. Building and Environment, 262, Article 111777. https://doi.org/10.1016/j.buildenv.2024.111777

4.6 DALEC

David Geisler-Moroder, University of Innsbruck, Austria;
Xuran Guo, Hunan University, China; University of Innsbruck, Austria

4.6.1 General Information

DALEC is an easy-to-use online tool for the calculation of energy-saving potentials in buildings and rooms with daylight systems and artificial light systems in early project stages. The calculations with DALEC take into account various types of buildings and façades including glare control as well as their impact on heating and cooling loads.

The usage of DALEC is offered here free of charge without warranty and liability of any kind whatsoever. It is under continuous further development, and therefore the current online-version of DALEC is to be seen as a prototype.

DALEC is accessible on www.dalec.org. The description provided here refers to the status of the software as online accessible on 21 March 2024.

4.6.2 Description of the Software

DALEC (Day- and Artificial Light with Energy Calculation) [1, 2] is an online concept evaluation tool for architects, building engineers, lighting designers and building owners. Although easy to use and its short calculation times, the software accounts for the complex thermal and light processes in buildings and allows a simple evaluation of heating, cooling and electric lighting loads. Location and orientation of the facade, climate data, thermal and photometric properties of the room, different shading and electric lighting systems are taken into account in the calculation.

Not only energy, but also user behavior is considered, e.g. in terms of overheating and glare protection, and visual and thermal comfort is evaluated. This innovative, holistic approach facilitates and accelerates the design of sustainable and energy-efficient buildings for new structures as well as for refurbishments. The energy optimization of façade and electric lighting solutions is highly simplified, enabling building design with reduced energy demands.

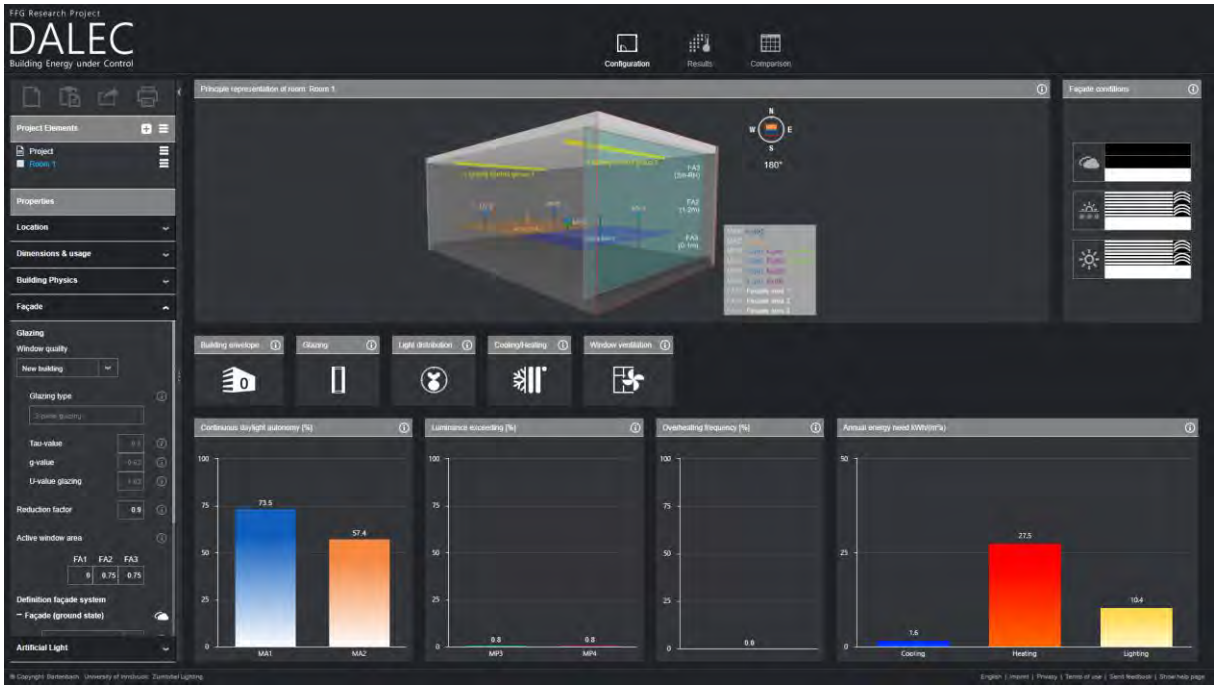


Figure 1: User interface of the DALEC web-tool (www.dalec.org).

DALEC performs lighting and energy calculations for simplified room or hall geometries. As a design tool for deciding on façades and artificial light variants, it is limited to a single façade per room or uniform skylight designs. It allows to choose from 3130 pre-defined locations worldwide and a set of typical building physics' settings for old, new, or Passive House standard buildings with varying thermal capacity. Horizontal obstructions

as well as protrusions (canopies) for solar shading are included in simplified form via angles or widths, respectively. Façade systems can be selected from a pre-defined list covering widely used solutions such as venetian blinds and diffusing or clear screens, together with possible controls (e.g., fixed angles or cut-off control, based on luminance or radiation thresholds). The same applies to the electrical lighting where the user can choose from prototypical light distributions or load own light distributions, again together with different control options (100% on, on/off, dimming).

Low Carbon, High Comfort Evaluations

All results on daylight performance (workplane illuminance, luminance at façade), solar gains, energy demands (electric lighting, heating, cooling), and resulting interior temperatures are reported on an hourly basis and can be exported as csv-file for further evaluations by the user. Additionally, vertical illuminances on eye level are reported which allow calculations of light dose as indicator for non-visual lighting effects. α-opic evaluations are not possible in the current version of the software.

With fixed factors, which can be set by the user, final energy results are converted into equivalent CO2 emissions and are reported in the online tool on monthly and annual basis. Again, using the reported detailed hourly results, the experienced user can calculate operational GHG emissions based also on dynamic factors mimicking the real energy mix on the grid. Embodied carbon cannot be evaluated with the tool and further information on the environmental impact of the investigated solutions (e.g., EPDs) is not available.

Validation

The daylight module of DALEC has been validated against measurements in a PASSYS test cell [2] with a reported average ND-RMSE of about 20%. The artificial lighting module has been compared to simulations with the established Dialux lighting design software with reported deviations of less than 10% for 96% of the results, and less than 5% for 80% of all results, respectively. The thermal module in DALEC is based on the standard ISO 13790, which has been compared by EnergyPlus and ESP-R by Kokogiannakis et al. [3]. Additionally, within the IEA SHC Task 56 “Solar Envelopes”, DALEC has been shown to deliver comparable results as other widely used software tools [4].

4.6.3 Example Simulation Project Results

Example results from DALEC:

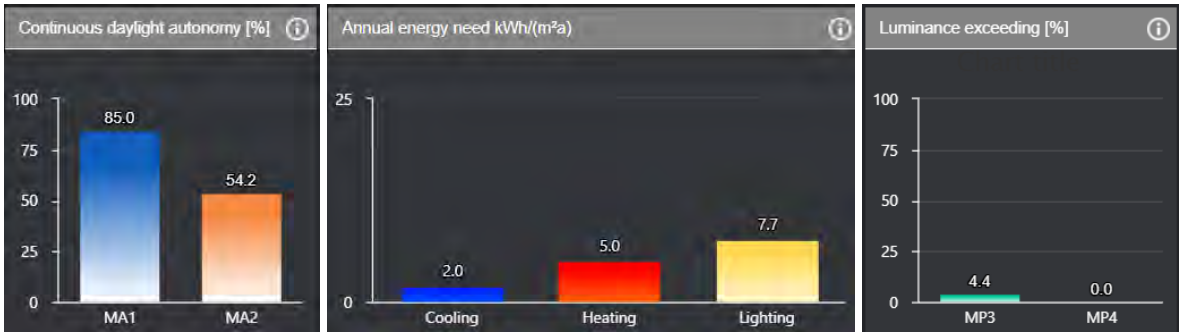


Figure 2: Daylight autonomy, annual energy need, and luminance exceeding in the office case

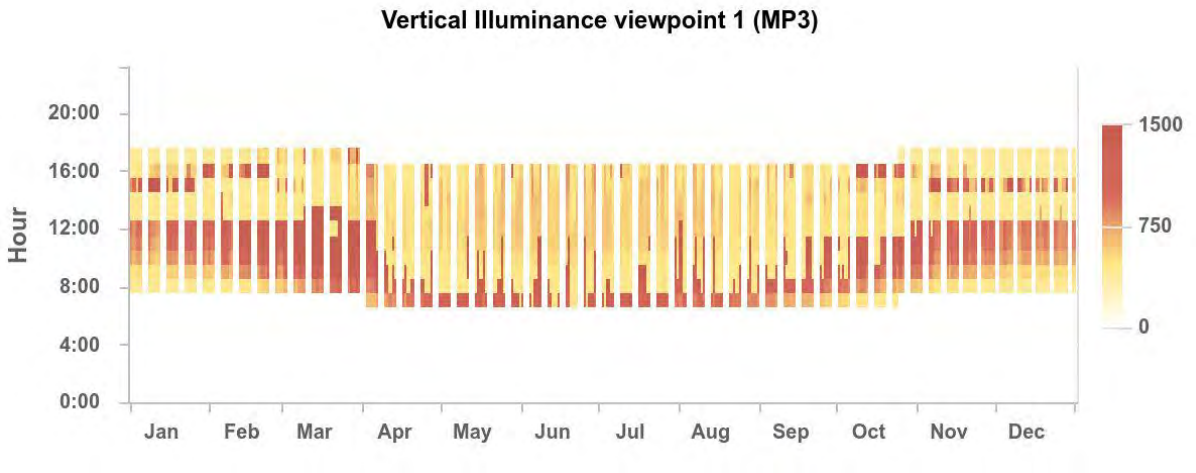


Figure 3: Annual vertical illuminance distribution at viewpoint in the office case

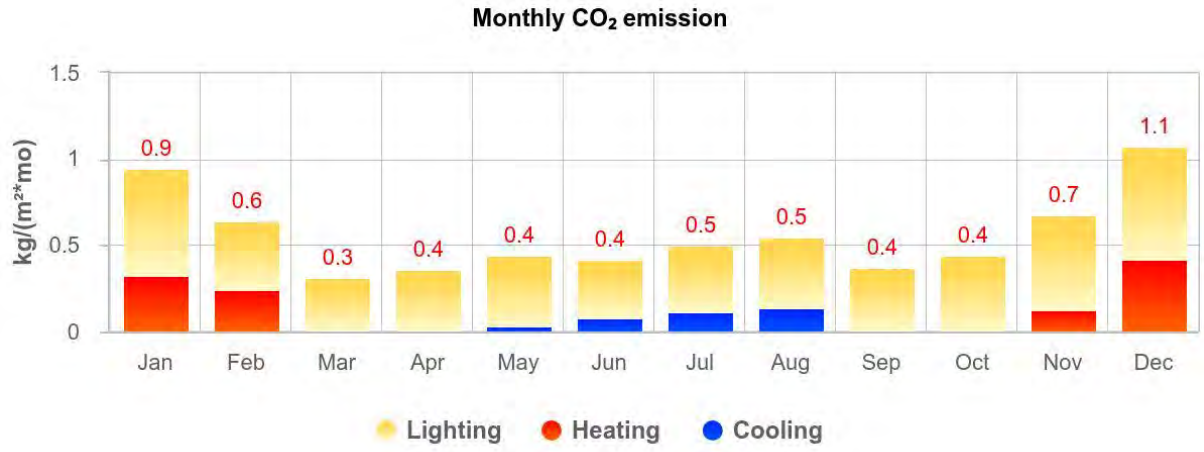


Figure 4: Monthly CO_2 emissions in the office case (cooling, heating, and lighting)

4.6.4 DALEC References

[1] DALEC – www.dalec.org, Online concept evaluation tool (accessed 21 March 2024).

[2] M. Werner, D. Geisler-Moroder, B. Junghans, O. Ebert, W. Feist, DALEC – A Novel Web-Tool for Integrated Day- and Artificial Light & Energy Calculation, Journal of Building Performance Simulation, Volume 10, Issue 3, 2017. https://doi.org/10.1080/19401493.2016.1259352

[3] G. Kokogiannakis, P. Strachan, J. Clarke. Comparison of the Simplified Methods of the ISO 13790 Standard and Detailed Modelling Programs in a Regulatory Context. Journal of Building Performance Simulation, Volume 1, Issue 4, 2008. https://doi.org/10.1080/19401490802509388

[4] IEA SHC Task 56: Building Integrated Solar Envelope Systems for HVAC and Lighting. System Simulation Results. Deliverable DC.2. 2020. https://doi.org/10.18777/ieashc-task56-2020-0005

4.7 DesignBuilder

Joao Francisco Walter Costa, Claudia Naves David Amorim, University of Brasilia, Brazil

4.7.1 General Information

DesignBuilder is a user-friendly modelling environment where you can work (and interact) with virtual building models. It provides a range of environmental performance data, such as energy consumption, carbon emissions, comfort conditions, daylight illuminance, maximum summertime temperatures, and HVAC component sizes. DesignBuilder enables you to generate a wide range of outputs and reports to help you compare the performance of design alternatives and optimize the building at any design stage based on the client's objectives. Importation from BIM and CAD design data is also possible. Typical uses of DesignBuilder include energy and thermal analysis, daylight and solar studies, HVAC and ventilation design, economic and lifecycle assessments – LCA, and embodied carbon emission studies, optimization and design decisions, and regulatory compliance. DesignBuilder also supports calculations for ASHRAE 90.1 and LEED energy models [1].

DesignBuilder is available on https://designbuilder.co.uk/. The description provided here refers to the status of the software as online accessible on 18 June 2025. A license is needed for professionals, and educational licenses are offered to educators and researchers with discounts.

4.7.2 Description of the software

DesignBuilder comprises a core 3-D modeler and 11 modules which work together to provide in-depth analysis for any building. The modules include a 3-D building and visualization modeler, a simulation module with integration with EnergyPlus, daylighting module with integration with Radiance, a module with CFD - Computational Fluid Dynamics – for the analysis of air properties in and around buildings and LEED/ASHRAE compliance tools. DesignBuilder is designed for architects, engineers, energy consultants, building developers, researchers, and educators [1].

The daylighting module is fully integrated with the core DesignBuilder thermal simulation feature, so, in general, no extra data needs to be added following previous energy simulation or certification project work. In particular building geometry, zone layouts, surface reflection, and glazing visible transmission properties from the thermal model are used in the daylighting calculations. This module is fully integrated with Radiance simulation engine. There are four types of daylighting calculations in DesignBuilder: point-in-time illuminance, annual climate-based daylight modelling (CBDM), right to light calculations, and daylight integrated with EnergyPlus to estimate annual savings in electric lighting [2]. Output for the daylighting module include [3]:

- Daylight factor (DF).
- sDA (Spatial Daylight Autonomy).
- ASE (Annual Sunlight Exposure).
- UDI (Useful Daylight Illuminance).
- Illuminance maps and point-in-time analysis.

Low carbon, High Comfort Evaluations

DesignBuilder supports the simulation of design strategies that reduce operational carbon emissions and improve thermal and visual comfort, by integrating all modules. Through the daylighting module, users can quantify daylight availability (sDA, ASE, UDI) and test dynamic shading controls based on standards, like IES LM-83-12 [4]. Outputs guide daylight design and help reduce reliance on electric light, with daylight integration. Additionally, the integration with CFD and thermal modules also supports evaluation of other comfort design criteria, such as air velocity, temperature distribution, and natural ventilation. Design Builder also provides calculations for daylighting credits for certification schemes such as LEED, BREEAM and Green Star [5].

DesignBuilder offers a comprehensive range of results to assess any building's performance. Typical results from the software include [3]:

- Energy use, temperature, humidity, and thermal comfort indicators (PMV/PPD);
- CFD-based airflow visualization;
- HVAC sizing and energy savings reports;
- Lifecycle assessment, embodied carbon and cost analysis;
- Daylighting performance metrics: DF, sDA, ASE, UDI;

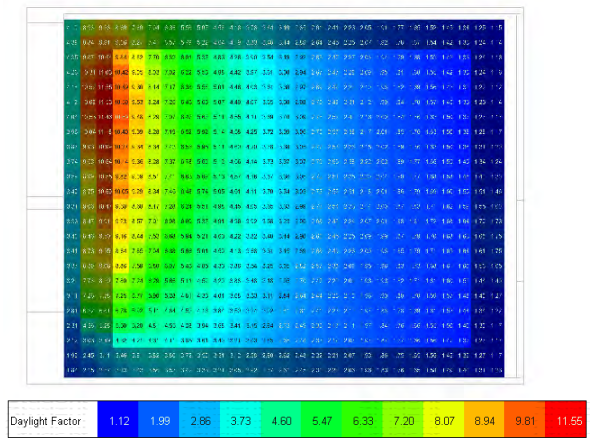
- Estimation of energy consumption for artificial lighting based on daylight availability, through the integration of the daylighting module and EnergyPlus simulation module.

Validation

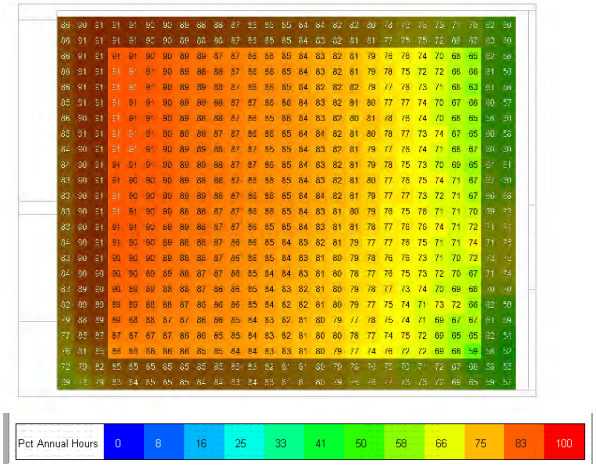
The daylighting module is fully integrated with Radiance, a simulation engine developed in 1984 by Greg Ward at the Lawrence Berkeley National Laboratory (LBNL). Radiance employs the backward ray-tracing method, combining deterministic modeling for direct light and specular reflections. Radiance simulation methods have been thoroughly validated through field measurements within the international research community [6].

Calculations are based on the full 3D geometry from DesignBuilder's visualization module and include interior/exterior glazing, shading devices, and component blocks [3]. Given that DesignBuilder integrates the Radiance engine for daylighting simulations, the precision of the input model plays a critical role in ensuring reliable results. For the Radiance calculations to accurately simulate the distribution of daylight within a space, users must pay particular attention to defining the building geometry and assigning correct optical properties to all relevant surfaces. This includes specifying the visible transmittance of the glazings, and reflectance of the surfaces, among other optical properties, and ensuring the outermost and innermost layers of constructions are appropriately configured. These parameters, accessible through the construction and material model data tabs, directly influence how light is reflected, absorbed, and transmitted in the simulation environment—therefore impacting both daylight performance metrics and model validation integrity [3].

4.7.3 Example Simulation Project Results



Spatial distribution of Daylight Factor (DF [%])



Spatial distribution of Daylight Autonomy (DA [%])

4.7.4 DesignBuilder References

[1] DesignBuilder - https://designbuilder.co.uk/, DesignBuilder Help v. 7.3 (accessed 10 June 2025).

[2] DesignBuilder: Help and Getting started - https://designbuilder.co.uk/helpv7.3/ (accessed 18 June 2025).

[3] DesignBuilder. Simulation documentation for DesignBuilder v.7.3. 2025. Available at: https://designbuilder.co.uk/download/sbem-dsm-manuals (accessed 20 June 2025).

[4] Illuminating Engineering Society. LM-83-1 - Approved Method: IES Spatial daylight autonomy (sDA) and annual sunlight exposure (ASE). 2023.

[5] Design Builder: Guidance for calculating daylighting credits for LEED, BREEAM, Green Star etc. https://designbuilder.co.uk/helpv7.3/Content/DaylightCreditCalculationGuidance.htm (accessed 20 June 2025).

[6] Radiance online - https://www.radiance-online.org/, 2019.

4.8 DIALux

Anna Pellegrino, Valerio R.M. Lo Verso, and Alberto Gremo (Politecnico di Torino, Turin, Italy)

4.8.1 General Information

- Version 13.2.0, available online on DIALux evo website https://www.dialux.com/it-IT/download

DIALux evo is a free lighting design software, widely spread among professionals It makes it possible for engineers, architects and lighting designers to create, calculate and visualize electric lighting designs for interiors, exteriors, streets and even emergency lighting; beside electric lighting, which is the main purpose of the tool, limited features to calculate daylighting are also available.

Dialux allows planning, calculating and visualizing the lighting of entire buildings with photometric curves provided by the manufacturers; as for daylighting, while also offering tools for daylight factor calculation, illuminances under daylight, energy assessment, and verification of compliance with indoor, outdoor or road lighting standards, also plotting out the results in a customizable, professional documentation.

DIALux evo is developed by DIAL Gmbh, and the current version is DIALux evo 5.13.2.0. It can be downloaded at: https://www.dialux.com/it-IT/download (last access: September 11, 2025). Version *Evo* does not require a license to run and allows professionals or students to download the software for free, consult a catalogue of luminaires from selected, partner members and run simulations without any additional charge. To unlock the most advanced features, including BIM operability and importing photometric files for custom lighting fixtures (such as *.ies* or *.ltd* files) a *Pro* plan is required.

4.8.2 Description of the Software

DIALux evo runs lighting simulations (mainly for electric lighting) using real photometric data provided in *.ies* and *.ldt* formats from selected partner members. Simulations are detailed and reliable, combining physical accuracy with the capability to model complex architectural environments in reasonably short time. This is made possible by the calculation kernel that relies on a photon shooter, improving the capabilities of the previous radiosity algorithm.
Buildings or road sections can be modelled inside the software, with a dedicated interface that includes street and façade elements, doors, windows and furniture inside an internal library.

SPEED: as stated by the developers, DIALux evo is built on a robust computational kernel that allows complex 3D geometries and large-scale architectural spaces to be efficiently handled. Unlike earlier lighting design tools, DIALux Evo integrates multiple environments and planes within a single project, avoiding the need to run separate simulations. This streamlined workflow enables lighting designers and architects to obtain results more quickly, even in projects with demanding geometric or material complexity. By directly importing luminaire data from manufacturers, the software reduces the time typically required for setup and calibration, thus accelerating the overall design process.

ACCURACY: Using photometric data provided by the manufacturers ensures that simulations in DIALux Evo are physically consistent with real-world lighting conditions. Each luminaire behaves exactly as specified by the manufacturer, allowing designers to make informed decisions with confidence. It is particularly important to highlight how in projects users can evaluate compliance with lighting regulation (including EN 12464-1:2021 for interiors, EN 13201:2015 for exteriors), energy standards (EN 15193:2008, not yet updated to EN 15193-1:2017 though) or evaluate visual comfort (again, according to EN 12464-1:2021).

Low Carbon, High Comfort and Energy Evaluations
DIALux eEvo offers a wide range of analyses for electric lighting, while only limited evaluations are available for daylighting.
Lighting analyses
The following analyses can be carried out:

- *Illuminance analysis:* this part of the program allows the calculation of illuminance values on user-defined or regulations-based calculation grids, such as working planes, floor, wall or ceiling surfaces, as well as inclined surfaces. The results can be expressed in terms of average, minimum and maximum illuminance and uniformity ratios, in compliance with international standards such as EN

12464-1 for indoor lighting and EN 13201 for outdoor lighting. For indoor lighting, the software also calculates the semi-cylindrical and cylindrical illuminance at eye level.

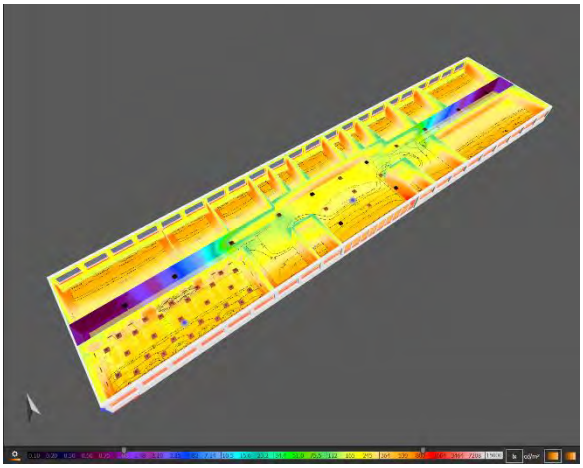
- *Glare analysis (UGR):* it includes the calculation of the Unified Glare Rating (UGR), which allows users to assess the risk of discomfort glare caused by luminaires according to the CIE tabular method reported in EN 12464-1: UGR can be calculated for individual points or user-defined grids, in both cases including 0-360° view directions, with a step that can be manually modified.
- *Daylight*: daylight simulations do not rely on weather data to run climatic simulations. The software allows evaluating the daylight factor on a self-generated work plane across the whole room with 1m offset from the walls, as well as on a user-defined grid; both punctual and averaged values are calculated for each grid, highlighting the minimum and maximum value. Both vertical windows and skylights can be included in the 3D model for the calculation. For specific point-in-time simulations it is also possible to calculate the illuminance values under clear, intermediate or overcast sky conditions according to CIE 110:1994. Besides, it is possible to combine daylight with electric lighting scenarios.
- *Visualizations and renderings*: the software generates photorealistic renderings of the illuminated environment.
- Luminaires are directly linked to manufacturer-verified photometric data (*.ies*/*.ldt*), ensuring that all analyses are physically accurate and based on real product performance.

Energy evaluation

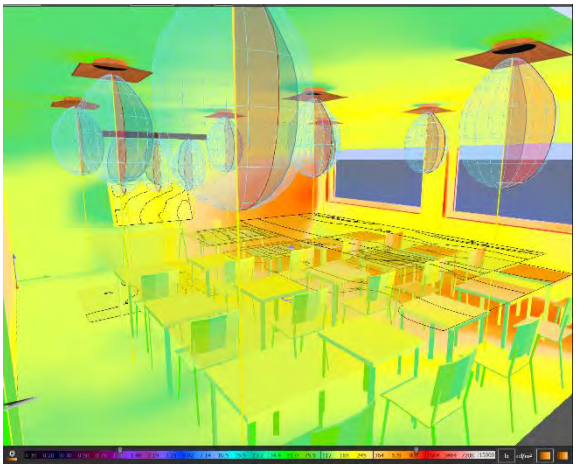
DIALux evo integrates an energy and efficiency assessment module that enables designers to evaluate the energy performance of lighting systems. The software calculates the installed lighting power density (W/m²) and proceeds to the calculation of the Lighting Energy Numeric Indicator (LENI) in accordance with the international standard EN 15193-1:2008 (it has not been updated yet to the latest version of the standard EN 15193-1:2017). Through LENI, DIALux evo quantifies the annual energy consumption of a lighting installation per square meter, considering not only the installed load but also the daylight provision and control strategies like dimming, or occupancy based. By simulating and comparing different scenarios, the program helps designers optimize both energy demand and lighting quality, ensuring that projects meet sustainability targets while reducing operational costs.

4.8.3 Example Simulation Project Results

As an example, results for the simulation of high school are shown (one floor only, for the sake of brevity): the spaces that were analysed include classrooms, laboratories, and a library.



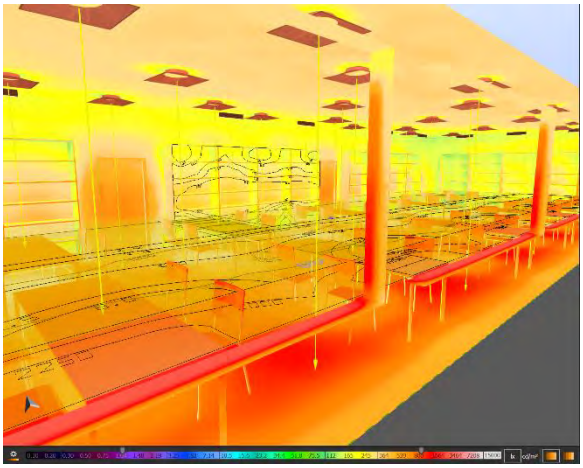
axonometric view of the whole floor, electric light only



false-colour view of illuminances in a classroom



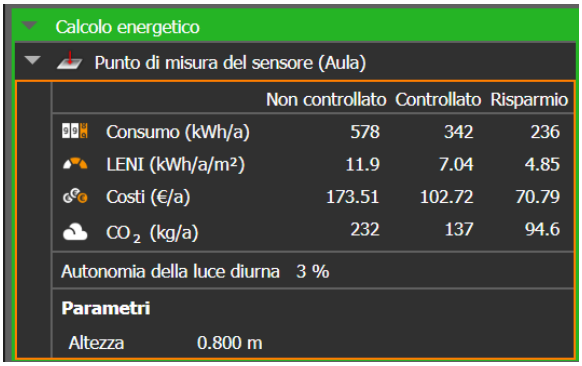
false-colour view of illuminances in the library (view 1)



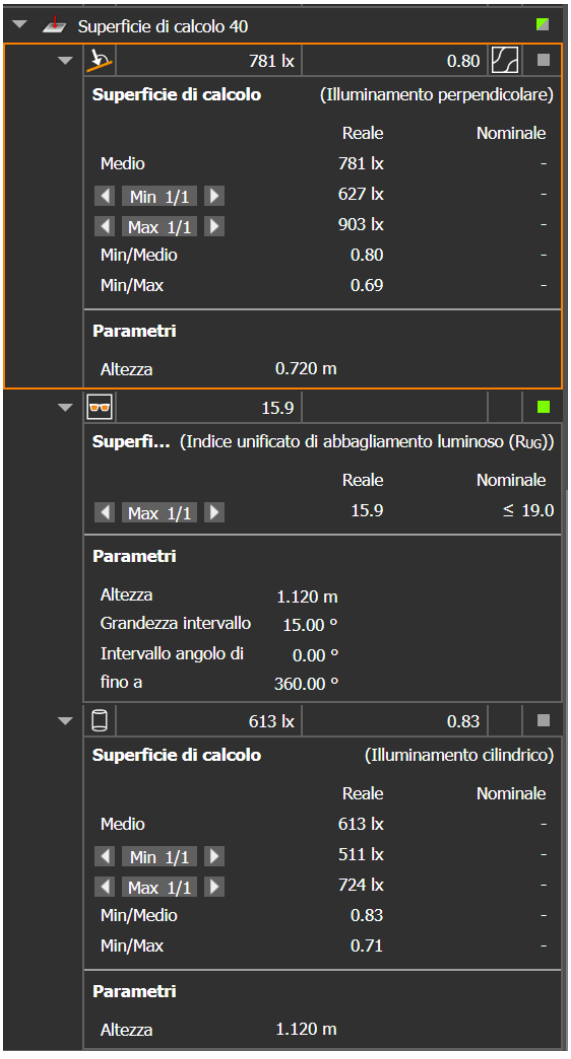
false-colour view of illuminances in the library (view 2)



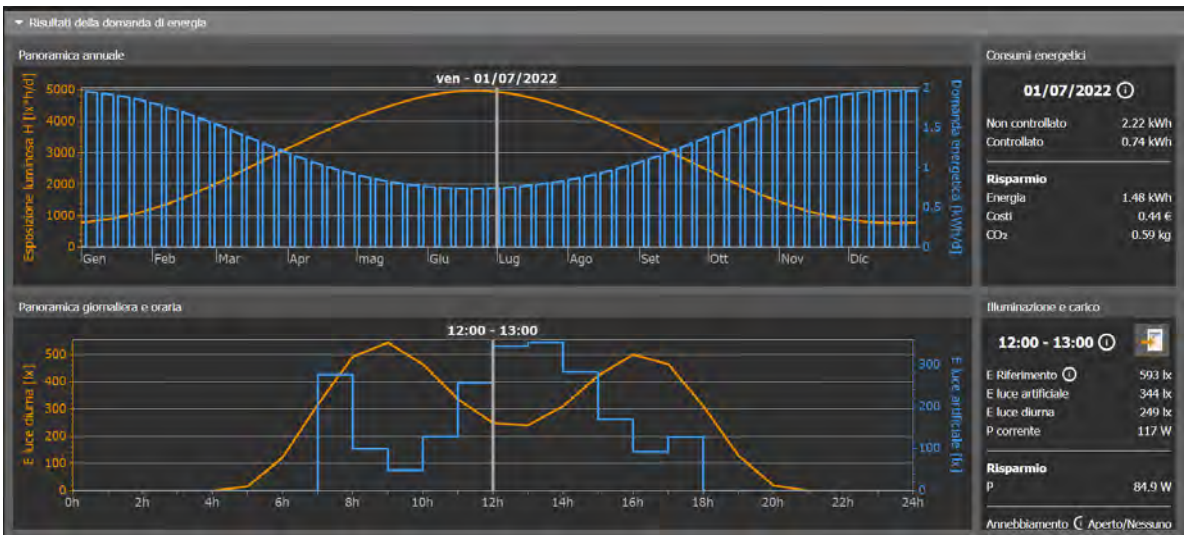
daylight factor results in the library



LENI and energy consumption for the entire floor, due to electric lighting only and to integration of electric and daylighting through a photo-sensor control



horizontal illuminance, UGR and cylindric illuminance in the library



graphs for the energy consumption due to electric lighting for the library; it was necessary to place a sensor at the centre of the room to automate luminaires usage, based on daylight provision, thus defining a “controlled” scenario that leads to energy savings; this calculation is enabled by the positioning of the sensor, yet it relies on EN15193 simplified method



render view of a classroom

4.8.4 DIALux References

[1] DIALux FAQs and User Guide – DIAL Gmbh: https://www.dialux.com/en-GB/support, Online support menu, including FAQs and user guide for relevant sub-topics (accessed September 16 2025).

[2] D. Witzel, DIALux evo – new calculation method, DIAL Gmbh https://www.dialux.com/fileadmin/documents/DIALux_evo-_New_calculation_method.pdf

4.9 DL-Light

Natalia Sokol, Gdansk University of Technology

4.9.1 General Information

- **Current version**: Available as a SketchUp plug-in, regularly updated by De Luminæ.
- **Website / Download**: https://deluminaelab.com/dl-light/en/df.html
- **License**: Annual personal license (€500 first year, €300 renewal for 2025). After expiry, the software reverts to evaluation mode.

4.9.2 Description of the Software

DL-Light [1, 2] is a daylight simulation extension for SketchUp, based on the **Radiance** ray-tracing engine [3, 4]. It enables the prediction of illuminance levels, daylight availability, and sunlight exposure in both building interiors and outdoor urban contexts. The integration within SketchUp allows users to set up geometrical and material properties directly in the 3D environment, while DL-Light manages the translation into Radiance input files, computation, and post-processing.

The workflow in DL-Light follows a structured sequence to ensure reliable simulation outcomes

DL-Light allows the assignment of optical properties to all modelled surfaces in SketchUp. Transparent elements (e.g., glazing) are characterised by their visible light transmittance, reflectance, and absorption. Opaque surfaces are defined by reflectance coefficients. The software ensures that all geometry is converted into consistent Radiance material descriptions before simulation.

Once material properties are defined, sensor grids can be placed within the SketchUp model. These grids serve as reference planes for illuminance calculation (e.g., working planes in offices, facade grids for rights-of-light studies, or external ground surfaces for sky view factor evaluation). In addition, the software supports the specification of calculation types: Daylight Factor, Daylight Autonomy, Annual Sunlight Exposure, or Sky View Factor.

With geometry and materials prepared, DL-Light automatically produces Radiance scene files (*.rad) and simulation scripts. These contain all information necessary for Radiance to compute illuminance distributions under standard skies or climate-based skies. Depending on the chosen metric, DL-Light either uses the **CIE overcast sky model** (for Daylight Factor) or processes hourly weather data from EPW files (for daylight autonomy and annual metrics).

Radiance ray-tracing is executed for the specified calculation type. For Daylight Factor analysis, point-by-point illuminance values are generated under the overcast sky, allowing the computation of average DF, minimum DF, and uniformity ratios, in accordance with EN 17037 and BRE guidelines. For climate-based simulations, daylight autonomy, spatial daylight autonomy, and annual sunlight exposure are computed using hourly illuminance values across the year.

Simulation results are mapped back into the SketchUp model, enabling direct interpretation in the 3D context. Additionally, DL-Light exports tabulated results to spreadsheets, allowing further analysis (e.g., compliance checks for LEED or BREEAM). Advanced modules support specialised assessments, including rights of light, sunlight exposure for urban studies, and sky view factor for outdoor spaces.

This workflow ensures that daylight predictions in DL-Light reflect both static (Daylight Factor) and dynamic (climate-based daylight availability) conditions, providing robust inputs for design evaluation and compliance checking.

Low Carbon, High Comfort Evaluations

DL-Light primarily addresses visual comfort and energy-related impacts of daylight availability. By enabling climate-based daylight simulations, it provides quantitative evidence for reducing electric lighting demand, thus contributing indirectly to carbon reduction. In addition, metrics such as annual sunlight exposure are relevant for

assessing risks of glare and overheating, supporting balanced solutions for visual and thermal comfort. Non sumulation of NIFs are offered.

DL-Light contributes to low-carbon, high-comfort design by integrating both building and urban-scale daylight analysis. At the urban scale, solar access analyses enable designers to optimise building layouts to maximise passive solar gains in winter while mitigating overheating in summer.

Validation

DL-Light's simulation kernel is Radiance, a reference daylight engine extensively validated in international studies. Furthermore, DL-Light has been benchmarked against the CIE 171:2006 test cases, confirming the accuracy of its predictions for standardised geometries and sky conditions.

4.9.3 Example Simulation Project Results

Results are provided as Radiance-based false-colour illuminance maps and as tabulated spreadsheets for compliance checks.

4.9.4 DL-Light References

[1] De Luminæ (2025). *DL-Light: Daylight Factor Module*. Retrieved from https://deluminaelab.com/dl-light/en/df.html
[2] De Luminæ (2025). *DL-Light User Documentation*.

4.10 ElumTools

Taoning Wang, LBNL (Lawrence Berkeley National Laboratory)

4.10.1 General Information

- Current Version: ElumTools 2024
- Official Website: https://lightinganalysts.com/elumtools/
- Developer: Lighting Analysts, Inc.
- Platform: Autodesk Revit Add-in
- License: Commercial
- Compatibility: Revit 2020-2025

ElumTools is a lighting calculation plugin for Autodesk Revit that uses the AGi32 radiosity engine to perform photometric calculations within BIM models.

4.10.2 Description of the Software

The software extracts geometry, materials, and fixture data from Revit models to perform lighting calculations without requiring model export.

Calculation Engine:
- AGi32 radiosity method
- Direct access to Revit model data
- In-place calculation and visualization

Electric Lighting:
- IES and EULUMDAT photometric files
- Revit fixture family integration
- Illuminance and luminance calculations
- Connected load computation

Daylighting:
- Point-in-time simulations
- CIE sky models (overcast, clear, intermediate)
- Perez all-weather sky model
- Daylight factor
- UGR calculations
- LEED v4 EQc7 Option 2 compliance (equinox calculations)

Materials:
- Revit material properties mapped to photometric properties
- Glass transmittance modeling
- Interior glass as daylight transition surfaces

Workflow:
- Calculation grids defined in Revit
- Parameters set through plugin interface
- Results rendered in Revit views

Target Users:
Architects, lighting designers, electrical engineers in BIM workflows.

Annual Metrics:
Point-in-time only. Annual climate-based metrics (sDA, ASE) require separate Licaso software.

Validation:
Results equivalent to AGi32 with matching model parameters.

Limitations:
- Revit platform dependency

- Annual daylighting requires additional software
- No energy simulation integration
- BSDF/complex fenestration not supported
- Spectral metrics not available

4.10.3 ElumTools References

[1] Lighting Analysts, Inc., https://lightinganalysts.com/elumtools/

[2] ElumTools Documentation, https://www.elumtools.com/docs/

4.11 frads

Taoning Wang, LBNL (Lawrence Berkeley National Laboratory)

4.11.1 General Information

- Repository: https://github.com/LBNL-ETA/frads
- Documentation: https://lbnl-eta.github.io/frads/
- Developer: Lawrence Berkeley National Laboratory
- License: Open Source
- Platform: Cross-platform
- Requirements: Python 3.8+, Radiance, EnergyPlus

frads is a Python framework for Radiance-based daylighting simulation and EnergyPlus integration, implementing matrix algebraic methods for annual calculations.

4.11.2 Description of the Software

The framework provides programmatic control of Radiance workflows through Python, automating multi-phase method simulations.

Multi-Phase Methods:
- 2-Phase through 6-Phase implementations
- Matrix-based annual calculations
- BSDF integration for complex fenestration
- Separation of direct and diffuse contributions

Matrix Calculations:
- Daylight coefficient matrices
- View matrices
- BSDF matrices
- Annual results via matrix multiplication with sky vectors

Capabilities:
- Annual metric calculation (DA, sDA, UDI, ASE)
- Climate file processing
- Workplane illuminance
- EnergyPlus integration
- Lighting control modelling

Control Systems:
- Daylight-responsive dimming
- Dynamic shading
- Integration with HVAC systems
- Annual energy calculations

Applications:
- Daylighting research
- Building energy analysis
- Complex glazing evaluation
- Custom workflow development

Target Users:
Researchers, building scientists, developers. Requires Python programming knowledge and Radiance understanding.

Validation:
Uses validated Radiance calculation methods. Accuracy dependent on matrix resolution and sampling parameters.

Limitations:

- Command-line only (no GUI)
- Programming knowledge required
- Learning curve for multi-phase methods
- Geometry definition via code or import
- Limited end-user documentation

4.11.3 frads References

[1] Wang, T., LBNL, https://lbnl-eta.github.io/frads/

[2] GitHub: https://github.com/LBNL-ETA/frads

[3] McNeil, A., Lee, E.S., "Radiance three-phase method validation," 2013

4.12 GB SWARE Dali

Xuran Guo, Hunan University, China; University of Innsbruck, Austria

Zhen Tian, Hunan University, China

4.12.1 General Information

GB SWARE Dali is a software tool for building daylighting and artificial lighting performance simulation. It is part of the GB SWARE green building performance simulation software suite (which also includes acoustic, lighting, thermal, airflow, and energy simulations) and is developed by Beijing Green Building Software Co., Ltd. [1]. The software is mainly intended for daylighting and lighting analysis in building design and green building assessment, and it is suitable for the design stage as well as for performance comparison, optimization, and evaluation of different design options.

The software version addressed in this report is GB SWARE Dali (version 20251201, trial license). The software is available via http://www.gbsware.cn/. The description in this section is based on the software functionality as of January 2026.

4.12.2 Description of the Software

GB SWARE Dali is a CAD based software tool for building daylighting and artificial lighting simulation. Its main calculation engine is based on Radiance. The software uses a graphical user interface built on a CAD platform and incorporates parametric information into geometric models, enabling integrated model creation, parameter input, and performance calculation. It supports the import of model files from common building design software, including AutoCAD, Revit, and SketchUp, and performs daylighting and lighting simulations based on these models. The software is mainly intended for architects, lighting designers, green building consultants, and researchers working on building daylight environmental and performance studies.

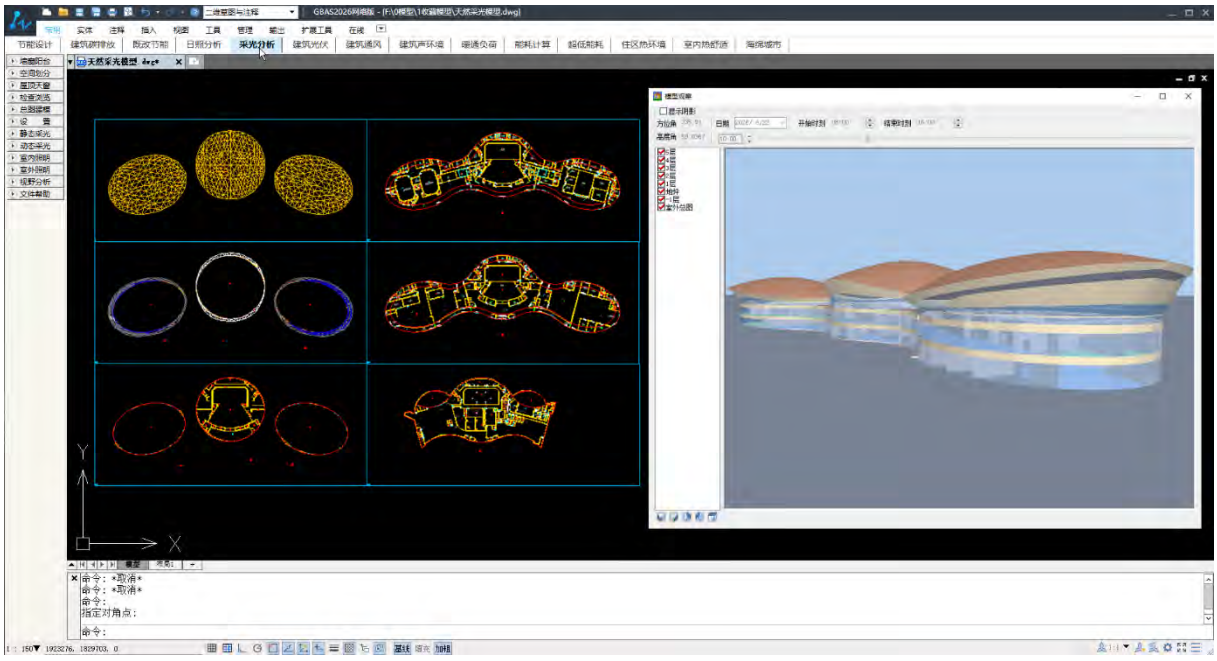


Figure 5: User interface of the GB SWARE Dali

GB SWARE Dali can be used for modeling and analysis of building daylighting and artificial lighting, covering a wide range of analyses related to the building light environment. The software supports static daylighting simulations for conventional glazing systems and can calculate daylight factors, illuminance, luminance, glare, and window view metrics. In addition, it supports climate-based daylighting analysis using annual weather data

and can calculate common dynamic daylighting metrics, such as DA, UDI, ASE, and sDA, as well as daylighting indicators related to LEED and WELL assessment systems, to evaluate daylighting performance under long term use conditions.

For artificial lighting analysis, GB SWARE Dali provides functions for both interior and exterior electric lighting, allowing the calculation of illuminance and luminance distributions, illuminance uniformity, and related lighting performance metrics for indoor and outdoor spaces.

In addition to engineering applications, GB SWARE Dali can also be used as a teaching tool in architecture and related academic programs for basic daylighting and lighting education and for demonstrating performance analysis methods. In the current version, support for Complex Fenestration Systems (CFS) is mainly provided through the import of Bidirectional Scattering Distribution Function (BSDF) data for simulation and calculation, and simplified three-phase and five-phase methods can be applied to enable fast calculation [2, 3].

Low Carbon, High Comfort Evaluations

The main analysis focus of GB SWARE Dali is on building daylighting performance, artificial lighting demand, and the evaluation of visual comfort metrics. The software supports the comparison and optimization of low energy and high comfort building design. It can output various daylighting and lighting performance results, as well as dynamic daylighting metrics based on annual simulations, to support the assessment of the visual environment quality of indoor spaces.

For visual comfort evaluation, the software supports analyses based on illuminance and luminance distributions and can calculate glare metrics under point-in-time conditions. It also provides window view evaluations, such as sky view ratio analysis. For non-visual comfort, the software can calculate Equivalent Melanopic Lux (EML) to assess the potential impact of the lighting environment on human circadian rhythms.

Validation

The daylighting and lighting calculations in GB SWARE Dali are based on the Radiance rendering and lighting simulation engine [3]. Radiance is a physically based ray-tracing engine that has been widely used and validated in building daylighting and lighting research. Based on this validated calculation engine, GB SWARE Dali integrates the computational capabilities of Radiance into a CAD working environment through a graphical user interface and a parametric modeling workflow, enabling efficient use in building design and green building assessment. The software shows good stability and practical performance for conventional daylighting and artificial lighting analyses, and it is particularly suitable for performance evaluation and comparison of multiple design options at the design stage.

However, in its current version, GB SWARE Dali still has several limitations:

1) in terms of result output, the software mainly provides aggregated statistical results and visual outputs, and point level data (e.g., in text or tabular form) must be extracted and processed by the user;
2) for daylighting and glare evaluation, the software does not support direct calculation of Daylight Glare Probability (DGP) and can only calculate Daylight Glare Index (DGI) under point in time conditions;
3) for dynamic daylighting simulations, GB SWARE Dali is mainly developed for users in China and includes a complete set of built in weather data covering China, which can meet the needs of dynamic daylighting simulations for building projects in different climate regions and weather conditions within China. However, the current version does not support user defined weather files, which may limit its applicability in regions beyond China or under specific climatic conditions.

4.12.3 Example Simulation Project Results

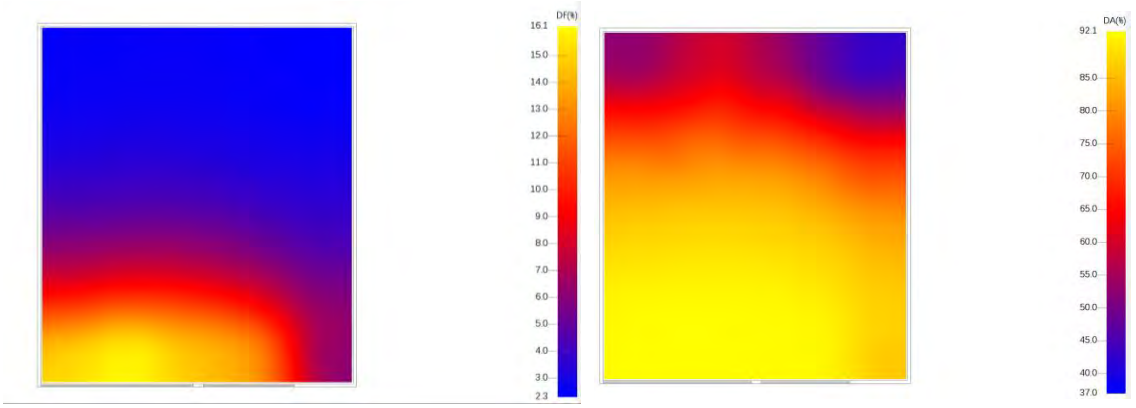


Figure 6: Spatial distribution of DF [%] (left) and DA [%] (right) for the office in context (Location: Beijing)

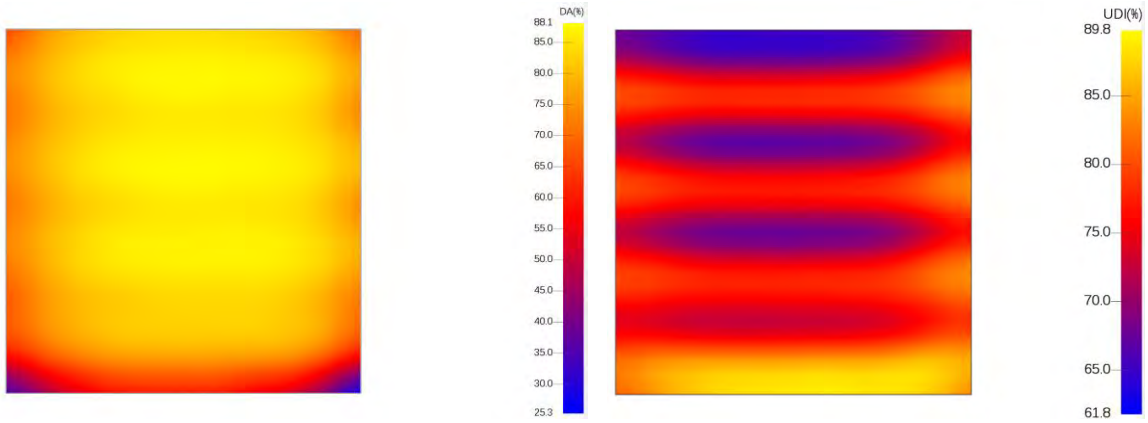


Figure 3: Spatial distribution of DA [%] (left) and UDI $_{100–3000}$ [%] (right) for the hall in context (Location: Beijing)

4.12.4 GB SWARE Dali References

[1] GB SWARE online - http://www.gbsware.com.cn/ (accessed 16 Jan 2026).

[2] Modified climate-based daylight modeling methods for buildings, Zhao, Y., Tian, Z., 2023. https://doi.org/10.1016/j.buildenv.2023.110598

[3] A fast matrix-based method for two-phase and three-phase daylight simulations, Zhao, Y., Tian, Z., 2024. https://doi.org/10.1016/j.enbuild.2023.113866

[4] Radiance online - https://www.radiance-online.org/ (accessed 16 Jan 2026).

4.13 IES VE

Josef Miller, University of Innsbruck

4.13.1 General Information

- **Current version:** IES VE 2024 Feature Pack 1 (released March 2025) (iesve.com)
- **Download / Website:** https://www.iesve.com/software/download (iesve.com)
- **License:** Proprietary commercial software, available via annual subscription; floating and node-locked options.

4.13.2 Description of the Software

IES Virtual Environment (IES VE) is a comprehensive simulation platform for the holistic analysis of building performance. The software combines modules for thermal analysis, energy consumption, daylight and lighting simulation, life cycle and environmental assessment as well as building control. Thanks to a modular architecture, any combination of analyses can be carried out in a single data model, with all results stored in a central, searchable project file.

Important core functions:

- Data integration & BIM interfaces: Bi-directional IFC import/export, direct connection to Revit and ARCHICAD via Speckle or proprietary BIM Navigator.
- Thermal & energy analysis: Hourly and minute-by-minute transient simulations, ASHRAE 140 validation, integrated HVAC system library.
- Light and daylight simulation: Radiance-based ray tracing, Climate-Based Daylight Modeling (CBDM), Daylight Coefficients Method, support for IES and Eulumdat-Luminaire data.
- LCA & Environmental Assessment: Embedded LCA framework (BRE Ecopoint, EN 15978), database linking to external LCA tools (OneClickLCA), material database Apache CDB.
- Control strategies & regulation: Predefined and freely customizable scenarios for integrated control of daylight and artificial lighting systems, connection to KNX and BACnet.
- Reporting & visualization: Interactive dashboards, 2D/3D visualizations, automated report generators (Excel, PowerPoint, HTML).

User interface & workflow

The user interface follows a project-oriented approach:

1. Model setup and parameter definition in the VE Data Editor.
2. Scenario definition (e.g. weather data, usage scenarios) and selection of desired modules.
3. Simulation starts from the VE Navigator with progress display and log export.
4. Results analysis in VE Results View with filters, interactive graphics and live link to 3D geometry.

Low Carbon, High Comfort Evaluations

IES VE enables the simultaneous optimization of CO_2 footprint and user comfort by:

- Linking operational data (electricity and heating energy) with life cycle analysis (GWP, ODP) for lighting, daylighting and HVAC systems.
- Detailed comfort metrics: Daylight Autonomy to ensure visual comfort; probabilistic glare rating (DGP) for daylight and UGR for artificial lighting simulations.
- Scenario analysis: Comparison of different control strategies (e.g. automatic blind control vs. manual light dimming) in terms of energy consumption and comfort ratings.
- Report generator: Consolidated dashboards that combine CO_2 equivalents, annual energy use and comfort indices in one report.

Validation

IES VE has been comprehensively validated:

- **Radiance Lighting:** Validation against CIE test cases and peer-reviewed studies (Ward & Shakespeare, 1998).
- **Thermal & Energy Modules:** ASHRAE Standard 140 benchmarks, results documented in the IES Knowledge Base Validation Report.

- **LCA Framework:** Verification of LCA output data against ISO 14040/44 requirements and EN 15978 guidelines.

4.13.3 Example Simulation Project Results

Typical results:

- Key energy figures: Annual primary energy consumption, peak power (heating/cooling), load profiles.
- Lighting and daylight parameters: room-related illuminance distribution, daylight autonomy (DA, cDA, sDA), DGP/UGR glare probability.
- Thermal comfort: room temperature profiles, operative temperature, PMV/PPD estimates.
- Life-cycle impact: GWP (kg CO_2-eq), cumulative energy, material impact through LCA analysis.

Reporting

Reporting for the reference areas (office and hall) is carried out in a harmonized format:

1. Introduction & methodology: scenario description, weather data, usage assumptions.
2. Presentation of results: Graphical dashboards, 2D plots and 3D visualizations of the key figures.
3. Comparative analyses: Comparison of different design and control options.
4. Summary & recommendations: Lowest energy consumption vs. best possible comfort.

4.13.4 IES VE References

[1] IES Virtual Environment 2024 Feature Pack 1 Release Notes, Integrated Environmental Solutions, 2025.

[2] Ward, G., Shakespeare, R., “Rendering with Radiance”, Morgan Kaufmann, 1998.

[3] IES VE Validation Reports: https://www.iesve.com/support/validation

[4] ASHRAE Standard 140, “Standard Method of Test for the Evaluation of Building Thermal Envelope”, ASHRAE, 2020.

4.14 Ladybug / Honeybee

Morteza Hosseini, Aalborg University Copenhagen, Denmark

4.14.1 General Information

Ladybug Tools is a free and open-source suite of environmental analysis plugins designed for Rhino/Grasshopper and Dynamo. Initiated by Mostapha Sadeghipour Roudsari in 2012, the project was born out of a desire to overcome fragmented, repetitive workflows and to promote better understanding of environmental building design. The first version was released in January 2013, featuring 28 components focused on weather data visualization, solar radiation, and sunlight hours analysis. The current version is 1.9, and it can be downloaded from Food4Rhino. Ladybug Tools is a comprehensive suite of free and open-source environmental analysis applications that integrate seamlessly with 3D modeling platforms such as Rhino/Grasshopper and Dynamo. The suite has evolved into a robust ecosystem of modular plugins that support a wide range of building performance simulations. Alternatively, users can explore the Pollination platform at pollination.solutions, which offers cloud-based simulation tools built on Ladybug Tools. For Grasshopper users, Ladybug Tools remains free and can be run directly within Rhino.

4.14.2 Description of the Software

At its core, **Ladybug** enables users to visualize climate data, analyze solar radiation, generate sun path diagrams, and perform orientation studies. It supports early-stage design decisions by providing intuitive 2D and 3D graphics that map environmental data directly onto building geometry. Ladybug includes tools such as the Tregenza Sky Dome, Radiation Rose, and Radiation CallaLily for detailed solar exposure analysis. It also facilitates automated shading design through conditional sun path filtering and supports multi-objective optimization using evolutionary algorithms like Octopus.

Building on Ladybug's foundation, **Honeybee** extends functionality to advanced daylighting and energy simulations. It connects to validated engines such as **Radiance**, **Daysim**, **EnergyPlus**, and **OpenStudio**, enabling detailed studies of daylight autonomy, glare, thermal comfort, HVAC sizing, and energy consumption. Honeybee automates geometry preparation, supports two-way import/export of simulation files, and provides rich visualization tools for both hourly and annual results. It allows users to customize simulation parameters and refine models for accuracy, including wall thickness, internal partitions, and material properties.

Relevant Categories According to Overview Matrix

These tools are suited for **R&D, early design, and detailed design**. In relation to **lighting simulation algorithms**, Hobeybee benefits from Ray tracing, the 3 Phase Method, 5 Phase Method, and Daylight Coefficient Method. For 5 &3 phase method and more professional analysis, you can use Honeybee[+]. Regarding electric lighting, it can import IES files and Import of luminaires (IES) and calculate annual electricity consumption. Additionally, it would be possible to calculate illuminance and luminance values. For more detail and professional electric lighting calculation, it is recommended to use the Honeybee legacy plugin.

Ladybug Tools offers a comprehensive suite of **daylighting simulation** features that support both early-stage and detailed design analysis. It enables point-in-time simulations as well as climate-based annual simulations, allowing users to evaluate daylight performance across different times and seasons. The platform provides outputs such as illuminance, luminance, and daylight factor values, which are essential for assessing visual comfort and compliance with daylighting standards. Advanced metrics like Daylight Autonomy (DA), Continuous Daylight Autonomy (cDA), and Spatial Daylight Autonomy (sDA) are also supported, offering insights into the usability of natural light throughout the year. Ladybug Tools incorporates a range of sky models including CIE standard skies and the Perez sky model, ensuring accurate representation of sky conditions. The simulations are sensitive to building orientation, and users can model daylight systems as geometry or import them as BSDF (Bidirectional Scattering Distribution Function) data for more precise optical behavior. Additionally, the software accounts for outdoor obstructions, enabling realistic shading and obstruction analysis in complex urban contexts. These

capabilities make Ladybug Tools a powerful resource for daylighting design, optimization, and compliance evaluation.

Ladybug Tools supports a wide range of **control strategies** for optimizing lighting performance and energy efficiency in buildings. It includes preset control strategies for both electric lighting and daylight systems, as well as integrated strategies that coordinate the operation of both systems to maximize daylight use while minimizing electricity consumption. In addition to these built-in options, users can define custom control strategies tailored to specific project needs, allowing for flexible and precise control over electric lighting and daylight-responsive systems. These user-defined strategies can be applied independently or in combination, enabling dynamic responses to changing daylight conditions. Ladybug Tools also supports the calculation of annual electricity consumption, making it possible to evaluate the impact of different control approaches on energy use and sustainability goals. This functionality is essential for performance-based design and compliance with daylighting and energy standards.

Ladybug Tools continues to expand its capabilities beyond traditional environmental analysis by integrating lighting and thermal simulations, enabling designers to evaluate the interplay between daylight availability, electric lighting demand, and thermal comfort in a unified workflow. This holistic approach supports performance-driven design decisions that balance energy efficiency with occupant well-being. Additionally, Ladybug Tools is increasingly compatible with Building Information Modeling (BIM) workflows, offering support for IFC (Industry Foundation Classes) import and export, which facilitates seamless data exchange between Ladybug and BIM platforms. This interoperability allows users to incorporate Ladybug's simulation results into broader project documentation and coordination processes, bridging the gap between parametric design environments and industry-standard BIM tools.

Ladybug Tools provides robust functionality for evaluating the visual effects of lighting in architectural spaces. For visual comfort, it supports electric lighting glare calculations using metrics such as Unified Glare Rating (UGR) and Visual Comfort Probability (VCP), as well as daylight glare assessments through indicators like Daylight Glare Probability (DGP) and Daylight Glare Index (DGI). These tools help designers identify and mitigate potential sources of discomfort caused by excessive brightness or contrast. In addition to glare analysis, Ladybug Tools includes features for evaluating access to outdoor views, focusing on the presence and extent of view rather than the content or clarity. This supports design strategies that enhance occupant well-being by ensuring visual connection to the exterior environment. Together, these capabilities enable comprehensive assessments of lighting quality, contributing to healthier and more comfortable indoor environments. Due to the parametric nature of Ladybug Tools and its ability to perform post-processing directly within the same visual scripting canvas, users have the flexibility to evaluate metrics such as the LEED view factor and other interrelated environmental performance indicators. This integrated workflow allows for customized analysis and seamless adaptation to project-specific sustainability criteria.

Currently, Ladybug Tools does not include dedicated components for conducting life-cycle assessment (LCA) of electric lighting or daylighting systems. However, due to its flexible parametric framework and the ability to perform custom post-processing within the same simulation environment, it is possible to approximate LCA-related evaluations by integrating external data and workflows into the existing modeling canvas.

In addition to its core functions, Ladybug Tools offers a wide array of environmental analysis capabilities that support performance-driven design from concept to detailed evaluation. It enables comprehensive weather data analysis through the visualization of EPW files, climate diagrams, and psychrometric charts, helping designers understand site-specific conditions. For solar studies, it provides radiation mapping, sun vector generation, and orientation optimization, allowing users to assess solar exposure and inform passive design strategies. Ladybug Tools also supports whole-building energy simulation using EnergyPlus and OpenStudio, including detailed modeling of HVAC systems and internal loads. Thermal comfort can be evaluated using both adaptive and PMV models, ensuring occupant well-being across varying climates and building types. The platform facilitates multi-objective optimization through integration with tools like Octopus and Wallacei, enabling designers to explore trade-offs and identify optimal design solutions. Its geometry preparation features automate zoning, surface adjacency detection, and opening generation, streamlining the setup of simulation-ready models. Finally, Ladybug Tools excels in visualization, offering interactive 3D graphics, mesh mapping, and parametric feedback loops that make environmental data accessible and actionable. These capabilities make Ladybug Tools an indispensable

resource for architects, engineers, researchers, and students committed to integrating environmental performance into the design process.

Low Carbon, High Comfort Evaluations

Ladybug Tools offers a wide range of analyses in the environmental design, visual, and thermal fields.
environmental design:

- Ladybug Tools offers robust capabilities for weather data analysis, enabling users to import and visualize climate information from standard EnergyPlus Weather (.EPW) files. The platform can automatically download and extract climate data from online sources, including associated files such as .stat and .ddy, and open them for further analysis. A dedicated component allows users to access key environmental parameters essential for daylighting and thermal/energy simulations, including location, dry bulb temperature, relative humidity, wind speed and direction, direct normal radiation/illuminance, diffuse horizontal radiation/illuminance, and global horizontal radiation/illuminance, among others. These data points are presented through interactive climate diagrams and psychrometric charts, providing a comprehensive understanding of site-specific conditions and supporting informed design decisions from the earliest stages of a project.
- The Sun Path Diagram component in Ladybug Tools visualizes the solar trajectory across the sky dome and outputs sun vectors that can be used for solar access analysis and shading design. These vectors help identify critical sun positions for evaluating exposure and optimizing shading strategies. Complementing this, the Shade Benefit component assesses the effectiveness of shading geometry by calculating the duration of blocked sun vectors across its surface. It visualizes the desirability of shade using a colored mesh, where deeper blue tones indicate areas that block more hours of sunlight and are therefore more beneficial—particularly for reducing glare and improving visual comfort. The analysis can also be tailored to specific conditions, such as peak cooling demand or heat stress periods, and the results are expressed in hours per square unit, quantifying the shading performance of each segment of the geometry.
- The Direct Sun Hours component calculates the number of hours a geometry receives direct sunlight using sun vectors generated by the SunPath component. This analysis is useful for shadow studies in outdoor environments and for estimating glare potential from direct sunlight indoors. The component relies on the CAD environment's ray intersection methods, which offer fast performance for simple geometries but may be less efficient for complex models or large numbers of test points. For more detailed or large-scale studies, it is recommended to use Honeybee-Radiance for higher accuracy and scalability.
- The Cumulative Sky Matrix component generates a matrix of radiation values for each patch of the sky dome using Radiance's gendaymtx function, based on either EPW or STAT file data. This matrix serves as a foundation for solar radiation studies. The Incident Radiation component uses this matrix to calculate the total solar radiation received by geometry, making it useful for evaluating photovoltaic potential, solar thermal energy collection, and the impact of building orientation on energy use and cooling system sizing. While the analysis excludes solar reflections, it crudely accounts for ground-reflected irradiance via an emissive ground hemisphere derived from the matrix's ground reflectance. The component uses ray intersection methods within the CAD environment, which are efficient for simple geometries but less scalable for complex models or large datasets. For high-fidelity studies involving reflections, Honeybee-Radiance is recommended.

Visual Analysis:

- The Annual Daylight component in Ladybug Tools runs a full-year daylight simulation for a Honeybee model, calculating hourly illuminance at each sensor point across the building. By default, it uses an enhanced 2-phase method that accurately traces rays from each sensor to the sun's position at every hour, making it suitable for evaluating Annual Sun Exposure (ASE) and the performance of dynamic shading systems. Alternatively, a standard 2-phase method can be used for faster simulations, though it approximates direct sunlight and is not recommended for ASE analysis. The results are used to compute key daylight metrics including Daylight Autonomy (DA), Continuous Daylight Autonomy (cDA), and Useful Daylight Illuminance (UDI), providing a comprehensive understanding of daylight availability and quality throughout the year.
- The Annual Irradiance component in Ladybug Tools performs a full-year simulation to calculate hourly solar irradiance (in W/m^2) at each sensor point in a Honeybee model. Using an enhanced 2-phase method, it accurately traces direct sunlight for each hour, making it suitable for evaluating peak irradiance and identifying worst-case solar loads—critical for cooling system design. Unlike cumulative radiation studies, this method provides more precise average irradiance and total radiation values. While it shares the same simulation framework as the Annual Daylight component, it focuses on broadband solar energy rather than visible light, offering deeper insights into thermal and energy performance.
- The Annual Glare component in Ladybug Tools performs a full-year simulation to calculate hourly Daylight Glare Probability (DGP) at each sensor point in a Honeybee model. It uses the image-less glare method developed by Nathaniel Jones, which efficiently estimates glare without generating renderings, making it suitable for large-scale or complex models. The resulting DGP values are used to compute Glare

Autonomy (GA)—the percentage of occupied time during which a view remains free from glare—providing valuable insights into visual comfort throughout the year.

- The Point-in-Time Grid-Based component in Ladybug Tools runs a snapshot simulation for a Honeybee model to evaluate lighting or solar conditions at a specific moment. It requires a defined sky condition and can output illuminance, irradiance, luminance, or radiance values across sensor grids. This allows designers to assess lighting performance, or solar exposure under targeted scenarios such as solstices, equinoxes, or critical design hours.
- The Point-In-Time View-Based component in Ladybug Tools generates High Dynamic Range (HDR) images of lighting conditions—such as illuminance, irradiance, luminance, or radiance—from a specific viewpoint at a given time. It requires a defined sky condition and supports parallel processing by splitting views into segments, which are later recombined with anti-aliasing and overture calculations to enhance image quality and pixel interpolation. This component is ideal for visualizing lighting effects, glare, and spatial perception from the occupant's perspective under targeted daylight or electric lighting scenarios.
- The Glare Post-Processing component in Ladybug Tools analyzes hemispherical fisheye HDR images to evaluate visual discomfort caused by glare. It calculates Daylight Glare Probability (DGP) along with other glare indices such as DGI, UGR, VCP, CGI, and UDP, using the evalglare function developed by J. Wienold at Fraunhofer ISE. This tool provides a detailed assessment of glare conditions based on luminance distribution in the image, supporting informed decisions for daylighting design and occupant comfort.
- The Daylight Factor component in Ladybug Tools calculates the ratio of indoor to outdoor illuminance under a standard overcast sky, expressed as a percentage. This metric is useful for evaluating daylight availability in climates with predominantly cloudy conditions. Since it assumes uniform sky conditions, the result is independent of building orientation.
- The Direct Sun Hours component in Ladybug Tools calculates the number of hours of direct sunlight received by sensor grids in a Honeybee model over the course of a year. Unlike the basic LB Direct Sun Hours tool, this component uses Radiance for simulation, allowing for greater scalability and accuracy when working with large numbers of sensors or complex geometries. It is ideal for evaluating solar access, shading effectiveness, and potential glare risks in both indoor and outdoor environments.
- The Sky View component in Ladybug Tools calculates the percentage of the sky dome visible from a surface in a Honeybee model. It can be run using either a uniform sky or a cloudy sky, with the latter yielding the Vertical Sky Component (VSC) when applied to vertical surfaces, as defined by the UK Building Research Establishment (BRE). The analysis accounts for transparency of obstructing geometry, adjusting visibility based on material transmittance. Sky View is useful for evaluating daylight access, urban canyon effects, and compliance with daylighting standards in dense environments.
- The Daylight Control Schedule component generates electric lighting schedules based on annual daylight simulation results, enabling accurate modeling of daylight-responsive lighting controls in energy simulations. It dims electric lighting according to whether sensor illuminance meets a specified target setpoint, and supports setups with multiple sensors per room, allowing for nuanced control strategies. Each sensor grid produces a separate schedule, reflecting spatial variations in daylight availability. When sensors are distributed across the floor, the resulting schedules represent idealized dimming behavior, optimized to maintain minimum required illuminance throughout the space. This component offers enhanced accuracy and flexibility compared to simpler control modeling tools.

Thermal Analysis:

- The Annual Loads component in Ladybug Tools runs a simplified energy simulation for Honeybee Rooms to estimate annual heating, cooling, lighting, equipment, and service hot water loads. It is designed for quick assessments where a margin of error up to 5% is acceptable. While it provides useful insights into building performance, it does not represent actual energy use, utility costs, or greenhouse gas emissions. For detailed analysis, the Model to OpenStudio (OSM) component should be used. This tool converts a Honeybee model into an OpenStudio Model (OSM) file, which can then be translated into an EnergyPlus IDF file for comprehensive simulation, including custom HVAC systems and advanced energy modeling.
- Generation Loads: Runs Honeybee objects with electricity-generating properties (e.g., PV-enabled Shades) through a quick energy simulation to estimate electricity production. This component only evaluates generation, not consumption. Connected Honeybee Rooms or other objects are treated as context shades that cast shadows on generator objects.
- PMV Comfort: Calculates Predicted Mean Vote (PMV), a thermal comfort model for conditioned indoor spaces with active heating or cooling. For naturally ventilated buildings, use the Adaptive model; for outdoor conditions, use models like UTCI or PET.
- HVAC Sizing: Parses peak loads and HVAC component sizes from an energy simulation SQL result file.
- Carbon Emission Intensity: Retrieves carbon emission intensity (CEI) from an EnergyPlus SQL file, using location and year (or custom electricity intensity) to compute emissions for electricity and district heating/cooling. Fixed factors are applied for on-site fuels: Natural Gas (277.36 kg/MWh), Propane (323.90 kg/MWh), and Fuel Oil (294.96 kg/MWh).
- Thermal Load Balance: Construct a complete thermal load balance from energy simulation results and honeybee Rooms or a Model

Validation

To validate the daylight simulation results for a classroom on February 28th at 12:00 PM under overcast sky conditions, point-based measurements of horizontal illuminance were conducted at 12 sensor points across the floor plane at a height of 75 cm using a calibrated DT-856A lux meter (Figure 1). Following the field measurements, a 3D daylight model of the classroom was developed using Rhinoceros 7.

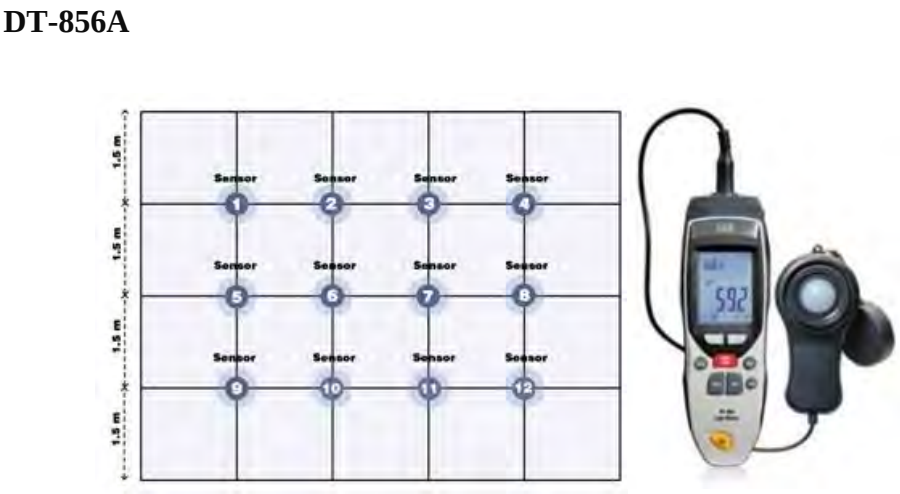


Figure 1. Sensor grid layout and measurement setup for daylight simulation validation.

Figure 2 presents a comparison between the measured and simulated illuminance values at each sensor point. The simulation results yielded a Normalized Mean Bias Error (NMBE) of exactly +9.00%, indicating that the simulated values are slightly higher than the measured data but remain within acceptable limits. According to ANSI/ASHRAE Standard 140, a model is considered calibrated if the NMBE is within ±10%, and this result satisfies that validation criterion. Furthermore, the Coefficient of Variation of the Root Mean Square Error (CVRMSE) was calculated to be 10.10%, confirming a small variation between simulated and measured values. These results support the reliability and accuracy of the daylight simulation model in representing actual indoor lighting conditions [1].



	1	2	3	4	5	6	7	8	9	10	11	12
Measured (lux)	343	403	379	355	572	646	641	584	1241	1215	1209	1385
Simulated (lux)	374	439	413	387	623	704	699	637	1353	1324	1318	1510

Figure 2. Comparison of measured and simulated illuminance values at sensor points.

Combination with LCA

In his master thesis, Iván Ares Igrexas developed a Grasshopper-based workflow to support the life-cycle assessment (LCA) of daylighting systems, creating a harmonized methodology for evaluating the environmental impact of windows, skylights, shading devices, and other daylighting components [3]. His master's thesis combined a comprehensive review of existing building LCA methodologies with the development of a practical assessment framework that integrates daylight performance and environmental impact, emphasizing that daylight quality should be evaluated alongside embodied carbon rather than in isolation. The Grasshopper-based tool can be directly coupled with Honeybee and thus can link daylight evaluation to LCA method.

4.14.3 Example Simulation Project Results

The results of the study on the daylight performance and visual comfort of different kinetic façade alternatives (Fig 3)—evaluated using sDA, UDI, EUDI, and DGP metrics for a south façade with an average window-to-wall ratio (WWR) of 0.57 and grid 4—are presented in Figures 4a and 4b. The analysis indicates that all façade alternatives satisfied the daylight performance criteria, with sDA, UDI, and EUDI values ranging from 83% to 100%, 96.37% to 97.90%, and 1.71% to 3.63%, respectively, and overall averages of 91.15%, 97.26%, and 2.5%. Individual UDI values for each user further demonstrate that the alternatives effectively met multiple occupants' daylight requirements simultaneously, with averages of 93.75%, 92.8%, and 94.07% for Tables 1, 2, and 3, respectively.

Regarding glare discomfort probability (DGP), all façade alternatives complied with the established criteria, with normalized values (0–100 scale) ranging from 24 to 38, corresponding to the perceptible and imperceptible zones. The average DGP values for users in Tables 1, 2, and 3 were 31, 32, and 31, respectively, indicating that most cases fell within the imperceptible zone. Based on these findings, it can be concluded that all façade alternatives meet the daylight performance requirements.

Figure 4c illustrates the electrical lighting load for various configurations of an interactive kinetic louver alternative, considering task lighting and individual user requirements. These configurations differ in louver type and arrangement, influenced by transitory sensitive area (TSA) radii. The façades controlled electrical lighting consumption between 0.09 and 0.55 kWh/m²/year, with an average of 0.24 kWh/m²/year. The proposed interactive kinetic façade demonstrates significant potential for reducing electrical lighting loads compared to the baseline case. However, despite achieving high performance in daylighting and lighting energy reduction, the alternatives do not fully meet LEED requirements.

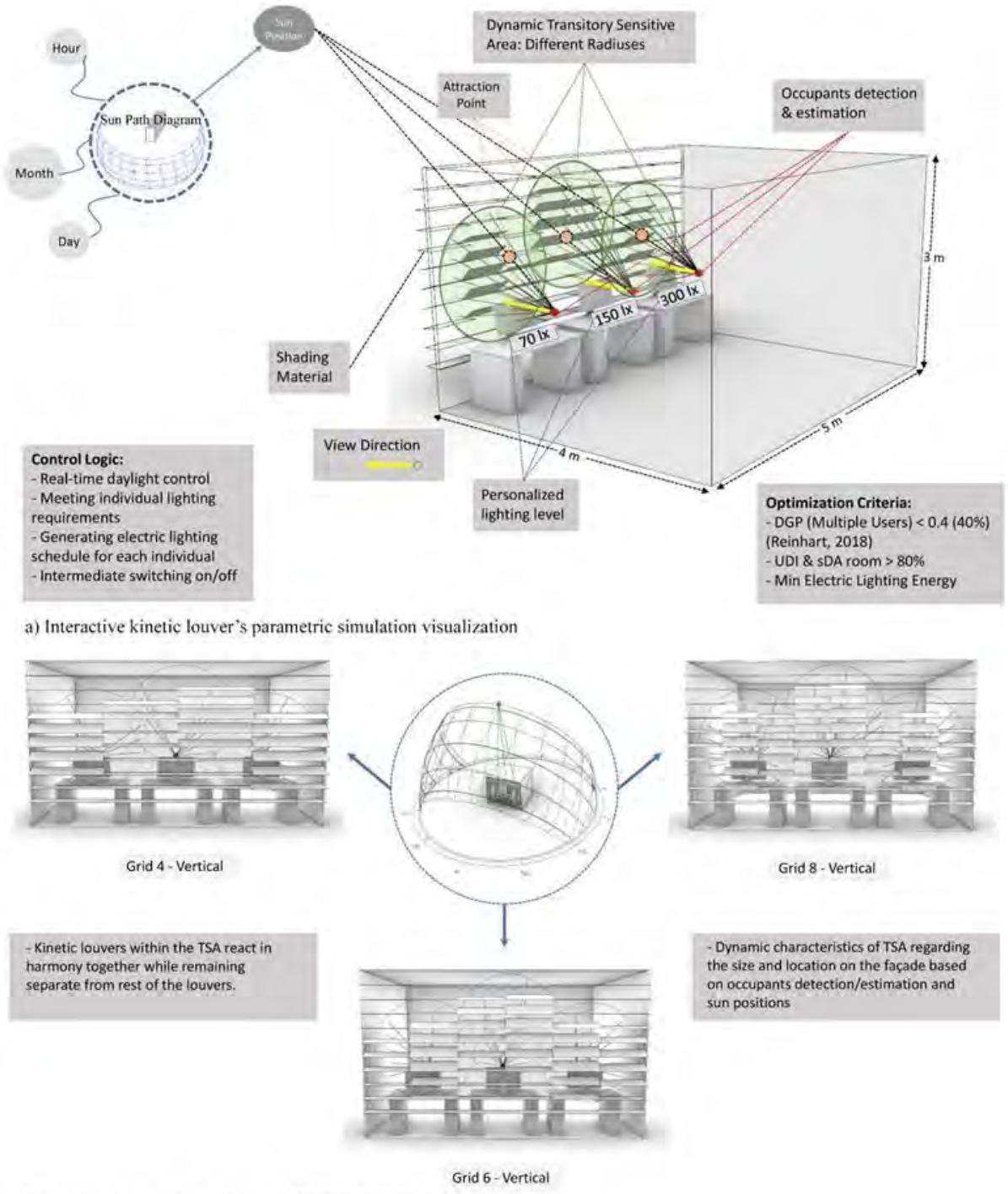
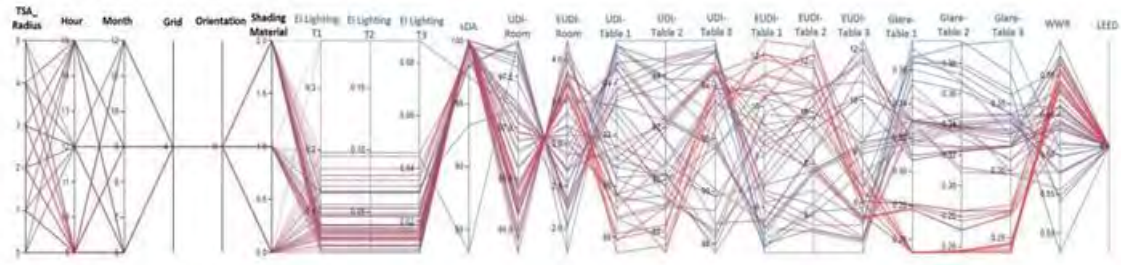
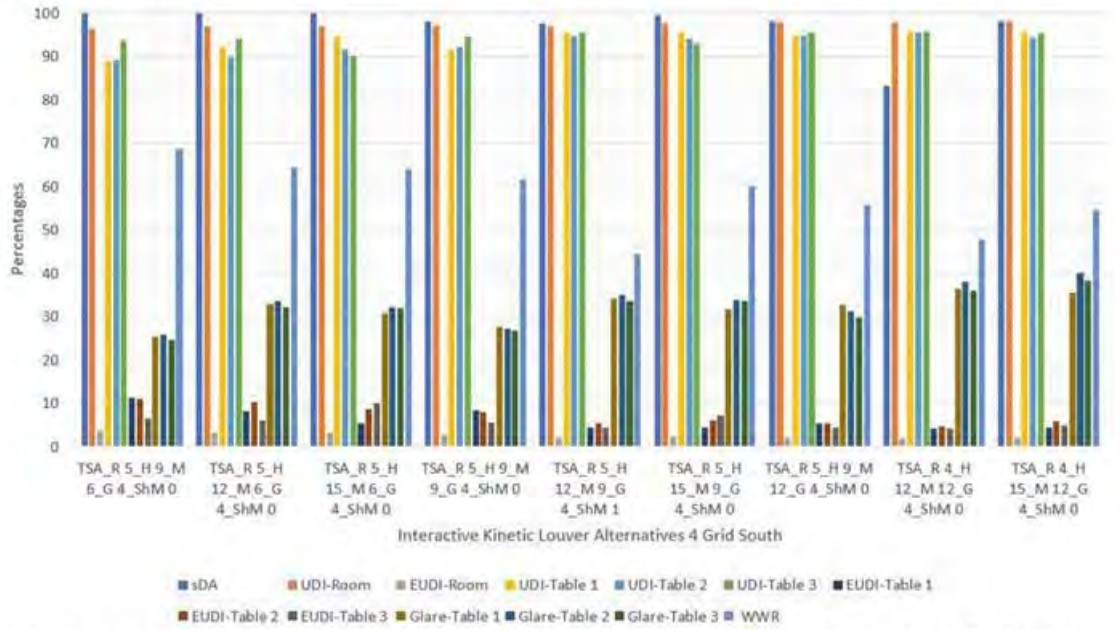


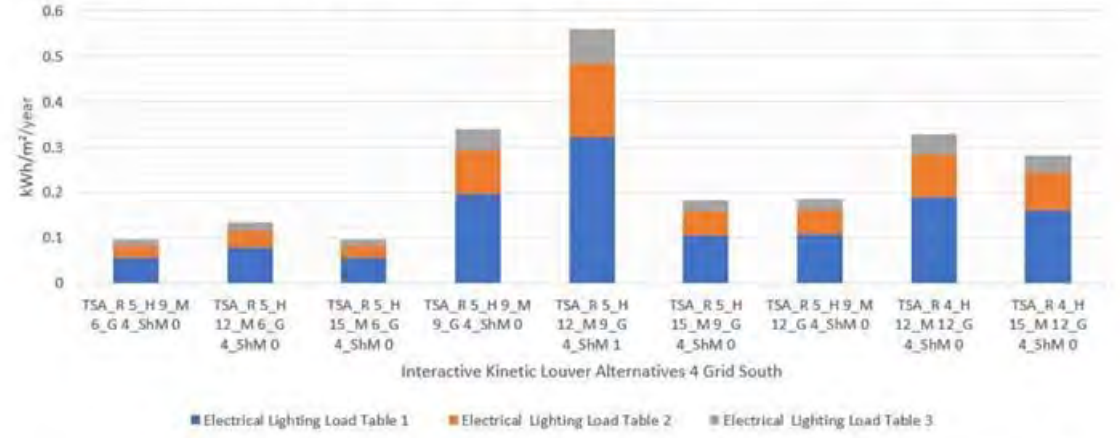
Fig 3. Workflow visualization of parametric daylight-glare-energy simulation for several alternatives with different grids and TSA sizes and locations.



a) Parametric exploration-optimization



b) Daylight performance evaluation based on climate-based daylight metrics and visual comfort evaluation through Daylight Glare Probability (Normalized between 0 and 100) for room and multiple users individually



c) Electrical Lighting load evaluation due to individual users' task lighting and preferred illuminance level of 300, 150, 70 lx for Tables 1, 2, 3 respectively.

Fig 4. Parametric exploration-optimization of interactive kinetic façade alternatives with Grid 4 on the South orientation-Singapore based on daylight performance-visual comfort-electric lighting for multiple occupants.

4.14.4 Ladybug / Honeybee References

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4.15 Lark

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4.15.1 General Information

Lark [1] is a free and open-source plug-in developed for the Rhino/Grasshopper environment, designed to support advanced spectral lighting simulations with a focus on non-visual and circadian effects of light [2]. Originally developed through a collaboration between Mehlika Inanici at the University of Washington and ZGF Architects LLP, Lark has evolved through multiple versions since its beta release in 2015, with version 1.0 officially released in 2022. Subsequent updates, including versions 2.0 and 3.0, have introduced new features and improvements contributed by an international team of researchers. Version 2.0 was developed by Clotilde Pierson (EPFL; Oregon State University) and Myrta Gkaintatzi-Masouti (Eindhoven University of Technology), with contributions from ZGF Architects LLP for the electric lighting simulation workflow and contributions for sky modelling by Priji Balakrishnan and Alstan J. Jakubiec. Lark v3.0 was subsequently developed by Bo Jung, Mehlika Inanici, Zining Cheng (University of Washington), and ZGF Architects LLP in 2023.

Lark simulations incorporate user-specified Radiance parameters alongside spectral characterisations of material surfaces, electric lighting sources, and sky conditions. According to the developers, the primary aim of Lark is to enhance the accessibility of spectral and circadian lighting analysis for architects, lighting designers, and researchers. In doing so, the tool facilitates more informed and evidence-based design decisions that account for both visual performance and the physiological impacts of light on human health [3].

4.15.2 Description of the software

Lark is a Radiance-based simulation tool [4] designated to evaluate both visual and non-visual effects of light in built environments. It uses the full spectral data to define skies, glazing, and material properties, enabling more accurate analysis than conventional tristimulus values RGB-based methods [1, 2].

The tool adopts a multi-spectral approach grounded in the work proposed by Ruppertsberg and Bloj [5, 6] and the N-step technique introduced by Yang and Maloney [7]. Withing this framework, the visible spectrum (380–780 nm) is divided into nine channels grouped into blue, green, and red bands [1]. Simulations are performed across these channels and subsequently integrated during post-processing, thereby enhancing the representation of spectral light–material interaction modelling. Lark incorporates full spectral inputs, including material reflectance properties, environmental context and sky conditions, which may be specified using global spectral data or correlated colour temperature (CCT).

This multi-spectral simulation framework overcomes key limitations associated with conventional RGB-based approaches, which can compromise accuracy in the assessment of colour-dependent lighting metrics and human photoreceptor responses. By employing full spectral reflectance data for both materials and environmental inputs, such as local sky conditions, glazing characteristics, interior material surfaces properties, observer position and the surrounding exterior environment, Lark offers an advanced simulation method for the evaluation of circadian lighting performance in built environments [1].

Lark v1.0 & v2.0 implemented three and nine channels, with nine channels categorised as follows: Blue [b1 (380,422), b2 (422,460), b3 (460,498)], Green [g1 (498,524), g2 (524,550), g3 (550,586)], Red [r1 (586,650), r2 (650,714), r3 (714,780)] for wavelengths ranging from 380 to 780 nm [1]. It enables the computation of range of lighting metrics, including photopic values (luminance and illuminance), as well as Alpha-opic metrics for point-in-time or periodic analysis in grid- or images-based spectral simulation. Lark v2.0 offered annual simulation using the Daylight Coefficient method [8] for dynamic daylight simulations. It also provided two sky models: CIE Standard Illuminant D65 and user-defined spectral power distributions (SPDs). While D65 is convenient, it may not reflect local conditions accurately, whereas measured SPDs are more precise but less accessible. To address the limitation, the version 3.0 has the option to choose between spectral and luminance-based Perez sky, for inclusion of solar spectra in addition to the sky. These flexible radiance sky generation options in gendaylit, use either direct and diffuse irradiance (-W) or global irradiance (-E), Perez sky modelling for three-channel simulations (-C option based on luminance to colour the sky).

Lark v3.0 built on version 1.0 and 2.0, extending its capabilities with features including neuropic metric calculations and improvements to SPD data processing [3]. It introduces a revised segmentation of its nine spectral channels,

distinguishing it from earlier versions: Blue 380-499 [b1 (380-419), b2 (419-459), b3 (459-499)], Green 499-587 [g1 (499-529), g2 (529-558), g3 (558-587)], Red 587-780 [r1 (587-608), r2 (608-630), r3 (630-780)]. This updated configuration enhances the utilization of each channel's output by aligning it more closely with photopic, melanopic, and neuropic efficiency functions. While the blue channel is partitioned into three equal intervals, the green and red channels are divided into unequal segments to more accurately capture the gradients of the melanopic and photopic response curves [9].

4.15.3 Validation

The validation of Lark has been examined in the literature through comparisons with both physical measurements and alternative simulation tools, generally demonstrating favourable performance [9-17]. Notably, Pierson et al. reported that Lark, while computationally more demanding than ALFA [18], yields higher accuracy under daylight conditions, highlighting its suitability for detailed spectral daylight analysis.

Quantitative validation studies suggest that Lark provide generally acceptable accuracy in predicting spectral irradiance. Evaluations of spectral daylight simulation Lark v1.0 for their visual, spectral, and colorimetric accuracy in complex outdoor scenes show higher variability [11]. In this study, Lark's simulated outputs were compared with high dynamic range (HDR) photographs across clear, morning, evening, and overcast sky conditions, revealing RMSE values of up to 31% in clear skies, 17% for overcast sky conditions, and the highest error of up to 38% for evening sky conditions, particularly in vegetated such as trees and grass ground cover.

Studies employing the nine-channel Lark v2.0 simulation for daylight spectral irradiance calculation report a median relative bias error (MRBE) within ±20% [16, 17, 19]. Comparison Lark v2.0 outputs against measurements from a physical neutral-coloured scale model indicate relative errors of up to 15% for daylight, 5% for electric lighting and 20% under combines daylight and electric lighting conditions [20]. In addition, Lark v2.0 simulations of different glazing types including clear and smart glazing under maximum and minimum colouration states have been validated against measured data under sunny and overcast sky conditions, yielding MRBE values within 5% [15].

A study on the most recent version of Lark (v3.0) [21] evaluates the accuracy of by comparing measured and simulated spectral irradiance and ipRGC-influenced light (IIL) responses at two desk positions in an office space under various lighting conditions. Lark showed slightly wavelength- and lighting condition- dependent biases. In daylight scenes, it estimated spectral irradiance accurately in the 460 to 650 nm range (median MRBE within ±20%) but underestimates spectral irradiance in the 380–460 nm range and overestimating it in the 650–715 nm range (up to 25% median MRBE). Under electric light, it generally underestimates irradiance across spectral bins except for a positive bias in the 422–459 nm range. Combined lighting conditions shows similar overestimation pattern but with reduced magnitude and lower median MRBE. Overall, in estimating spectral irradiance for most bins in daylight and direct electric light estimates fell within ±20% MRBE. Lark also generally estimates IIL responses and photopic illuminance within ±30%, improving to ±10% under direct electric [21].

As interest in spectral lighting simulation continues to grow, Lark remains a widely adopted tool for investigating design strategies and compliance with circadian lighting recommendations [10, 22-24]. Nevertheless, challenges persist, particularly in improving usability and accessibility of input data, which remain critical barriers to broader adoption in both research and professional practice. Lark is a powerful tool for simulating light, but it remains difficult to use despite the growing interest in such tools within industry. Although Lark includes predefined templates for point-in-time and period-based analyses, their application in professional lighting design practice can be challenging. Based on observations from design office environments, these templates are often perceived as unclear or difficult to implement by users. This can create confusion during the setup process, particularly for practitioners who are not highly experienced with spectral simulation workflows. As a result, the intended efficiency of these predefined analysis options is not always fully realised in practice.

A major challenge is the large amount of detailed and complex input data required to run simulations in Lark. Spectral light simulations tools rely heavily on accurate inputs, including materials spectral reflectance, glazing spectral transmittance, luminaires photometric distribution and model geometry [15, 21], which are often uncertain in various stages of design. In addition, using Lark effectively requires significant expertise, as users must understand its parameters and interpret complex outputs. While Lark is powerful, its complexity and input demands can limit its practical usability in architectural and lighting design practice.

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4.16 LightStanza

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4.16.1 General Information

- Website: https://lightstanza.com/
- Developer: LightStanza LLC (uses Radiance engine)
- Platform: Web-based
- License: Commercial (subscription)
- CAD Support: Revit, Archicad, SketchUp, general 3D formats

LightStanza is a cloud-based daylighting analysis platform that uses the Radiance simulation engine through a web interface.

4.16.2 Description of the Software

The software performs Radiance calculations on cloud servers, eliminating local software installation and computational requirements.

Simulation Engine:
- Radiance ray-tracing
- Cloud-based computation
- Distributed processing across servers

Annual Simulations:
- Climate-based daylight modeling
- Spatial Daylight Autonomy (sDA)
- Annual Sunlight Exposure (ASE)
- Compliance with LEED v4, WELL, EN17037

Point-in-Time:
- Date/time-specific calculations
- Daylight factor
- Illuminance distributions
- Luminance calculations

Glare:
- Daylight Glare Probability (DGP)
- Annual and point-in-time analysis
- Automated glare point detection

Features:
- Automatic blind generation for LEED calculations
- 2D plan generation from 3D geometry
- Cloud-based project storage
- Result sharing capabilities

Workflow:
- Model import via file upload
- Parameter configuration through web interface
- Server-side calculation
- Online result visualization

Target Users:
Architects, daylighting consultants, sustainability professionals, LEED consultants.

Validation:
Inherits Radiance engine validation from published research.

Limitations:

- Internet connection required
- Subscription-based access
- Limited electric lighting database
- Advanced Radiance features abstracted from user
- Less suitable for detailed electric lighting design

4.16.3 LightStanza References

[1] LightStanza LLC, https://lightstanza.com/

[2] LightStanza FAQ, https://lightstanza.com/lightstanza-frequently-asked-questions/

4.17 OpenStudio

Taoning Wang, LBNL (Lawrence Berkeley National Laboratory)

4.17.1 General Information

- Website: https://openstudiocoalition.org/
- Developer: NREL
- Platform: Cross-platform
- License: Open Source (BSD)
- Integration: SketchUp plugin, standalone application

OpenStudio is an open-source software development kit for building energy modeling, combining EnergyPlus thermal/energy simulation with Radiance daylighting analysis.

4.17.2 Description of the Software

OpenStudio provides a framework for whole-building energy simulation that integrates daylighting results with thermal and energy calculations.

Radiance Integration:
- 3-Phase method for annual daylighting
- Daylight coefficient method for static calculations
- Automated matrix generation
- Workplane illuminance calculations

Annual Metrics:
- Spatial Daylight Autonomy (sDA)
- Annual Sunlight Exposure (ASE)
- Daylight Autonomy (DA)
- Continuous Daylight Autonomy (cDA)
- Useful Daylight Illuminance (UDI)

Glare:
- DGP simplified calculations
- User-defined glare sensor placement
- Annual and point-in-time assessment

Geometry:
- SketchUp modeling
- IDF/OSM file import
- Non-rectilinear spaces supported
- Interior partition modelling

Energy Integration:
- Radiance results feed EnergyPlus schedules
- Lighting load adjustments based on daylight
- Annual energy consumption
- Heating and cooling load calculations

Control Systems:
- Preset dimming strategies
- User-defined lighting controls
- Shading device controls (subset of EnergyPlus options)
- Hourly control response

Output:
- CSV format daylighting metrics
- EnergyPlus SQL results database

- JSON export option
- Results Viewer interface

Target Users:
Building engineers, energy modelers, sustainability consultants, researchers.

Validation:
Radiance validation through published literature. EnergyPlus validated per ASHRAE Standard 140.

Limitations:
- Learning curve for both Radiance and EnergyPlus
- Limited to 3-Phase method (5-Phase not available)
- Interface less refined than commercial software
- Radiance measure limited to illuminance calculations
- Spectral and circadian metrics not included

4.17.3 OpenStudio References

[1] OpenStudio Coalition, https://openstudiocoalition.org/

[2] Radiance Tutorial, https://openstudiocoalition.org/tutorials/radiance_tutorial/

[3] NREL OpenStudio Documentation, https://nrel.github.io/OpenStudio-user-documentation/

4.18 OWL

Marshal Maskarenj, Sergio Altomonte, Catholic University of Louvain, Belgium

4.18.1 General Information

OWL (*'Occupant Wellbeing through Lighting'*) is a spectral lighting simulation software and framework developed at the Catholic University of Louvain. OWL builds on the Radiance engine, and is designed to help facade and lighting designers and researchers explore how light affects people – via metrics for visual sufficiency, comfort, non-visual/circadian well-being, while also estimating the energy use for space lighting. As a set of visual scripting components written in Python, OWL is currently implemented for Rhino/Grasshopper, although its structure is intended to remain adaptable across platforms in near future. Each version of OWL addresses a layer of complexity in lighting analysis:

- OWL 1.0, the first version of the tool, provides point-in-time evaluations of both visual and non-visual metrics for specific occupant positions and viewpoints indoors [1]. This first version relies on Ladybug and Honeybee components for Radiance evaluations.
- AnnuOWL, the next release, extends the evaluation to the annual timescale (hence *Annual+OWL*). It computes daylight metrics across sensor grids, along with proxy measures of visual comfort and circadian autonomy [2]. For this, original components are introduced to bring Radiance-based simulation capacities directly into the workflow pipeline, without the need for external tool support.
- SpectrOWL, the most recent addition, focuses on spectral detail (hence *Spectral+OWL*). It performs annual simulations across 81 spectral channels, accounting for both diffuse daylight and direct sunlight in the view. SpectrOWL supports both grid-based and image-based calculations (with image-based restricted to point-in-time analyses), and makes it possible to track non-visual metrics such as melanopic Equivalent Daylight Illuminance (mEDI) for every hour of the year. In doing so, it allows users to test compliance with recommendations such as those of Brown et al [3]. It also introduces support for electric lighting simulations (including energy use estimation with clustered luminaire scheduling), and the incorporation of the effects introduced by spectral variations in external daylight throughout the year.

The development of OWL has been supported by the FNRS Belgium. OWL and AnnuOWL are freely available on their project websites (**OWL**: https://marshalmaskarenj.github.io/OWL_Web/ ; **AnnuOWL**: https://marshalmaskarenj.github.io/AnnuOWL_Web/), together with extended documentations, video tutorials, and open-source code provided on GitHub. With a modular design throughout components, OWL is conceived as a growing family of tools that can adapt to different design environments, with advances in spectral lighting research.

4.18.2 Description of the Software (Family)

All tools within the OWL family (currently) rely on Rhino for geometry inputs, and on local file paths for other input data, such as weather files, spectral files, luminaire details, etc.

OWL 1.0 evaluates point in time spectra under the unobstructed skydome, and also for the user's viewpoint – and further estimates non-visual metrics using its components for CIEs026 and Lighting Research Center's circadian lighting calculators. The Spectral Sky models are core to OWL, which use the *luminance to CCT* conversion models by Diakite-Kortlever and Knoop [4]. Within OWL workflow, a user must only define the geometry (via the Rhino side), the view position (from Rhino views), the location of the weather file, and the hour of the year, as inputs. Optionally, they can also change the CIE sky type *(assuming the CIE model component is used)* and change the mask from fisheye (default) to binocular or human-vision masks. This yields, as output, the non-visual metrics (LRC, and CIEs026) both under the unobstructed sky-dome, and for a vertical field of view of an observer, for a given hour of the year.

(*Functionality*) For the skydome, the component for the Perez all sky model *(as alternative, user can also choose to use CIE model with defined sky type)* generates luminance across 145 Tregenza patches, each with a defined altitude-azimuth from the zenith. Inputs for the sky model-components are supported by other components that extract relevant information from the EPW file, for a user-defined hour of the year. The evaluated patch-luminance is then translated to patch-CCT using the spectral sky models, which is further converted to patch-SPD using the CIE015 reconstruction process. With cosine correction, the spectral radiance from each patch is aggregated for each spectral bin, to generate the spectral quality of daylight (SPD in 2-nm bins between 380 and 780nm) under the unobstructed sky for the defined hour of the year. The

spectral data is then processed to generate LRC's circadian stimulus metrics (CS, CLa), and CIEs026 alpha-opic metrics [5], with respective calculators. For the observer's point of view, the hemispherical (fisheye) luminance map is first generated using image-based evaluation in Radiance *(supported by Ladybug/Honeybee components)* – which is then converted to patch luminance *(by consolidating the pixel values for each of the 145 masks in horizontal field of view)* – and a similar pipeline is employed to generate non-visual metrics from any defined viewing position indoors, for a defined hour of the year.

(*Limitations*) Although dynamic variations in sky spectra are incorporated, a limitation of OWL1.0 is that ambient bounces are not accounted-for within indoor evaluations. This tool therefore does not support evaluations of indoor wall materials. Only the direct sky (or sun) component of daylight within an observer's field-of-view is accounted for, while contributions from internal and external bounces are ignored. Additionally, the evaluations are conducted for point-in-time analysis, while annual evaluations (i.e., for design recommendations) are not conducted. Despite these limitations, the quick (almost real-time) evaluations for different points-in-time makes OWL1.0 very promising for parametric evaluation studies.

AnnuOWL extends the capacities of OWL1.0 by proposing original components for evaluating hourly metrics for daylight, across a grid of vertical sensors facing four principal orientations. The user needs to define the geometry (with distinct materials), together with the path to the weather and spectral data files. Additionally, the observer positions and the grid spacing (in x- and y- axes) must be defined. User can optionally change the sensor height, the thresholds for metrics (e.g. DA, UDI, etc), working hours (start and close of business, first day of week), etc. The calculations are intensive, considering multiple grid and observer positions (across 4 orientations) across annual hours. To support this, AnnuOWL offers the possibility to display a pre-simulated case, for which a user needs to toggle the cache button to 'True', and connect the component to any file within a pre-simulated case folder, for a quick visualization (and to support comparisons).

(*Functionality*) To generate the annual spectral data (i.e. the SPD of the sky facing zenith, for each annual hour for any location), a calculator is provided to pre-evaluate the hourly spectra. The luminance-to-CCT-to-SPD workflow of OWL 1.0 (*which combines Perez model with spectral sky models and with CIE015 reconstruction procedure)* is used within this calculator, which takes relevant inputs from the EPW file, to generate a text-based annual spectral file (called *.AOWL format). This calculator typically requires about 20 minutes to convert an EPW to AOWL file, and is a one-time conversion per location/EPW file. The path to this AOWL file is specified in the AnnuOWL workflow. Within the evaluations, 2-phase Radiance is employed to evaluate 3-channel illuminance values for the horizontal grid *(with materials defined, and an ambient bounce set at 5 as default).* Calculations are performed at desk height, and for the observer's position at four vertical orientations at the seated head height *(which are adjustable by the user)*. The grid-based annual evaluations are then translated to annual daylight metrics of (cumulative) daylight autonomy (DA/cDA), useful daylight illuminance (UDI), and average illuminance, each with adjustable thresholds. In parallel, the vertical illuminance values are used for evaluating proxy-metrics for non-visual well-being and visual comfort for each occupant position.

(*Limitations*) The incorporation of annual variations in sky spectra and of ambient bounces for considering material influence, together with multi-point annual simulations support AnnuOWL as a promising early-stage design recommendation tool. However, the lack of electric lighting evaluations, the 3-channel evaluations with proxy metrics, and the lack of direct sun (especially for discomfort glare metrics) limits its capacities for detailed and physically accurate evaluations. Also, while the BSDF cannot be incorporated, the blinds may be physically modeled. Despite these limitations, the relatively fast simulation time (especially for occupant-centric workflow) makes AnnuOWL a promising tool for conducting occupant-centric parametric evaluations.

SpectrOWL further addresses the limitations of AnnuOWL by introducing an 81-channel multi-bin spectral simulation workflow, that incorporates the spectral variations in daylight through different hours of the year. With an input interface similar to AnnuOWL, a user must define the geometry for each layer with distinct materials, together with 81-channel spectral attributes for each layer. In case the spectral data does not match the expected input format (between 380-780 nm in 5nm bins), interpolation is performed when the spectral data (e.g. from SpectralDB) is defined with its start value and bin-size. Additionally, the user can define the sensor positions (i.e.. grid, height, & separation, along with user position & head-height) and the luminaire placement (and attributes, as .ldt or .ies format), together with other thresholds such as for AnnuOWL.

(*Functionality*) By combining the 2-phase DDS capacities within 81-channel simulations, SpectrOWL generates 27 subfolders: each of which distinctly evaluate attributes (as RAD, RTM, and OCT), and subsequently the daylight matrices (MTX). Together with the weather (WEA), these matrices further generate

3-channel (x27 times within subfolders) irradiance (as ILL) -- which are then translated to a CSV file for specific hours. This calculation itself runs within a subroutine, where the AOWL file is binned into annual hours having their sky spectra (using CCT as indicator) falling between user-defined CCT-bins. Here, the mid-value CCT is used to generate 81-channel SPD for those hours, which are then translated into 3-channel for each of the 27 subfolders for the respective hours – and where 'gendaymtx -c Rval Gval Bval weaFile > location.smx' is employed within the pipeline for generating respective daylight matrices. Effectively, for different hourly bins representing sky spectra, within 27 instances of 3-channel simulations, the 2-phase radiance DDS simulations are carried out with material attributes for each layer for the hours within the spectral bin – which are then aggregated for the annual hours, and for the 81-channels. This spectral data is thereafter translated to melanopic and other spectral metrics for non-visual well-being. In parallel, for a given point in time, multichannel evaluations using image-based analysis are also conducted, generating 27 HDR files that represent all 81 channels. These are then read and merged into an 81-channel dataset, which is then reduced to a melanopic and photopic image – while also supporting the user to evaluate the spectral radiance for any pixel within the fisheye image (together with non-visual metrics). The incorporation of electric lighting simulation capacity further allows SpectrOWL to evaluate energy use for lighting, and support the unmet hours by setting a threshold illuminance value for a defined sensor position. Python SciPy Optimize, using the simplex method, evaluates the dimming level for each cluster based on this sensor position – and estimates the electric lighting energy use (and also cost, by setting the unit pricing). Additionally, the evaluation of daylight factor (DF) and Annual Sunlight Exposure (ASE) are also incorporated within grid-based evaluations, adding to the four for AnnuOWL. User is also allowed to limit the simulation hours by defining the starting and end date – and does not need to perform calculations for the entire 8760 annual hours.

(*Limitations*) The electric lighting simulation capacity has yet to be advanced to multispectral evaluations, and the BSDF support is not yet incorporated within the multi-channel 2-phase DDS evaluations.

Low carbon, High comfort Evaluations

Although OWL family can evaluate visual metrics (*daylight factor, and climate-based daylight metrics*), being within the Rhino Grasshopper environment allows the capacity to incorporate components from other workflow for such measures (and also for, e.g. LCA, thermal evaluations, CFD, etc.) – and the focus within OWL development has remained on improving capacities for non-visual metric evaluations. To this aim, OWL1.0 advances the capacity for incorporating dynamic variations in daylight's spectral composition within simulation workflows, and AnnuOWL extends the point-in-time, view/position-in-space to multipoint/view annual hourly simulation capacities for supporting early-stage recommendations for facade and lighting design and operations. SpectrOWL further advances the capacities with multi-channel (81 channels with 5-nm bin between 380-780nm) evaluations, together with direct sky component, which enhances the accuracy in evaluating human factors such as discomfort glare and non-visual/circadian well-being – which resonate with the *high comfort* aspect. Additionally, the incorporation of electric lighting simulation with cluster-level dimming, supported by SciPy Optimize for matching the unmet hours through adequate modulation in intensity – and thereafter the calculation of total hours of aggregated lighting-use per cluster, energy use per cluster (and incurred costs for electric lighting), supports the *low-carbon* aspect of the evaluation. This advancement is beyond the previous capacities of evaluating proxy metrics such as daylight autonomy and useful daylight illuminance.

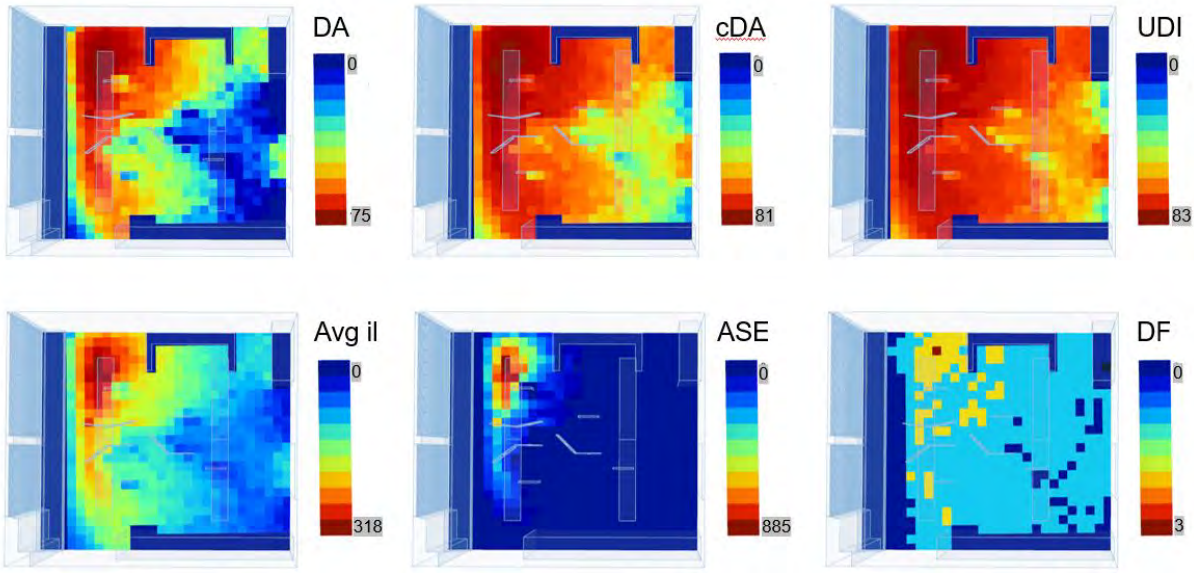
Validation

OWL is built on Radiance, the physically-based lighting simulation engine developed by Greg Ward originally at LBNL. Radiance employs backward raytracing to model light transport, and is extensively validated against field measurements across decades of international research. The reliability of OWL's predictions is therefore grounded in the established validation for Radiance. Additionally, OWL tools incorporate models and methods from published literature, including spectral sky models, the CIE 026 toolbox (for α-opic quantities) and LRC's calculator (for circadian metrics), the CIE 015 reconstruction procedure, etc. The accuracy of outcomes further depends on the reliability of meteorological input data, typically provided in EPW weather files.

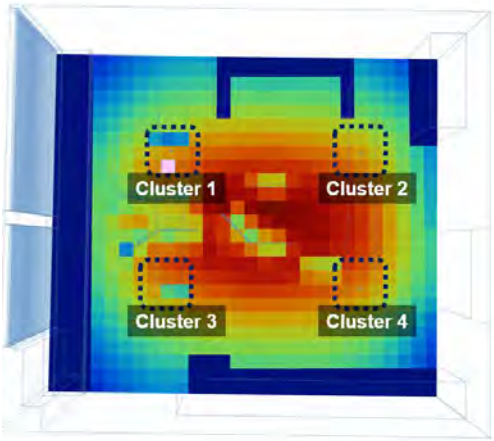
No direct experimental validation has yet been performed for these complex metrics -- especially those supported by SpectrOWL: such as annual spectral evaluations that account for spectral variation across different hours of the year. These outputs should therefore be interpreted based on the combined assumptions of the underlying methods: Radiance calculations, literature-based spectral models, and the reliability of the weather data together with the level of details in the user-defined geometry and material properties used as inputs for the evaluations.

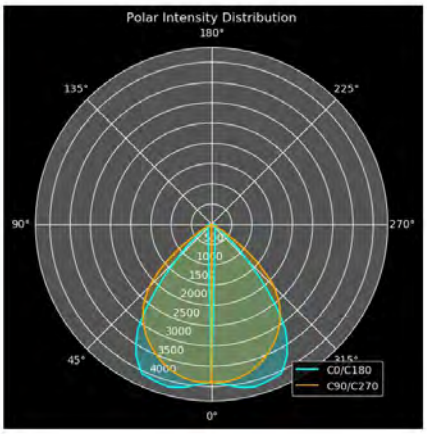
4.18.3 Example Simulation Results

- **Climate based daylight metrics over the grid**

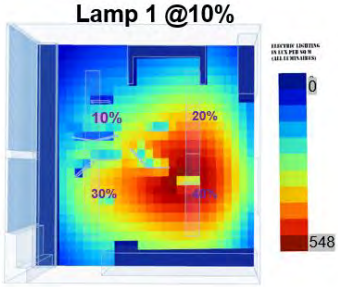


- **Electric lighting and unmet hour simulation**

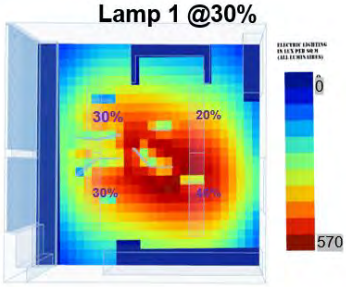




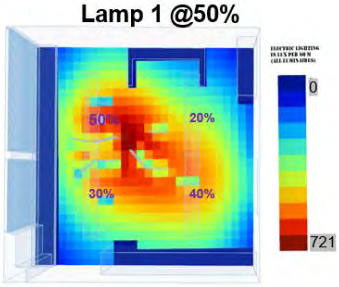
Lamp 1 @10%



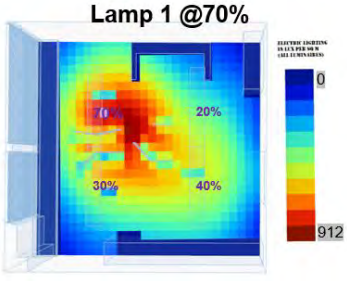
Lamp 1 @30%



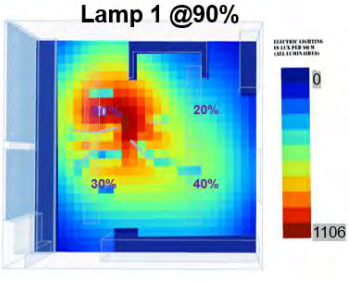
Lamp 1 @50%

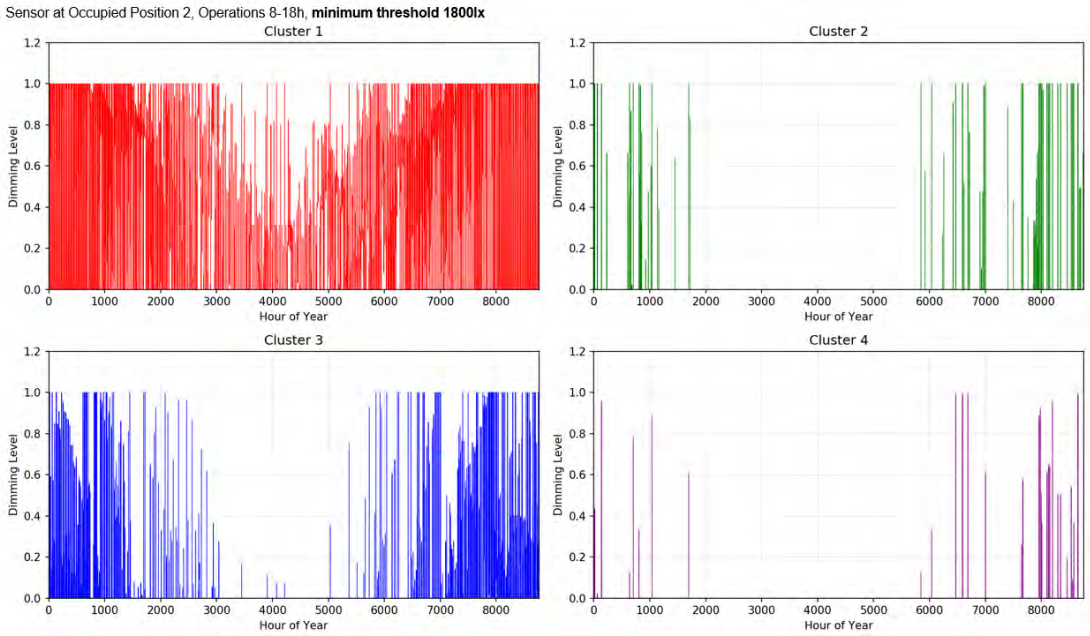


Lamp 1 @70%

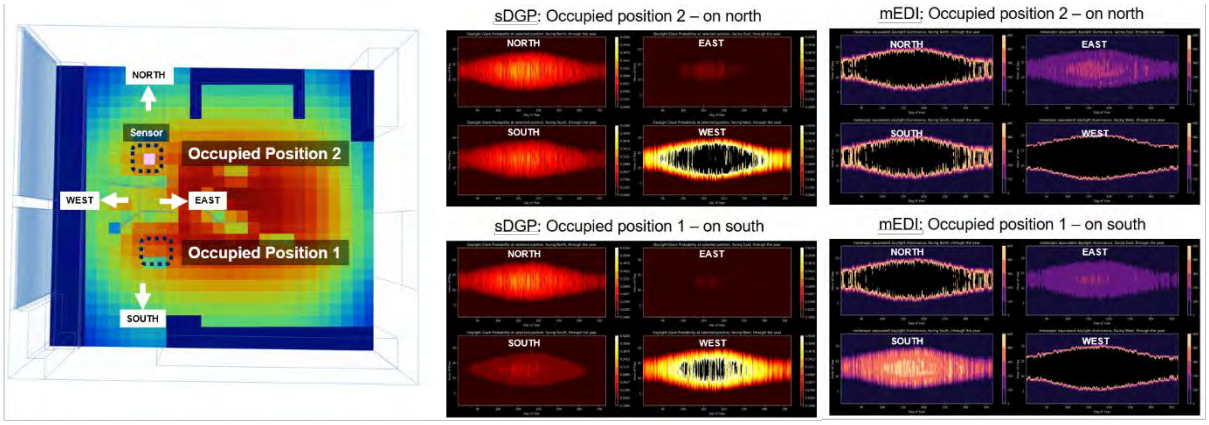


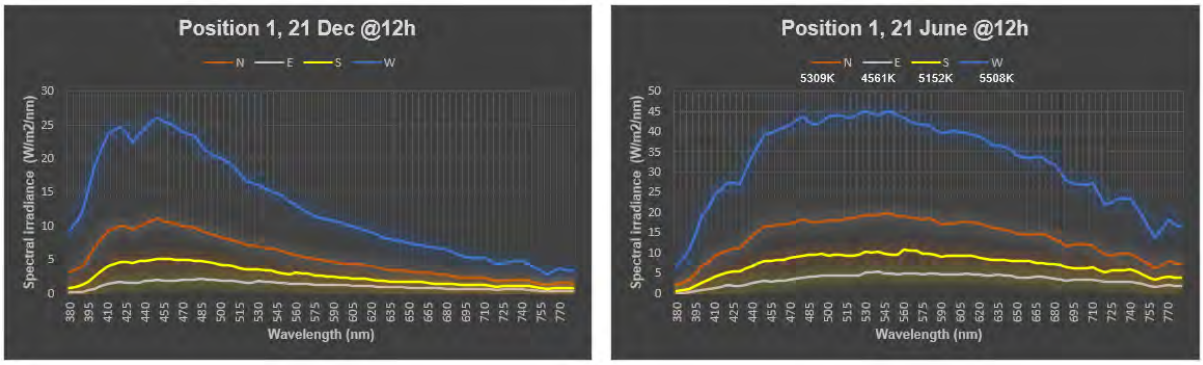
Lamp 1 @90%





- **Visual (comfort) and Non-visual (circadian well-being) evaluations**





4.18.4 OWL References

[1] M Maskarenj, B Deroisy, S Altomonte. A new tool and workflow for the simulation of the non-image forming effects of light, Energy and Buildings, Volume 262, 2022, 112012, https://doi.org/10.1016/j.enbuild.2022.112012.

[2] M Maskarenj, S Altomonte. Annual Evaluation of Daylight Sufficiency and Human-Centred Daylight Metrics: A New Simulation Tool and Workflow. SSRN: http://dx.doi.org/10.2139/ssrn.4698735

[3] TM Brown, GC Brainard, et al. Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults. PLoS Biol. 2022, 20(3), e3001571. http://doi.org/10.1371/journal.pbio.3001571

[4] A Diakite-Kortlever, M Knoop. Forecast accuracy of existing luminance-related spectral sky models and their practical implications for the assessment of the non-image-forming effectiveness of daylight. Lighting Research & Technology. 2021, 53(7), 657-676. https://doi.org/10.1177/1477153520982265

[5] LJM Schlangen, LLA Price. The Lighting Environment, Its Metrology, and Non-visual Responses. Front Neurol. 2021, 12:624861. https://doi.org/10.3389/fneur.2021.624861.

4.19 PKPM

Boyu Mao, Luo Tao; China Academy of Building Research, China

4.19.1 General Information

PKPM Green and Low-Carbon series software [1][2] provides comprehensive coverage in civil, industrial, and healthy building sectors. It incorporates over twenty modules, including energy-efficient design, evaluation and optimization of sustainability and health indicators, as well as simulations for wind environment, daylight, acoustics, thermal performance, HVAC airflow organization, indoor health and comfort design, and a green building toolkit. The software supports multi-platform operation (e.g., CAD, BIM) and adheres to more than 200 Chinese energy standards (such as the national standard GB55015), over 20 ultra-low energy building design standards, and more than 100 green building evaluation and design standards applicable in China. Integrating authority, intelligence, and openness, the software has been repeatedly recognized with national and provincial awards, including the Huaxia Award and Scientific and Technological Progress Award. It serves over 10,000 users across China, and its building energy conservation design module is officially designated by construction authorities in Shanghai, Tianjin, Chongqing, Chengdu, and other regions. It is the first green building performance simulation software in China to pass five rigorous certifications:

2016: Performance validation in a wind tunnel laboratory;

2017: Product appraisal by the Science and Technology Development Promotion Center of the Ministry of Construction;

2018: Endorsement by Tsinghua University, the lead compiler of the Chinese standard JGJ/T 449-2018;

2019: Recognition in the National Excellent Energy-Saving and Environmental Protection Product Technology Review;

2020: Appraisal by the National Building Engineering Technology Research Center, confirming international advanced levels.

In 2020, the project it contributed to, “Research and Application of Green Building Standard System Construction and Performance Improvement Technology,” received the first-class Huaxia Construction Science and Technology Award.

4.19.2 Description of the Software

FUNCTION HIGHLIGHT

Cross-Platform Operation and Multi-Data Model Support: The software supports operation across platforms such as AutoCAD, Revit, and BIMBase, as well as domestic platforms like ZWCAD and GstarCAD. It also enables the reading of various model formats, including TArch .

Domestically Developed Core for Energy Consumption and Carbon Emission Calculation: It incorporates a self-developed, proprietary core engine for calculating building energy consumption and carbon emissions, addressing key technological challenges and reducing external dependencies .

Support for the Latest Design Standards: The software complies with the most recent national and regional standards in China concerning energy efficiency, ultra-low energy consumption building design, carbon emission assessment, green building evaluation and design, as well as energy efficiency performance measurement .

Intelligent Wizard-Guided Operation: Featuring an intelligent guidance system, the software provides step-by-step operational prompts, significantly reducing the learning curve and making it accessible to users with varying levels of expertise.

Multi-Region Certifications and Industry Awards: The energy efficiency module is officially designated for use by construction departments in Shanghai, Tianjin, Chongqing, and Chengdu. It has obtained six major industry certifications and was awarded the first prize of the Huaxia Construction Science and Technology Award .

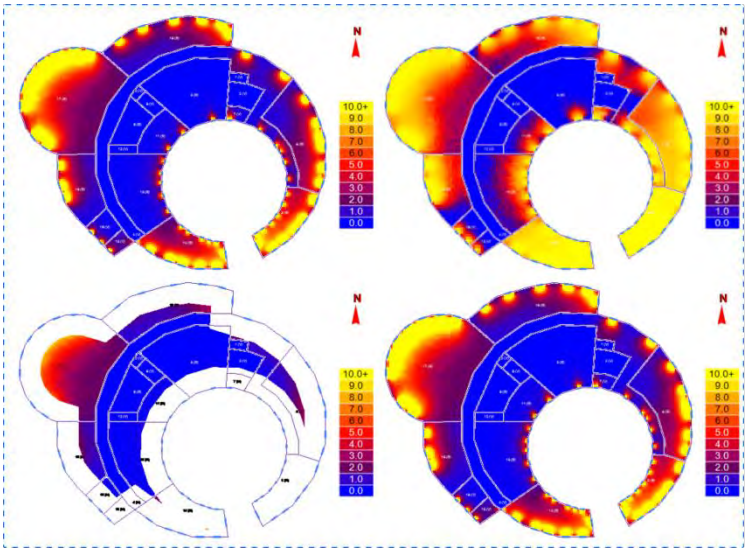
Automated Report Generation: It automatically generates detailed, traceable, and audit-compliant calculation reports for civil building energy efficiency, industrial building energy efficiency, and energy efficiency performance evaluation.

Room Matching Function: This function allows for quick extraction and matching of room data from drawings. It can also intelligently align room information across different professional modules, eliminating the need for repetitive parameter input.

Unified Model for Multiple Applications (Multi-Model Integration): The software facilitates rapid modeling of indoor and outdoor environments. A single model can be utilized across all functional modules—including energy efficiency, carbon emission analysis, ultra-low energy consumption simulation, and assessments for wind, daylight, acoustics, and thermal performance—without the need for redundant modeling efforts.

4.19.3 Example Simulation Project Results

Daylight simulation



One-Click Simulation: The software features an exclusive one-click function, enabling users to complete building daylight simulation analysis with just four mouse clicks—launch the software, load the model, initiate calculation, and generate reports. This streamlined process ensures zero operational barriers for users.

Professional Calculation Methods: It supports comprehensive and authoritative calculation methods, including window-to-floor area ratio, formula-based calculations, overcast sky steady-state simulations, annual 8,760-hour dynamic hourly analyses, and glare evaluation with visual field analysis. The software leverages multi-core parallel computing to ensure high computational efficiency.

Multi-Scheme Comparison: As a unique highlight, the software allows simultaneous simulation and comparison of multiple daylighting design schemes. This supports design optimization, component selection, and cost-effectiveness assessments by providing side-by-side performance metrics.

Automated Optimization Suggestions: When suboptimal indoor daylighting is detected, the software generates actionable optimization recommendations, offering designers clear guidance for improvements such as window adjustments or light-enhancing components.

Visualized Results & Automated Reporting: The software automatically produces intuitive visual outputs (e.g., daylight factor distribution, annual illuminance maps) and generates traceable, compliance-ready reports aligned with green building design and review standards.

4.19.4 PKPM References

[1] Beijing Glory PKPM Technology Co., Ltd., https://product.pkpm.cn/productDetails?productId=14, 2020.

[2] Beijing Glory PKPM Technology Co., Ltd., https://product.pkpm.cn/productDetails?productId=19, 2020.

4.20 Radiance

By David Geisler-Moroder (University of Innsbruck), Greg Ward (Anyhere Software), Taoning Wang (Lawrence Berkeley National Laboratory)

4.20.1 General Information

Radiance [1] is a physically-based cross-platform backward ray-tracing tool that is mainly used for lighting and daylighting simulation. Radiance development was started in 1985 by its principal author, Greg Ward, at Lawrence Berkeley National Laboratory (LBNL). Current source code of the official release, 6.0.2, may be downloaded from https://www.radiance-online.org, and the unofficial HEAD (alpha) release is also available. An associated Github site provides up-to-date, compiled packages for each of the major operating systems: Windows, Mac, and Linux [2].

4.20.2 Description of the Software

The rendering method is based on hybrid deterministic and stochastic (Monte Carlo) backwards ray tracing. Optimizations are designed to be consistent in all cases, meaning they converge to the correct answer, though they may not be completely free of estimation bias. Radiance simulation methods have been thoroughly validated through field measurements within the international research community. Architects and engineers rely on Radiance to predict accurately the light levels and appearance of space with various artificial lighting and daylighting concepts prior to construction. Researchers also use it to evaluate new lighting products. The software can be used in each stage of lighting design for daylighting and artificial lighting simulations. It allows the simulation of a wide variety of space geometries and lighting conditions.

Radiance was originally developed for electric lighting simulation. To this date, Radiance has many features to support the physically-accurate modeling of electric lighting using a **.ies* file that describes the luminous output distribution of a lighting fixture. Radiance also has the capability to model the flux transfer through luminaire to support luminaire designers. Radiance deploys efficient algorithms for multi-source and large-source sub-sampling, which enables designers to render large complex electrical lighting scenes while maintaining physical accuracy.

Daylight modeling development started in the late 80s and is being constantly expanded and improved. Simulations can be performed using different CIE skies (clear, uniform, overcast) or the Perez all weather sky model. With an additional plugin even the 15 new CIE skies are available. The Perez model is also the basis for annual daylight simulations based on measured climate data. The 3- and 5-phase methods allow users to efficiently perform annual daylight calculations even including complex daylighting systems that are characterized by their BSDFs. Evaluation tools that e.g., allow the calculation of glare indices such as the Guth VCP, UGR, DGI, or DGP complement the Radiance software toolkit. Radiance has been validated against the CIE 171:2006 “Test Cases to Assess the Accuracy of Lighting Computer Programs” [3,4].

More recently, hyperspectral simulation capabilities have been introduced, with full-spectrum solar and sky models computed using atmospheric absorption and scattering calculations. The latest version supports spectrally measured materials and glazings, and introduces efficient multi-band matrix calculations for efficient annual simulations for a new variety of applications such as melanopic stimulus and horticultural lighting.

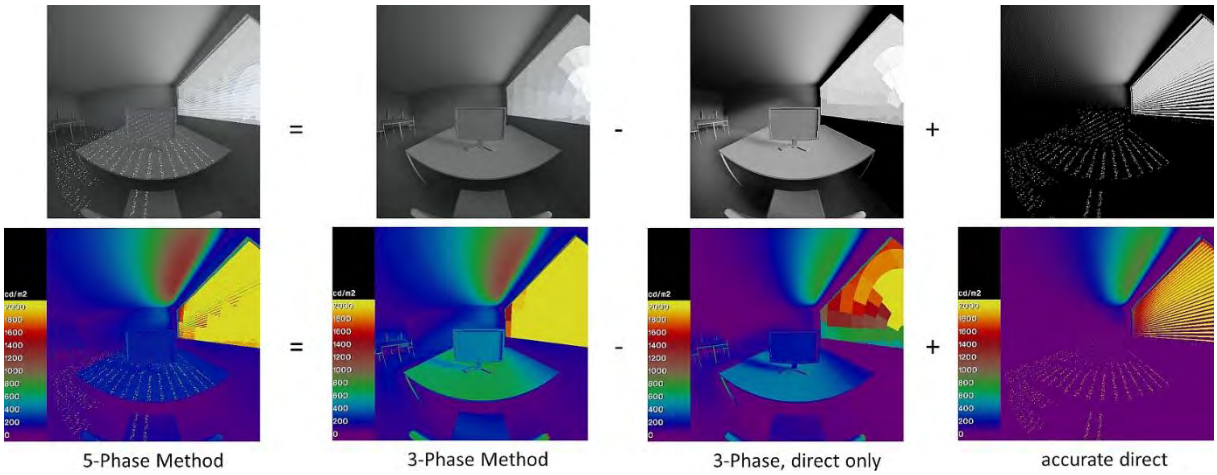
Radiance follows the Unix toolbox model, and consists of nearly 200 individual programs, including tools for modelling and translating scene geometry, luminaire data and material properties. It takes 3D geometric models as input to calculate physically correct results and high-quality renderings (luminance / illuminance values and images). False-color and isoline presentations simplify the understanding of the results. There are few limitations on geometry and materials, which can be defined based on built-in models or via data input based on measurements of color and bidirectional scattering distribution functions (BSDF).

As a simulation tool, Radiance does not include a 3D modeler. The geometry and material definitions must be provided as text files. While defining the geometry directly in Radiance can be challenging, there are many methods to import CAD geometry via converted files. 3D geometry can for example be imported with the obj2rad tool from .obj files produced by tools such as Rhino, exported from Sketchup with the su2rad plug-in or directly exported from Ecotect in .rad and .mat file formats. From .obj input, there is also a tool for compiling geometry into a native geometric mesh format that handles hundreds of millions of triangles in a modest memory footprint.

Radiance exports RGBE HDR images in the original HDR file format that can be converted to various image formats such as .bmp, .gif, .pict, .ppm, .ps or .tiff for external usage. The point grid calculation results of luminance and illuminance are exported in text format that can be further used in a spreadsheet for evaluations. The latest official release also supports a hyperspectral radiance (HSR) image format with a user-selected spectral range and sample count per pixel.

Advanced functions for Complex Fenestration Systems

To better account for specular reflections, Radiance does not only work with matrix based BSDF data but is also able to generate and use variable-resolution BSDFs. The 3- and 5-phase-methods allow users to efficiently perform annual daylight calculations even including complex daylighting systems that are characterized by their BSDFs.



Example simulation showing the single steps of the 5-Phase Method: 5-Phase Method result, 3-Phase Method result, direct solar contribution from 3-Phase Method, and high accurate direct solar contribution (from left to right).

Moreover, Radiance allows a combined usage of a system's BSDF and its geometry to provide an improved calculation of the direct sun contribution as well as a more realistic visualization.

BSDFs files that are described in the Window XML format can be imported for the ray-tracing simulations. Standard formats include Klems' full, half or quarter representation (145x145, 73x73 or 41x41 patches) and tensor tree variable resolution BSDFs, but all other discretization basis can be used if properly defined in the XML header.

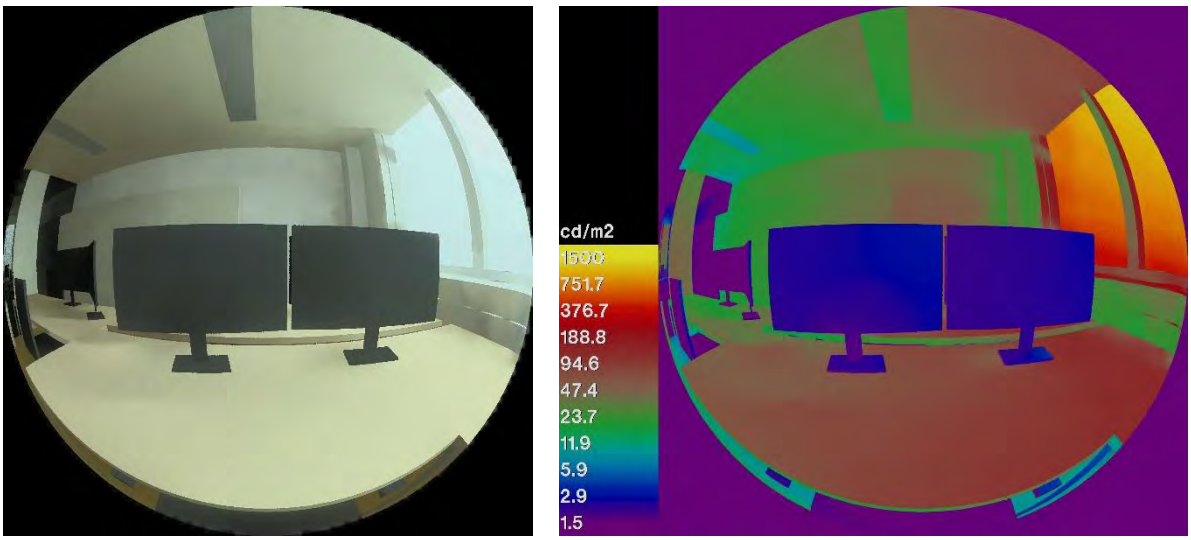
New C++ and Python APIs

The latest official release includes new C++ library APIs that cover all the important simulation and rendering capabilities in Radiance. *Pyradiance*, a Python interface, has been built atop of the C++ API, calling other Radiance command-line tools to facilitate new application designs. The *frads* system co-developed with *pyradiance* directly automates annual daylight simulations that are otherwise cumbersome to script using the default Radiance tools.

The *pyradiance* interface and *frads* are developed and maintained by Taoning Wang of LBNL. The C++ interface was created by Greg Ward under subcontract.

4.20.3 Example Simulation Software Results

Results for the reference rooms “Office” and “Hall” are included in the appendix. Here we show a hyperspectral rendering for one view inside the reference office room.



Hyperspectral rendering with Radiance for the reference office room under overcast sky conditions.

4.20.4 Radiance References

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[6] G. Ward, R. Mistrick, E.S. Lee, A. McNeil, J. Jonsson, “Simulating the Daylight Performance of Complex Fenestration Systems Using Bidirectional Scattering Distribution Functions within Radiance”, 2011.

4.21 RELUX

Adam Bladowski, Gdańsk University of Technology

4.21.1 General Information

Relux [1] is a professional, physically-based lighting design and simulation environment for electric lighting and daylighting. Development began in the early 1990s in Switzerland and has continued under Relux Informatik AG (Basel), which today distributes ReluxDesktop as a free planner's tool and maintains a broad ecosystem of manufacturer data, BIM plug-ins, and domain-specific extensions. Current installers and release notes (e.g., 2025.1.x) are available at relux.com; ReluxDesktop runs on Windows 10/11 (64-bit); macOS/Linux use requires virtualization and supports up-to-date workflows including IFC/gbXML import, GLDF/IES/EULUMDAT photometry, and Revit/AutoCAD integration via ReluxCAD. [1,2]

4.21.2 Description of the Software

Relux's computation core uses a hybrid approach that couples backward ray tracing for view-dependent effects and image synthesis with a radiosity-type solution for efficient diffuse interreflections. In daylight simulations, the sky hemisphere is evaluated through Radiance's indirect light process, while direct sun and electric sources are treated deterministically; quality presets expose the number of indirect bounces and sampling depth to trade accuracy for speed. This design lets Relux deliver fast point-by-point illuminance predictions and high-quality renderings in the same project, a balance valued by practitioners during iterative design. [1,3]

Relux has been validated against CIE 171:2006 "Test Cases to Assess the Accuracy of Lighting Computer Programs". Independent testing on ReluxDesktop 2019 reported agreement within the tolerances of the CIE suite across a wide set of electric-lighting and indoor daylight cases, supporting its use for compliance-oriented calculations and comparative studies. The validation report, methodology, and datasets are published and citable. [4,5]



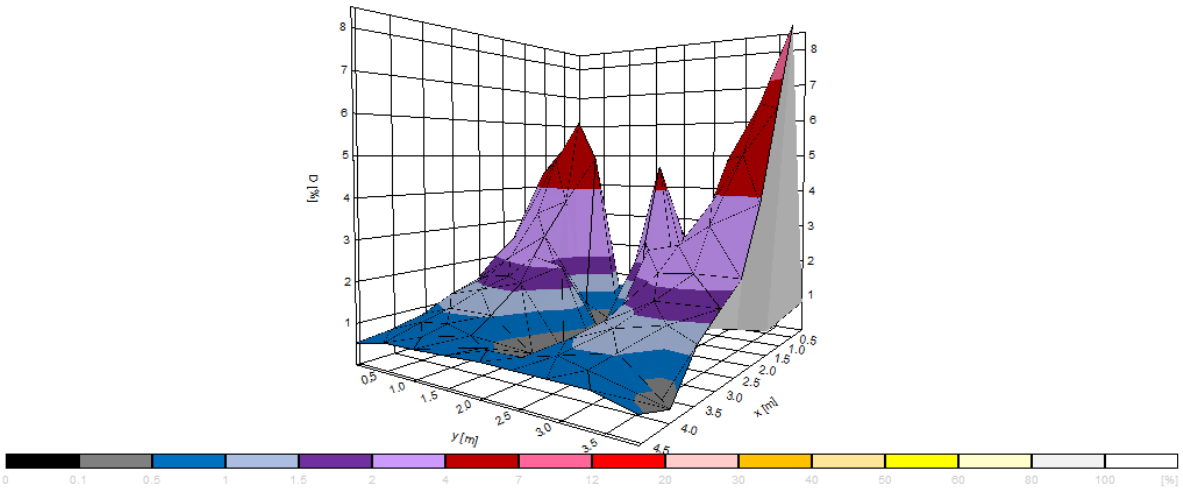
Relux was originally oriented toward electric lighting practice. It natively consumes manufacturer photometry (.ies, .ldt) and newer lighting data containers (IESXML, GLDF), enabling physically accurate luminous intensity distributions, lamp spectra/CCT metadata, and luminaire geometry to be used directly in calculations. Designers can lay out luminaires (arrays, along lines/paths), compute horizontal/vertical/cylindrical illuminance on user-

defined grids, and assess normative criteria such as UGR for discomfort glare at specified observer locations. Reports include summary statistics (Ē, Emin/Emax, uniformity), power density and energy indicators (e.g., LENI per EN 15193), and formatted luminaire schedules. [1,2]

Daylighting in Relux supports standard CIE sky models (overcast, clear, intermediate) and point-in-time sun–sky evaluations with location, date, and time control. Classical Daylight Factor (DF) workflows are provided for overcast reference conditions; for clear/intermediate skies, Relux predicts direct sun patches and diffuse sky contributions and outputs illuminance grids, false-color maps, and isolux plots. While Relux focuses on static and point-in-time daylight evaluations rather than fully climate-based annual metrics (sDA/ASE), its DF- and time-step-based results are widely used in integrated design workflows and energy estimates. In practice, many Task 61 workflows combine Relux's rapid point-in-time/DF analyses with broader, climate-based assessments where needed. [1,2]

For complex fenestration and shading, Relux supports explicit geometric modeling of systems such as venetian blinds, light shelves, and anidolic/louvered elements with appropriate material definitions (diffuse/specular). In mainstream practice, this covers a wide range of façade/shading concepts. For highly anisotropic optics, Relux supports geometric modeling and manufacturer-provided approximations; full arbitrary BSDF file import (e.g., XML/Klems, tensor trees) is generally handled in Radiance workflows. Nonetheless, Relux's hybrid engine and geometric modeling allow detailed qualitative and quantitative studies of redirected daylight in many real-world projects. [2]

Relux follows a GUI-centric workflow rather than a Unix-style toolbox. It reads BIM and CAD geometry via IFC and gbXML as well as DWG/DXF for 2D/3D content, helping transfer room boundaries, openings, and surface properties from architectural models. The ReluxCAD for Revit plug-in offers a bidirectional connection: spaces and materials move from Revit to Relux for calculation; luminaire selections, placements, and results synchronize back to the BIM. ReluxCAD for AutoCAD provides a similar bridge for DWG-centric projects. These integrations, alongside GLDF (a joint Relux–DIAL initiative), streamline data flow between manufacturers, BIM, and simulation. [1,2]



Relux provides multiple result modalities to support both engineering checks and communication:

- Tabular exports (including Excel for road/tunnel lighting results) and summaries for documentation and post-processing.
- False-color and isoline plots on plans/sections for immediate spatial comprehension.
- Ray-traced renderings and luminance false-color images for appearance and glare diagnostics.
- Glare evaluations via UGR at defined viewpoints.
- Report generation (PDF/RTF) compiling inputs, methods, and results for client deliverables.
- Since release 2024.1, ReluxDesktop integrates real-time rendering (via Enscape) for interactive visualization. [1,2]

In the context of integrated lighting (daylight + electric), IEA SHC Task 61 documents workflows in which Relux is used for luminaire design/placement, DF and point-in-time daylight checks, glare control (UGR), and energy/performance assessments aligned with European standards, often in tandem with BIM and controls engineering. These documented procedures, case studies, and practitioner personas illustrate how Relux's speed and manufacturer-linked libraries support iterative, standards-compliant design from early concept through detailed specification. [2,6,7]

Relux also offers domain-specific extensions (e.g., road/tunnel lighting, obtrusive light, energy certification for Swiss norms) that implement international and national standards in specialized workflows. While such modules are outside the scope of this short synthesis, they reflect Relux's emphasis on compliance-ready calculation and its close coupling to practice. [1]

File I/O and converters. Geometry import leverages IFC/gbXML/DWG; luminaire data via IES/EULUMDAT/IESXML/GLDF; outputs include images (PNG/JPG), tabular data (CSV/Excel), and full project reports. For inter-tool workflows, Relux's BIM plug-ins and adoption of GLDF are the primary bridges to other design platforms and manufacturer ecosystems. [1,2]

In sum, Relux combines a validated hybrid simulation core with BIM-aware, manufacturer-connected tooling. For researchers and designers, it offers fast, reliable point-by-point predictions, standards-aligned glare/DF workflows, and high-quality visualizations, making it a practical counterpart to climate-based and BSDF-centric toolchains when speed, interoperability, and product realism are paramount. [1,2,4]

4.21.3 RELUX References

[1] Relux Informatik AG (ReluxDesktop, ReluxCAD, company and product information), https://relux.com, 2025.

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[3] Relux Knowledge DB, ReluxDesktop – Daylight calculations (sky evaluated via Radiance's indirect process), 2023.

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4.22 Sefaira

Taoning Wang, LBNL (Lawrence Berkeley National Laboratory)

4.22.1 General Information

- Website: https://sefaira.com/
- Developer: Sefaira (Trimble)
- Platform: SketchUp and Revit plugins
- License: Commercial (subscription)
- Engines: Radiance, Daysim

Sefaira is building performance analysis software integrated into SketchUp and Revit, providing daylighting, energy, and thermal analysis.

4.22.2 Description of the Software

The software uses Radiance and Daysim simulation engines to calculate daylighting performance, with results presented through plugin interfaces.

Daylighting Analysis:
- Annual climate-based simulation (Daysim)
- Point-in-time analysis (Radiance)
- Ray-traced sensor-based calculations

Annual Metrics:
- Spatial Daylight Autonomy (sDA)
- Annual Sunlight Exposure (ASE)
- Percentage well-lit floor area
- Percentage overlit area
- LEED v4 daylighting credit metrics

Point-in-Time:
- Hourly illuminance calculations
- Daylight factor
- Direct sunlight analysis

Energy Analysis:
- Energy Use Intensity (EUI)
- Annual consumption by end-use
- HVAC load calculations
- Integration with daylighting results

Workflow:
- Modeling in SketchUp or Revit
- Parameter configuration through plugin
- Server-side calculation
- Results display in host application

Visualization:
- Performance dashboards
- Illuminance false-color maps
- Metric summaries
- Export capabilities

Target Users:
Architects, building designers, sustainability consultants.

Validation:
Based on Radiance and Daysim validation studies published in peer-reviewed literature.

Limitations:

- Platform-dependent (SketchUp or Revit)
- Advanced Radiance controls abstracted
- 5-Phase method support limited
- Spectral and circadian metrics not available
- Subscription-based pricing
- Less suited for detailed research applications

4.22.3 Sefaira References

[1] Sefaira, https://sefaira.com/

[2] Sefaira Daylighting Documentation, https://support.sefaira.com/

4.23 TRNSYS

Giovanni Ciampi, Michelangelo Scorpio, Sergio Sibilio, University of Campania, Italy

4.23.1 General information

TRNSYS [1, 2] is a highly flexible, graphically driven simulation environment designed for modeling transient systems. TRNSYS 18 is a dynamic simulation software widely used for modeling thermal and energy systems, with a strong focus on building performance analysis. It features a modular structure, allowing users to simulate multizone buildings, HVAC systems, renewable energy technologies, and control strategies. The core of TRNSYS is its transient system modeling approach, enabling accurate time-dependent simulations. The software consists of two main components:

- the Kernel (Simulation Engine) – This core computational unit reads and processes input files, solves system equations iteratively, checks for convergence, and plots system variables. Additionally, it includes built-in utilities for thermophysical property calculations, matrix operations, linear regressions, and data interpolation.
- the Component Library – TRNSYS provides an extensive modular library with over 150 pre-built models (called Type), covering a wide range of applications from HVAC systems, renewable energy technologies, and multizone buildings to wind turbines, electrolyzers, economic models, and weather data processors. Each component operates independently, allowing users to customize existing models or develop new ones, ensuring adaptability for cutting-edge research and engineering applications.

TRNSYS includes TRNSYS3D (a plugin for SketchUp™) that allows the user to draw multizone buildings and import the geometry (including building self-shading and internal view factors for radiation exchange) directly from the powerful SketchUp interface into the TRNSYS Building environment (TRNBuild).
A key component, Type 56, models the thermal behavior of buildings with detailed multizone configurations. TRNSYS 18 integrates TRNBuild for user-friendly building data input and Simulation Studio for visual project assembly. It also supports external tools like DaySIM [3, 4] and Radiance [5], enhancing daylight modeling and detailed energy analysis. The software is highly customizable, allowing users to create custom components and expand simulation capabilities.

4.23.2 Description of the Software

TRNSYS 18 [1, 2] integrates daylight and artificial lighting simulation through DaySIM [3, 4], enabling a combined assessment of thermal and daylighting performance within a multizone building model. DaySIM is a dynamic daylight simulation engine based on Radiance [5], capable of predicting illuminance levels, annual daylight availability, and glare indices. TRNSYS incorporates DaySIM by allowing the exchange of daylighting data with the building thermal model in Type 56 [6]. In TRNSYS, daylight modelling is integrated into the system, following a structured process to ensure accurate simulation results. In particular, the interaction between TRNSYS and DaySIM follows these 5 steps [2, 6]:

- Definition of Radiance materials. To begin, it is essential to define the optical properties of materials within the Radiance framework. For windows, parameters such as transmittance, reflectance, and absorption must be assigned to ensure realistic light interactions. Conversely, opaque surfaces require absorption coefficients, which TRNBuild can automatically assign to simplify the setup process.
- Daylight model setup in TRNBuild. Once the material properties are defined, the next step is configuring the daylight model within TRNBuild. The user specifies sensor points within each zone where daylight illuminance will be measured. Additionally, TRNBuild enables the definition of daylight-dependent lighting control strategies, allowing for dynamic adjustments of artificial lighting based on available natural light. To fully integrate daylight calculations, the daylight mode in each thermal zone must be activated.
- Generation of Radiance files (Figure 7). With the model set up, TRNSYS automatically generates Radiance input files (*.rad) representing the building geometry and its optical properties. These files serve as the foundation for daylight coefficient calculations, which detail how different parts of the sky contribute to the internal illuminance levels. At this stage it is possible to characterize the internal surfaces of the building, defining a corresponding Radiance material (*Figure 8*).
- Integration of daylight data in TRNSYS Simulations. During the TRNSYS simulation, the pre-calculated daylight coefficients are employed to compute real-time illuminance values for the specified sensor points. These values play a crucial role in adjusting internal gains, as artificial lighting can be regulated based on

daylight availability. A control algorithm determines whether artificial lighting is needed and, if so, how much should be used to maintain the desired illumination level.

- Daylight-based shading and comfort evaluation. Beyond lighting control, TRNSYS allows for dynamic shading adjustments based on daylight conditions. This feature reduces glare and overheating, enhancing visual and thermal comfort. The comfort model integrates daylight-related factors, ensuring a comprehensive analysis that balances the benefits of natural lighting with indoor thermal conditions.

This structured workflow ensures daylight simulation in TRNSYS accurately reflects real-world conditions, enhancing energy efficiency and occupant comfort.
In addition, TRNSYS offers two different methods to calculate daylight coefficients (Figure 7):

- Classic method. It calculates daylight coefficients for specific dates and times, making it suitable for predefined scenarios where lighting conditions do not vary significantly over time. This approach relies on predefined weather data corresponding to the selected location, ensuring simulations are based on real-world climate conditions. However, a key limitation of this method is that the computed coefficients remain fixed throughout the simulation. This means they cannot adapt to changes in building orientation, shading conditions, or seasonal variations, potentially reducing the accuracy of daylight predictions in dynamic environments.
- DDS (Daylight coefficient Dynamic System) method. This method is used for a more advanced and flexible approach and computes a comprehensive set of 2,305 daylight coefficients, evenly distributed across the sky dome. Unlike the Classic Method, the DDS approach is independent of building orientation and location, making it more adaptable to different shading scenarios, seasonal variations, and building configurations. While this method provides greater accuracy in daylight predictions, it comes at the cost of higher computational demand, requiring more processing power and storage capacity. However, the DDS method is a more reliable choice for projects where precise daylight performance analysis is essential.

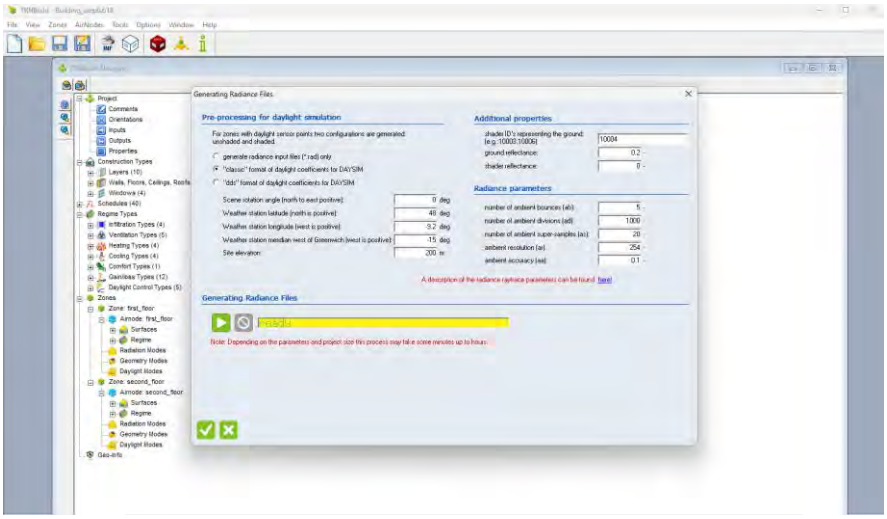


Figure 7: Generating radiance files in TRNBuild.

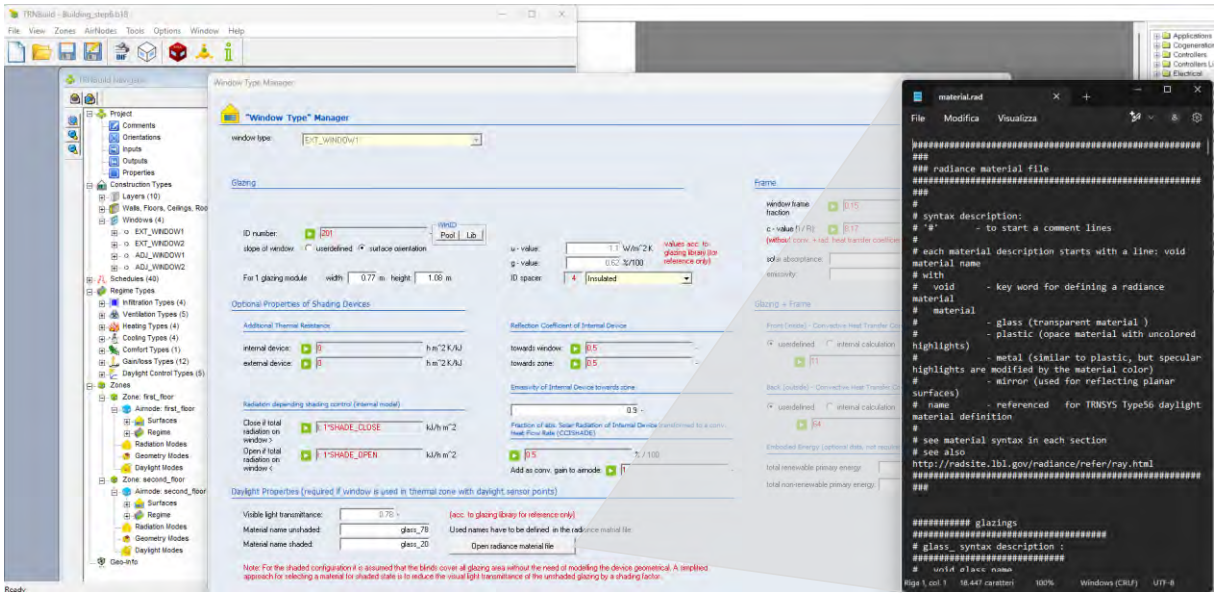


Figure 8: Radiance material files - "Window Type Manager".

Both methods serve distinct purposes, allowing users to balance computational efficiency and accuracy depending on the complexity of their daylight simulation needs.
During the simulation runtime, TRNSYS uses the real-time sky condition data from weather files (e.g., TMY) to update the illuminance levels at each sensor point.
TRNSYS 18 enables advanced artificial lighting control that interacts with the daylight model (Figure 9):

- sensor-based dimming: adjusts artificial lighting intensity based on the measured daylight illuminance;
- threshold-based ON/OFF control: lights turn on when daylight is below a predefined illuminance threshold;
- continuous dimming with OFF mode: artificial lighting can gradually dim when daylight is sufficient and turn off completely when unnecessary.

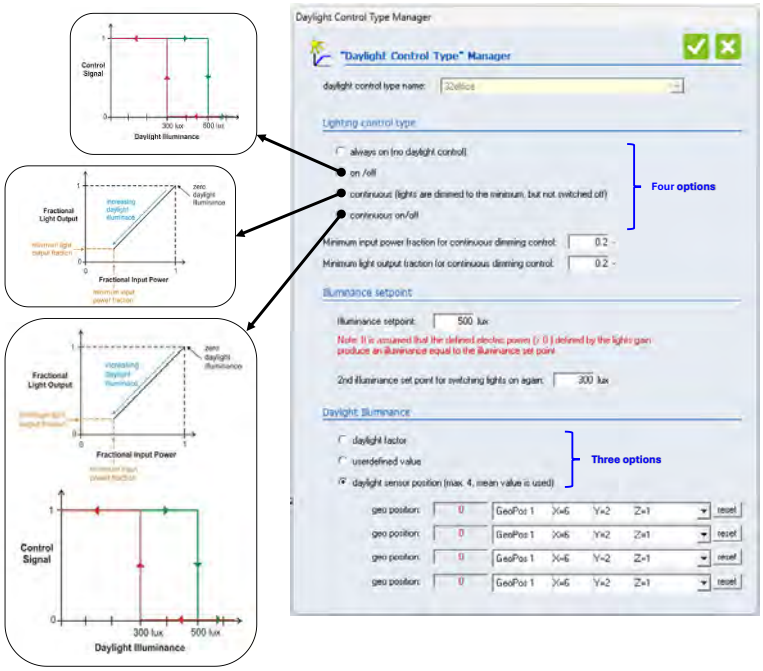


Figure 9: Artificial lighting control type.

TRNSYS calculates the energy demand for artificial lighting based on the chosen control method. It can also evaluate the impact of daylighting strategies on reducing lighting energy consumption.
TRNSYS integrates dynamic shading control to optimize thermal comfort and visual comfort. Two shading states are supported:

- Unshaded mode (shd0). Using this shading state, all movable shading devices (blinds, louvers, etc.) are open, allowing maximum daylight penetration.
- Shaded mode (shd1). In this case, all shading devices are closed and are usually used to reduce glare and solar heat gains.

In TRNSYS, users can choose between two different approaches for shading control (Figure 10), depending on the level of automation and customization required [6]. The selection is based on the project's specific needs, such as optimizing daylight utilization, reducing glare, and improving indoor thermal comfort.

- Basic shading control. It is usually used for a simplified and automated approach, and in this mode, shading devices (such as blinds or louvers) are activated automatically when daylight levels or glare exceed a predefined threshold. This threshold is set based on illuminance values (measured in lux) to ensure occupants are protected from excessive brightness while benefiting from natural light. Once the daylight level falls below the threshold, the shading devices are deactivated, allowing more natural light to enter. This method is particularly useful when consistent glare control is needed, such as in offices, classrooms, or residential areas with large windows. It helps maintain a comfortable indoor environment without requiring manual intervention.
- Custom control logic. It is usually used for more advanced and tailored shading strategies. This option allows shading devices to be controlled based on custom schedules, external inputs, or complex logic functions. For example, users can set different shading configurations depending on the time of day, season, occupancy patterns, or specific building automation system inputs. This approach is ideal for projects that require dynamic adaptation to varying lighting conditions, such as buildings with smart shading systems or adaptive façade technologies. Users can integrate external sensors (such as outdoor weather stations or room occupancy sensors) to fine-tune the shading response, ensuring optimal energy efficiency and occupant comfort.

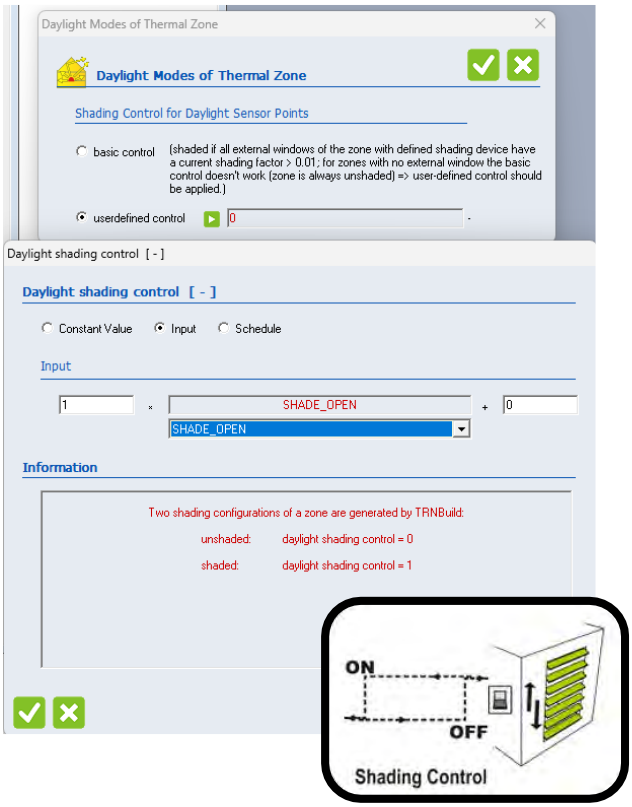


Figure 10: Daylight shading control type.

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In case the goal is simple daylight protection with minimal setup, Basic Shading Control is the most efficient option, while if the project requires more control over shading behaviour (e.g., integrating daylight optimization with HVAC systems or personalized user preferences), then Custom Control Logic is the better choice. By selecting the most appropriate shading control strategy, users can enhance visual comfort, reduce artificial lighting demand, and improve overall energy performance in their buildings.

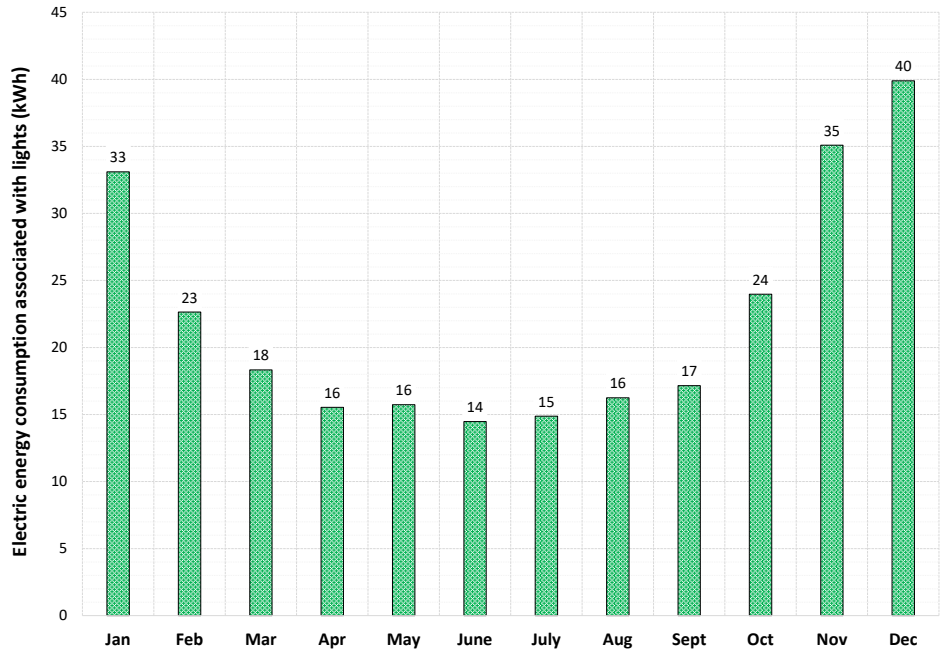
Low carbon, High Comfort Evaluation

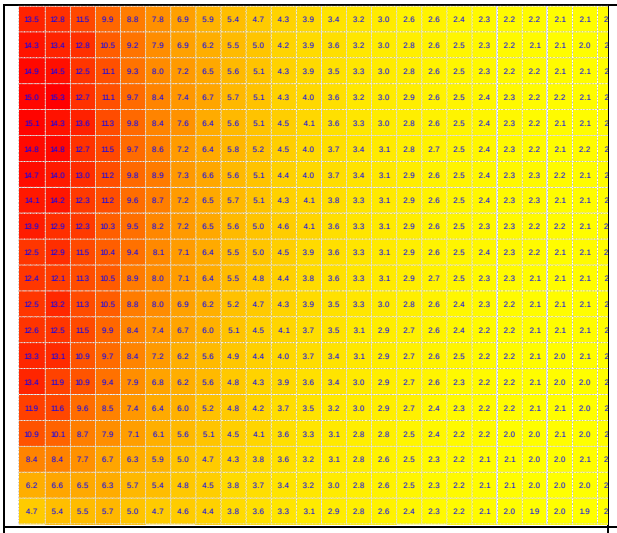
TRNSYS provides a powerful framework for evaluating low-carbon strategies while ensuring high occupant comfort through advanced daylight and artificial lighting modeling. By integrating DaySIM, TRNSYS enables dynamic daylight simulations, optimizing natural light utilization to reduce energy demand for artificial lighting.

The software adjusts artificial lighting levels through sensor-based daylight controls in response to real-time daylight availability, minimizing electricity consumption while maintaining visual comfort. Additionally, dynamic shading controls prevent glare and overheating, improving thermal comfort without excessive reliance on mechanical cooling.

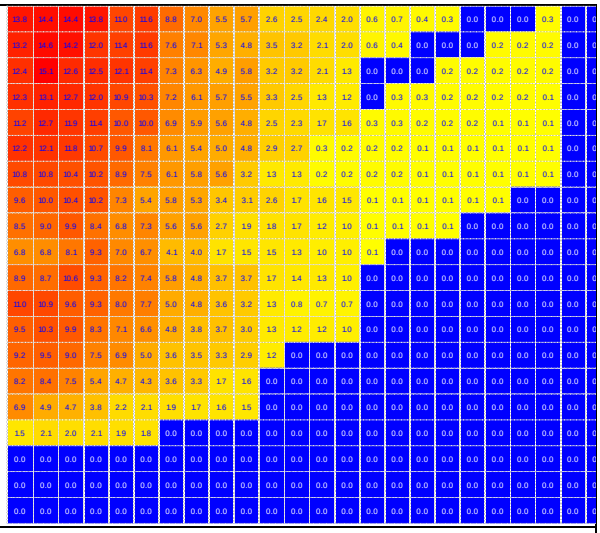
By coupling energy efficiency measures with human-centric lighting strategies, TRNSYS helps designers and engineers develop sustainable building solutions that lower carbon footprints while enhancing indoor environmental quality.

4.23.3 Example Simulation Project Results





Spatial distribution of Daylight Factor (DF [%])



Spatial distribution of Daylight Autonomy (DA [%])

4.23.4 TRNSYS References

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[6] M. Hiller et al., "Multizone Building Modeling with Type56 and TRNBuild," Trnsys 18.

4.24 Unreal Engine

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4.24.1 General information

Unlike static rendering software, game engines typically employ a mix of optimized lighting techniques, lower-resolution models, and textures, along with substantial pre-processing, to achieve such high frame rates. Consequently, while real-time rendering does not reach the same level of photorealism as static renders, advancements in GPU ray tracing are narrowing the gap in visual fidelity. Game engines can use a comprehensive software development ecosystem to interface with external data sources, APIs, and third-party software tools. This connectivity is crucial for facilitating research endeavors that necessitate the integration of various analytical tools or libraries, thereby enhancing the overall functionality and versatility of the development environment [1]. Unreal Engine [2] is one of the widely used real-time 3D creation tools available today. Developed by Epic Games, it was initially designed as a game engine but has since evolved into a versatile platform utilized across various industries, including film, architecture, simulation, and virtual production. Unreal Engine offers an extensive toolkit for game developers, enabling the design, simulation, and rendering of high-fidelity 3D content. It features a robust rendering engine that delivers cutting-edge graphics and a sophisticated physics engine to facilitate realistic interactions within the game environment. It also includes advanced sound processing capabilities and a versatile scripting framework that allows visual scripting with Blueprints and traditional C++ programming for game logic implementation. The engine is optimized for high levels of detail and supports complex animations, empowering developers to craft immersive and dynamically rich gaming experiences.

4.24.2 Description of the Software

Specifically for light, Unreal Engine offers high-fidelity rendering, real-time ray tracing, and advanced global illumination, making it ideal for photorealistic visualizations in architecture, film, and AAA gaming industries. Unreal provides also tools such as Lumen system and Lightmass, as well as lighting management software packages offering a wide array of parameters. Blueprint Visual Scripting allows designers and artists to create complex interactions without writing traditional code. Despite this, their deficiencies in providing targeted solutions for assessing photometric quantities indicate they are not yet fully equipped for direct application in lighting design.

Light Types

Unreal Engine offers diverse light types, enabling the configuration of various lighting scenarios suitable for both small and expansive environments. Each light type incorporates mobility settings that dictate its interaction with scene elements, influencing the performance and behavior of the lighting system.

For large exteriors or to provide lighting and shadowing through interior openings, can be used:

- Directional Lights are the primary outdoor light or any light that needs to appear as if casting light from extreme, or near infinite, distances;
- Sky Light captures the background of the scene and applies it to the Level's geometry.

For lighting smaller areas, the following options can be used:

- Point Lights act as a light bulb, casting light in all directions from a single point;
- Spot Lights emit light from a single point in a direction limited by a set of cones;
- Rect Lights emit light from a rectangular surface in a direction.

Lighting is defined using physically based units, enabling the input of known, measurable values for achieving accurate and realistic illumination. Various light types accommodate different lighting units, while the Post Process effect for Eye Adaptation (also known as Auto Exposure) further enhances realism in rendering. IES profiles for luminaires are supported. Specifically, light properties can be divided into different categories, such as Light, Light Profiles, Lightmass, or Light Function, for dozens of parameters. In addition to Unreal Engine's predefined Light Types, emissive Materials are an economical and efficient method to simulate glowing surfaces or light emissions. With the appropriate configurations, these Materials can function as genuine light sources,

illuminating the surrounding environment, or they can self-illuminate, enhancing visual fidelity without casting additional light into the scene [2].

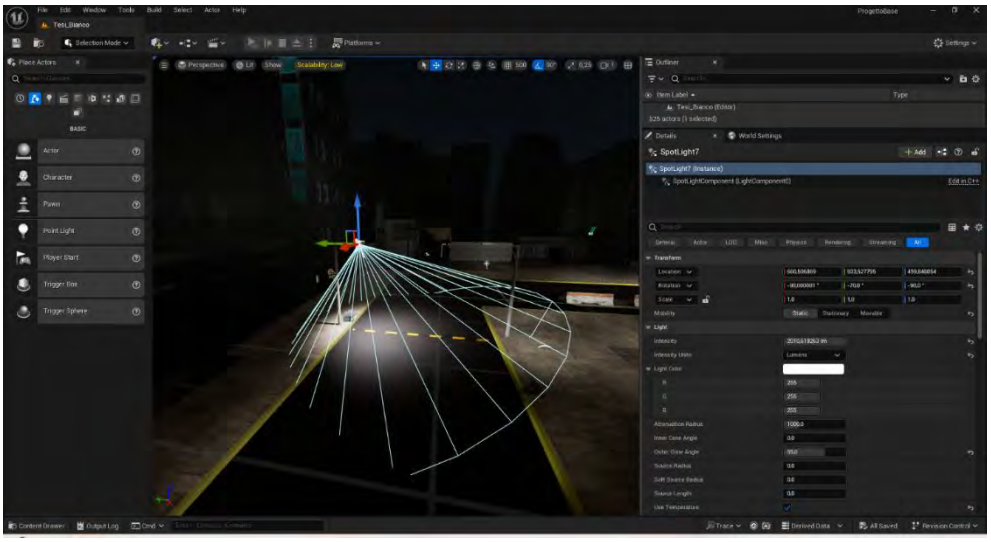


Figure 11: Spot light effects and some setting parameters.

Materials setting

Unreal Engine facilitates the specification of surface properties for objects within a scene using materials. Essentially acting as a "paint" for meshes, materials dictate the visual characteristics of surfaces and detail their interactions with light. They encompass various attributes, including color, reflectivity, roughness, and transparency.

Physically Based Rendering (PBR) is a methodology that mimics real-world light behavior. PBR-based materials yield a more accurate and visually authentic representation than traditional shading methods that rely predominantly on artistic intuition for parameter settings. These materials are defined by four primary attributes — Color, Roughness, Metallic, and Specular — that directly correlate with measurable physical properties, enhancing realism in rendered scenes.

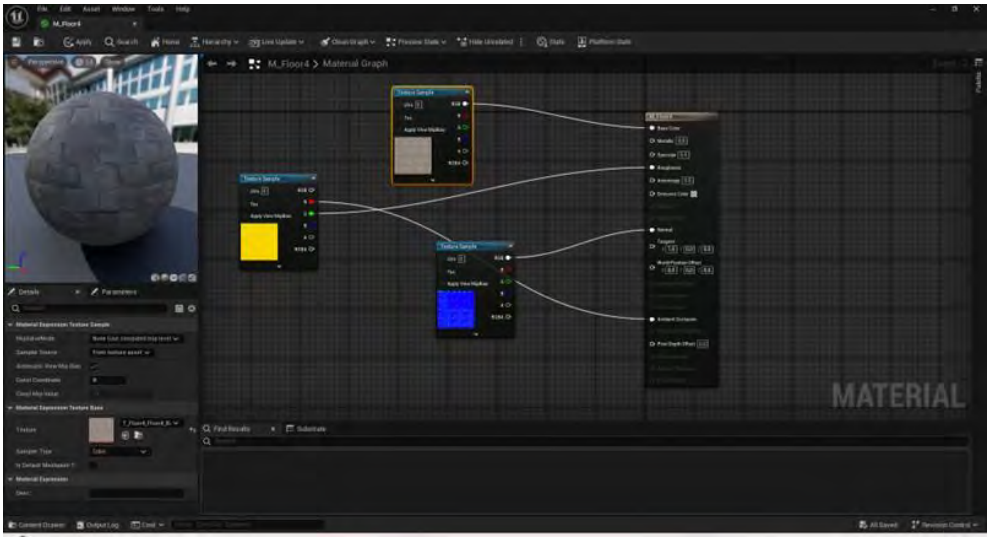


Figure 12: Materials attributes.

Lumen system and Lightmass

Lumen is the default global illumination and reflection system in Unreal Engine 5, engineered specifically for next-generation console performance. It facilitates fully dynamic lighting, utilizing advanced techniques for diffuse interreflection with infinite bounces and indirect specular reflections. Global illumination is a sophisticated rendering technique that models the complex interaction of light with surfaces and materials, ensuring realistic lighting and reflections in 3D scenes. The Lumen option leverages ray tracing methodologies to deliver precise simulations of indirect lighting. It captures diffuse interreflections with theoretically infinite bounces, as well as single and multiple specular reflections, resulting in a highly accurate and immersive visual experience. The primary ray tracing capabilities are integrated within the Lumen global illumination and reflections system, enabling the generation of high-fidelity images characterized by physically-based shadowing, ambient occlusion, reflections, and comprehensive global illumination effects.

Lightmass generates lightmaps, capturing light interactions such as area shadows and diffuse interreflections. It is specifically designed for precomputing the lighting contributions of stationary and static lights, allowing for enhanced realism in scenes by accurately representing complex light behavior.

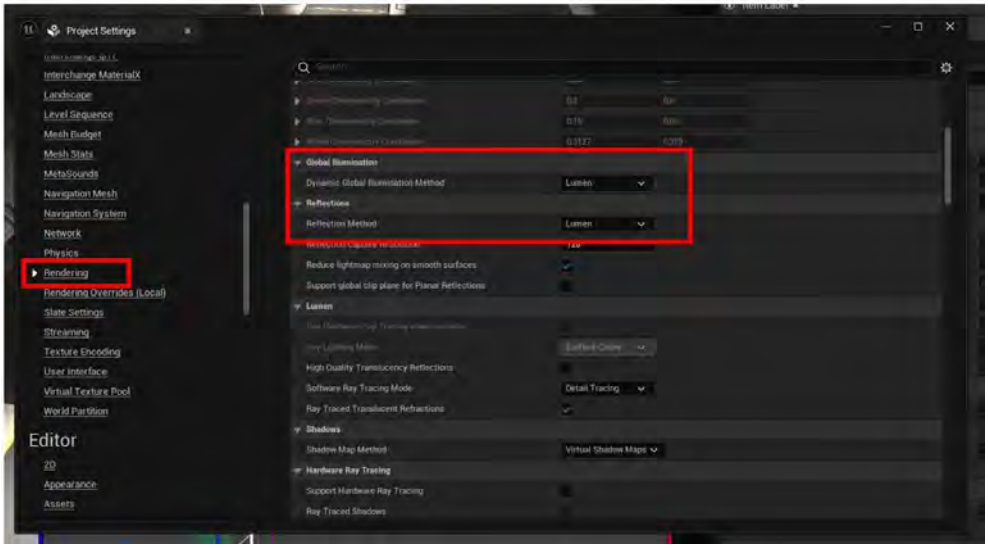


Figure 13: Lumen system for Global illumination and Reflection.

Low carbon, High Comfort Evaluation

The HDR histogram function enables quantification of the luminance values across the scene's surface. Illuminance values are also provided over the hemisphere of the surface patch, computed forcing to be a perfect white diffuse only surface. Luminance values can also be measured using the "pixel inspector" function (only in Unreal Engine 4).

Objective measurements in the head-mounted display can be performed to assess the quantity and quality of light reaching the user's eyes [3–5]. Subjective assessments can be used to investigate the perceived quality and comfort, as well as the lighting preferences of people [6].

VR can help reduce carbon emissions thanks to its ability to easily create accurate virtual spaces with different design solutions that are perceived as real and can be shared worldwide. Unreal Engine can be used to create virtual prototypes of vehicles, instead of constructing full-scale car models from clay, [7], installations [8] or stadium [9], helping in substantially minimizing the engineering costs associated with vehicle development, enhancing efficiency and reducing time-to-market while maintaining design precision.

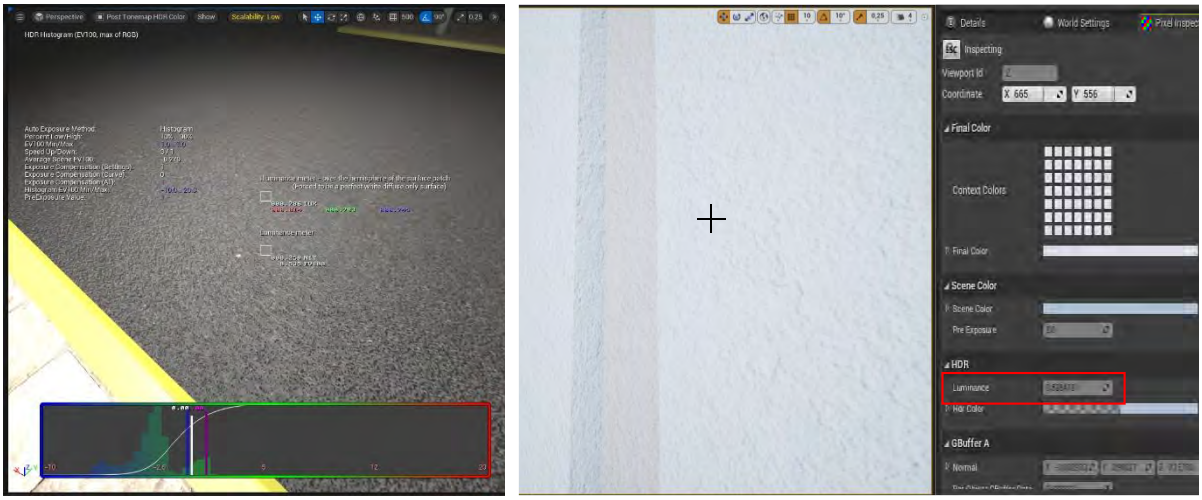
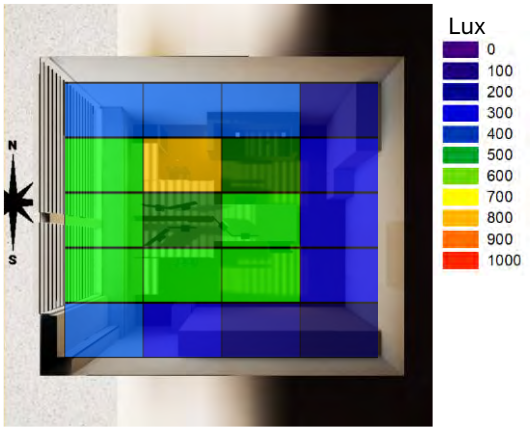


Figure 14: HDR histogram and pixel inspector (only for UE4) functions for luminance and illuminance measurement.

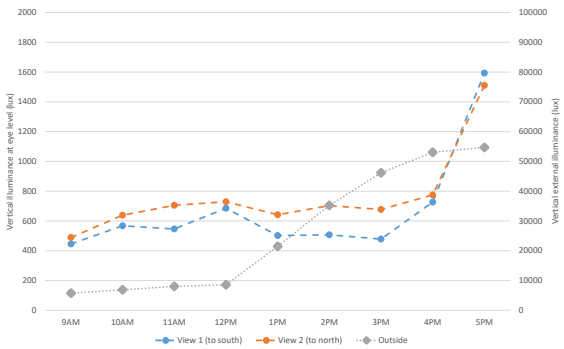
Validation

The proper setting of these parameters allows for creating a correct virtual environment from a photometrical point of view. The ability of Unreal Engine 4 in reproducing daylight [10,11] and electric light [12,13] was investigated using different approaches. The SunSky actor in Unreal Engine 4 reported deviation in simulating daylight of 126 % (in simple environment) and 162 % (in complex environment) using Light map approach, of 44 % (in simple environment), 30 % (in complex environment) using Ray-tracing bounce 3 approach, and 19.8 % (in simple environment), 15.8 % (in complex environment) using Ray-tracing bounce 7 approach [10]. Properly setting some parameters (Inner/Outer cone angle and Luminous flux) for spot light in Unreal Engine 4 can ensure an accurate luminance and illuminance distribution in the virtual environment, achieving percentage differences ranging from -6.1% to 6.7% (compared to a simple environment in DIALux evo) and from -5.0 % to 9.7 % (compared to a real complex environment) on horizontal surfaces [12]. Emissive surfaces coupled with IES files can also be used to ensure a correct light distribution and brightness perception in the virtual environment [13].

4.24.3 Example Simulation Project Results



Horizontal illuminance values (daylight + electric light)



Vertical daylight illuminance values

4.24.4 Unreal Engine References

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4.25 VELUX Daylight Visualizer

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4.25.1 General Information

VELUX Daylight Visualizer (DVIZ) is a dedicated daylight simulation tool aimed at supporting architects, designers, and engineers in evaluating daylight performance during early design phases. It predicts and documents daylight levels and visual appearance prior to construction, with an emphasis on intuitive modelling and accurate calculation methods.

Current version: VELUX Daylight Visualizer 3
Website / download site: http://viz.velux.com
License information: Free to use, distributed by VELUX A/S

4.25.2 Description of the Software

In DVIZ, the first step is to assign the optical properties of building materials. For transparent elements, such as glazing, users can specify visible light transmittance either via predefined products or custom user-defined glass types. For opaque surfaces, properties such as reflectance, specularity, and roughness can be set directly or imported from CAD models. These parameters ensure that daylight interactions within the space are represented realistically.

Once materials are defined, the user configures the daylight model. This involves creating or importing the geometry of the test space, inserting windows, and defining external obstructions. Sensor grids can then be specified at relevant positions (e.g., workplanes, floors, ceilings) where daylight metrics such as illuminance or daylight factor will be calculated. In climate-based simulations, hourly daylight availability is assessed using local EPW weather data.

DVIZ uses a daylight coefficient approach to compute the contribution of sky and sun patches to the illuminance levels at each sensor point. Users can select simulation modes such as still images, annual overviews, animations, or CBDM analyses. Render outputs can represent illuminance, luminance, or daylight factor, displayed through false-colour maps, ISO-contours, or numerical grid values. Advanced workflows allow the inclusion of BSDF data for complex fenestration systems, supporting evaluation of redirecting and scattering elements.

During annual simulations, DVIZ computes a range of climate-based daylight metrics, including Total Annual Illuminance (TAI), Daylight Autonomy (DA), Spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI), and Fraction of Sensor Area (FSA). These metrics are calculated for each sensor grid and provide detailed temporal and spatial insights into daylight sufficiency. Results can be exported for further analysis or directly compared with regulatory thresholds.

DVIZ allows users to model shading through simple overhangs, fins, or more advanced BSDF-based representations of blinds and redirecting systems. These can be evaluated in terms of their impact on daylight sufficiency and annual performance. While DVIZ does not compute glare indices (e.g., DGP), it provides luminance renderings and daylight sufficiency metrics that indirectly inform comfort assessments. In this way, the tool supports the integration of daylight-based design strategies aimed at improving visual comfort and reducing energy demand for electric lighting.

Features

- **Geometry creation:** simplified 3D modelling of rooms, walls, roofs, openings, and shading; insertion of VELUX window products; addition of furniture for scale.
- **3D Importer:** supports SketchUp (.skp), AutoCAD (.dwg/.dxf), and OBJ formats for complex models.
- **Material definition:** customisable surface reflectances, roughness, specularity, textures, and glazing transmittance.
- **Simulation outputs:**

- *Luminance* (cd/m²) for visual comfort and glare studies
- *Illuminance* (lux) for daylight availability
- *Daylight Factor* (%) under CIE Standard Overcast Sky
- *Climate-Based Daylight Modelling (CBDM)*: annual, hourly simulations using local climate data, accounting for orientation, direct sunlight, and variability in daylight conditions
- **Rendering modes:** still images, annual overview (12 snapshots per year), animations, and CBDM analyses.
- **Camera views:** plan, section, and perspective with flexible positioning.
- **Output options:** false-colour maps, contour plots, grid-based values, and average values for selected areas.

Target users: architects, lighting designers, engineers, and students engaged in daylight analysis

Low Carbon, High Comfort Evaluations

The software contributes to sustainable design by assessing daylight availability and reducing reliance on electric lighting, thereby supporting energy-efficient and low-carbon building strategies. Its outputs are directly relevant to lighting comfort, through evaluation of daylight factors, illuminance levels, and CBDM-based metrics for annual daylight sufficiency; to visual comfort, by assessing luminance distributions and exposure to direct sunlight; and to environmental impact, by enabling CBDM simulations that optimise passive daylighting strategies to reduce artificial lighting demand while improving comfort. Unlike some research-oriented tools, Daylight Visualizer does not compute non-visual (circadian) metrics such as melanopic EDI, but its combination of static (DF) and dynamic (CBDM) daylight metrics supports evidence-based, energy-conscious design aligned with IEA Task 70 objectives.

Validation

Daylight Visualizer 2 has been validated against **CIE 171:2006 – Test Cases to Assess the Accuracy of Lighting Computer Programs**, in collaboration with ENTPE (École Nationale des Travaux Publics de l'État, France). Reported results demonstrate:

- **Maximum error:** < 5.13 %
- **Average error:** < 1.29 %

These findings confirm its reliability compared to established reference test cases.

Recent validation studies confirm DVIZ's accuracy in CBDM:

- **CBDM validation (2024):** Extensive inter-model comparison with Radiance Four-Component Method (4CM) across residential and commercial case studies (Summer House, IT Factory). Agreement was typically within **±5% and never worse than ±10%**, establishing DVIZ as equivalent to Radiance-4CM for TAI, SDA, and FSA metrics.
- **BSDF validation (2024):** Evaluation of complex fenestration systems (double glazing and redirecting venetian blinds) against Radiance 3-Phase Method showed **comparable results**, though with systematic deviations depending on sensor grids. Best matches were found for direct transmission-dominated sensors, while underestimation occurred in cases with strong indirect contributions.
- **Light redirection validation:** DVIZ demonstrated capacity to simulate advanced systems (e.g. light shelves, blinds), with performance dependent on BSDF input quality.

These independent reports demonstrate that DVIZ is one of the few non-Radiance-based CBDM tools rigorously validated against Radiance reference methods.

4.25.3 Example Simulation Project Results

The software generates:

- Illuminance distribution maps and daylight factor analyses under CIE Standard Overcast Sky.
- CBDM outputs, (DA, sDA, UDI) based on annual climatic datasets, capturing direct sunlight, seasonal variability, and orientation effects.
- Luminance renderings, providing realistic impressions of daylight appearance in interiors.
- Annual animations and overview plots to illustrate daylight sufficiency and distribution.

Outputs can be expressed through false-colour images, ISO contour plots, or numerical grids, with the option of averaging across user-defined areas. These results allow comparative studies with other simulation environments such as Radiance or DAYSIM.

4.25.4 VELUX Daylight Visualizer References

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5 VR technologies potential in (day)lighting design

Over the years, with changing social habits, light has become a tool for influencing people's mood and performance, implicating the need to apply lighting solutions to meet regulatory requirements, as well as to satisfy the expectations and needs of occupants in the direction of human-centric design [1,2]. This change in perspective and use of light has led to the need to adapt the design tools and methodologies. Conventional methods, mainly based on objective assessments, cannot provide enough information about people's subjective responses to different lighting solutions. Researchers have explored more unconventional methods for evaluating design solutions, moving beyond traditional objective metrics such as illumination distribution, luminance, and glare levels to assess the subjective effects these designs have on user perceptions. In this scenario, virtual reality (VR) has emerged as a significant unconventional tool in various domains, mainly due to its capacity to provide immersive sensory experiences, especially in applications that encompass the analysis of complex and interrelated phenomena [3], as well as training [4]. Inspired by the vast potential of VR, academia has begun to explore its application in (day)lighting design [5,6]. Regardless of the VR systems' potential, as confirmed by research, several challenges persist, particularly concerning the technological constraints of the equipment. Key issues include the limited luminance achievable in head-mounted displays (HMD), restricted field of view, resolution capabilities, and the inherent characteristics of the optical systems employed. Simultaneously, the design of daylighting and electric lighting systems depends on the simulation of digital models of proposed architectural structures. An accurate assessment of light availability and variability is essential, as it is critical to building performance. This evaluation is strictly linked to energy consumption and low-carbon emissions, as well as plays a vital role in ensuring visual comfort and enhancing occupant well-being. Although the importance of energy consumption and the environmental impact of a design solution, there are currently only a few examples that timidly try to use VR for energy and environmental purposes.

VR platforms have undergone significant advancements, presenting various leading options that address various applications, including lighting design. Table 5.1 provides an overview of the main VR platforms and a comparative analysis, emphasizing their capabilities relevant to lighting design.

Table 5.1. Up-to-date HMD comparison and capability for lighting design

HMD	Resolution (pixel per eye)	Field of View	Refresh rate (Hz)	Weight (grams)	Main software working with	Affordability	Usability for lighting design
Oculus Quest 3 [7]	2064 x 2208	110° horiz. 96° vert.	72, 90, 120	515	Unity, Unreal Engine	Affordable	Beginners and prototyping
HTC Vive pro 2 [8]	2448 x 2448	120°	90, 120	-	Unreal, Enscape, Unity	Moderate	Lighting visualization
Valve Index [9]	1440 x 1600	About 140º	90, 120, 144	-	SteamVR, Unreal	Moderate	Interaction and rendering
PlayStation CUH-ZVR2 [10]	960 x 1080	100°	90, 120	600	Limited (PlayStation)	Affordable	Entry-level creative concepts
Varjo XR-4 [11]	3840 x 3744	120° horiz. 105° vert.	90		Unity, Unreal, VRED, Revit	Expensive	Enterprise-level photorealism
Apple Vision Pro [12]	23 million pixels (both eyes)	100° - 120°	90, 96,100	650	Unity, Unreal, proprietary Apple tools	Expensive	Lighting visualization photorealism

For lighting design, the choice of a VR platform depends on the intended application and budget. Varjo is ideal for high-end, photorealistic simulations, while Oculus and HTC Vive balance cost and capability effectively. Ease of setup and use is another essential aspect to consider, especially for professionals looking to adopt VR without extensive technical expertise. Platforms like Oculus are highly user-friendly, while high-end solutions like Varjo demand more resources and expertise for optimal use. Summarizing, for architectural lighting and detailed simulations, HTC Vive and Varjo offer superior capabilities. On the other hand, Oculus and PlayStation VR are more suitable for entry-level or creative concept visualization.

Regarding the software for VR, Table 5.1 shows that most of the HMDs are compatible with Unreal Engine and Unity. Unreal Engine offers high-fidelity rendering, real-time ray tracing, and advanced global illumination, making it ideal for photorealistic visualizations in industries like architecture, film, and AAA gaming. Unity, known for its user-friendly interface, excels in versatility and is widely used for mobile games, AR/VR, and interactive applications. Unreal's Lumen system and Lightmass provide superior lighting tools, while Unity's high-definition render pipeline (HDRP) adds realism with modular lighting setups. Table 5.2 lists the capabilities of Unreal Engine and Unity for lighting design deduced from technical data provided by the developer. Although the two lighting management software packages offer a wide array of parameters, their deficiencies in providing targeted solutions for assessing photometric quantities indicate they are not yet fully equipped for direct application in lighting design. In recent years, several new VR development tools have emerged, also based on Unreal Engine and Unity, aimed to deliver a streamlined user interface designed to enhance and simplify the overall user experience, catering to both developers and end-users [13–15].

Table 5.2. Unreal Engine and Unity capability for lighting design.

Parameter	Unreal Engine	Unity
Photometric Surface Properties	Supports detailed material properties (e.g., reflectance, roughness, and metallicity) using PBR	Supports surface reflectance, roughness, and emissive properties using PBR
Luminous Intensity Distribution	Supports IES profiles for luminaires, enabling realistic lighting simulations	Supports IES profiles, though setup can be more manual than in Unreal
Illuminance	Can visualize illuminance using lightmass heatmaps or custom tools	Requires third-party plugins or custom scripting
Luminance	Provides real-time luminance values using post-processing tools and ray tracing	Possible via HDRP with post-processing or plugins
Glare	Supports glare visualization via post-processing or lens effects	Requires custom tools or scripts for glare simulations

VR to support lighting solutions for high comfort and well-being

Specifically for daylighting and electric lighting design, VR represents a multipurpose tool that allows the creation of virtual lit environments with different levels of detail for different scopes and is an essential tool for assessing lighting systems from users' perspectives.

The research collectively reinforces that VR technology offers professionals and industries a valuable platform for visualizing and comparing various lighting schemes in architectural spaces, allowing informed, efficient, and cost-effective design decisions to satisfy specific project and client requirements [16,17]. The implementation of VR is increasingly relevant in lighting design, enabling the visualization of lighting schemes and their impact on space

from objective and subjective points of view by ensuring correct (il)luminance distributions and provoking perceptions similar to those in the real environment, respectively [5,6]. Previous research has mainly focused on evaluating the accuracy of simulating light propagation and recreating the sensory experiences felt by users in real environments. Rockcastle et al. [18] examined how people perceive illuminated spaces in VR. High dynamic range (HDR) images of a physical space under various lighting conditions were captured and shown to people using an HTC Vive Pro HMD. The results suggest that VR can effectively simulate real-world lighting for assessing subjective ratings of visual comfort, pleasantness, evenness, contrast, and glare in well-lit electric scenes. Sina et al. [19] examines the effects of biophilic design attributes, namely retail greenery and correlated color temperature (CCT), on consumers in 3D VR fashion retail environments. Outcomes underline the scarce number of studies using VR for retail lighting and provide information on the effects of greenery and CCT on consumers' responses and emotions. Zocchi et al. [20] utilized electroencephalography (EEG) to explore neuronal responses to variations in light perception between physical and virtual environments. Results indicated a strong correlation for waves linked with arousal, while different behavior for waves linked to valence.

The lighting industry started to use VR, creating virtual lit environments to encourage customers to approach lighting design and facilitate the transfer of the design idea to the final users. Performance in lighting [21] uses VR to facilitate users' approach to lighting design, allowing them to see the various lighting solutions in an immersive environment. Signify [22] take advantage of VR to enable customers to evaluate and interact with lighting solutions before purchase, facilitating a more informed buying decision. Zumtobel provides an online platform called "Mobile VR", which allows users to experience various lighting scenarios using a smartphone [23].The Lighting Practice [24] relies heavily on VR technology to explain their work and the effects of their lighting design solutions. For example, they refer to the choice of materials in the design process. For the project Brighter Brunnshög, VR was used to support the design of the light installations [25,26]. Comparing the small number of examples reported above with the significant number of lighting companies in Europe [27], it becomes clear how little widespread is the use of VR for lighting.

Summarizing, VR can support the design of lighting solutions for high-comfort and well-being by:

- Encouraging healthier building design: immersion into the planned building to test comfort ahead;
- Favoring detailed subjective analysis: subjective responses are a crucial aspect to consider in human-centered design aimed to guarantee visual comfort and well-being;
- Taking advantage of participatory project/design planning: the possibility of showing and collaborating with the community/client from the beginning of the project fosters people's acceptance and satisfaction.

VR to support low-carbon lighting solutions

Climate change related to anthropogenic activities is one of the foremost global threats. Reducing carbon emissions is the only way to mitigate its devasting effects on humans and nature, calling for efforts to minimize polluting sources and adopt virtuous behaviors [28]. Energy consumption for lighting in buildings accounts for more than 30% [29,30], highlighting the importance of the correct choice of components, suitable design, and education on properly using lighting systems to reduce carbon emissions. In the last few years, VR has also found application in promoting choices and conscious design aimed at adopting low-energy and environmental impact solutions. VR can help reduce carbon emissions thanks to its ability to easily create accurate virtual spaces with different design solutions that are perceived as real and can be shared worldwide. The implications of integrating VR technology into the interior design process with a specific focus on its effects on carbon emissions were explored in [31]. The authors argued the potentiality of VR to involve the clients in the design process and the possibility of using electricity from renewable energy sources to reduce carbon emissions linked to the VR system. Others explore using VR as an educational tool to induce eco-sustainable behavior [32]. Compared with other solutions, VR can influence future behavior and decisions, allowing the visualization of long-term effects and tangible images, as well as the presentation, evaluation, and testing of planned actions with users. VR can also support product development and optimization of the production process [33] and project progress. Luo H. [34] developed a VR game to educate people about carbon emissions and the protection of the environment, as well as to encourage people to follow sustainable practices. As an example, BMW has adopted Unreal Engine to create virtual prototypes of its vehicles instead of constructing full-scale car models from clay, which necessitated considerable time and resources for adjustments across multiple iterations, streamlining the design process significantly. The introduction of virtual prototyping enables designers to make rapid modifications within minutes, facilitating quicker approvals within days. This shift has substantially minimized the engineering costs associated with vehicle development, enhancing efficiency and reducing time-to-market while maintaining design precision [35]. Rueda and her team leverage VR in the design and creation of their installation "Nebula Shroom Grove",

employing a sustainable approach that minimizes material usage, time, and energy consumption [36]. During the initial concept phase, VR facilitated the visualization of the design and allowed for the assessment of scale in an immersive environment. Discrepancies between the VR visualizations and the original renders emerged early in the process, prompting the use of advanced modelling software such as Rhino, Twinmotion, and Unreal Engine. This iterative design process enabled the team to refine the visual and structural aspects of the installation, ensuring both aesthetic intentions and structural requirements. The digital environment streamlined the execution of repetitive modifications and provided the digital documentation required for constructing the 32 individual structures composing the installation, a task that would have been impractical with manual adjustments. Zaha Hadid Architects [37] used VR to evaluate the pitch aspect ratio for every seat and the sunlight reaching seated people before the construction of the Xi'an International Football Center. Using VR, the design team was able to test the FOV of the fans and the effectiveness of the roofing systems in providing natural light while protecting against overheating from sunlight. Once more, every component was represented in the engine, allowing the team to assist stakeholders in assessing the design's accuracy while incorporating all necessary details for the project, resulting in energy, materials and time savings. The International Energy Agency (IEA) brings together international experts and stakeholders in its projects to network science and practice around topics of energy efficiency, sustainability and climate neutrality. In the IEA SHC Task 70 / EBC Annex 90 "Low Carbon, High Comfort Integrated Lighting" [38]; the topic of VR and its applicability in lighting design is one of the topics being investigated at the interface between research and application.

Specifically for daylighting and lighting, VR would help to reduce carbon emissions by:

- Design optimization: visualize daylighting (sunlight exposure, daylight availability, glare) and electric lighting solutions (light distribution, contrast);
- Energy management training: compare scenarios with different energy-efficient practices and show their impact on carbon footprint to the building operators and facility managers;
- Occupant engagement and education: educate building occupants about sustainable practices and energy-saving behavior engagingly and interactively;
- Virtual prototyping: model and test product functionality, performance, and characteristics for (day)lighting before physical prototyping.

5.1 International survey on professionals' expectations for VR

Despite academic efforts and achievements in demonstrating the possibilities and limitations of VR for lighting, as well as proposing methods to simulate the behavior of light in VR as closely as possible to the physical world, there remains a significant gap in translating this theoretical knowledge into practical applications within the professional domain.

To the best of the authors' knowledge, there has been a lack of research examining the integration of VR technologies within the field of lighting design. Specifically, there is a notable absence of studies investigating the adoption levels of VR among lighting designers, as well as their experiences regarding the utilization, perceived advantages, and challenges encountered when incorporating VR into their professional workflows.

At the same time, the few examples of companies/practitioners using VR specifically for lighting purposes indicate a disconnection between VR technology's capability and its usability or appeal to professionals, accentuated by a notable lack of software documentation. Lack due to the fact that VR software is not specifically tailored for lighting design, so manuals are often lacking or insufficiently detailed. This oversight means that designers may encounter challenges when effectively integrating lighting elements into their VR environments, as the guidance provided may not fully address the complexities and considerations essential for optimal lighting design.

Therefore, the true potential of VR technologies for professional planning activities in the field of (day)lighting solutions should be thoroughly investigated. In this scenario, the research activities of the International Energy Agency (IEA) Solar Heating-Cooling (SHC) program Task 70/ Energy in Buildings and Communities (EBC) program Annex 90 ''Low Carbon, High Comfort Integrated Lighting" – Subtask C4 ''Simulation methods for integrative lighting design and VR possibilities" [38] aim to demonstrate the potential of VR technologies in (day)lighting design, specifically focusing on the transfer from research to practice.

With the aim to pinpoint the usage and potential of VR among lighting professionals, identifying the challenges they face and the benefits they perceive, an international online survey was prepared and shared among professionals using VR. For the purposes of this study, we define professionals as individuals actively engaged in lighting research and design, such as architecture, lighting design, interior design, landscape design, urbanism

and real estate. The complete documentation and analysis of the survey, as well as a comparison with the academic literature, are presented in [39].

The survey was structured into four sections to capture comprehensive insights into the use and implications of virtual reality in advanced lighting design.

- **Section I:** “Demographics and General VR Use” aimed at gathering baseline demographic information and general usage patterns of VR among respondents.
- **Section II:** “VR Application in Practice” delved into the specific applications of VR in professional settings, focusing on its utility and adoption in lighting design projects.
- **Section III:** “Complexity of VR Experiences”, explored the depth and complexity of VR implementations, seeking to understand how these technologies are used to meet professional needs.
- **Section IV:** “Lighting in VR” specifically addressed the integration and simulation of lighting within VR environments, targeting insights into how lighting design is represented and tested within virtual spaces.

The survey included 30 questions of various types to ensure depth and nuance in responses, including multiple-choice and single-choice questions, Likert scales (ranging from 1 to 6), and open-ended questions. The entire questionnaire is reported in Appendix B.

5.1.1 Objectives

The survey is strategically designed to uncover and bridge the gap between academic research and professional practice within the realm of lighting design, with a specific focus on the use and potential of VR and AR technologies. It aims to delve into the sophisticated applications and expectations surrounding VR/AR in lighting design. By identifying the commonalities and differences in how VR/AR is utilized and valued across different activity domains, the survey aspires to pinpoint why VR/AR technologies may not be as widely adopted in professional day and electric lighting design as expected.

The ultimate objective is to leverage these insights to propose targeted research and development initiatives to address the identified barriers to adoption. By understanding the specific challenges, misconceptions, or knowledge gaps that hinder the embrace of VR/AR by lighting professionals, the survey seeks to formulate actionable strategies that can facilitate the wider acceptance and utilization of these digital tools. In doing so, it hopes to foster a more seamless integration of low-carbon, user-centric lighting solutions that capitalize on the advancements in digital design technologies, thereby closing the gap between academic innovation and professional application in lighting design.

The primary respondents targeted through this survey were professionals actively engaged in the lighting field, with a particular emphasis on those specializing in daylighting solutions. This focus aimed to capture expert insights into the practical applications and challenges of integrating VR technologies in advanced lighting design.

The survey was distributed via social media channels (primarily LinkedIN) and during the IEA SHC Task 70 / EBC Annex 90 workshops among a professional network comprising individuals and groups actively involved in the Task with the request to further distribute it in their professional surroundings to reach the intended audience. This approach ensured that the survey reached professionals with relevant expertise and interest in integrating digital technologies in lighting design, thereby maximizing the relevance and impact of the gathered data.

5.1.2 Results from the international survey

Demographics and General VR Use

The responses to the online survey were collected from August to December 2023. We received 57 responses, 44 from professionals (77%) and 13 from working students (23%). This distribution highlights the presence of VR technology across different career stages among lighting experts. The diversity in nationalities, with 31 countries represented, can be attributed to the survey’s distribution through IEA SHC Task 70 / EBC Annex 90 participants and various social platforms. The survey specifically targeted professionals with academic or commercial backgrounds who have an interest in VR applications within lighting design or working with them.

However, the number of responses may reflect the limited adoption of VR in professional lighting design practice. This challenge in recruiting participants stems from VR technology still being in its early stages of integration within the field. Respondents predominantly came from the public sector (58%), including researchers (16%),

while 33% came from the private sector, and 9% were self-employed. This distribution highlights the interest in VR technologies across diverse organizational settings. As expected, since the survey was distributed among lighting professionals, the lighting domain emerged as the most common professional focus, followed by architecture, urban planning, and research, indicating a strong link between VR applications and spatial design professions. The users' work experience levels varied widely, with a notable presence of veterans (more than 20 years of experience), suggesting that seasoned professionals are keenly exploring VR's potential alongside newcomers to the field. The relationship among the nature of the company, the activity domain, and the proficiency in using VR is displayed in Figure 5.1.

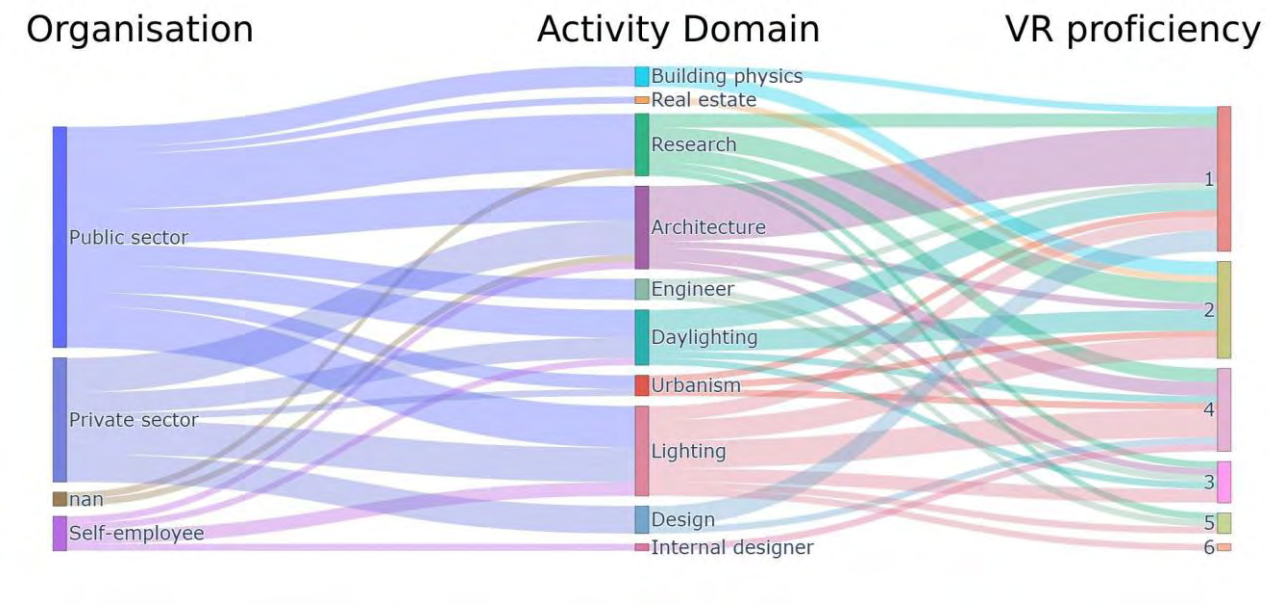
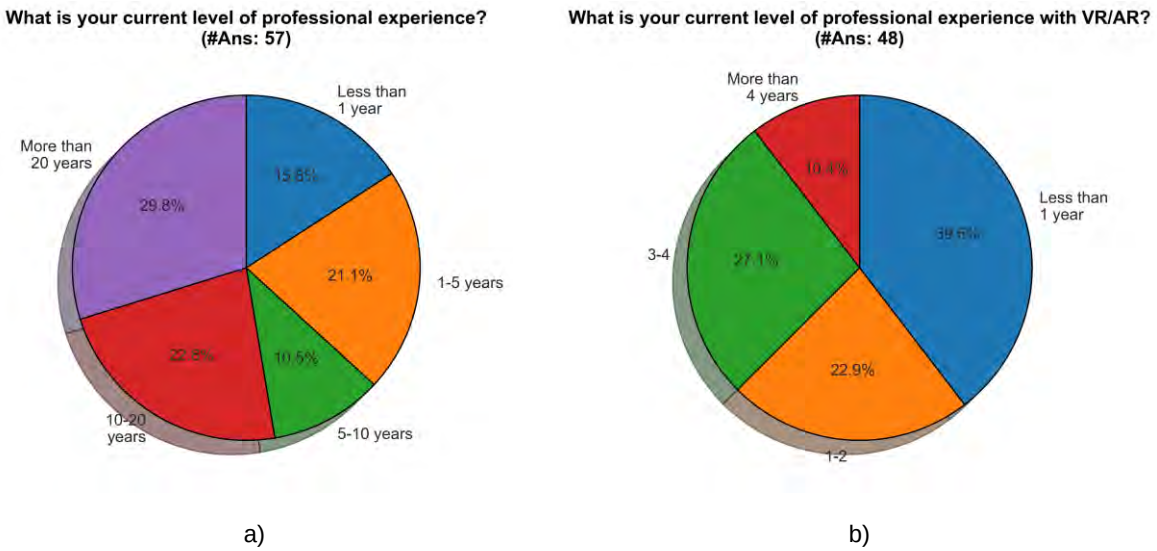


Figure 5.1. Sankey diagram of the relationship among the company, activity domain, and proficiency (1 - novice, 6 - expert) in VR.

The age distribution of the respondents, with 23% up to 30 years, 33% between 31 and 40, 26% between 41 and 50, and 18% at age 51 or above, reflects a typical distribution of professionals working in the lighting domain [40].

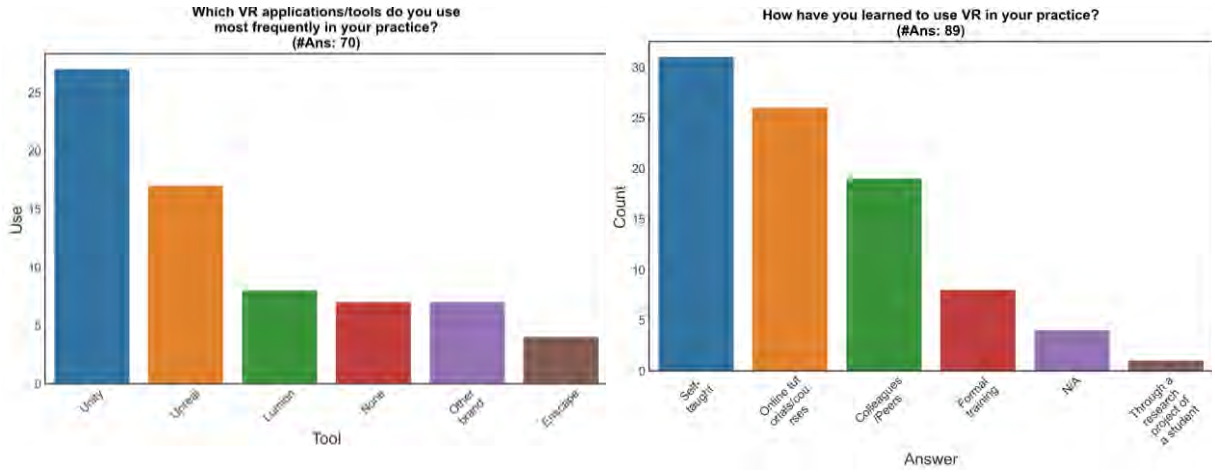
Figure 5.2a shows the distribution of the participants' level of professional experience, showing the coverage of a wide range of people with different experiences. Nearly 83% of respondents are familiar with VR/AR technologies, reflecting their growing penetration in professional fields. Most respondents have less than one year of experience with VR/AR technologies (40%), indicating an increasing interest and recent adoption among professionals. It is followed by those with 1-2 years (23%) of experience, 3-4 years (27%), and more than 4 years (10%), showcasing a range of familiarity levels within the community. Figure 5.2b shows the relation between professional expertise and VR/AR experience.

Figure 5.3a underlines Unity (46% of respondents) and Unreal Engine (28% of respondents) as the most used VR tools, while Figure 5.3b demonstrates the most popular methods of learning VR tools in practice. In particular, the results highlight that self-taught (54% of respondents), online tutorials/courses (46% of respondents), and colleagues/peers (33% of respondents) are much less used than formal courses (14% of respondents). Multiple answers were possible for these two questions.



a) b)

Figure 5.2. Demographics and general VR use results: a) level of professional experience and b) level of professional experience with VR/AR. The difference in the number of answers in the two graphs is due to the fact that 9 people learnt or acknowledged VR but did not use VR in practice.



a) b)

Figure 5.3. a) Used VR tools and b) how VR was learned.

VR Application in Practice

The second section of the survey was prepared to identify the usage frequency of VR, the preferred tools and applications, and the primary purposes of using VR in professional work.

Results indicate that the frequency of VR usage among those who have adopted the technology in practice varies. It is generally low, with nearly half of the respondents using it rarely (46%) or never (24%), 14% use VR monthly, while only 8% use it weekly or daily. This suggests that while VR technology is being explored, its integration into regular practice is still evolving.

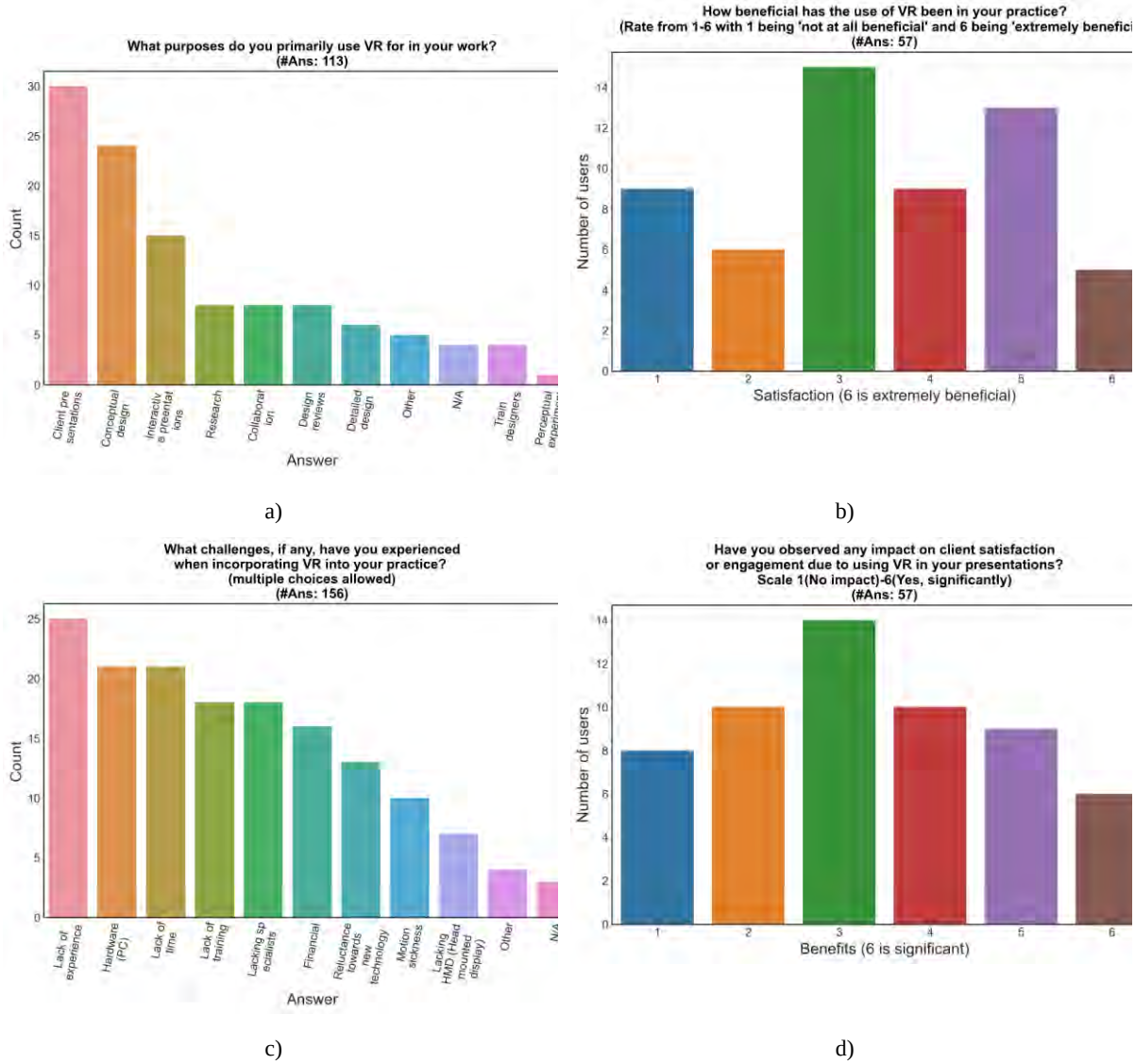
Figure 5.4a shows that VR is primarily used for underlining the “Client presentation” (53% of respondents), the “Conceptual design” (42% of respondents), and the “Interactive presentation” (26% of respondents).

Figure 5.4b exhibits the perceived benefit of using VR in practice (rate from 1 being “not at all beneficial” to 6 being “extremely beneficial”), which is evaluated on average neutral, mean value (M) = 3.46 and standard deviation (SD) = 1.56.

Figure 5.4c displays the challenges professionals face in incorporating VR into their practice. The challenge can be mainly divided into three groups: learning (lack of experience, training, and specialists), technological (hardware and lack of HMD), and resources (time and financial). A not neglectable number of participants point at “Reluctance towards new technologies” and “Motion sickness”.

Figure 5.4d displays the perceived impact on client satisfaction or engagement due to using VR (rate from 1 being “No impact” to 6 being “Yes, significantly”). The results suggest a nearly neutral impact of VR (M = 3.35, SD = 1.55)

When asked if VR technology will become a standard tool in architectural design, participants are mainly divided between “Yes, I believe” (54%) and “Unsure” (37%).



a) b)

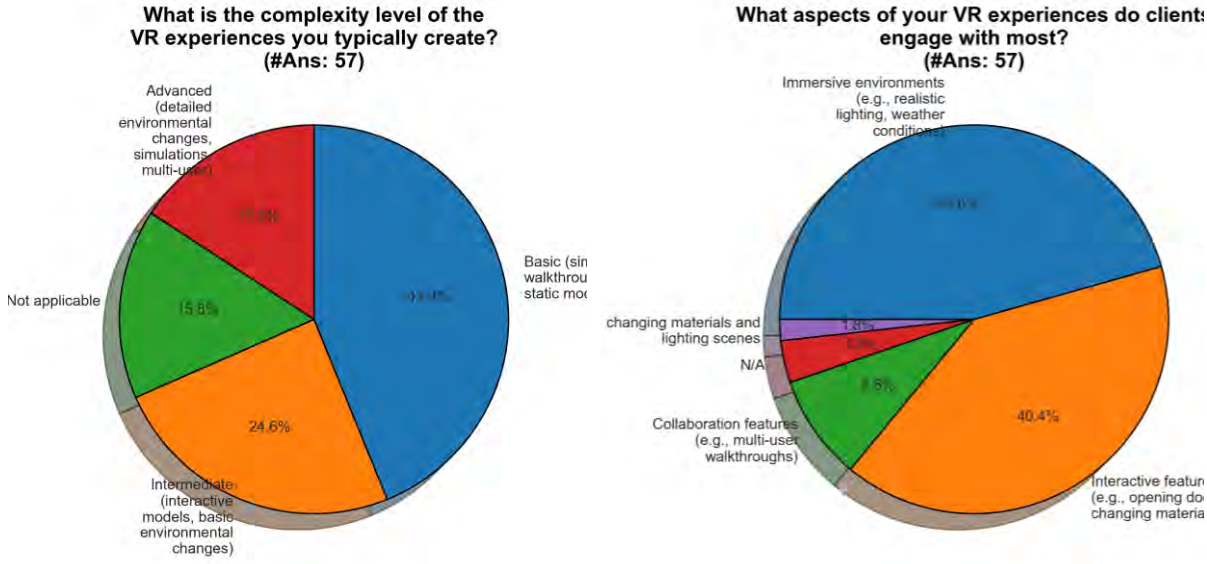
c) d)

Figure 5.4. Results for questions about VR application in practice: a) main purposes the VR is used for, b) perceived benefit of using VR in practice, c) challenges faced in incorporating VR in practice, and d) perceived client satisfaction. For questions (a) and (c), multi-answers were possible.

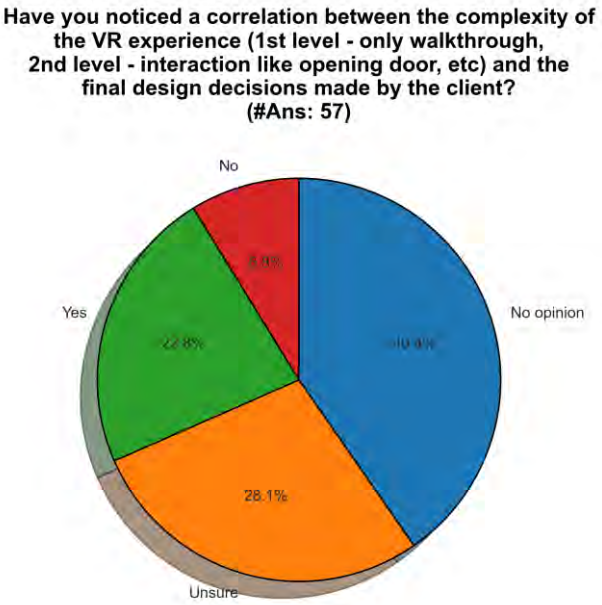
Complexity of VR Experiences

This section investigated the breadth and complexity of VR applications to comprehend how these tools are used to fulfil professional demands. As illustrated in Figure 5.5a, most projects created are basic (47%), such as static models or simple walkthroughs, while only 14% of the projects are advanced (detailed environment changes, simulations, or multi-user). Results suggest that clients are engaged mainly with immersive environments

characterized by realistic lighting or weather conditions (46%) and interactive features characterized by opening doors or changing materials (40%) (Figure 5.5b). According to the participants, there is no clear link between the complexity of the VR experience and the client's final design decision, with only 23% of the participants answering "Yes" to this question. (Figure 5.5c)



a) b)



c)

Figure 5.5. Results for questions about the complexity of VR experiences: a) created VR experience complexity level, b) aspects engaging clients, and c) correlation between VR experience complexity and client's final design decision.

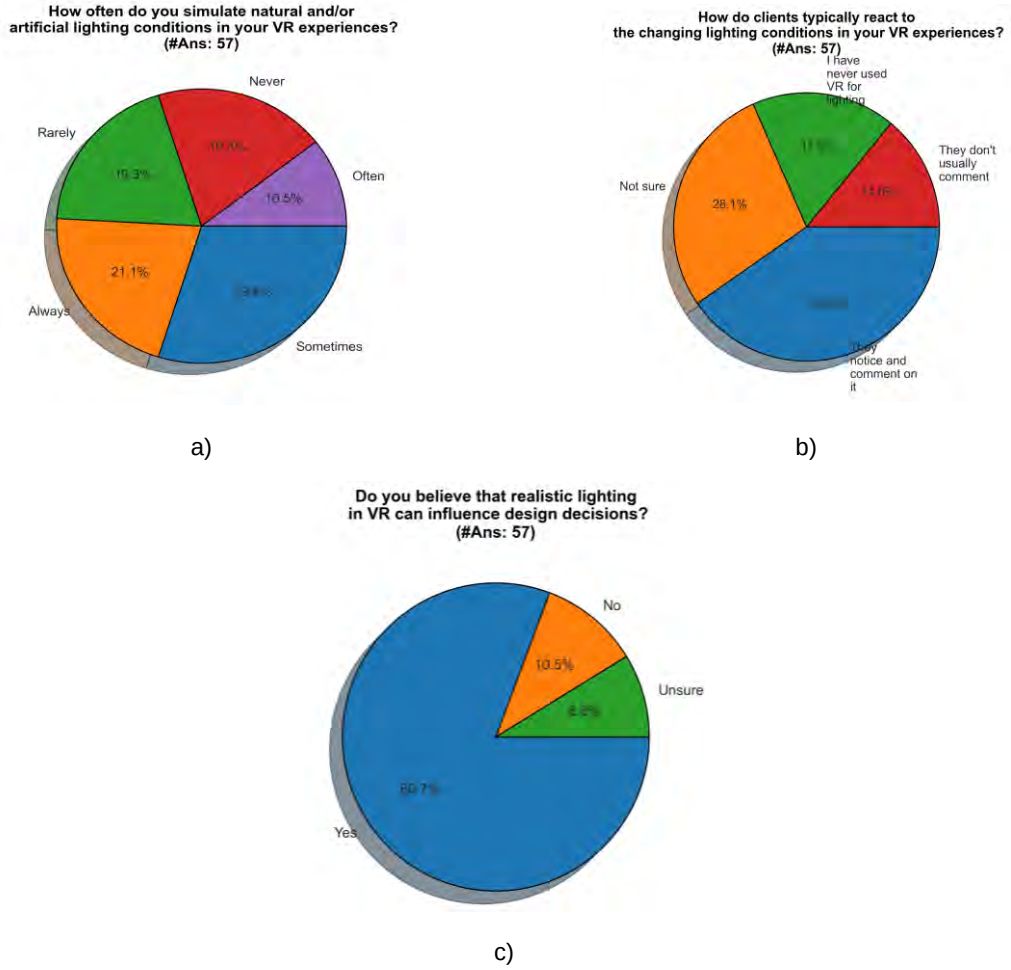
Lighting in VR

This survey section was formulated specifically to investigate the integration and simulation of lighting in virtual reality environments, aiming to understand how daylight and electric lighting is modelled in VR, as well as the potential impact of realistic lighting on design decisions.

Regarding the simulation frequency of daylight and/or electric lighting, as reported in Figure 5.6a, people who answered “Always” were only 21%. In contrast, most participants answered “Sometimes” or “Rarely”, 30% and 19%, respectively. The answer “Never” can be justified by the fact that some participants claimed that they had never used VR in practice.

Figure 5.6b shows the responses to the question, “How do clients typically react to the changing lighting conditions in your VR experiences?”. The results suggest that clients generally react to different lighting conditions (40% responded “They notice and comment on it”). The answers “Not sure” (28%) could be explained by a lack of confidence of professionals with the effects that lighting can have on clients’ perception of VR scenarios.

In slight contrast with clients’ reaction (Figure 5.6b), 81% of participants in the survey believe that realistic lighting in VR can influence design decisions, as displayed in Figure 5.6c.



a) b)

c)

Figure 5.6. Results from lighting in VR: a) frequency of (day)lighting simulation, b) client reaction to light conditions, and c) influence of realistic lighting.

Figure 5.7 exhibits the comparison among the answers of participants to three questions used to examine which quality level they consider important to use VR for lighting in practice. Specifically, they were asked to rate the following sentences: “The photometric accuracy in reproducing lighting distribution is important to use virtual reality for lighting”, “The aesthetical quality of the virtual environment is more important than light distribution accuracy”, and “Using virtual reality, a plausible light environment is enough for lighting professionals”. Participants agree with the importance of ensuring photometric accuracy of lighting distribution (M = 4.26, SD = 1.61). At the same time, they are neutral about the question if the aesthetical quality is more important than an accurate light distribution (M = 3.44, SD = 1.50). They rather do not consider the plausibility of lit virtual environments enough for lighting professionals (M = 3.00, SD = 1.41).

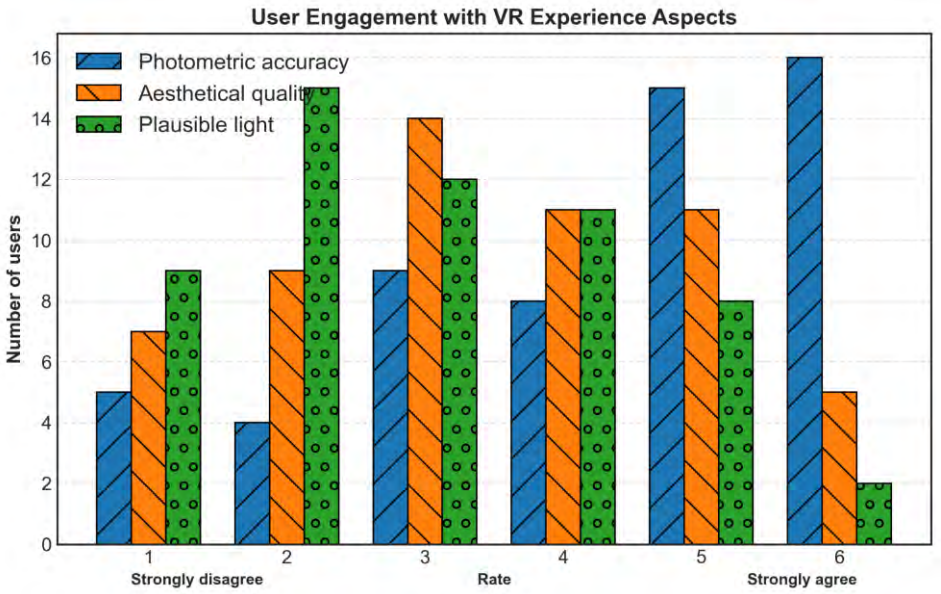


Figure 5.7. Comparison among the quality of light simulation in VR scenarios considered significant by users.

5.1.3 Insights from professional practice on VR for lighting design

Despite the wide use of virtual reality in many areas, its use in professional lighting design is not yet clearly defined. The first interesting outcome of the international survey is that VR for lighting begins to be used in many sectors (public, private, and self-employed), different activity domains (architecture, lighting, design, or daylighting), and professional experience (from less than one year to more than 20 years). Despite the widespread use of VR, the professional experience with VR/AR reported by participants is relatively low (about 40% use VR for less than one year), as shown in Figure 5.2b. The low professional experience with AR/VR also seems to be reflected in the frequency of VR use in practice, the application of VR in practice, and the complexity of scenarios presented to clients. The low level of experience can justify the rare use of VR in practice (46% of respondents rarely, 24% never; see Section 3.2), the purposes VR is mainly used for, namely presentation and conceptual design (about 48%, as in Figure 5.4a), and the basic environments which are largely prepared for client presentations (44%, as in Figure 5.5a).

At the same time, the low experience level in AR/VR technology can be explained by the need for formal training. Most knowledge acquired is based on self-study, online material, or information from colleagues (Figure 5.3b). The challenges associated with VR also reflect this in many cases – “Lack of experience”, “Lack of training”, and “Lack of specialists” are all among the most important arguments (Figure 5.4c).

Nevertheless, the use of VR is perceived as a benefit in practical applications (Figure 5.4b) since it can influence client satisfaction (Figure 5.4d) with interactive features and immersive environments (Figure 5.5b).

Separate reasoning should be made about the results related to the use of VR for lighting design (Survey, Section IV) since participants provided opposing answers, which is mainly due to the unclear role that light plays in VR projects, and, probably, the lack of experience with AR/VR technologies, and how the VR use was learned. More in detail, about 49% of professionals declare that they have rarely or sometimes simulated natural and/or artificial lighting conditions in VR experiences (Figure 5.6a). This strongly contrasts with the fact that a VR scenario cannot be separated from lighting (natural or artificial) to make it visible to users. These results require even more careful analysis if we consider that 40% of professionals note that clients typically react to changing lighting conditions, and 81% say that a realistic lighting environment can influence design decisions.

Regarding the quality of the light distribution in virtual environments for lighting design, professionals are clearly inclined to seek the photometric accuracy of light distribution in virtual environments (Figure 5.7).

Generally, professionals’ ideas about VR are that it will become a standard tool in architectural design (54% answered “Yes”), can rather not fully replace traditional lighting simulation software (M = 3.16, SD = 1.42), and has to be used in conjunction with traditional simulation systems (M = 4.23, SD = 1.51).

Finally, **Figure** shows the aspects that professionals (excluding the responses from researchers) would see improved in VR to be used for lighting. From the figure, it is possible to deduce that the relevant aspects are:

- the accuracy in reproducing daylight and electric lighting (mentioned five times);
- the perception of virtual environments (mentioned two times);
- a more user-friendly system (cited two times).

Some specific responses yield interesting information. For example, one participant working in the lighting domain and using VR daily wrote, “Haven´t found the limits yet”, confirming the wide possibilities of VR systems.

An engineer working in the public sector and using VR rarely indicated: “Better understanding of light distribution”. A self-employer working in daylight design, self-taught, and using VR monthly communicated: “luminance range of headsets (to simulate high luminance levels), simulating accurate daylight and artificial lighting in different game engines (there is no research to compare and evaluate light distribution, contrast, illuminance, and luminance in different engines and real environments)”. Compared with results in Section II, these comments underline the missing dissemination of scientific results in those channels used by the self-taught.

Another stimulating comment was provided by a professional working in the public sector as a lighting designer, using VR daily, who proposed improvements for “Remote medical telehealth and Emotional Health” – a comment that could open the way to new fields of application for VR for health control and management.

The aspects the researchers would like to see implemented in VR for lighting align with those that emerged from the scientific literature review (Figure 5.8).

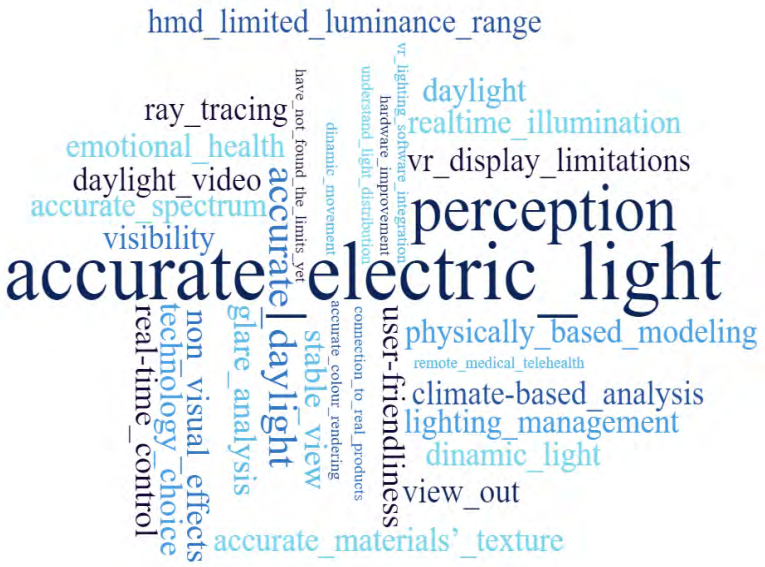


Figure 5.8. Words cloud of aspects of lighting simulation in VR professionals would like to see improved.

5.1.4 Practical application of VR in lighting design

According to the survey findings, the first aspect to be addressed is to create awareness for the importance of correct light simulation in VR projects and, more specifically, for lighting projects. In fact, Figure 5.6a calls for action to clarify the key role of light in VR projects better. The confusion may be explained by the fact that VR software, such as Unreal Engine or Unity, is not explicitly developed for light and, sometimes, the information provided in the documentation is incomplete or not specifically thought for lighting design. In this case, training programs and specific documentation specifically designed for lighting design in VR could help clarify the role of light in virtual environments and encourage its adoption.

The quest for virtual environments that accurately model lighting phenomena, in conjunction with the limited professional experience with VR technologies and the identified constraints, highlights the necessity for straightforward, intuitive, and open-source solutions that leverage academic findings while addressing the practical needs of professionals. More in detail, academia suggests different methods to ensure the correct photometric distribution of light inside the virtual environment. Although some of them are too complex to be translated into the professional world, others can be easily applied in the professional world. Some examples of

simple reference environments for each type of method, accompanied by simple and clear guidelines, could allow professionals to incorporate these techniques into their workflows easily. The process could be further bolstered by making available the supporting material for the correct simulation of light distribution, such as HDRI clear sky sphere [41], calibrated HDR images [42,43] or a database of calibrated light sources to use in VR [44], as well as providing guidelines in the appropriate channels, communities, and websites frequented by self-taught practitioners in the field.

The dialogue between academia and the lighting and simulation software industries would make more tools, documentation, and support available to professionals who want to incorporate VR into their workflows, helping them to overcome challenges such as lack of experience, user-friendly systems, and lack of specialists, as well as make available specific plugins or functions that allow to assess the compliance with regulatory and standards requirements easily and rapidly. In this context, the initiatives of IEA SHC Task 70 / EBC Annex 90 play a pivotal role in facilitating and accelerating these engagements. By fostering collaboration among researchers, industry stakeholders, and professionals, these efforts could enhance the accessibility of research findings through an open-source platform, thereby promoting innovation and application within the field.

The ability of VR to create virtual environments that accurately simulate real-world lighting conditions or visualise the outcomes of various lighting design alternatives can also present a significant opportunity to optimise resource usage. This approach can reduce material waste, save time, and lower energy consumption while also facilitating the education and adoption of low-carbon lighting solutions. As a result, it enables users to experience the comfort of efficient lighting solutions without compromising on sustainability. Similarly, the lighting industry could benefit from using VR in new product development, as it could avoid building full-scale prototypes, make real-time changes and interact more effectively with customers to meet their expectations while reducing environmental impact.

On the contrary, other aspects are still open. For example, how the users perceive light, colour, and glare in the HMD. Currently, it remains unclear to what extent the limitations imposed by existing hardware on achievable luminance values, contrast, resolution, and field of view influence users' final judgment regarding the perception of a real environment once built.

Although the research is focused on using VR for lighting, the outcomes can represent helpful information for all those applications not explicitly aimed at lighting design but where the correct distribution of light plays a key role, such as fire departments or crowd evacuation. Effective lighting plays a crucial role in guiding crowds during emergency events, significantly impacting evacuation efficiency and occupant safety [45–48]. Consequently, the correctness of (il)luminance distributions and the interaction of light with surfaces is essential. In these fields, VR represents an advantageous tool for assessing the effectiveness of innovative design solutions and providing operators a safe training environment. By combining various design solutions for lighting systems, whose light emission is appropriately simulated using one of the methods proposed by the academia, alongside factors such as smoke conditions and crowd density in VR, it is possible to conduct comprehensive analyses of diverse scenarios, otherwise impossible. VR technologies facilitate the collection of objective, subjective, and physiological data. Given the variability of potential situations, it is desirable to develop specialised training programs tailored for practitioners in the field.

5.1.5 Limitations

This study faces several limitations that affect the generalizability and scope of its findings, primarily due to the limited number of lighting professionals actively working with VR technology. The field remains niche, and as a result, the 57 responses received, while seemingly few, represent a significant portion of this highly specialized group. The response rate was shaped by the survey's specific focus and its online distribution period, spanning from August 2023 to December 2023. Although targeted networks were utilized to recruit participants, this method introduces potential biases, as it primarily attracted individuals already engaged with or interested in VR for lighting design. Consequently, the findings largely reflect the perspectives of researchers and professionals within this small and specialised community, rather than those of the broader population of lighting professionals or other stakeholders.

Since there was no prior data on the adoption and use of VR among lighting professionals, the questionnaire was intentionally designed to be concise and straightforward. A highly technical questionnaire might have risked disengaging respondents, potentially leading to lower response rates. To avoid this, certain technical aspects,

such as glare, glare calculation methods (e.g., unified glare rating), and correlated colour temperature (CCT), were omitted. Future research should expand on these aspects, including:

- The ability of VR tools to simulate lighting metrics, such as UGR and CCT;
- The interoperability of VR applications with industry-standard tools like Radiance and DIALux;
- The influence of VR technology on energy modelling and compliance with sustainability standards.

These additions would provide a broader and more comprehensive understanding of VR's potential impact on professional lighting design practices.

Another key limitation of this study is the lack of a detailed exploration of the cost-benefit trade-offs of using VR in lighting design. While financial barriers are identified as a challenge to VR adoption, the survey does not explicitly investigate how the perceived benefits of VR—such as improved visualization, design accuracy, or client satisfaction—offset these costs. Addressing this gap would provide a clearer understanding of whether VR is a cost-effective and essential tool for achieving effective lighting design for buildings. Future studies should explicitly consider these trade-offs to better inform decision-making about VR's value in lighting design.

5.2 VR for (day)lighting design – summary and findings

Over the years, with changing social habits, light has become a tool for influencing people's mood and performance. This underscores the necessity for lighting design strategies that effectively balance compliance with regulatory standards while also addressing the nuanced expectations of users.

The research provides an overview of the level of VR diffusion and use among lighting professionals. The synopsis is essential because of the profoundly different way VR for lighting is considered and used in academia and the professional world. In addition, methods for linking academic knowledge to the practical issues highlighted by professionals, as well as actionable solutions for overcoming gaps and, thereby, facilitating the integration of virtual reality into everyday professional activities were proposed.

Different methods have been proposed by academia for creating illuminated virtual environments that closely mirror real-world settings, significantly influencing the selection of experimental designs, the choice of VR technologies, and the perception of limitations. The main objectives of scientific activities are the accuracy of virtual models in reproducing daylight and electric light illuminance and luminance distribution, how they are perceived by people compared to the real ones, and their effects on physiological parameters. These objectives can be achieved thanks to the researchers' in-depth knowledge and expertise in VR technologies, as well as the time dedicated to VR and training. The scientific literature dedicated to the use of VR in lighting research suggests that:

- Unreal Engine and Unity are the most used VR software;
- filmic TMO is generally used for projects using Unreal Engine;
- HTC Vive Pro is the most used HMD;
- the limited luminance range in HMDs and the TMO are the main limitations detected.

To assess the extent of VR adoption and usage among lighting sector professionals, an international survey was designed and distributed to individuals within the sector who are either users or familiar with virtual reality technologies. The international survey indicates that most practitioners agree that VR will become a standard tool in design and has the potential to influence design decisions. The main challenge for them and all VR/AR users is the constant development of VR/AR technology, especially regarding tools and software. The survey results underline that VR for lighting is used mainly in the public sector for architectural and lighting activities. Respondents are familiar with VR/AR technologies (about 83%), with most having less than one year of experience (40%). This shows increasing interest and recent adoption among professionals. More than two thirds of the respondents either rarely (46%) or never (24%) use VR; seeming like VR technology is still in the early stages of development, and its use in everyday practice is still evolving.

Due to a lack of experience, time, and training, the environments developed are essentially basic (44%), namely static models or simple walkthroughs, and generally used for client presentations (26%) or conceptual design (21%). Despite this, respondents recognise the benefit of using VR in practice and client satisfaction. This awareness may also explain why professionals (like researchers) recognise the need for a physically correct light simulation when using VR for design, and plausible illuminated scenarios are no longer considered enough.

The survey underlines that the challenges professionals face in incorporating VR into workflow are related to the need for more experience and training, better integration of VR tools with other systems, and the shortage of VR specialists. Resources (financial and time-wise) are likewise limiting factors for the widespread adoption of VR technology in professional lighting design practice.

The study underscores the need for collaboration between academia and industry to enhance the accessibility and application of VR in professional lighting design workflows. Networking projects such as IEA SHC Task 70 / EBC Annex 90 support this. The possibilities and limitations identified in the scientific literature regarding the applicability of VR for imitating real lighting scenarios and implied user perception can be used for implementation in real lighting design. A key challenge here is the provision of easy-to-use VR tools, ideally embedded in standard lighting design software.

Simple environments in which daylight and/or electric light are modelled with a defined accuracy should be made available on open-source platforms, possibly for different VR software. Several important aspects, such as the capability of VR tools to simulate key lighting metrics like Unified Glare Rating (UGR), interact with widely used industry tools, such as Radiance and DIALux, as well as to be used for energy and environmental modelling, should be investigated to get valuable insights. Investigating the cost-benefit ratio achievable by adopting VR for lighting design, virtual prototyping, and optimising sustainable lighting solutions could help in a more conscious and widespread use of VR.

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6 Conclusions and Recommendations

6.1 Current capabilities of software systems for integrated lighting design

The review shows that a broad range of digital tools is currently available to support lighting simulation, visualization, and related building performance analyses. The software descriptions in this report were prepared to summarize each package's application areas and capabilities for daylighting, electric lighting, visual and non-visual performance, building performance links, and life-cycle-related analyses. Overall, many of the technical capabilities needed for low-carbon, high-comfort lighting design already exist.

Current tools can address practical questions such as daylight availability, electric lighting performance, glare, energy demand, lighting controls, visualization, and, in selected cases, spectral or non-visual evaluation. The example results in the report include daylight factor, sDA, ASE, UDI, glare indicators, melanopic EDI, electric lighting energy use, and HVAC-related outputs, depending on the software and case study. This demonstrates that simulation tools can already support decision-making across different design phases.

At the same time, the software landscape remains fragmented. No single tool covers all design phases, metrics, modelling requirements, and user needs equally well. Some tools are strong in daylight or electric lighting calculations, others in visualization, energy analysis, or advanced spectral workflows.

The overview also shows that tool limitations must be carefully considered. Some tools could not support spectral simulations, DGP calculations, BSDF import, or the inputs needed for melanopic EDI calculations. In other cases, shading, glazing, or electric lighting assumptions had to be simplified or handled outside the intended daylighting workflow. Therefore, tool selection should always be driven by the specific design question and by awareness of each tool's assumptions.

In conclusion, software systems are already available to solve many practical lighting design problems, but their capabilities are distributed across a scattered tool landscape. The value of this report – and in particular the tabular overview of the features of the individual tools – is to help users navigate that landscape by documenting tool capabilities, limitations, and example applications in a structured way.

6.2 Current use of Virtual Reality in lighting design

Virtual Reality is a promising approach for lighting design because it allows users to experience lit environments from an immersive, first-person perspective. VR can support visualization, communication, user-perspective assessment, and perception-oriented evaluation, while also showing that the role of light in projects is not always fully understood in practice.

At present, VR is still emerging as a professional lighting design tool. Research has explored VR for perception of daylit spaces, visual evaluation, calibration of virtual light sources, and wayfinding or evacuation studies. However, common VR environments such as Unreal Engine and Unity were not originally developed as lighting design software, and their documentation and workflows are not always oriented toward lighting professionals. VR platforms may require additional processing to obtain lighting quantities relevant for design. For example, in one workflow, illuminance values had to be derived from luminance values measured on diffusing white surfaces at calculation points, rather than being directly obtained through a standard lighting simulation grid. This illustrates that VR can be useful for immersive experience and communication, but is not yet a general replacement for validated lighting simulation software; however, when combined with such software, it can offer significant added value.

Overall, VR tools are available and useful, but their role in lighting design is not yet mature. Their broader use requires stronger links to physically based lighting simulation, clearer documentation, easier workflows and interfaces or integration with lighting simulation software, as well as better support for photometric quantities, glare, spectral aspects, and non-visual metrics.

6.3 Recommendations for practical application and future research

6.3.1 Practical application of the software overview

The software overview should be used as a decision-support resource, not as a ranking. Practitioners should first define the design task (such as daylight access, electric lighting, glare, controls, energy use, spectral effects, non-visual effects, input for LCA, or visualization) and then select tools accordingly. For informed use of the tools, continuing education (e.g., via conferences, workshops, discourse, cross comparisons with reference models) can support a deeper understanding of the capabilities, limitations, and tradeoffs of the underlying models and assumptions built into the tools.

Because no single tool covers all needs, users should expect to work with toolchains. One tool may be suitable for daylight metrics, another for electric lighting, another for energy analysis, and another for visualization or communication. The example simulations should be used to understand not only what tools can calculate, but also where simplified inputs, missing functions, or deviations from the templates may influence outputs. To ensure design intent is carried through into operations, leverage advancements in digitalisation within and across building systems to achieve high performance over the life of the installation.

6.3.2 Practical application of VR in lighting design

VR should be applied as a complement to conventional lighting simulation, especially for immersive communication, design review, client engagement, and perception-oriented evaluation. It should not replace validated simulation workflows when quantitative metrics are required.

For practical use, lighting accuracy in VR must be addressed explicitly. Users should document assumptions about light sources, materials, daylight, luminance, and photometric behavior, and should avoid relying only on visually plausible scenes. A key practical need is stronger integration between lighting simulation tools and VR platforms such as Unreal Engine and Unity, including improved data exchange, calibrated material and light-source libraries, and workflows that preserve known simulation accuracy.

6.3.3 Recommendations for future software development and research

Future research and development should focus on interoperability, validation, usability, and integration. Better exchange of geometry, materials, spectral data, luminaire data, BSDF data, control logic, climate data, and simulation outputs is needed to connect daylight, electric lighting, controls, building performance, non-visual effects, LCA, and VR workflows more effectively.

Further work is also needed on spectral and non-visual simulation. Some tools already offer advanced workflows, while others lack spectral support or the inputs needed for evaluations of non-visual effects of light, e.g., melanopic EDI calculations. Shared datasets, benchmark models, and clearer guidance would help make these methods more accessible. Collaborative, sustained effort is needed to build and maintain standardized international databases, including: long-term weather data (sun, sky including atmospheric conditions), spectrally- and spatially-resolved data for LED sources, luminaires, windows, BIPV, shading, and daylighting materials/ systems, indoor and outdoor materials and finishes, and sensors.

The reference rooms presented in Section 2 (and documented in the accompanying Technical Report T70.C4.2 of this IEA SHC Task 70 / EBC Annex 90[6]) can (and should) be used by experts when developing new software tools, adding features, and testing software. These reference models are particularly well-suited for spectral simulations used to evaluate non-visual effects of light.

For VR, future research should develop lighting-specific workflows for main engines such as Unreal Engine, Unity, and similar platforms, including validation of photometric accuracy, glare, spectral effects, non-visual effects, and links to established lighting simulation tools.

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Appendix A: Example Simulation Results

ClimateStudio

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Office

Simulation run by:

- Alberto Gremo, September 11, 2025

Software and hardware:

- ClimateStudio, version 2.1.9170.20218
- Timestep calculations: progressive path tracing approach from Radiance raytracer engine
- Simulation settings
  - Default configuration:
    - Settings for raytracing calculation = -ab 6 -as 4096

    Advanced radiance settings can be specified in the interface

    There are no differences between simulations performed for specific project development phases, since the software has been optimised to run simulations in short timespans
  - Settings for hardware configuration:
    - Max CPU threads = 9
    - Weight limit 0.01
- Sky model: Default sky model for annual simulation (Perez from weather data)
- Spectral: not available
- Total run time for annual simulation, general hardware description: 40.8 sec, on DELL Latitude 5550, Intel i7-1355U, 10 core CPU, 16 GB RAM

General comments on the simulation, deviations from the templates, other:

- To represent the typical practitioner behaviour, materials have been chosen among the internal database made available by the software, choosing samples as close as possible to provided reflectance weighted for V(λ); the full datasheet of the alternative materials is provided below

Layer name	Material name	measured VLR V(λ)	simulated VLR V(λ) using CS library
ceiling	Dupont White 105	71.84%	72.2%
chairs	Munsell N 2.0	2.60%	2.7%
couch	Munsell MCC FOLIAGE (6.7GY 4.2-4.1)	12.58%	12.7%
cupboard	White Plastic Chair	65.55%	66.2%
desk_legs	Grey Fabric Pin Board	30.78%	29.4%
desks	White Stool	65.58%	64.9%
door	White Painted Wooden Door	85.66%	85.7%
exterior_ground	Exterior Concrete Floor	22.02%	22.0%
exterior_facade	Grey Aluminium Façade Cladding	20.01%	20.0%
floor	Yellow Brick	40.08%	39.9%
interior_walls	White exterior wall plaster	86.88%	86.6%
luminaires	Dupont White 105	-	72.2%
monitors	Hair Gray Black	2.35	2.4%
window_frame	White Rolling Cabinet	86.31%	86.1%

- To avoid biased results due to the ceiling structure, the material properties of the ceiling have been assigned to the luminaire area as well
- Glazing and shading system has been modelled as commonly drafted by practitioners, searching for a material already present inside the ClimateStudio library. However, since venetian blinds are not present in the database, a fabric blind layer has been specifically modelled, with a visible transmittance as close as possible to the visible transmittance of the glazing combined with the 75° venetian blind (gathered through "Bauing_ILM_Lamelle_+75" *.csv* file, at line 1172 under *Identifying Information,* Tvis = 2.99%, hence as a ratio of visible transmission values, Tvis blind layer = 2.99%/66.11% = 4.52%); the full datasheet of the assigned materials is provided below, including the glazing assigned to the interior wall.

	glazing	shade	Glazing+shade	interior wall glass
name	Solexia-Sungate 400 (3)	SilverScreen ED04 tan+pearl/silver		Sungate 400 (2)
VLT	66%	4%	2.64%	88%
VLR	11%/13%	59%/59%	n.a.	7%/6%

- Shading usage schedule follows the rule set in LM-83: the curtain is deployed whenever >2% of regularly occupied area is hit by DHI> 1000 lx, according to the default settings in the software; whenever closure condition is no longer met (assessed hourly), blinds are re-opened
- The upper surface of the couch has been lowered by 2cm to avoid hiding sensors
- Chairs have been moved to remain between sensor rows, avoiding potentially biased results
- The area of the ceiling containing the luminaires has been modelled with the same reflectance properties as the ceiling
- In order to evaluate the percentage of area with >2% DF, a data processing in the *.csv* file (exported from *ClimateStudio*) was necessary, as *ClimateStudio* interface for Daylight Factor calculation provides only minimum, mean and median DF, but allows punctual results to be exported as *.csv* files
- UDI values do not explicitly report the percentage of area where illuminance values fall within 100-3000 lx, so results have been obtained by querying the *.csv* files that can be output from *ClimateStudio* interface
- *ClimateStudio* provides four UDI values, corresponding to $UDI_{<100}$ (*failing*), $UDI_{100-300}$ (*supplemental*), $UDI_{300-3000}$ (*autonomous*), $UDI_{>3000}$ (*excessive*); however, target values can be customisable by users; summing up $UDI_{100-300}$ and $UDI_{300-3000}$ it is possible to obtain the required $UDI_{100-3000}$v (see previous comment)
- *ClimateStudio* adopts different threshold to identify glare categories from EN 17037:2021: more specifically, the DGP classes are imperceptible (DGP ≤34%), perceptible (34%< DGP ≤38%), disturbing (38%< DGP ≤45%) and intolerable (DGP >45%); for this reason, $F_{DGP=0.38,exceed}$ is provided instead

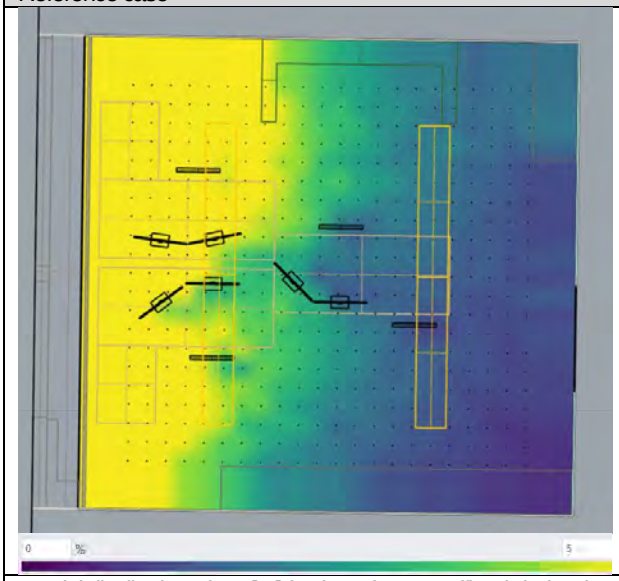
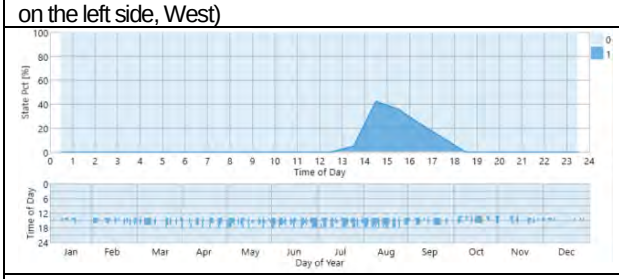
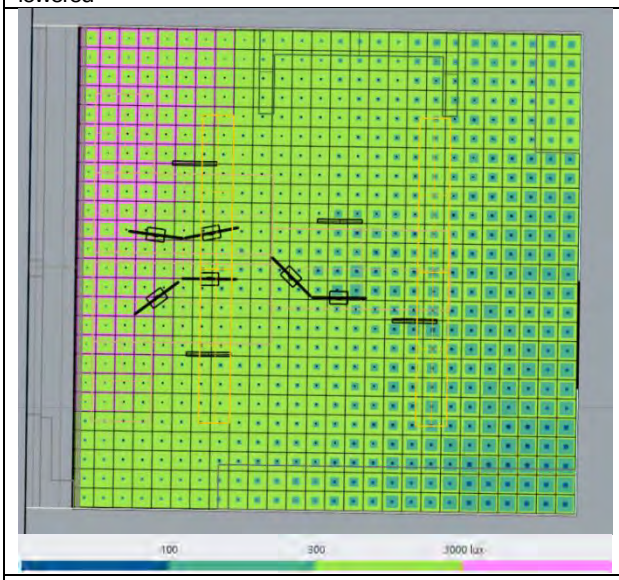
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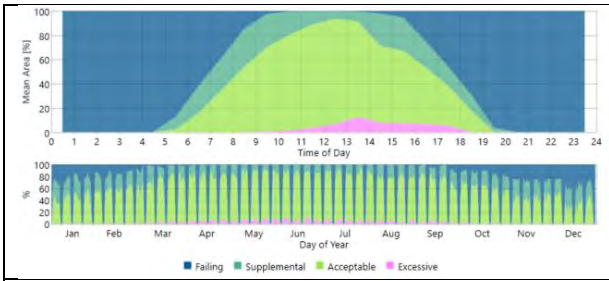
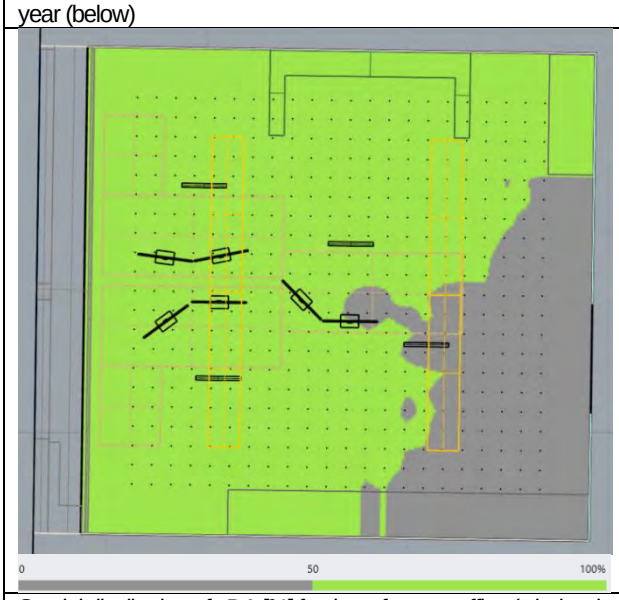
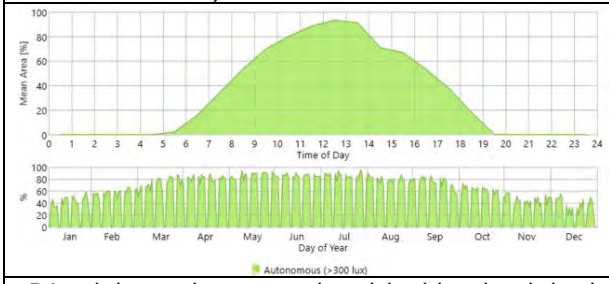
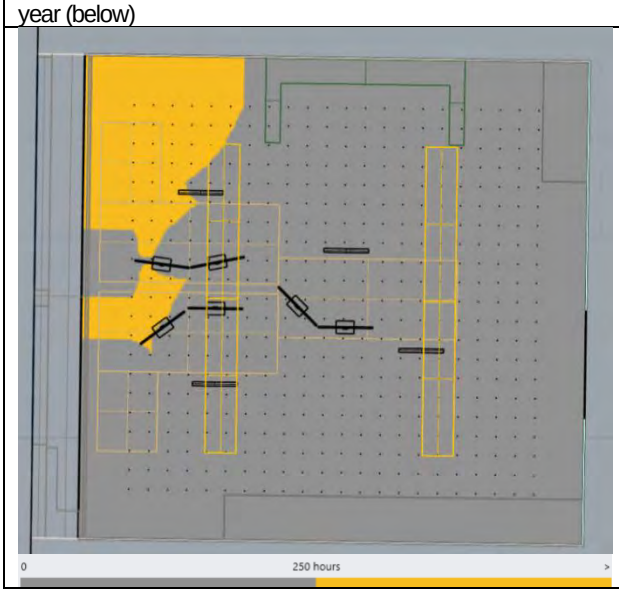
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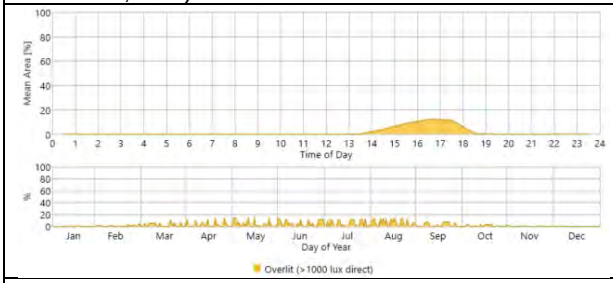
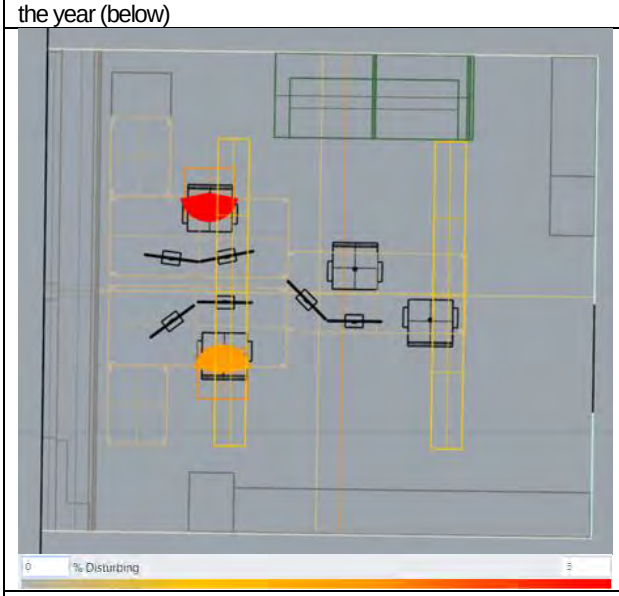
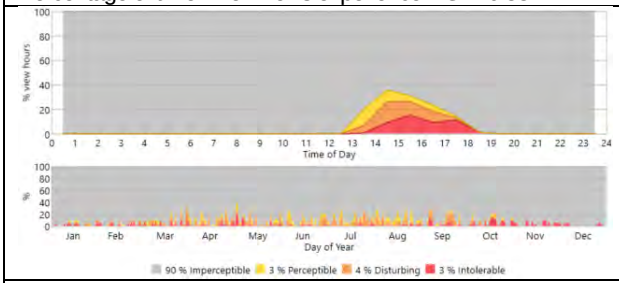
Results Office

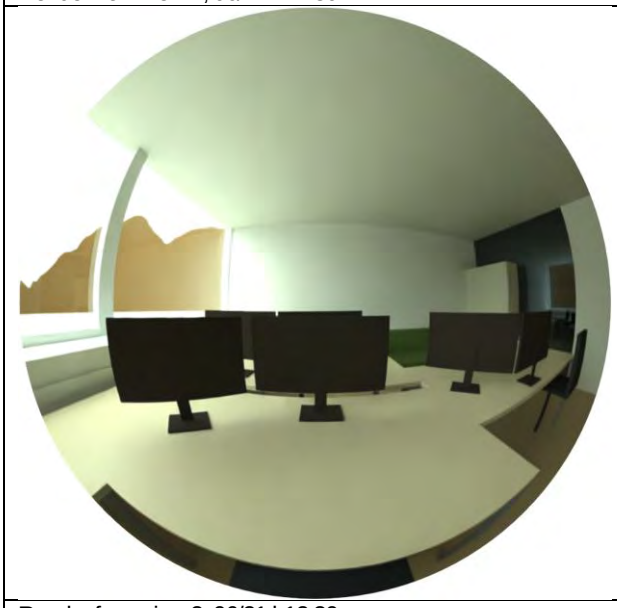
	Metric	Reference case	Context
Daylight Factor (CIE overcast sky)	**DF min**	0.76%	NA
	DF max	14.31%	NA
	DF avg	3.91%	NA
	% area with at least 2% DF	63.42%	NA
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	92.9% (no blinds) 79.2% (blinds deployed 16.62% of occupied time)	NA
	$ASE_{1000,250h}$	8.66% (no blinds) 0.00% (blinds deployed 16.62% of occupied time)	NA
	% area with at least 50% $UDI_{100-3000}$	100.0% (no blinds) 100.0% (blinds deployed 16.62% of occupied time)	NA
	$F_{DGP=0.38,exceed}$ for view 1	12.0% (blinds deployed 7.92% of occupied time)	NA
	$F_{DGP=0.38,exceed}$ for view 2	3.0% (blinds deployed 2.03% of occupied time)	NA
Circadian lighting	**mel-EDI**	NA	NA
Electric lighting	**Annual electricity use for electric lighting**	NA	NA
	Operating hours	NA	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

Example graphical output:

Reference case	Context
	NA
Spatial distribution of DF [%] for the reference office (window is on the left side, West)	NA
	NA
Usage profile of blinds in the reference office, state 0 represents the blinds retracted while state 1 corresponds to the blinds lowered	NA
	NA
Spatial distribution of UDI for the reference office (window is on the left side, West)	NA

	NA
UDI variation graph across a selected day (above) or during the year (below)	NA
	NA
Spatial distribution of sDA [%] for the reference office (window is on the left side, West)	NA
	NA
sDA variation graph across a selected day (above) or during the year (below)	NA
	NA

Spatial distribution of ASE for the reference office (window is on the left side, West)	NA
	NA
ASE variation graph across a selected day (above) or during the year (below)	NA
	NA
Percentage of time when views experience DGP>0.38	NA
	NA
DGP variation graph across a selected day (above) or during the year (below)	NA

	NA
Render from view 1, 06/21 h12.30	NA
	NA
Render from view 2, 06/21 h12.30	NA

Specific comments on the simulation for the reference case "office":

- For mountains modelling, the provided file "*shading lines*" has been modelled through *Grasshopper* script, as open surface resulting from a *loft* in 1000m distance from the centre of the windows
- A matte material with around VLR = 10% has been applied to the external obstructions previously modelled from the shading lines (specifically, the material chosen for these simulations is named *Kiwi Outside*)
- Annual simulations have been performed with an 8am-6pm occupancy schedule in *custom* mode; alternatively, the final user can specify the reference regulation and standard, such as LEED or BREEAM, to filter out useful data and verify the compliance to such protocols
- View sensors for DGP calculation have been modelled as separate sensors, so as to better define their position and view direction; however, *ClimateStudio* considers them as separate analysis sensors, providing for both of them a percentage of blinds deployment that is different from the one considered for Daylight Autonomy
- In glare results interface, users can read the portion of space where DGP >38% for at least 5% of occupied hours, or alternatively select one view direction and query the likelihood to experience glare from that perspective during the year, according to the aforementioned categories

Hall

Simulation run by:

- Alberto Gremo, September 10, 2025

Software and hardware:

- ClimateStudio, version 2.1.9170.20218
- Timestep calculations: progressive path tracing approach from Radiance raytracer engine
- Simulation settings
  - Simplified configuration for the final user:
    - Settings for raytracing calculation = -ab 6 -as 4096
    - There are no differences between simulations performed for specific project development phases, since the software has been optimised to run simulations in short timespans
    - Further, advanced radiance settings can be specified in the interface
- Sky model: Default sky model for annual simulation (Perez from weather data)
- Spectral: not available
- Total run time for annual simulation, general hardware description: 1min 00.51sec, on DELL Latitude 5550, Intel i7-1355U, 10 core CPU, 16 GB RAM
- Settings for hardware configuration:
  - Max CPU threads = 9
  - Weight limit 0.01

General comments on the simulation, deviations from the templates, other:

- To represent the typical practitioner behaviour, materials have been chosen among the internal database made available by the software, choosing samples as close as possible to provided reflectance weighted for V(λ); the full datasheet of the alternative materials is provided below

Layer name	Material name	measured VLR V(λ)	simulated VLR V(λ)
factory_ceiling	Plastic Ceiling Vent E14 526	72.33%	72.3%
factory_floor	Dark Grey Floor Tiles	20.06%	20.1%
factory_rooflight_frame	Aluminium window mullion	51.54%	51.5%
factory_walls	Grey Painted wall	45.83%	45.8%

- Glazing system required to be modelled as a single surface with diffusing features, whose Tvis has been set close to the provided one; the translucent material was assigned as a Kalwall glazing, whose features are reported below:

	Glazing
name	Kalwall 70mm AirCrystalWhite Tvis 37%
VLT	37%
VLR	19%/25%

- In order to evaluate the percentage of area with >2% DF, a *.csv* analysis was necessary; *ClimateStudio* interface for Daylight Factor calculation provides only minimum, mean and median DF, but allows punctual results to be exported as *.csv* files
- UDI values do not explicitly report the percentage of area where illuminance values fall within 100-3000 lx, so results have been obtained by querying the *.csv* files that can be output from *ClimateStudio* interface
- *ClimateStudio* provides 4 UDI values, corresponding to $UDI_{<100}$ (*failing*), $UDI_{100\text{-}300}$ (*supplemental*), $UDI_{300\text{-}3000}$ (*autonomous*), $UDI_{>3000}$ (*excessive*); however, target values can be customisable by users; summing up $UDI_{100\text{-}300}$ and $UDI_{300\text{-}3000}$ it is possible to obtain the required $UDI_{100\text{-}3000}$
- *ClimateStudio* adopts glare categories different from EN 17037:2021, more specifically it labels them as imperceptible (DGP ≤34%), perceptible (34%< DGP ≤38%), disturbing (38%< DGP ≤45%) and intolerable (DGP >45%); for this reason, $F_{DGP=0.38,exceed}$ is provided instead

Description of alternative context for factory hall:

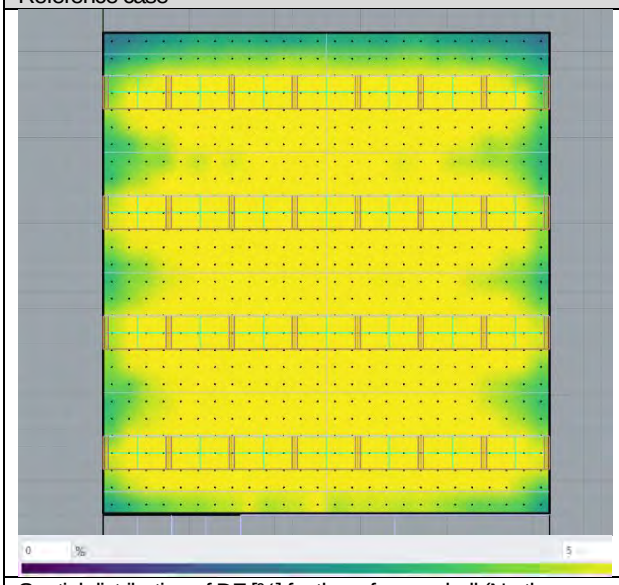
- NA

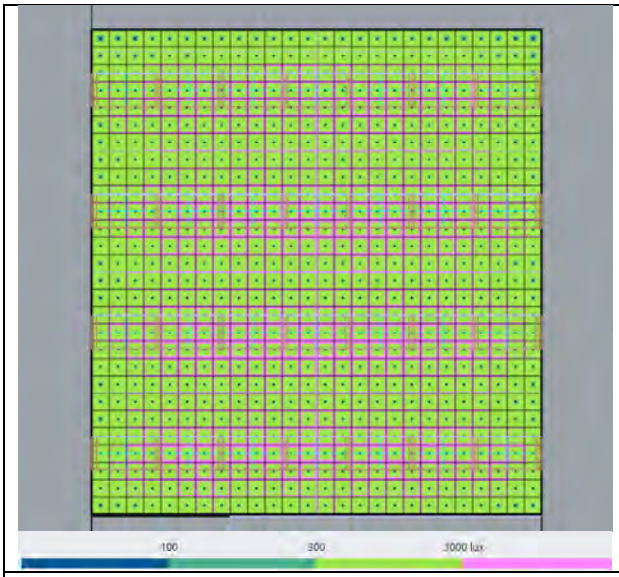
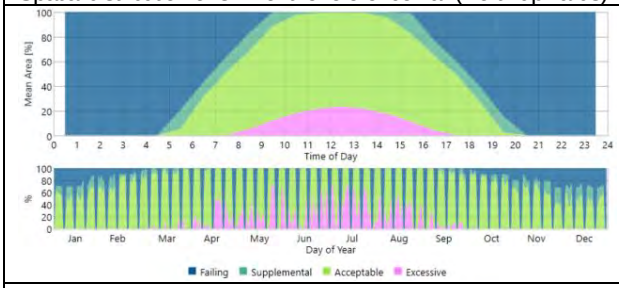
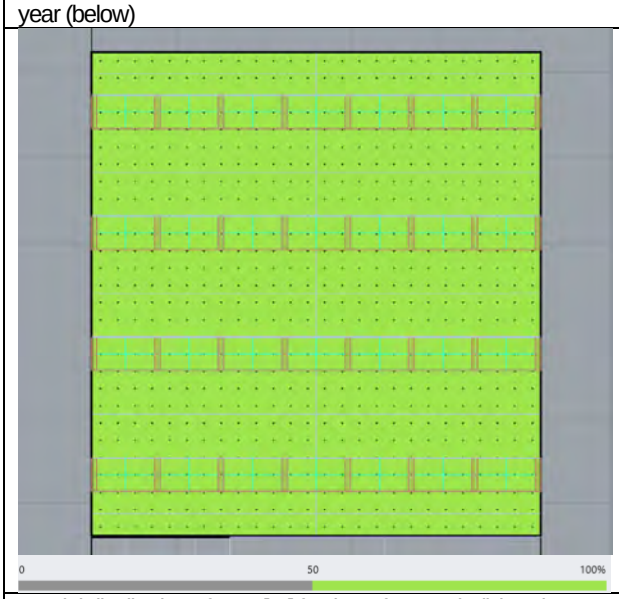
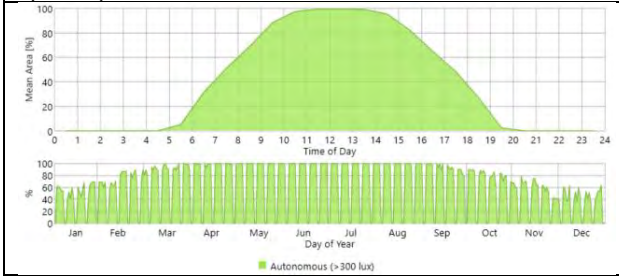
Results Hall

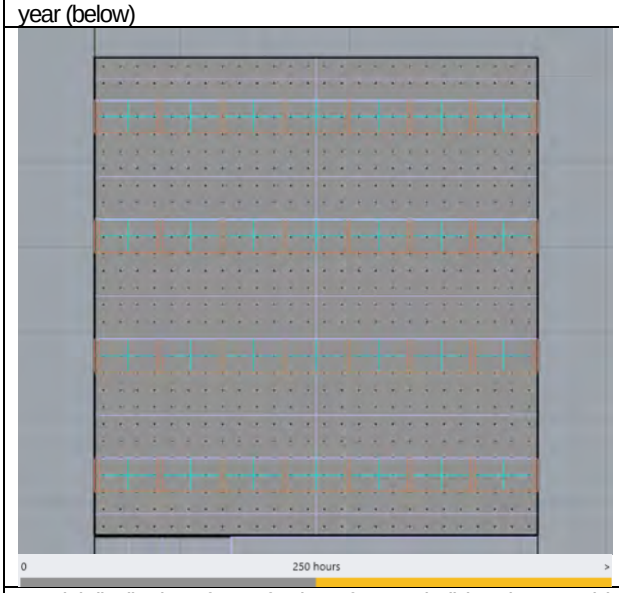
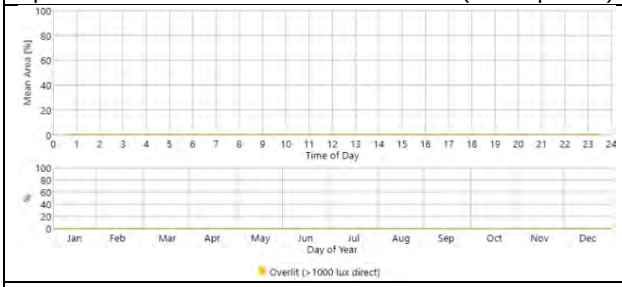
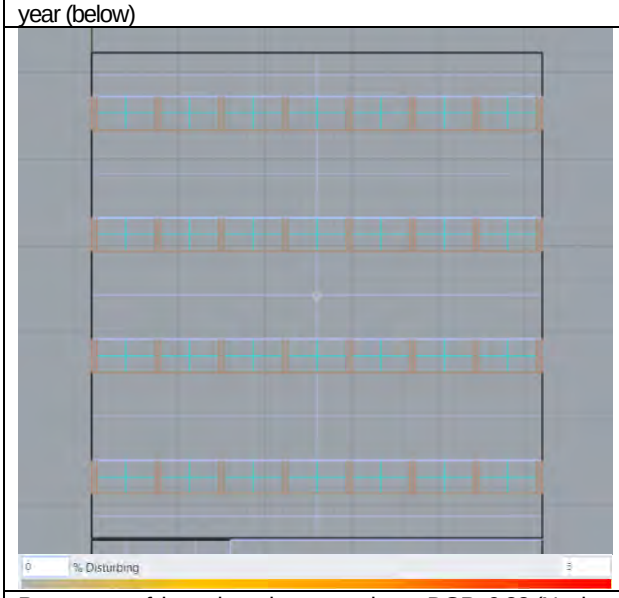
	Metric	Reference case	Context
Daylight Factor (CIE overcast sky)	**DF min**	1.97%	NA
	DF mx	7.74%	NA
	DF avg	5.56%	NA

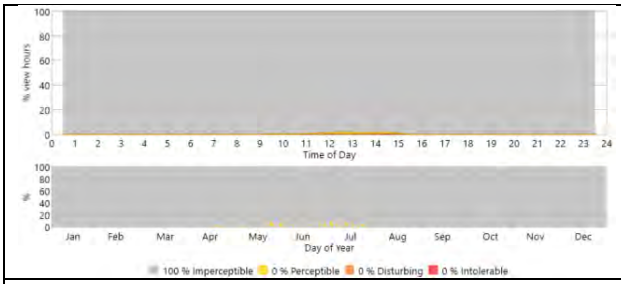
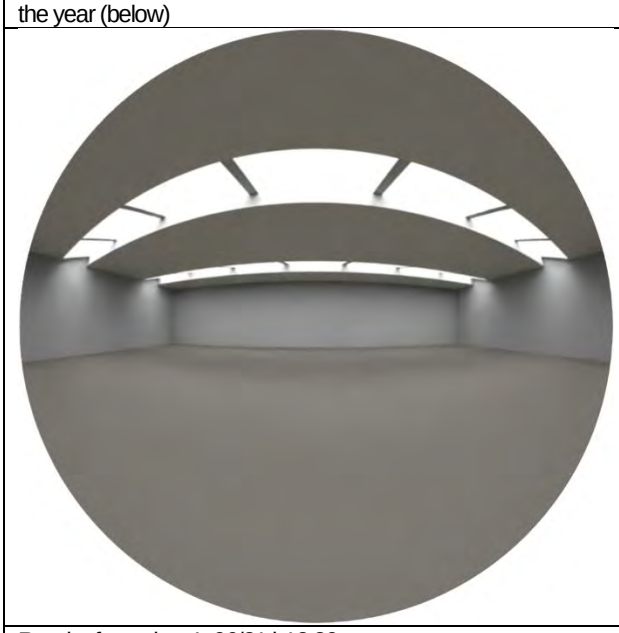
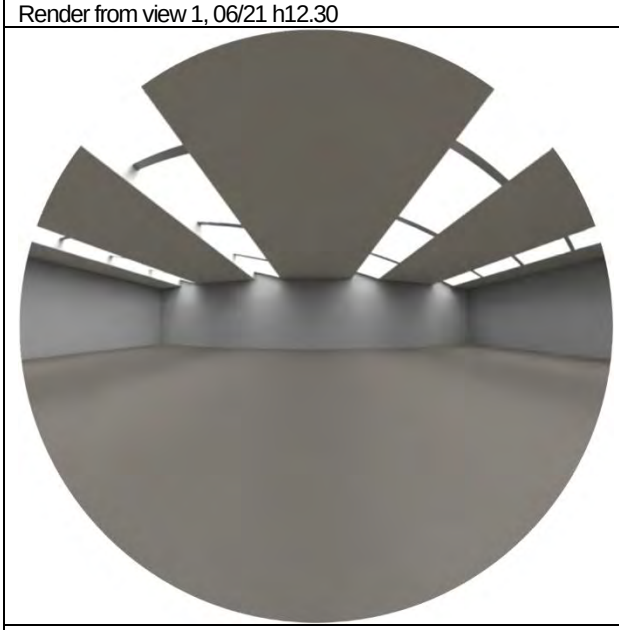
	% area with at least 2% DF	99.86%	NA
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	100.0%	NA
	$ASE_{1000,250h}$	0.00%	NA
	% area with at least 50% $UDI_{100-3000}$	100.0%	NA
	$F_{DGP=0.38,exceed}$, view 1	0.00%	NA
	$F_{DGP=0.38,exceed}$, view 2	0.00%	NA
	$F_{DGP=0.38,exceed}$, view 3	0.00%	NA
	$F_{DGP=0.38,exceed}$, view 4	0.00%	NA
Circadian lighting	**mEDI**	NA	NA
Electric lighting	**Annual energy demand for electric lighting**	NA	NA
	Operating hours	NA	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

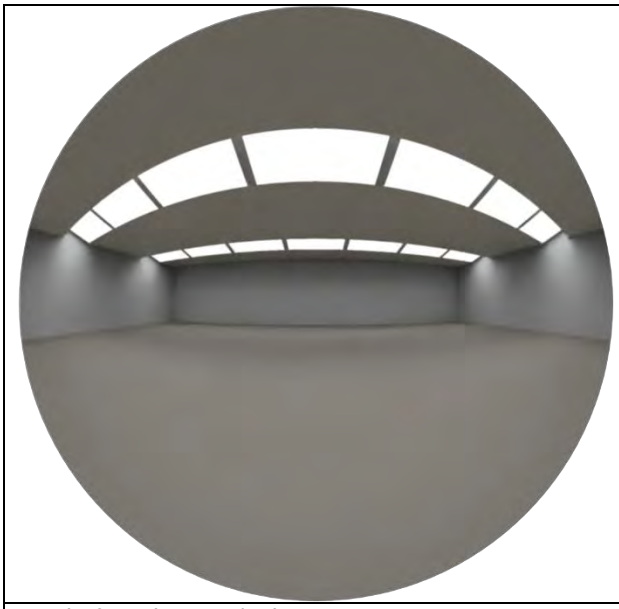
Example graphical output: e.g. Spatial daylight distribution (DA or DF distribution)
(please provide also tabular results (text files) for the sensor grid behind the figures and high-resolution image files)

Reference case	Context
	NA
Spatial distribution of DF [%] for the reference hall (North upwards)	NA

	NA
Spatial distribution of UDI for the reference hall (North upwards)	NA
	NA
UDI variation graph across a selected day (above) or during the year (below)	NA
	NA
Spatial distribution of sDA [%] for the reference hall (North upwards)	NA
	NA

sDA variation graph across a selected day (above) or during the year (below)	NA
	NA
Spatial distribution of ASE for the reference hall (North upwards)	NA
	NA
ASE variation graph across a selected day (above) or during the year (below)	NA
	NA
Percentage of time when views experience DGP>0.38 (North upwards)	NA

	NA
DGP variation graph across a selected day (above) or during the year (below)	NA
	NA
Render from view 1, 06/21 h12.30	NA
	NA
Render from view 2, 06/21 h12.30	NA

	NA
Render from view 3, 06/21 h12.30	NA
	NA
Render from view 4, 06/21 h12.30	NA

Specific comments on the simulation for the reference case “hall”:

- Annual simulations have been performed with an 8am-6pm occupancy schedule in *custom* mode; alternatively, the final user can specify the reference regulation and standard, such as LEED or BREEAM, to filter out useful data and verify the compliance to such protocols
- View sensors for DGP calculation have been modelled as separate sensors, so as to better define their position and view direction; however, *ClimateStudio* considers them as separate analysis sensors, providing for both of them a percentage of blinds deployment that is different from the one considered for Daylight Autonomy
- In glare results interface, users can read the portion of space where DGP >38% for at least 5% of occupied hours, or alternatively select one view direction and query the likelihood to experience glare from that perspective during the year, according to the aforementioned categories

DALEC

David Geisler-Moroder, University of Innsbruck, Austria;

Xuran Guo, Hunan University, China; University of Innsbruck, Austria

Simulation run by:

- David Geisler-Moroder, Xuran Guo, February, 2026

Software and hardware:

- DALEC, accessed 15 Feb 2026
- Online project link: https://dalec.zumtobel.com/#/project/e22a6160b47e40f3b4afd1f25206ceef

- **Timestep calculations:**
  Unknown, Information not provided by the user interface

- **Simulation settings**
  Default settings

- **Sky model:**
  Default (information on sky model, atmospheric data, etc. not provided as a configurable setting by the software tool)

- **Spectral:**
  Not available

- **Total run time for annual simulation, general hardware description:**
  The results are generated instantly in the web interface, with no computation time required

General comments on the simulation, deviations from the templates, other:

- In the current version, the software does not support modelling or model import, so the built-in model was used
- In the current version, some parameters cannot be defined by the user, and the default values provided by the software were applied, such as surface reflectance
- In the current version, the software does not support horizontal sensor grids and corresponding illuminance outputs, so the related metrics (e.g. sDA, ASE, and UDI) could not be calculated or reported
- In the current version, the software does not calculate DGP, but it provides hourly illuminance and luminance values for the whole year
- Façade control strategy
  - Office
    - Glare protection was activated when the luminance on the inner façade exceeded 5000 cd/m²
    - Solar protection was activated when the solar radiation on the outer façade exceeded 120 W/m², active during the period from 10 April to 27 October
    - The façade control was applied using external venetian blinds with a fixed slat angle of 45°.
  - Hall
    - Solar protection was activated when the solar radiation on the outer façade exceeded 150 W/m², active during the period from 10 April to 27 October.
    - The skylight control was applied using an external diffuse screen (film roller blind) with a transmittance of 0.20 and a reflectance of 0.55.
- Simulation settings and boundary conditions
  - Thermal mass
    - Effective thermal capacity: Medium, corresponding to 165,000 J/(m²·K)
    - Energy-equivalent air exchange rate: New building, 0.22 per hour
  - Window / night ventilation
    - Air exchange rate during night ventilation: 0.40 per hour
    - Activation limit (window opening temperature threshold): 24 °C
  - Indoor temperature setpoints
    - Office: 20–26 °C (min–max)
    - Hall: 18–26 °C (min–max)
  - Internal heat gains
    - Other internal loads (PCs, occupants, etc.): 7 W/m²
  - Energy system and conversion factors
    - Seasonal performance factor (SPF): Cooling 3.5, Heating 3.0, Lighting 1.0
    - Primary energy factor (PEF): 2.6 (cooling, heating, lighting)

- CO_2 emission factor: 680 g/kWh (cooling, heating, lighting)
- Energy price: 0.16 €/kWh (cooling, heating, lighting)

Description of alternative context for office:

- Location: Beijing, China (No Daylight saving time)

Description of alternative context for factory hall:

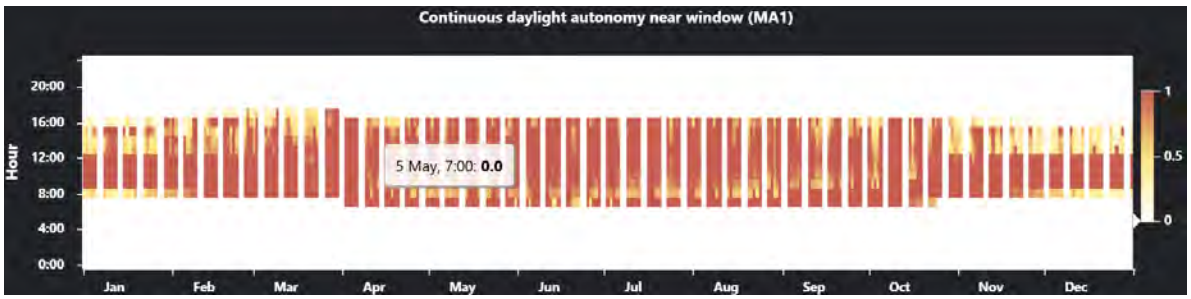
- Location: Beijing, China (No Daylight saving time)

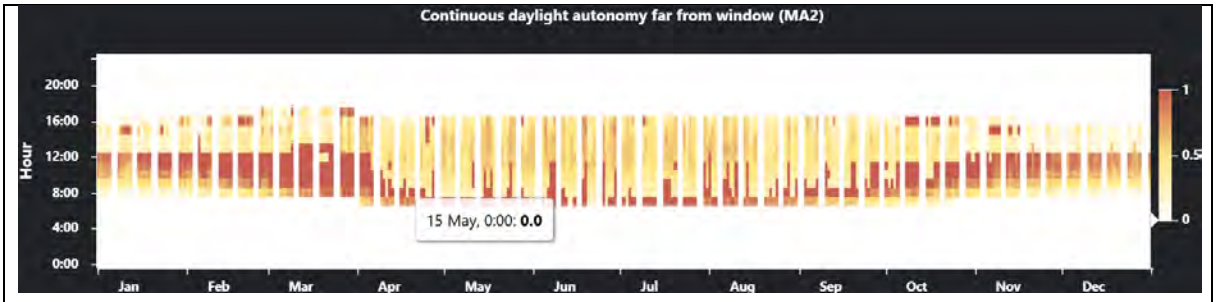
Results Office

	Metric	Reference case	Context (Location: Beijing)
Daylight Factor (CIE overcast sky)	DF min	NA	NA
	DF mx	NA	NA
	DF avg	NA	NA
	% area with at least 2% DF	NA	NA
Daylight metrics based on annual results	$sDA_{300,50\%}$	NA	NA
	$ASE_{1000,250h}$	NA	NA
	% area with at least 50% $UDI_{100\text{-}3000}$	NA	NA
	$F_{DGP=0.40,exceed}$ for view 1	NA	NA
	$F_{DGP=0.40,exceed}$ for view 2	NA	NA
Circadian lighting	mEDI	NA	NA
Electric lighting	Annual electricity use for electric lighting	7 kWh/(m²·yr) 210 kWh/yr	6.7 kWh/(m²·yr) 201 kWh/yr
	Operating hours	-	-
Annual electricity use for HVAC (zonal level)	Heating	5 kWh/(m²·yr) 150 kWh/yr	5.5 kWh/(m²·yr) 165 kWh/yr
	Cooling	2 kWh/(m²·yr) 60 kWh/yr	12 kWh/(m²·yr) 360 kWh/yr
	Ventilation	-	-
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	Heating	150 kWh/yr (electricity)	165 kWh/yr (electricity)
	Cooling	60 kWh/yr (electricity)	360 kWh/yr (electricity)
	Ventilation	-	-

Example graphical output:

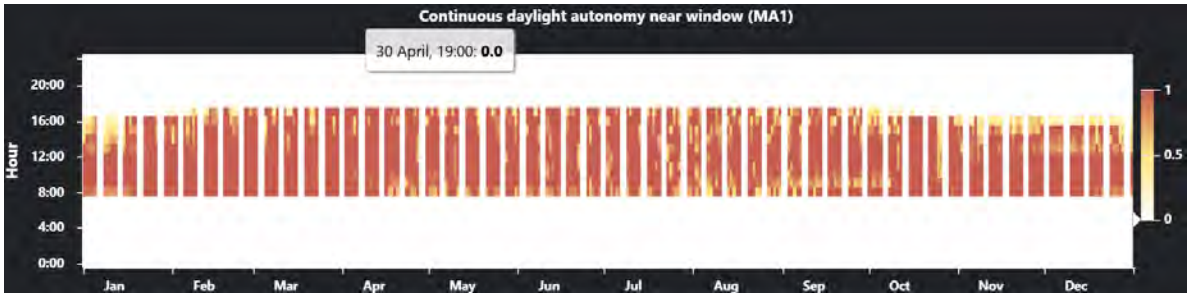
Reference case

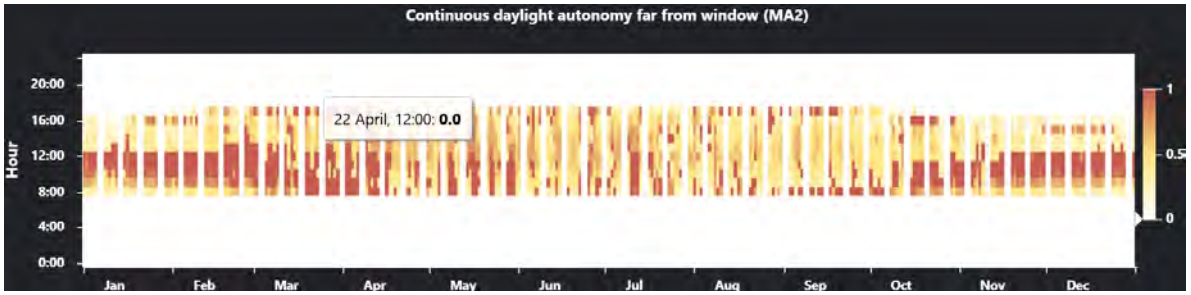




Hourly continuous daylight autonomy (cDA) for the near window (MA1) and deep room (MA2) measurement areas, calculated relative to a target average work-plane illuminance of 500 lx

Context
(Location: Beijing)





Hourly continuous daylight autonomy (cDA) for the near window (MA1) and deep room (MA2) measurement areas, calculated relative to a target average work-plane illuminance of 500 lx

Specific comments on the simulation for the reference case “office”:

- Surface reflectances were set to 60% for the walls, 90% for the ceiling, and 40% for the floor
- The window starts at a height of 1 m above the floor, with an active window area of 75% WA

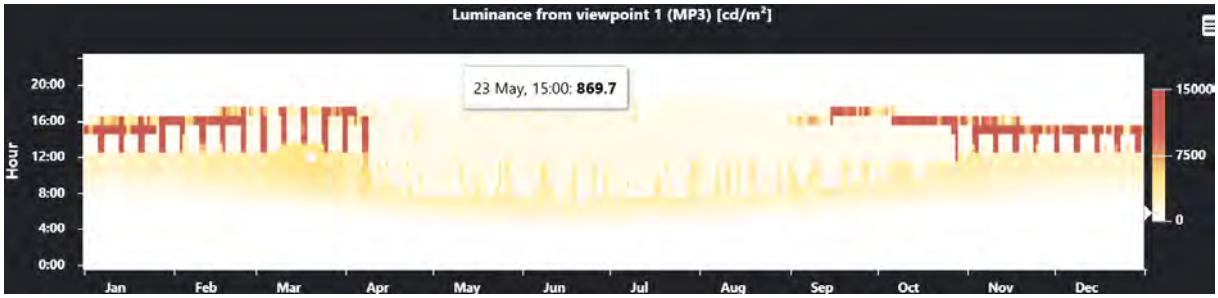


Fig. 1. Hourly maximum luminance in cd/m^2 at the façade seen from viewpoint

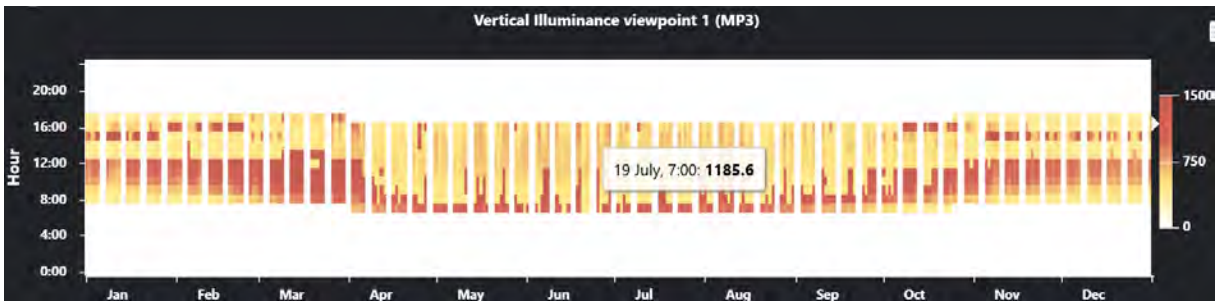


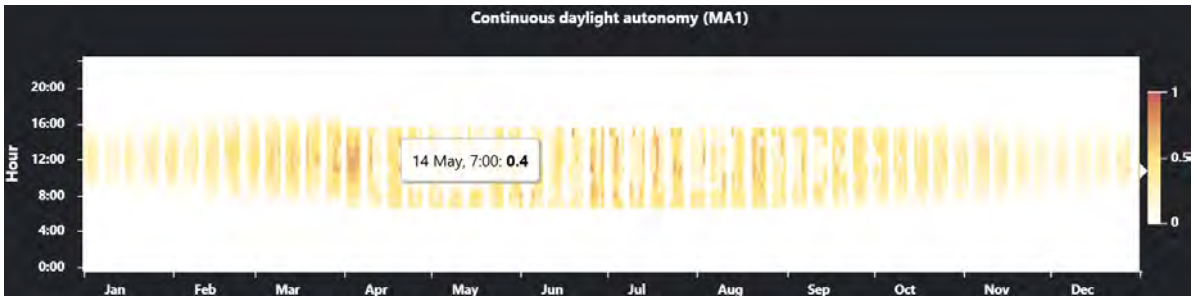
Fig. 2. Hourly vertical illuminance in lux at viewpoint from day- and artificial light

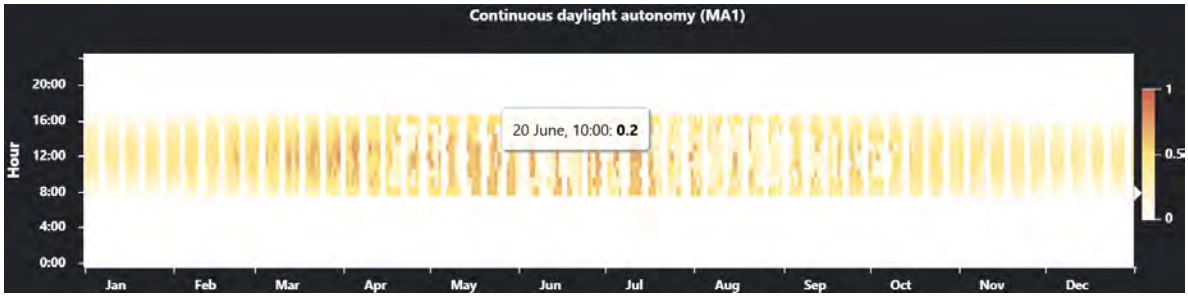
Results Hall

	Metric	Reference case	Context (Location: Beijing)
Daylight Factor (CIE overcast sky)	**DF min**	NA	NA
	DF mx	NA	NA
	DF avg	NA	NA
	% area with at least 2% DF	NA	NA
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	NA	NA
	$ASE_{1000,250h}$	NA	NA
	% area with at least 50% $UDI_{100\text{-}3000}$	NA	NA
	$F_{DGP=0.40,exceed}$, view 1	NA	NA
	$F_{DGP=0.40,exceed}$, view 2	NA	NA
	$F_{DGP=0.40,exceed}$, view 3	NA	NA
	$F_{DGP=0.40,exceed}$, view 4	NA	NA
Circadian lighting	**mEDI**	NA	NA
Electric lighting	**Annual energy demand for electric lighting**	8.4 kWh/(m²·yr) 14112 kWh/yr	7.8 kWh/(m²·yr) 13104 kWh/yr
	Operating hours	-	-
Annual electricity use for HVAC (zonal level)	**Heating**	77.1 kWh/(m²·yr) 129528 kWh/yr	66.8 kWh/(m²·yr) 112224 kWh/yr
	Cooling	0.2 kWh/(m²·yr) 336 kWh/yr	8.9 kWh/(m²·yr) 14952 kWh/yr
	Ventilation	-	-
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	129528 kWh/yr (electricity)	112224 kWh/yr (electricity)
	Cooling	336 kWh/yr (electricity)	14952 kWh/yr (electricity)
	Ventilation	-	-

Example graphical output:

Reference case



Hourly continuous daylight autonomy (cDA) for the measurement area, calculated relative to a target average work-plane illuminance of 500 lx
Context (Location: Beijing)

Hourly continuous daylight autonomy (cDA) for the measurement area, calculated relative to a target average work-plane illuminance of 500 lx

Specific comments on the simulation for the reference case “office”:

- The skylight area was set to 15% of the total roof area.

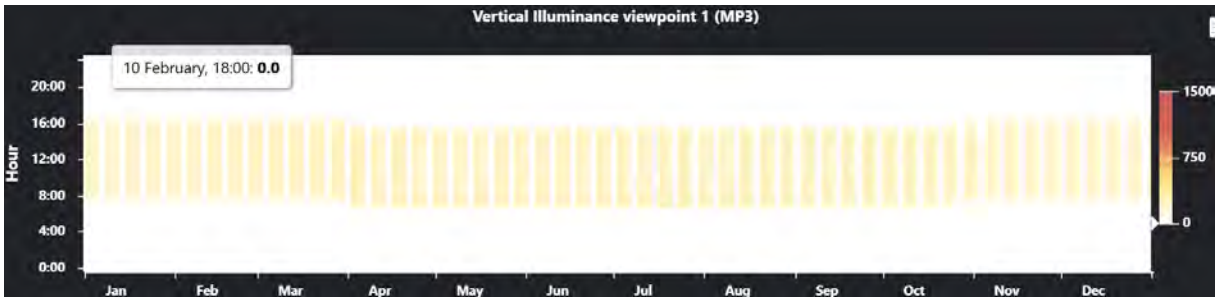


Fig. 4. Hourly vertical illuminance in lux at viewpoint from day- and artificial light

DesignBuilder

Joao Francisco Walter Costa, Claudia Naves David Amorim, University of Brasilia, Brazil

Simulation run by:

- Joao Francisco Walter Costa, Claudia Naves David Amorim, June 30, 2025

Software and hardware:

- DesignBuilder, version 7.3
- Timestep calculations:
- 1) backwards raytracing
- Simulation settings
  - Configurable by the end user:
    - Settings for raytracing calculation [provide values for key settings; e.g. number of reflections, ambient bounces, etc.]
      - Ambient bounces (-ab): 7
      - Ambient accuracy (-aa): 0.18
      - Ambient divisions (-ad): 4096
      - Ambient supersamples (-as): 2048
      - Ambient resolution (-ar): 1024
    - Specify the phase of the project the software was run for, e.g., simulations were intended for 1) early conceptual phase, 2) design development or 3) final specifications phase. [assuming the simulator will configure settings per desired level of accuracy]
      - 1) Early conceptual phase and 2) design development
- Sky model: 1) default (information on sky model, atmospheric data, etc. not provided as a configurable setting by the software tool), 2) Perez with MF: 4 subdivisions for sun disk, etc.
  - Climate files inserted:
    - AUT_Innsbruck.11200_IWEC.epw
    - DEU_Stuttgart_107380.epw
  - Perez all-weather sky model
- Spectral: 1) not available
- Total run time for annual simulation, general hardware description:
  - Approximately 17 minutes and for the Office, and 170 minutes for the Hall, on Notebook DELL/Intel® Iris ® XE Graphics, Windows 11, Intel Core i7, 16 GB RAM, with integrated GPU NVIDIA GeForce MX330 with VRAM 18 GB.

General comments on the simulation, deviations from the templates, other:

- The import of the geometry in the Rhino 3dm. file could not be directly imported to DesignBuilder, even using intermediary softwares, such as Revit or Autocad to change the geometry and file's format. Consequently, we had to model all the geometry in DesignBuilder itself for the "office" and the "hall".
- Import of the .ies or ReluxLum EulumDat File (.ldt) file of the lighting system was not possible, so only the power density, luminaire efficiency, and illuminance targets were configured. Color temperature of 4000 K were not considered in the simulations of electric lighting, as no spectral data was inputted. All simulations were considered with a neutral spectrum.
- The energy consumption for lighting was simulated, but this calculation was carried out in EnergyPlus and this output was not calculated in the "Daylighting Mode" using the Radiance simulation engine. This was recognized as a limitation of the software.[7] The focus of DesignBuilder for the input data for electric lighting is on energy efficiency and thermal comfort.
- It was not possible to import the BSDF data of complex fenestration systems in DesignBuilder. This was also recognized as a limitation of the evaluated software.
- Software does not support spectral simulations. All surfaces were modelled spectrally neutral with RGB values all set to V(l) value. Reflectance values and visible transmittances of the glasses were configured as spectrally neutral.
- Regarding non-visual effects of light, DesignBuilder does not support the necessary input for the calculations. Consequently, results of Mel-EDI were not calculated.
- DesignBuilder does not support the configuration of views and the calculation of DGP – daylight glare probability. Therefore, the results of DGP were not calculated.

Description of alternative context for office: Context "Innsbruck" – Same as template, but without the venetian blind system.

- Location: Innsbruck, Austria: AUT_Innsbruck_111200_IWEC.epw

[7] More information about the configuration of the electric lighting can be found at https://designbuilder.co.uk/helpv7.0/Content/_General_lighting.htm. Last accessed on 30 June 2025.

- Orientation: west
- Glass properties: SHGC 0.416, Tvis 0.610, Uvalue = 0.550 W/m²K – simplified input for the glazing system both configured for the template and the alternative context as DesignBuilder does not support the import of BSDF – xml files.
- The only difference in the alternative context for the office is that we turned off the window shading – venetian blind system. This was done to test the accuracy of the model in DesignBuilder to simulate the specified window shading – venetian blind system in the opening's tab in the construction model. The aim was to verify if differences in the results were found between the template and the context without the venetian blind system.
- The HVAC system – for both the template and the alternative context (without the venetian blind system) – was assessed using the zone total cooling and heating energy loads.
- Deviations from the template were described and commented after the results for "office".

Description of alternative context for factory hall: Context "no diffusing property of the skylight" – same configurations as the template, without the skylight's diffusing property configured in the template.

- Location: Stuttgart, Germany: DEU_Stuttgart_107380.epw
- Orientation – for both contexts, skylights oriented to the north.
- Glass properties: SHGC 0.349, Tvis 0.393, Uvalue = 0.980 W/m²K – simplified input for the glazing system, both configured for the template and the alternative context, as DesignBuilder does not support the import of BSDF – xml files. In the template, the skylight was configured as 100% diffusing for Radiance simulation engine.
- In the alternative context, we simulated the without the skylight's diffusing property (i.e. 0% diffusing). That was the only option in DesignBuilder to simulate the diffusing layer of the skylight and the intention was to test it to verify the impact on the simulations.
- The only difference in the alternative context for the factory hall is that we did not consider the diffusing property of Rooflight configured in DesignBuilder.
    - Context - template: as close as possible to the template with the diffusing property of the skylight configured for Radiance calculations.
    - Alternative context: the same configurations, but no diffusing property for the skylights.
- The HVAC systems – for both the template and the alternative context (without the diffusing skylight) – were assessed using the zone total cooling and heating energy loads.
- Deviations from the template were commented after the results of the simulations for the "hall".

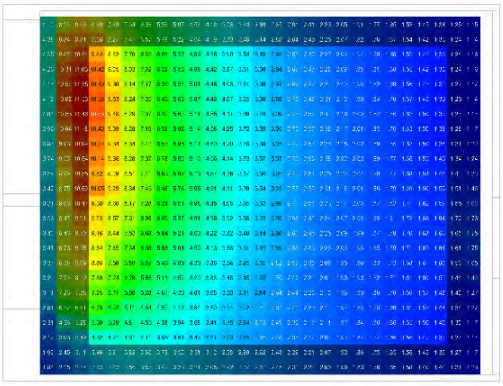
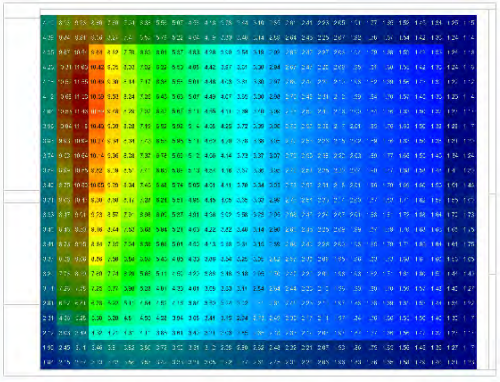
Results Office

	Metric	Reference case – Innsbruck	Context – same context as the reference case without the venetian blind system
Daylight Factor (CIE overcast sky)	**DF min**	1.12%	1.12%
	DF mx	11.55%	11.55%
	DF avg	4.01%	4.01%
	% area with at least 2% DF	63.5%	63.5%
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	100%	99.03%
	$ASE_{1000,250h}$	13.94%	13.94%
	% area with at least 50% $UDI_{100-3000}$	100%	100%
	$F_{DGP=0.40,exceed}$ for view 1	NA	NA
	$F_{DGP=0.40,exceed}$ for view 2	NA	NA
Circadian lighting	**mEDI**	NA	NA
Electric lighting	**Annual electricity use for electric lighting**	87.34 kWh/year – 3.23 kWh/m²year	87.34 kWh/year – 3.23 kWh/m²year
	Operating hours	884 hours/year (16.95h/week x 52)	884 hours/year (16.95h/week x 52)
	Heating	NA	NA

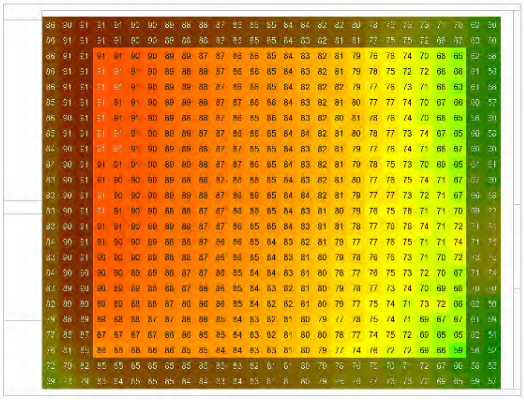
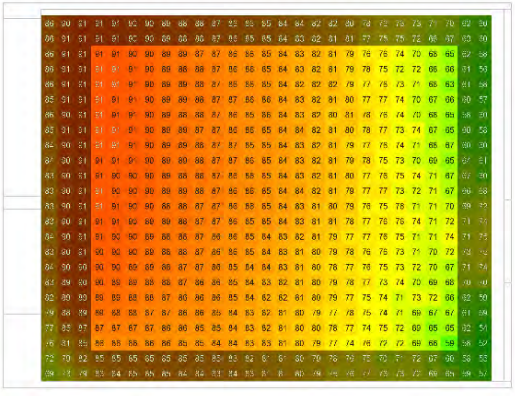
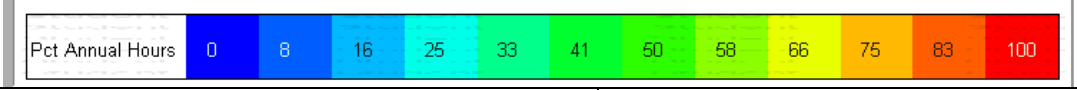
Annual electricity use for HVAC (zonal level)	**Cooling**	NA	9.94 kWh/m²year assuming an air-conditioning system with CoP 5
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	324 kWh with natural gas (291.9 kWh – zone total heating and CoP 0.90)	324 kWh with natural gas (252.55 kWh – zone total heating and CoP 0.90)
	Cooling	1341.29 kWh – zone total cooling	258 kWh for CoP 5 (1341.29 kWh – zone total cooling)
	Ventilation	NA	NA

Example graphical output:

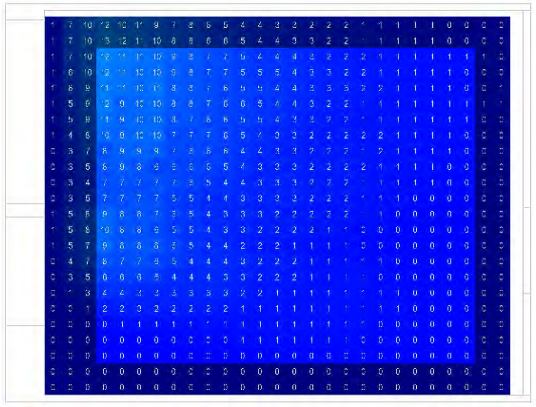
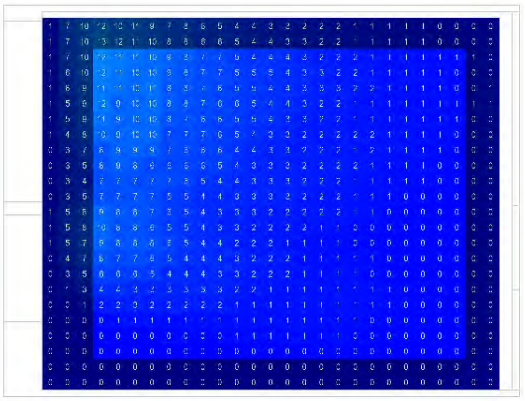
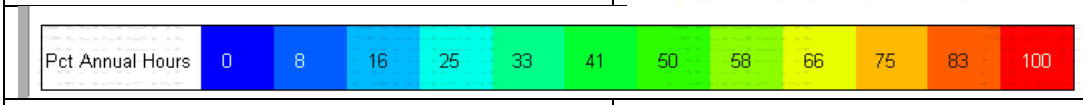
Daylight factor

Reference case – Innsbruck with the configured venetian shading system	**Context – Innsbruck: Without the venetian shading system**
	
	
Spatial distribution of Daylight Factor (DF [%]) for the reference office (window is on the left side, West)	Spatial distribution of Daylight Factor (DF [%]) for the office in Innsbruck without the venetian blinds (window shading)

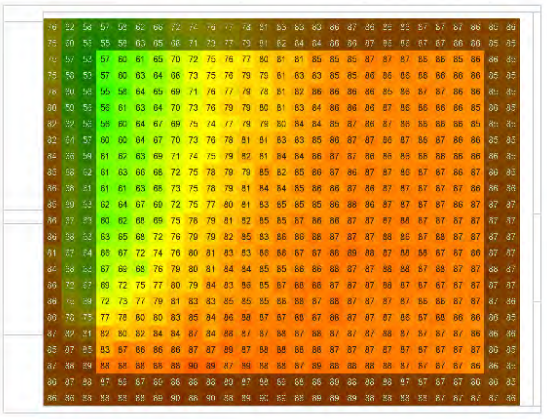
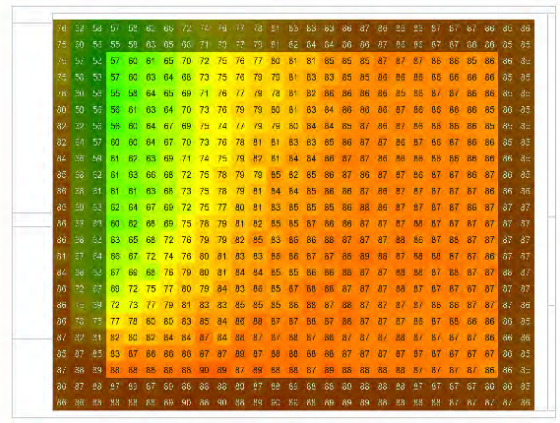
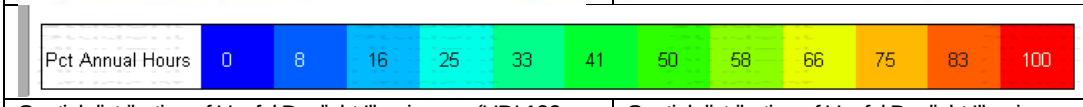
Daylight autonomy – 300 lux

Reference case – Innsbruck with the configured venetian shading system	**Context – Innsbruck: Without the venetian shading system**
	
	
Spatial distribution of Daylight Autonomy (DA [%]) for the reference office (window is on the left side, West)	Spatial distribution of Daylight Autonomy (DA [%]) for the office in Innsbruck without the venetian blinds (window shading)

ASE 1000 lux/250 hours

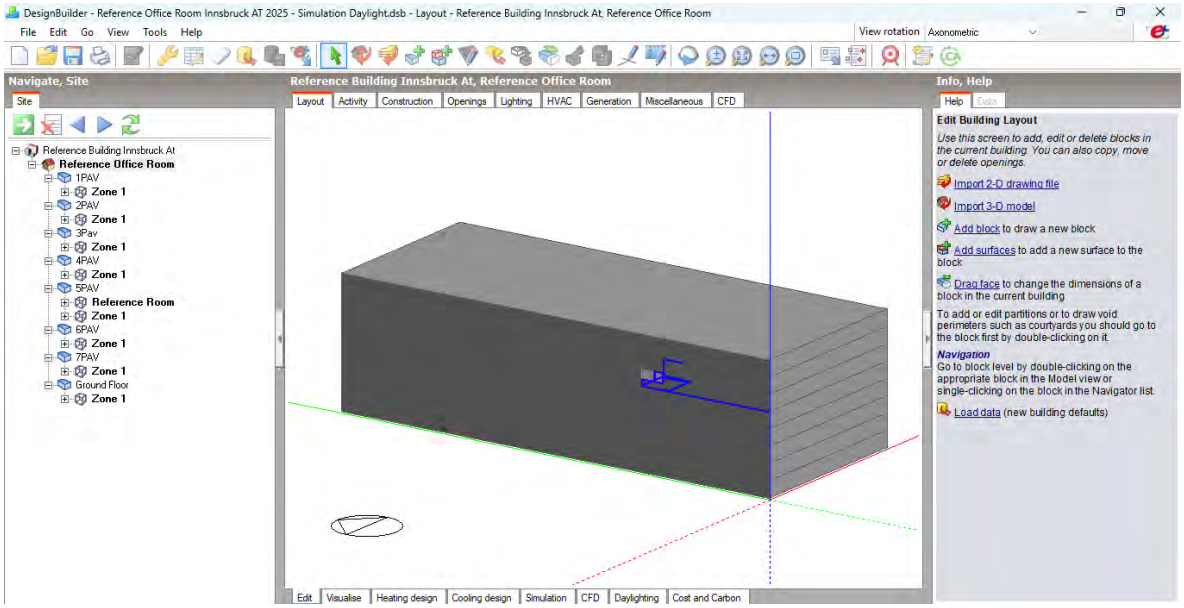
Reference case – Innsbruck with the configured venetian shading system	Context – Innsbruck: Without the venetian shading system
  	
Spatial distribution of Annual Sunlight Exposure (ASE1000/250) [%]) for the reference office (window is on the left side, West)	Spatial distribution of Annual Sunlight Exposure (ASE1000/250) [%]) for the office in Innsbruck without the venetian blinds (window shading)

UDI 100-3000 lux

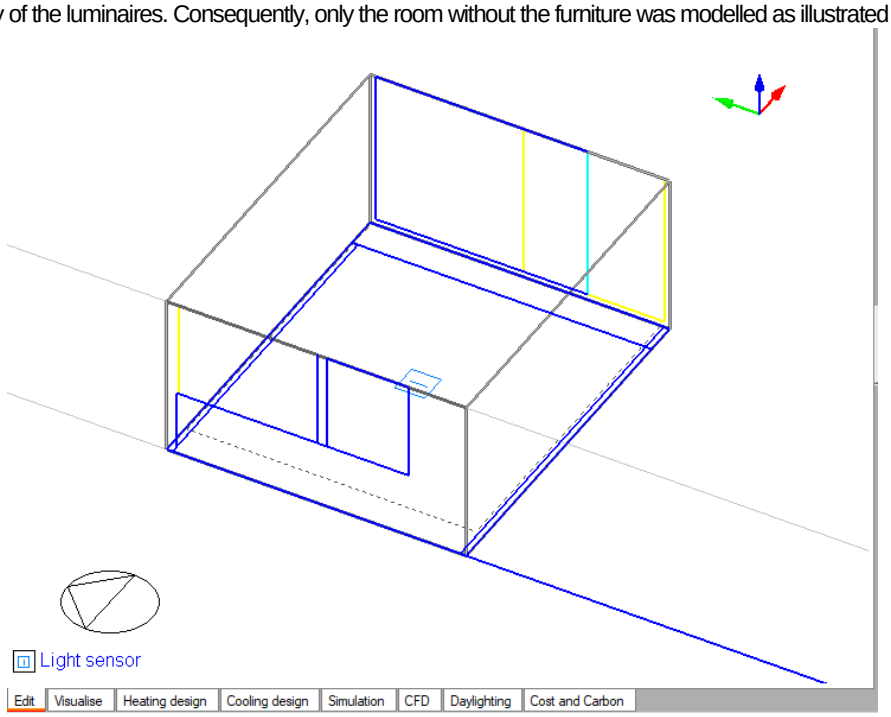
Reference case – Innsbruck with the configured venetian shading system	Context – Innsbruck: Without the venetian shading system
  	
Spatial distribution of Useful Daylight Illuminance (UDI 100-3000 [%]) for the reference office (window is on the left side, West)	Spatial distribution of Useful Daylight Illuminance (UDI 100-3000 [%]) for the office in Innsbruck without the venetian blinds (window shading)

Specific comments on the simulation for the reference case “office”:

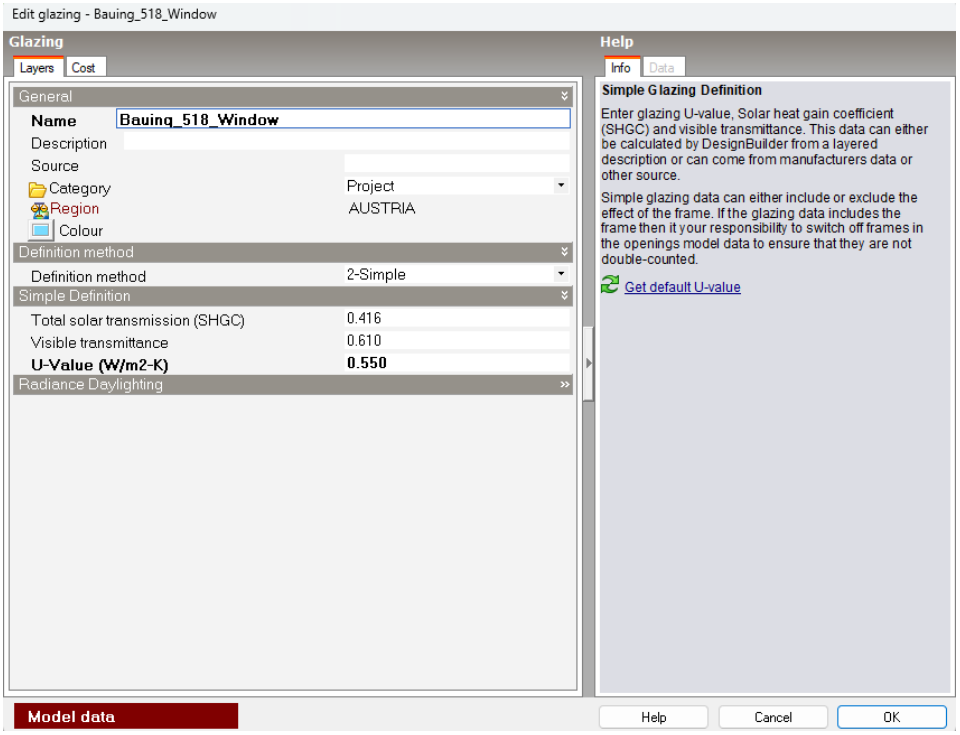
- The file “lab518_shading_lines” was considered for the simulations of the office – template and alternative context - and the shading lines of the horizon were properly configured as specified in the template.
- The import of the geometry in the Rhino 3dm. file could not be directly imported to DesignBuilder, even using intermediary softwares, such as Revit or Autocad. Consequently, we had to model all the geometry in DesignBuilder itself, adding all zones and configuring all materials’ properties, as shown in the figure below.



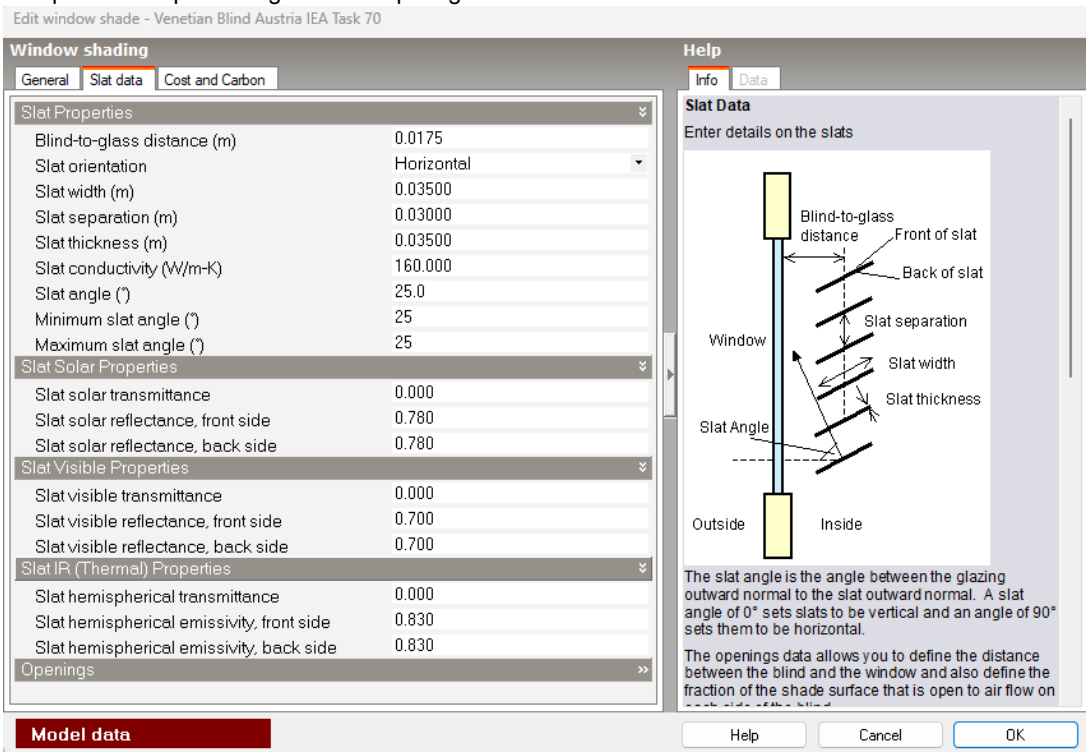
- It was not possible to import the geometry of the furniture, including the couch, chairs, desks, computers and the geometry of the luminaires. Consequently, only the room without the furniture was modelled as illustrated in the figure.



- The external window was configured as a single-pane glass, with properties configured of SHGC, Tvis and Uvalue – with a simpler definition as shown in the figure.



- It was not possible to import the BSDF data for the venetian blinds (Bauing_ILM_Lamelle_+00.xml). The window shading system had to be manually configured using the option "window shading" in the opening tab according to the template's description configured in the openings' tab.



- Additionally, the window shading – venetian blinds were configured using the 2% trigger according to the standard IES LM 83-12 – i.e. when more than 2% of the horizontal grid receives more than 1000 lux of direct sunlight, the shading system is activated. This meant that the configuration according to the specified limitation of the vertical irradiance of more than 120W/m² at the façade was not configured for daylighting simulations, even inputting this information for the thermal model – at the opening tab in the "edit mode". The configuration as specified in the template is used in EnergyPlus calculations at the simulation mode, but not for daylighting simulations.
- No changes were found for the simulations with window shading (venetian blind system) and without the window shading system as described in the results. This is probably explained because the import of BSDF data of the

BAUING_ILM_Lamelle could not be inputted, so the correct optical behavior of this venetian shading system was not properly simulated through the Radiance engine.

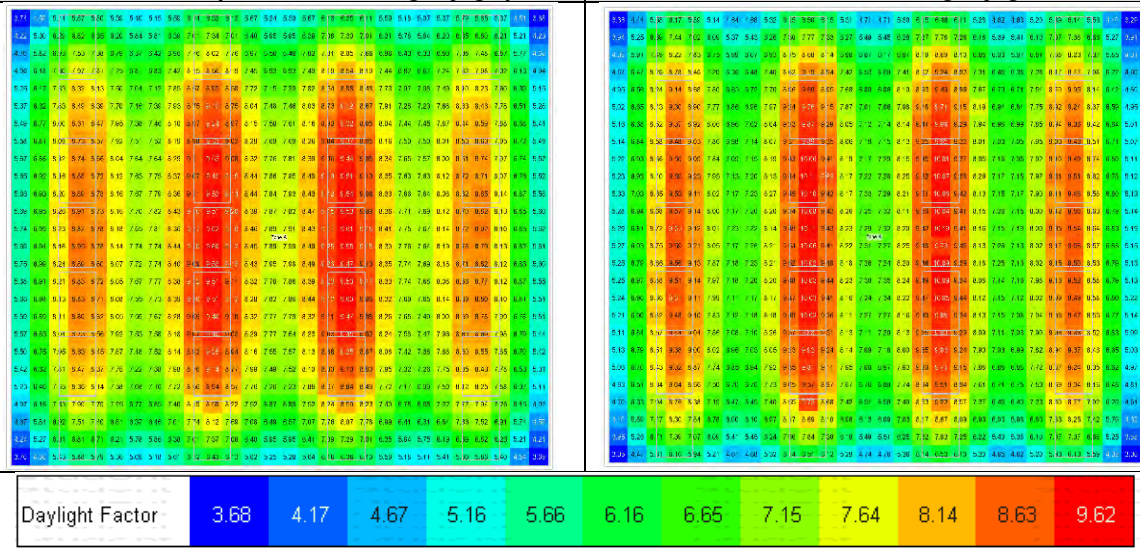
- Additionally, in DesignBuilder it was not possible to configure the window shading according to the vertical irradiance of more than 120 W/m² at the façade for daylight calculations. It was only permitted to configure the dynamic shading system according to the IES LM 83-12 Standard for the "Daylighting Mode". These two deviations from the template made it difficult to understand the reasons for the similarities in the results of both the template and the alternative context for the "office".
- Assumptions for the HVAC calc:
    - HVAC setpoints and schedule: for heating, 12°C and 22° C with CoP 0.90 for natural gas
    - Cooling setpoint: 24° C with CoP 5.
    - For HVAC, the total cooling and heating energy loads were calculated.
- No changes were seen between the template and the simulated alternative context for the "office" for annual energy use for HVAC.
- The energy consumption for lighting was simulated, but this calculation was carried out in EnergyPlus and this output was not calculated in the "Daylighting Mode" using the Radiance simulation engine. This was among the many deviations from the template that explained the same results of the energy consumption for electric lighting in both contexts – template and alternative context for the "office".

Results Hall

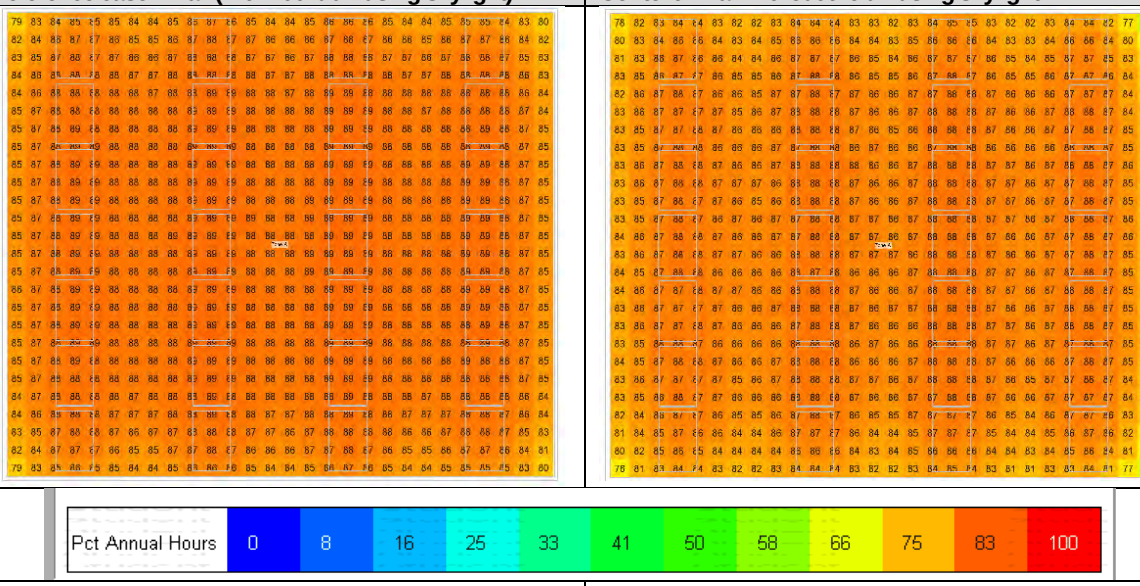
	Metric	Reference case – Hall with the diffusing property of the skylight	Context – Hall without the diffusing property of the skylight
Daylight Factor (CIE overcast sky)	**DF min**	3.67%	3.28%
	DF mx	9.62%	10.19%
	DF avg	7.52%	7.57%
	% area with at least 2% DF	100%	100%
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	100%	100%
	$ASE_{1000,250h}$	0%	44.64%
	% area with at least 50% $UDI_{100\text{-}3000}$	95.74%	100%
	$F_{DGP=0.40,exceed}$, view 1	NA	NA
	$F_{DGP=0.40,exceed}$, view 2	NA	NA
	$F_{DGP=0.40,exceed}$, view 3	NA	NA
	$F_{DGP=0.40,exceed}$, view 4	NA	NA
Circadian lighting	**mEDI**	NA	NA
Electric lighting	**Annual energy demand for electric lighting**	2514.71 kWh – 3.45 kWh/m²year	2514.71 kWh – 3.45 kWh/m²year
	Operating hours	663 h (12.75 h/week × 52 sem).	663 h (12.75 h/week × 52 sem).
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	6.99 kWh/m²year with air-conditioning system with CoP 5 (5088 kWh/year – electric lighting)	6.99 kWh/m²year with air-conditioning system with CoP 5 (5088 kWh/year – electric lighting)
	Ventilation	-	-
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	23531 kWh with natural gas (zone heating 21178 kWh – zone total heating and CoP 0.90)	23531 kWh with natural gas (zone heating 21178 kWh – zone total heating and CoP 0.90)
	Cooling	Zone cooling 25440.76 kWh – air-conditioning with CoP 5	Zone cooling 25440.76 kWh – air-conditioning with CoP 5
	Ventilation	NA	NA

Graphical outputs with tabular files attached

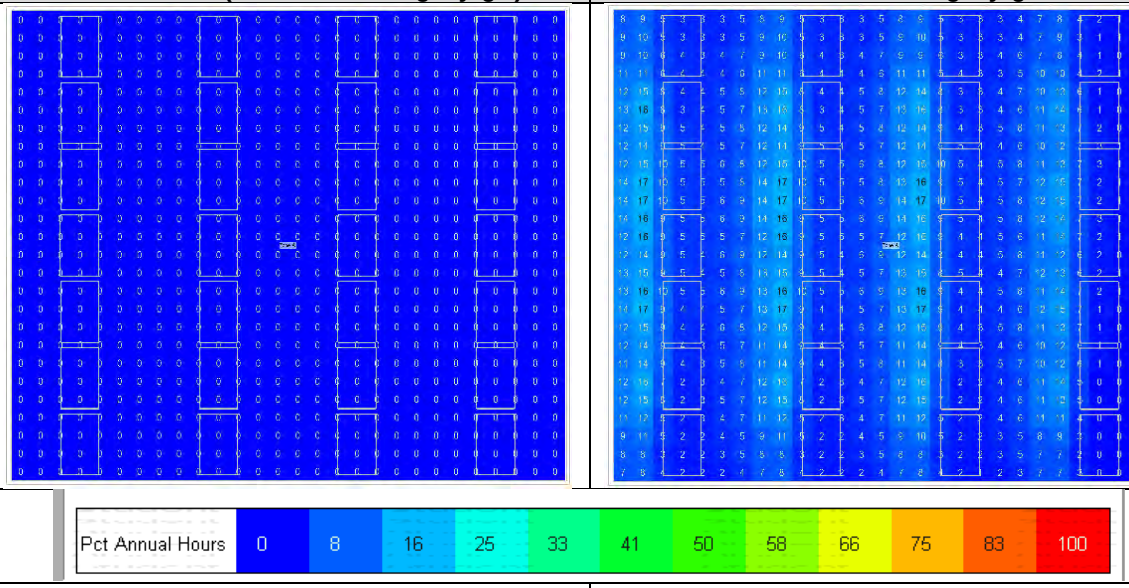
Daylight factor

Reference case – Hall (with 100% diffusing skylight)	Context – Hall without the diffusing skylight
	
Spatial distribution of Daylight Factor (DF [%]) for the hall with the 100% diffusing glazing	Spatial distribution of Daylight Factor (DF [%]) for the hall without the 100% diffusing glazing

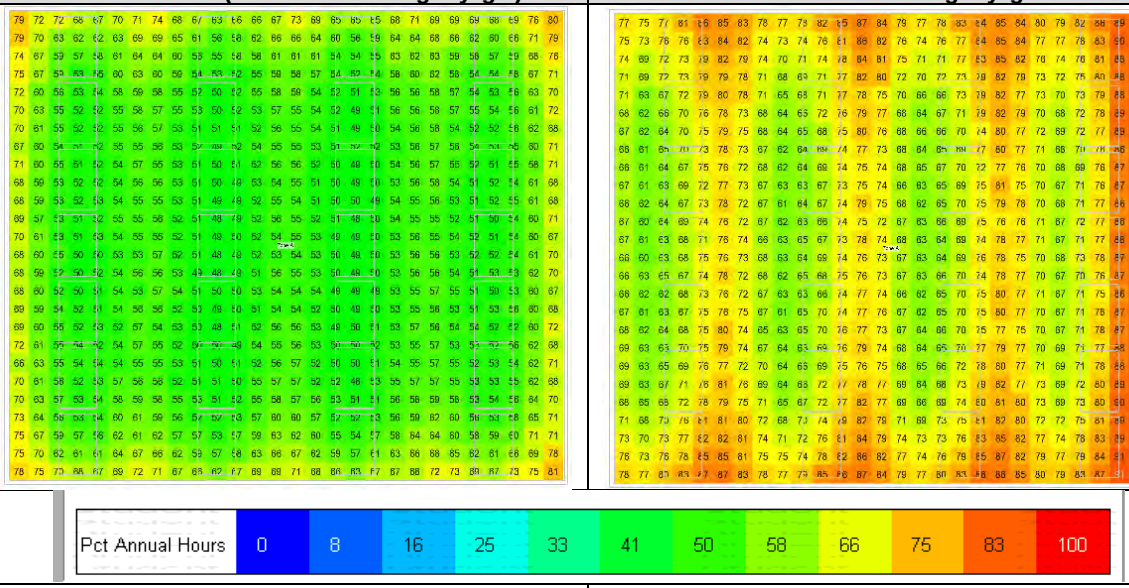
Daylight autonomy – 300 lux

Reference case – Hall (with 100% diffusing skylight)	Context – Hall without the diffusing skylight
	
Spatial distribution of Daylight Autonomy (DA [%]) for the hall with the 100% diffusing glazing	Spatial distribution of Daylight Autonomy (DA [%]) for the hall without the 100% diffusing glazing

ASE 1000 lux/250 hours

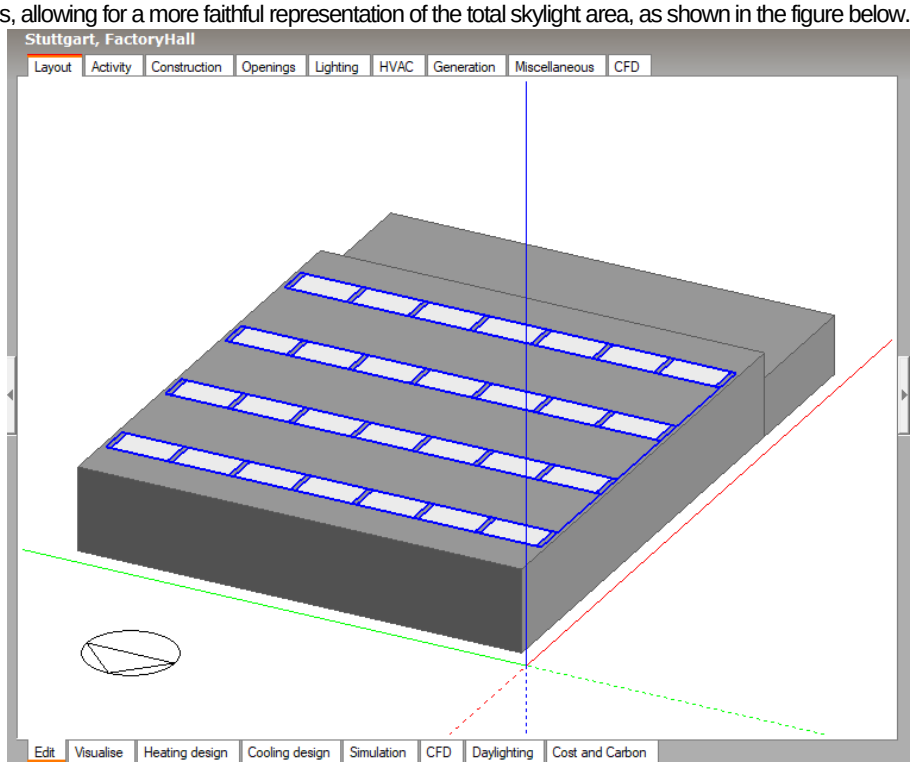
Reference case – Hall (with 100% diffusing skylight)	Context – Hall without the diffusing skylight
	
Spatial distribution of Annual Sunlight Exposure (ASE1000/250 [%]) for the hall with the 100% diffusing glazing	Spatial distribution of Annual Sunlight Exposure (ASE1000/250 [%]) for the hall without the 100% diffusing glazing

UDI 100-3000 lux

Reference case – Hall (with 100% diffusing skylight)	Context – Hall without the diffusing skylight
	
Spatial distribution of Useful Daylight Illuminance (UDI 100-3000 [%]) for the hall with the 100% diffusing glazing	Spatial distribution of Useful Daylight Illuminance (UDI 100-3000 [%]) for the hall without the 100% diffusing glazing

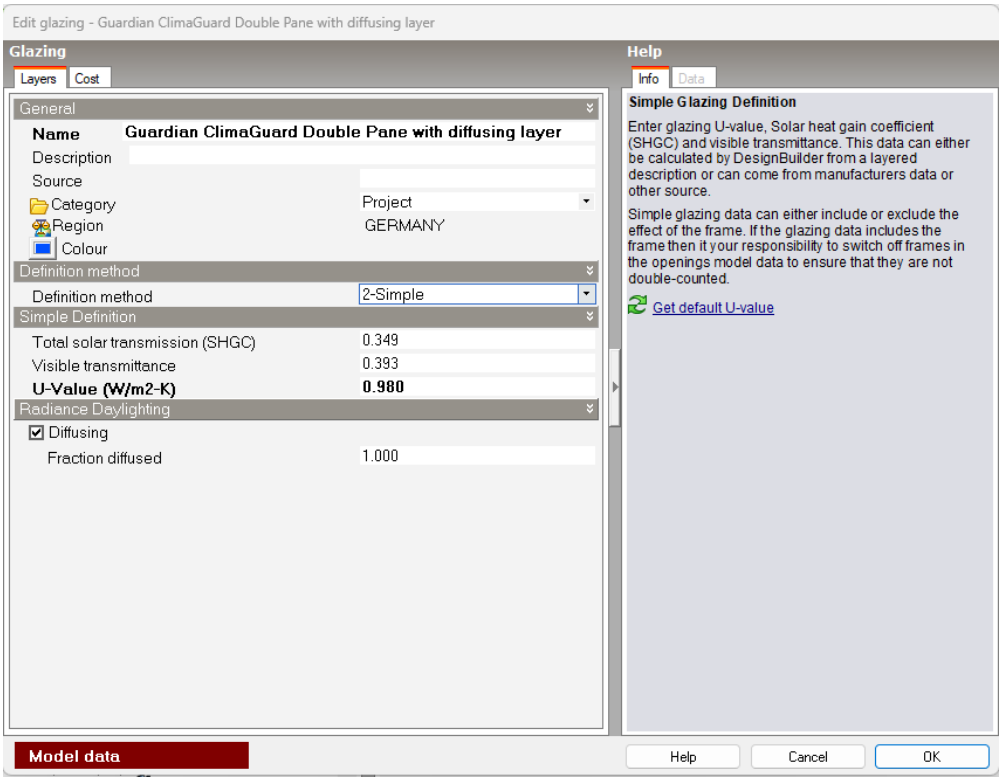
Specific comments on the simulation for the reference case "hall":

- The import of the geometry in the Rhino 3dm. file could not be directly imported to DesignBuilder, even using intermediary softwares, such as Revit or Autocad. Consequently, we had to model all the geometry in DesignBuilder itself.
- Due to geometric and modeling constraints within DesignBuilder v7.3, it was not possible to accurately represent the inclined geometry of the rooflights with its real 15° slope. The software's interface imposes limitations on complex angled roof elements and restricts flexible surface subdivision, making it extremely difficult to match both inclination and total glazed area. As a result, the apertures, corresponding to the skylights, were modeled as flat, horizontal surfaces, allowing for a more faithful representation of the total skylight area, as shown in the figure below.



- It was not possible to import the BSDF file for the window system *T70_ReferenceHall-Skylighy.xml.* Therefore, the glass properties were entered with a simpler setting and the diffusing layer was only configured by checking the option "Diffusing" in Radiance Daylighting in the openings' tab, with the percentage of 100% - for a perfectly diffusing window. The intention was to test the sensitivity of DesignBuilder to configure diffusing glazing materials and the effect on the daylight simulations' results.[8]

[8] More information about the diffusing layer can be found at https://designbuilder.co.uk/helpv7.0/Content/_Glazing_layer_data.htm. Last accessed on 30 June 2025.



- Import of the. ies or ReluxLum EulumDat File (.ldt) file of the lighting system was not possible, so only the power density, luminaire efficiency, and illuminance targets were configured. In total, 70 luminaires were considered to keep the illuminance level of 500 lux[9]. Color temperature of 4000 K was not considered in the simulations of artificial (electric) lighting, as no spectral data was inputted. All simulations were considered with a neutral spectrum.
- The energy consumption for electric lighting was simulated, but this calculation was carried out in EnergyPlus and the diffusing property of the skylight was not considered in these calculations. That probably explained why there were no changes in the final energy consumption for electric lighting.
- Assumptions for the HVAC calc:
    - HVAC setpoints and schedule: for heating, 12°C and 22° C
        - Assuming it is natural gas, CoP 0.90.
    - Cooling setpoint: 24° C with CoP 5 – Chiller/scroll compressor.
- The aim of the two contexts for the Hall, with and without the 100% diffusing fraction of the skylights, was to test the influence of this configuration and differences were seen in the results of the daylight simulations.
- According to the simulation results, there were significant differences in ASE values, of 45%, and a 5% difference in the results of UDI 100-3000 lux. These results confirmed that the diffusing property configured for the skylight was considered during the daylight calculations performed in Radiance.
- However, the energy consumption for electric lighting, cooling, and heating did not change. They were calculated in EnergyPlus in DesignBuilder and the calculations did not take into account the diffusing properties of the configured skylight.
- As DesignBuilder does not allow the import of BSDF files, this probably had an impact on daylight calculation and the output results for sDA, UDI and ASE. Additionally, the diffusing layer of the skylight had to be set using a simplified configuration and this was considered only for the daylight simulations.
- Given the results observed, DesignBuilder appears to be more appropriate for early design and design development stages. Its limitations - particularly the lack of support for importing BSDF data for complex fenestration systems and detailed luminaire photometry - make it less suitable for final specification phases and this led to less accurate results.

[9]References: Zumtobel Lighting GmbH. (2018). The lighting handbook (6th ed.). Dornbirn, Austria. https://www.zumtobel.com/PDB/teaser/EN/lichthandbuch.pdf.
OSRAM. (2002). *Manual luminotécnico prático*. OSRAM Brasil.

DIALux

Anna Pellegrino, Valerio R.M. Lo Verso, and Alberto Gremo (Politecnico di Torino, Turin, Italy)

Office

Simulation run by:

- Alberto Gremo, September 11, 2025

Software and hardware:

- **DIALux evo, version 5.13.2.0**
- Timestep calculations: Unknown, Information not provided by the user interface
- Simulation settings
  - Default settings
  - There are no specific differences between simulations depending on the phase of the project; however, the user can specify whether accounting for direct contribution only (to speed up the process) or define specific light scenes in advance to simulate them separately
- Sky model: sky models are based on CIE 110:1994 (clear, overcast or intermediate sky)
- Spectral: not available
- Total run time for simulation, general hardware description: 18.29 sec, on DELL Latitude 5550, Intel i7-1355U, 10 core CPU, 16 GB RAM

General comments on the simulation, deviations from the templates, other:

Daylight:

- *DIALux* does not support spectral simulations
- The venetian blind has been omitted, since the software does not allow to simulate dynamic elements
- *DIALux* does not support climate-based simulations

Electric lighting:

- Energy calculations can be launched according to a pre-defined template suggested for the user, following EN 12464-1:2021, EN 12464-2:2014, EN 15193:2008, DIN V 18599:2007, CIE 97:2005, CIE 154:2003; in such a template no edits are allowed, with a sensor plane height equal to 80cm (instead of 75cm)

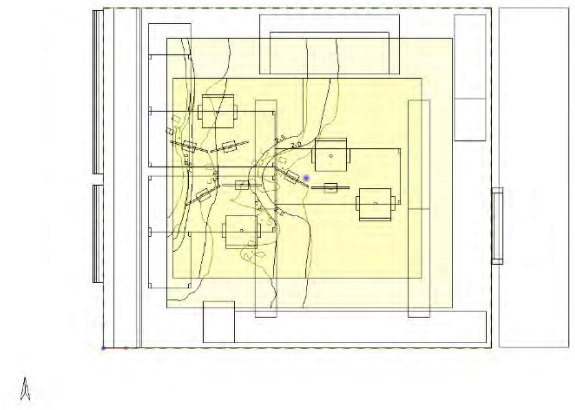
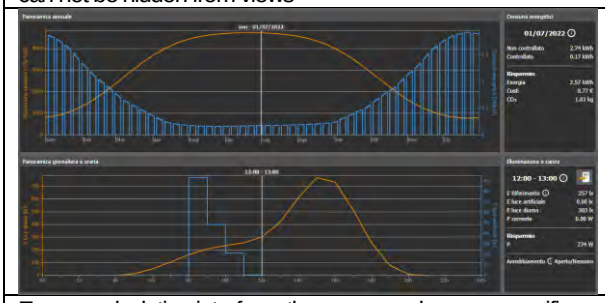
Description of alternative context for office:

- NA

Results Office

	Metric	Reference case	Context
Daylight Factor (CIE overcast sky)	**DF min**	0.63%	NA
	DF max	8.63%	NA
	DF avg	2.62%	NA
	% area with at least 2% DF	NA	NA
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	NA	NA
	$ASE_{1000,250h}$	NA	NA
	% area with at least 50% $UDI_{100\text{-}3000}$	NA	NA
	$F_{DGP=0.40,exceed}$ for view 1	NA	NA
	$F_{DGP=0.40,exceed}$ for view 2	NA	NA
Circadian lighting	**mEDI**	NA	NA
Electric lighting	**Annual electricity use for electric lighting**	227 kWh / yr (with sensor) 713 kWh / yr (no sensor)	NA
	LENI	8.43 kWh / m^2 / yr (with sensor) 26.5 kWh / m^2 / yr (no sensor)	NA
	Operating hours	2543 h	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

Example graphical output:

Reference case	Context
	NA
Spatial distribution of DF [%] for the reference office (window is on the left side, West); two overlapping grids are displayed, since *DIALux* automatically creates a default sensor plane with 1m offset from walls for daylight factor calculation, that can not be hidden from views	NA
	NA
Energy calculation interface; the user can choose a specific day and time of the year to verify electric usage profile depending on daylight conditions	NA

Specific comments on the simulation for the reference case "office":

- The building, office room and furniture had to be re-modelled inside *DIALux*, since a full-scale import of all the elements could have led to potential errors in the file reading, such as fully transparent surfaces
- For mountains modelling, the provided file "*shading lines*" has been modelled through *Grasshopper* script, as open surface resulting from a *loft* in 80m distance from the centre of the windows, exported as *.3ds* model (without any information about lights or materials) and then imported in *DIALux* interface
- A matte material with VLR = 10% has been applied to the external obstructions previously modelled from the shading lines
- To enable the calculation of the daylight factor, it is necessary to provide date and time for an overcast sky, even though results are unaffected by user choice

Hall

Simulation run by:

- Alberto Gremo, September 9, 2025

Software and hardware:

- DIALux evo, version 5.13.2.0
- Timestep calculations: Unknown, Information not provided by the user interface Simulation settings
  - Default settings
  - There are no specific differences between simulations depending on the phase of the project; however, the user can specify whether accounting for direct contribution only (to speed up the process) or define specific light scenes in advance to simulate them separately

- Sky model: sky models are based on CIE 110:1994 (clear, overcast or intermediate sky)
- Spectral: not available
- Total run time for annual simulation, general hardware description: 2min 11.49sec, on DELL Latitude 5550, Intel i7-1355U, 10 core CPU, 16 GB RAM

General comments on the simulation, deviations from the templates, other:

Daylight:

- *DIALux* does not support spectral simulations
- *DIALux* does not support climate-based simulations
- Skylights had to be modelled as planar skylights, ignoring the 15° angle provided by the reference file; this is due to the limitations of *DIALux* modelling, that do not allow to create a shed structure for the roof
- As a result of the edits for the roof structure, ceiling material had to be applied also to the skylight structure, since *DIALux* does not allow to assign multiple materials on a single surface

Electric lighting:

- Energy calculations can be launched according to a pre-defined template suggested for the user, following EN 12464-1:2021, EN 12464-2:2014, EN 15193:2008, DIN V 18599:2007, CIE 97:2005, CIE 154:2003; in such a template no edits are allowed, with a sensor plane height equal to 80cm (instead of 75cm)

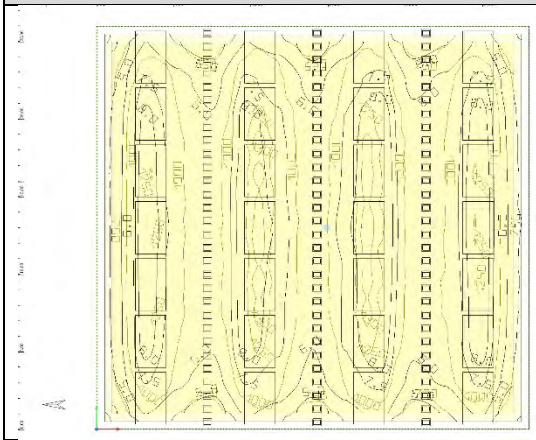
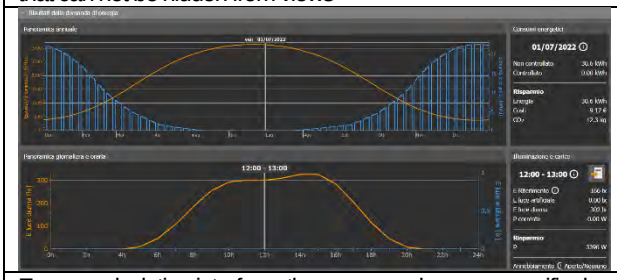
Description of alternative context for factory hall:

- NA

Results Hall

	Metric	Reference case	Context
Daylight Factor (CIE overcast sky)	**DF min**	3.10%	NA
	DF max	9.06%	NA
	DF avg	6.69%	NA
	% area with at least 2% DF	NA	NA
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	NA	NA
	$ASE_{1000,250h}$	NA	NA
	% area with at least 50% $UDI_{100\text{-}3000}$	NA	NA
	$F_{DGP=0.40,exceed}$, view 1	NA	NA
	$F_{DGP=0.40,exceed}$, view 2	NA	NA
	$F_{DGP=0.40,exceed}$, view 3	NA	NA
	$F_{DGP=0.40,exceed}$, view 4	NA	NA
Circadian lighting	**mEDI**	NA	NA
Electric lighting	**Annual energy demand for electric lighting**	1947 kWh / yr (with sensor) 7946 kWh / yr (no sensor)	NA
	LENI	2.67 kWh / m^2 / yr (with sensor) 10.9 kWh / m^2 / yr (no sensor)	NA
	Operating hours	2192 h	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

Example graphical output:

Reference case	Context
	
Spatial distribution of DF [%] for the reference hall (indication towards north is provided in the view); two overlapping grids are displayed, since *DIALux* automatically creates a default sensor plane with 1m offset from walls for daylight factor calculation, that can not be hidden from views	
	
Energy calculation interface; the user can choose a specific day and time of the year to verify electric usage profile depending on daylight conditions	

Specific comments on the simulation for the reference case “hall”:

- The hall had to be re-modelled inside *DIALux*, since a full-scale import of all the elements could have led to potential errors in the file reading, such as fully transparent surfaces
- Luminaire position was not specified, so they have been placed in the three bands between the skylights, 30 luminaires per row (a total of 90 luminaires, complying to CEN/TR 15193-2); this choice was supported by the lack of position-related metrics, such as uniformity or UGR that could be affected by different positions on the ceiling.
- To enable the calculation of the daylight factor, it is necessary to provide date and time for an overcast sky, even though results are unaffected by user choice

GB SWARE Dali

Xuran Guo, Hunan University, China; University of Innsbruck, Austria

Simulation run by:

- Xuran Guo, January, 2026

Software and hardware:

- GB SWARE Dali, version 20251201

- **Timestep calculations:**
  Backwards raytracing

- **Simulation settings**
  Settings for raytracing calculation:
  Two accuracy levels are provided and can be selected by the end user, allowing a balance between computational efficiency and simulation accuracy.
  Low-accuracy setting:
  -ab 4 -ad 256 -as 20 -ar 32 -aa 0.15 -st 1 -lw 0.05 -dj 0.7 -dr 0 -dp 32
  High-accuracy setting:
  -ab 5 -ad 1000 -as 20 -ar 300 -aa 0.1 -lr 6 -st 0.1500 -sj 1.0000 -lw 0.004 -dj 0.0000 -ds 0.200 -dr 2 -dp 512

- **Sky model:**
  Default (information on sky model, atmospheric data, etc. not provided as a configurable setting by the software tool)

- **Spectral:**
  Not available

- **Total run time for annual simulation, general hardware description:**
  1 min 1 s (Office, high-accuracy setting, annual daylight simulation)
  2 min 27 s (Hall, high-accuracy setting, annual daylight simulation)
  Computed on a Lenovo ThinkBook 16p G6 IAX laptop equipped with an Intel Core Ultra 9 275HX processor (8 performance, 16 efficiency cores) and 32 GB RAM

General comments on the simulation, deviations from the templates, other:

- Since the current version of the software does not support custom weather files, the Beijing weather file provided by the software was used as a reference

Description of alternative context for office:

- Location: Beijing, China

Description of alternative context for factory hall:

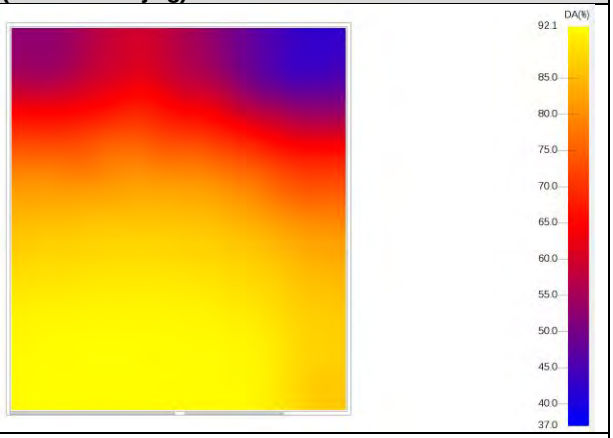
- Location: Beijing, China

Results Office

	Metric	Reference case	Context (Location: Beijing)
Daylight Factor (CIE overcast sky)	**DF min**	NA	2.30%
	DF mx	NA	16.10%
	DF avg	NA	5.62%
	% area with at least 2% DF	NA	100.00%
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	NA	70.00%
	$ASE_{1000,250h}$	NA	35.00%
	% area with at least 50% $UDI_{100\text{-}3000}$	NA	NA
	$F_{DGP=0.40,exceed}$ for view 1	NA	NA
	$F_{DGP=0.40,exceed}$ for view 2	NA	NA
Circadian lighting	**mEDI**	NA	NA

Electric lighting	**Annual electricity use for electric lighting**	NA	NA
	Operating hours	NA	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

Example graphical output:

Reference case	**Context (Location: Beijing)**
NA	
Spatial distribution of Daylight Autonomy (DA [%]) for the reference office (window is on the below, West)	Spatial distribution of Daylight Autonomy (DA [%]) for the office in context (window is on the below, West)

Specific comments on the simulation for the reference case "office":

- Artificial lighting was not included in the simulation.
- All reported values can be directly obtained from the software output and are available in visualized form.
- When calculating sDA, shading is applied when more than 2% of the analysis points receive direct sunlight, following the requirements of IES LM 83 12.
- The average value of $UDI_{100–3000}$ can be directly obtained, and corresponding visualization maps (e.g., Fig. 1) can be generated; however, the percentage of area with at least 50% $UDI_{100–3000}$ cannot be directly calculated by the software.
- DGP cannot be calculated, whereas DGI can be calculated for point-in-time conditions.

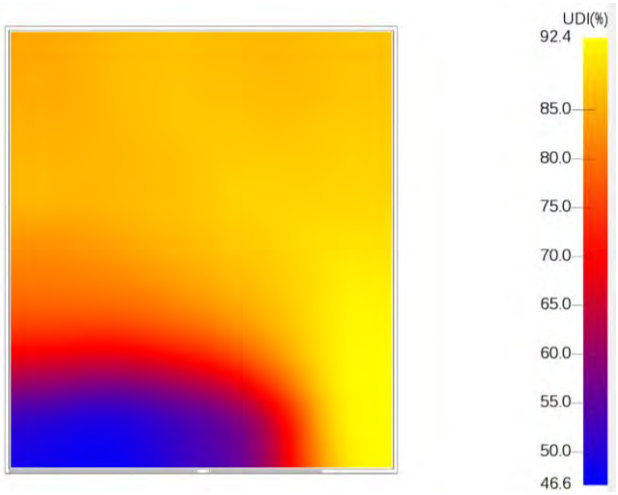
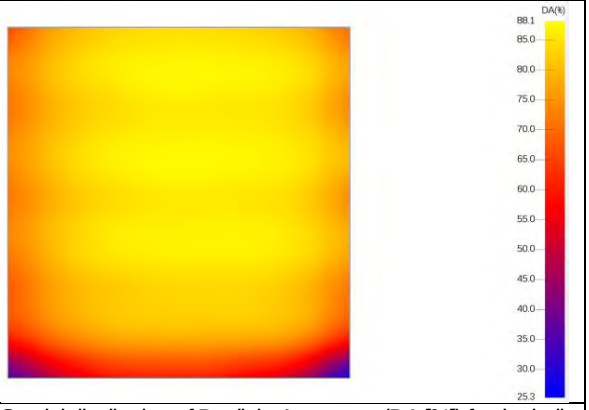


Fig. 1. Spatial distribution of $UDI_{100–3000}$ (%) for the office in context (window is on the below, West)

Results Hall

	Metric	Reference case	Context (Location: Beijing)
Daylight Factor (CIE overcast sky)	**DF min**	NA	1.60%
	DF mx	NA	6.60%
	DF avg	NA	4.57%
	% area with at least 2% DF	NA	99.00%
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	NA	3%
	$ASE_{1000,250h}$	NA	88%
	% area with at least 50% $UDI_{100\text{-}3000}$	NA	NA
	$F_{DGP=0.40,exceed}$, view 1	NA	NA
	$F_{DGP=0.40,exceed}$, view 2	NA	NA
	$F_{DGP=0.40,exceed}$, view 3	NA	NA
	$F_{DGP=0.40,exceed}$, view 4	NA	NA
Circadian lighting	**mEDI**	NA	NA
Electric lighting	**Annual energy demand for electric lighting**	NA	NA
	Operating hours	NA	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

Example graphical output:

Reference case	Context (Location: Beijing)
NA	
Spatial distribution of Daylight Autonomy (DA [%]) for the reference hall (skylights)	Spatial distribution of Daylight Autonomy (DA [%]) for the hall in context (skylights)

Specific comments on the simulation for the reference case "hall":

- The BSDF of the skylight could not be defined, glass with the same transmittance was used instead, without diffusing effect.
- Artificial lighting was not included in the simulation.
- All reported values can be directly obtained from the software output and are available in visualized form.
- When calculating sDA, shading is applied when more than 2% of the analysis points receive direct sunlight, following the requirements of IES LM 83 12.
- The average value of $UDI_{100–3000}$ can be directly obtained, and corresponding visualization maps (e.g., Fig. 2) can be generated; however, the percentage of area with at least 50% $UDI_{100–3000}$ cannot be directly calculated by the software.

- DGP cannot be calculated, whereas DGI can be calculated for point-in-time conditions.

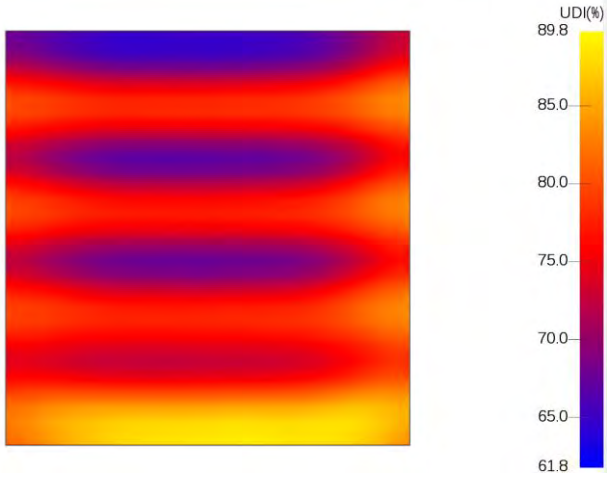


Fig. 2. Spatial distribution of UDI $_{100–3000}$ (%) for the hall in context (skylights)

LadybugTools

Morteza Hosseini, Aalborg University Copenhagen, Denmark

Simulation run by:

- Seyed Morteza Hosseini, June 27, 2025

Software and hardware:

- Ladybug Tools, version 1.8
- Timestep calculations: 1) backwards raytracing
- Simulation settings
  - If configurable by the end user:
    - Settings for raytracing calculation [-ab 5 -ad 15000 -as 2048 -c 1 -dc 0.5 -dp 256 -dr 1 -ds 0.25 -dt 0.25 -lr 6 -lw 6.67e-07 -ss 0.7 -st 0.5.]
    - Settings for renderings [key settings]: "-ab 5 -ad 15000 -as 2048 -c 1 -dc 0.5 -dp 256 -dr 1 -ds 0.25 -dt 0.25 -lr 6 -lw 6.67e-07 -ss 0.7 -st 0.5"
    - Specify the phase of the project the software was run for, e.g., simulations were intended for 1) early conceptual phase, 2) design development or 3) final specifications phase. [assuming the simulator will configure settings per desired level of accuracy]. It can possible to run simulation using Ladybug Tools in all three phases.
- Sky model: 1) default (information on sky model, atmospheric data, etc. not provided as a configurable setting by the software tool), 2) Perez with MF:4 subdivisions for sun disk, etc. Both options are possible through Ladybug Tools.
- Spectral: 1) not available.
- Total run time for annual simulation, general hardware description: **2.7 min**, on HP ZBook Studio G4 (2019), Intel(R) Core (TM) i7-7700HQ CPU @ 2.80GHz, 7 core CPU (4 performance, 3 efficiency cores), 16 GB RAM

General comments on the simulation, deviations from the templates, other:

- Software does not support spectral simulations, all surfaces were modelled spectrally neutral with RGB values all set to V(l) value

Description of alternative context for office: Context "Tehran"

- Tehran, weather data file, (semi-arid cool climate)

Description of alternative context for factory hall: Context "Tehran"

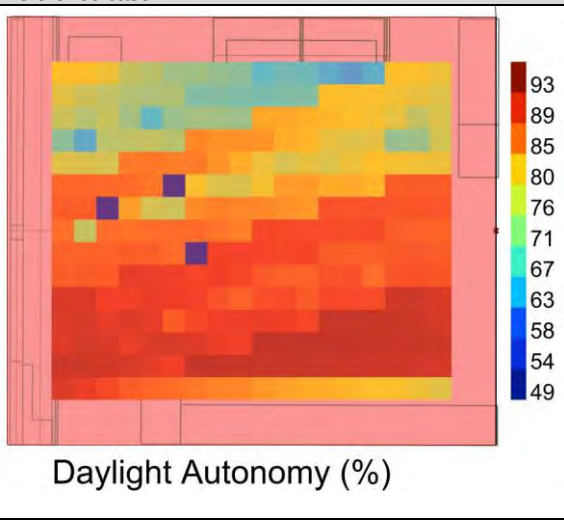
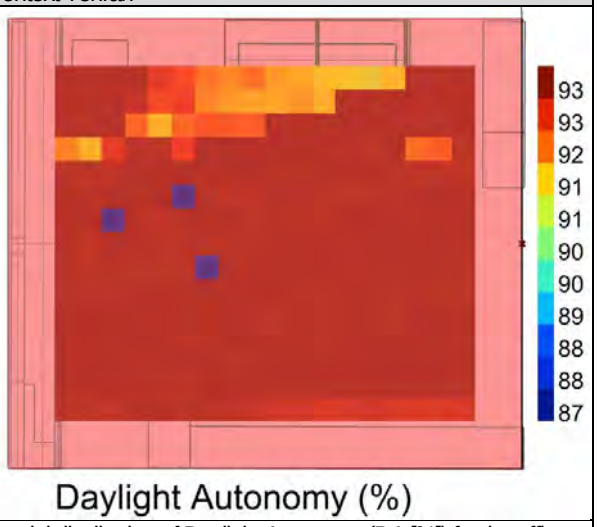
- Tehran, weather data file, (semi-arid cool climate)

Results Office

	Metric	Reference case	Context Tehran
Daylight Factor (CIE overcast sky)	**DF min**	0.0017 %	0.0017 %
	DF mx	11.67%	11.67%
	DF avg	3.72%	3.72%
	% area with at least 2% DF	61.71%	61.71%
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	98.88%	99.25%
	$ASE_{1000,250h}$	15.93%	47.78%
	% area with at least 50% $UDI_{100\text{-}3000}$	99.25%	82.96%
	Average $UDI_{100\text{-}3000}$	81.36%	71.32%
	$F_{DGP=0.40,exceed}$ for view 1	8.88%	26.11%
	$F_{DGP=0.40,exceed}$ for view 2	18.74%	41.75%
Circadian lighting	**mEDI**	NA	NA
Electric lighting	**Annual electricity use for electric lighting**	NA	NA
	Operating hours	NA	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level,	**Heating**	NA	NA
	Cooling	NA	NA

specify fuel – e.g., natural gas for heating)	**Ventilation**	NA	NA

Example graphical output:

Reference case	Context Tehran
	
Spatial distribution of Daylight Autonomy (DA [%]) for the reference office (window is on the left side, West)	Spatial distribution of Daylight Autonomy (DA [%]) for the office in context Tehran (window is on the left side, West)

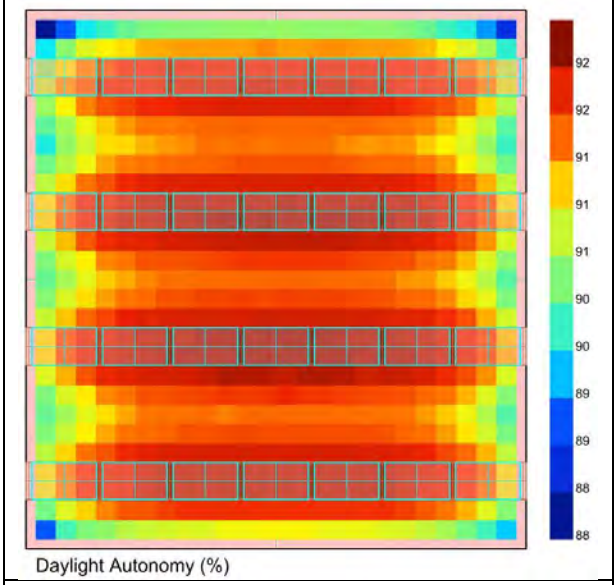
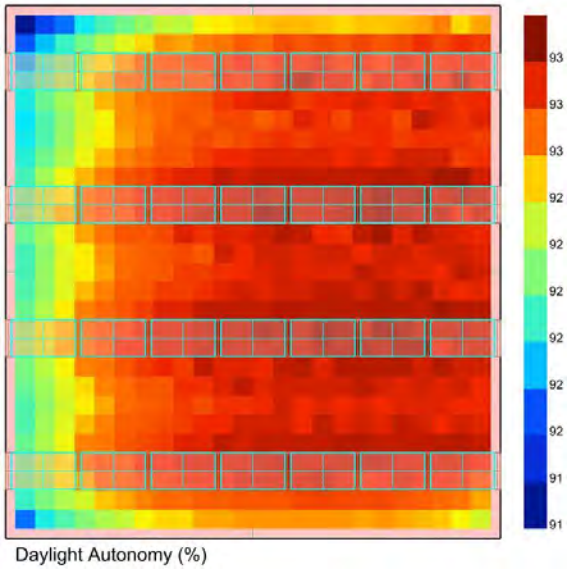
Specific comments on the simulation for the reference case “office”:

- Software Ladybug Tools can report glare for both options of a single view point and grid (point in time and annually). The simulation was run two times for Glare Analysis.

Results Hall

	Metric	Reference case	Context Tehran
Daylight Factor (CIE overcast sky)	**DF min**	7.29 %	7.29 %
	DF mx	20.38%	20.38%
	DF avg	15.39%	15.39%
	% area with at least 2% DF	100%	100%
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	100%	100%
	$ASE_{1000,250h}$	40.28%	82.1%
	% area with at least 50% $UDI_{100\text{-}3000}$	47.99%	1.85%
	Average $UDI_{100\text{-}3000}$	51.88%	22.64%
	$F_{DGP=0.40,exceed}$, view 1	44.03%	70.14%
	$F_{DGP=0.40,exceed}$, view 2	33.89%	69.7%
	$F_{DGP=0.40,exceed}$, view 3	34%	70.38%
	$F_{DGP=0.40,exceed}$, view 4	33.7%	69.45%
Circadian lighting	**mEDI**	NA	NA
Electric lighting	**Annual energy demand for electric lighting**	NA	NA
	Operating hours	NA	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

Example graphical output:

Reference case	Context Tehran
	
Spatial distribution of Daylight Autonomy (DA [%]) for the reference hall (skylights facing North)	Spatial distribution of Daylight Autonomy (DA [%]) for the hall in context Tehran (skylights facing North)

Specific comments on the simulation for the reference case “hall”:

-Software Ladybug Tools can report glare for both options of a single view point and grid (point in time and annually). The simulation was run 4 times for Glare Analysis for each Scenario (Reference and Context).

OWL

Marshal Maskarenj, Catholic University of Louvain, Belgium

Simulation run by:

- Marshal MASKARENJ, May/June 2025

Software and hardware:

- OWL (AnnuOWL+SpectrOWL)

- **Timestep calculations:**
- 2-phase DDS using Radiance. 3-channel for visual metrics (grid based + fDGP+ vertical metrics in 5 orientations),
- 81-channel for non-visual metrics (mEDI in 5 orientations).

- **Simulation settings**
- Settings for raytracing calculation [provide values for key settings; e.g. number of reflections, ambient bounces, etc.]
  - 5 ambient bounces/ab for daylight coefficients (1 for black room and direct sun),
  - ambient divisions/ad of 10000 (256 for direct sun),
  - limit weight/lw of 0.0001 (0.001 for DDS),
  - 16 parallel threads (n).
  - Sensor-based illuminance calculation mode enabled (-I+) in rfluxmtx and rtcontrib.
  - For direct sun, no jittering applied (-dj 0, -dt 0).

- **Specify the phase of the project the software was run for:**
  Simulations were intended for
  - 1) early conceptual phase (3-channel evaluations for grid and fDGP),
  - 2) design development (81-channel evaluations + electric light optimization and operations)

- **Sky model:**
  - sun disk generated by Reinhart sky subdivision with MF:6 (5165 sun patches) with angular size of sun at 0.533 degrees.
  - Custom radiance sky component for 3-channel evaluations, but with dynamic sky color per CCT bin via gendaymtx-based colored sky (-c R G B), aimed to have a spectrally dynamic simulation (with -m 1 for annual scenes and for black room model).
  - The sun model remains white colored in 3-channel and 81-channel simulations (with -m 6).

- **Spectral**:
  - 3-channel for most evaluations,
  - 81-channel (with varying sky-spectra each annual hour in 10 CCT-bands) for multispectral mEDI evaluations

- Total run time for annual simulation, general hardware description:
- **Hardware**: Laptop: Lenovo Legion 15 2021, Processor: 11th Gen Core i7-11800H @2.3 GHz, 16GB RAM, 4GB graphics card.
- Runtime described after each simulation.

General comments on the simulation, deviations from the templates, other:

- Factory hall base geometry simulated without the diffusing layer. (Diffusing layer added for alternative context.)
- 3 phase yet to be developed; so BSDF not used for 'Office' geometry base case. (Blinds physically modeled in the alternative case.)
- For multispectral simulations, annual sky spectra in 81 channels was pre-calculated using spectral sky models, and annual hourly sky spectra was binned in 7 bands (<3000K,3000K to 4000K,4000K to 5000K,5000K to 6000K,6000K to 7000K,7000K to 8000K, >8000K) prior to running multispectral simulations. The simulations therefore are for spectrally dynamic skies for each annual hour.

Description of alternative context for office: Blinds (fully open model) physically modeled in the geometry.

Description of alternative context for factory hall: Diffusing layer with 60% translucency added to the roof light glass.

Results Office

	Metric	Reference case	Context (with open blinds 0°)
Daylight Factor (CIE overcast sky)	**DF min**	0	0
	DF mx	9.45	2.87
	DF avg	2.22	0.73
	% area with at least 2% DF	39.03	1.27
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	60.25%	28.42%
	$ASE_{1000,250h}$	39.03%	7.07%
	% area with at least 50% $UDI_{100-3000}$	77.22%	74.54%
	$F_{DGP=0.40,exceed}$ for view 1 Point on south	0, 0, 0, 9.38% (N, E, S, W)	0, 0, 0, 0%
	$F_{DGP=0.40,exceed}$ for view 2 Point on north	0, 0, 0, 20.91% (N, E, S, W)	0, 0, 0, 2.03%
Circadian lighting	**mEDI**	3, 3 (N); 0, 0 (E); 1, 3 (S); 3, 3 (W)	1, 1 (N); 0, 0 (E); 0, 1(S); 3, 3 (W)
Electric lighting	**Annual electricity use for electric lighting**	8.94 KWh (sensor on position 2 (point on north)	15.85 KWh
	Operating hours	91.25 hours (operating 8-18h all days of the year)	161.77 hours
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

Specific comments on the simulation for the reference case "office":

- For base case (without blinds), simulation took 12 minutes for daylight + electric light, and 25 minutes for multispectral evaluations ~ 37 minutes
- For alternative case (blind physically modeled), simulation took 23 minutes seconds for daylight + electric light and 29.5 minutes for multispectral evaluations ~ 52 minutes.
- Spectral sky binned in 7 bands: <3000K (6h), 3000-4000K (10h), 4000-5000K (12h), 5000-6000K (519h), 6000-7000K (770h), 7000-8000K (623h), and >8000K (2438h) for Innsbruck.
- Multispectral simulations generated 8760 x 81 channel data for both occupied position across four orientations, which was reduced to mEDI evaluations.

Results Hall

	Metric	Reference case	Context (with translucent layer)
Daylight Factor (CIE overcast sky)	**DF min**	0%	0%
	DF mx	14.5%	8.42%
	DF avg	8.25%	4.68%
	% area with at least 2% DF	77.7%	77.7%
	$sDA_{300,50\%}$	77.7%	77.56%
	$ASE_{1000,250h}$	77.7%	77.35%

Daylight metrics based on annual results			
	% area with at least 50% $UDI_{100-3000}$	77.7%	77.77%
	$F_{DGP=0.40,exceed}$, view 1	0.9% (N)	0%
	$F_{DGP=0.40,exceed}$, view 2	0% (E)	0%
	$F_{DGP=0.40,exceed}$, view 3	0% (S)	0%
	$F_{DGP=0.40,exceed}$, view 4	0% (W)	0%
Circadian lighting	**mEDI**	3 (N), 3 (E), 3 (S), 3 (W)	1 (N), 1 (E), 1 (S), 1 (W)
Electric lighting	**Annual energy demand for electric lighting**	3.6 kWh (sensor at occupant position)	4.8 kWh
	Operating hours	66.67 hours (operating 8-18h all days of the year)	88.94 hours
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

Specific comments on the simulation for the reference case "hall":

- Simulation took 10 minutes for Annual Daylight evaluations (grid + vertical) + 8 minutes for electric light simulation + 24.5 minutes for multispectral evaluations, so total being ~ 43 minutes for base case – and an equivalent amount of time for alternative case for Hall Geometry.
- Pre-calculation of annual spectral sky data took ~30 minutes to generate the text-based spectral sky file (one time effort)
- Spectral sky binned in 7 bands: <3000K (10h), 3000-4000K (7h), 4000-5000K (11h), 5000-6000K (481h), 6000-7000K (758h), 7000-8000K (578h), and >8000K (2534h) for Stuttgart.
- Multispectral simulations generated 8760 x 81 channel data for each occupied position across four orientations, which was reduced to mEDI evaluations.

PKPM

Boyu Mao, China Academy of Building Research, China

Simulation run by:

- Boyu Mao, December, 2025

Software and hardware:

- PKPM GBP, version 2025.8.30
- Timestep calculations: Unknown, Information not provided by the user interface
- Simulation settings: Default settings
- Sky model: default (CIE standard sky)
- Spectral: not available
- Total run time for annual simulation, general hardware description: Due to the inability to customize annual climate data, a full-year simulation analysis was not performed.

General comments on the simulation, deviations from the templates, other:

This software is strictly aligned with Chinese standards such as the Green Building Evaluation Standard. It can be used as a judgment tool to assess compliance with a limited set of parameters defined in these standards. However, its functionality has extremely limited room for expansion and is not recommended for use as a research tool.

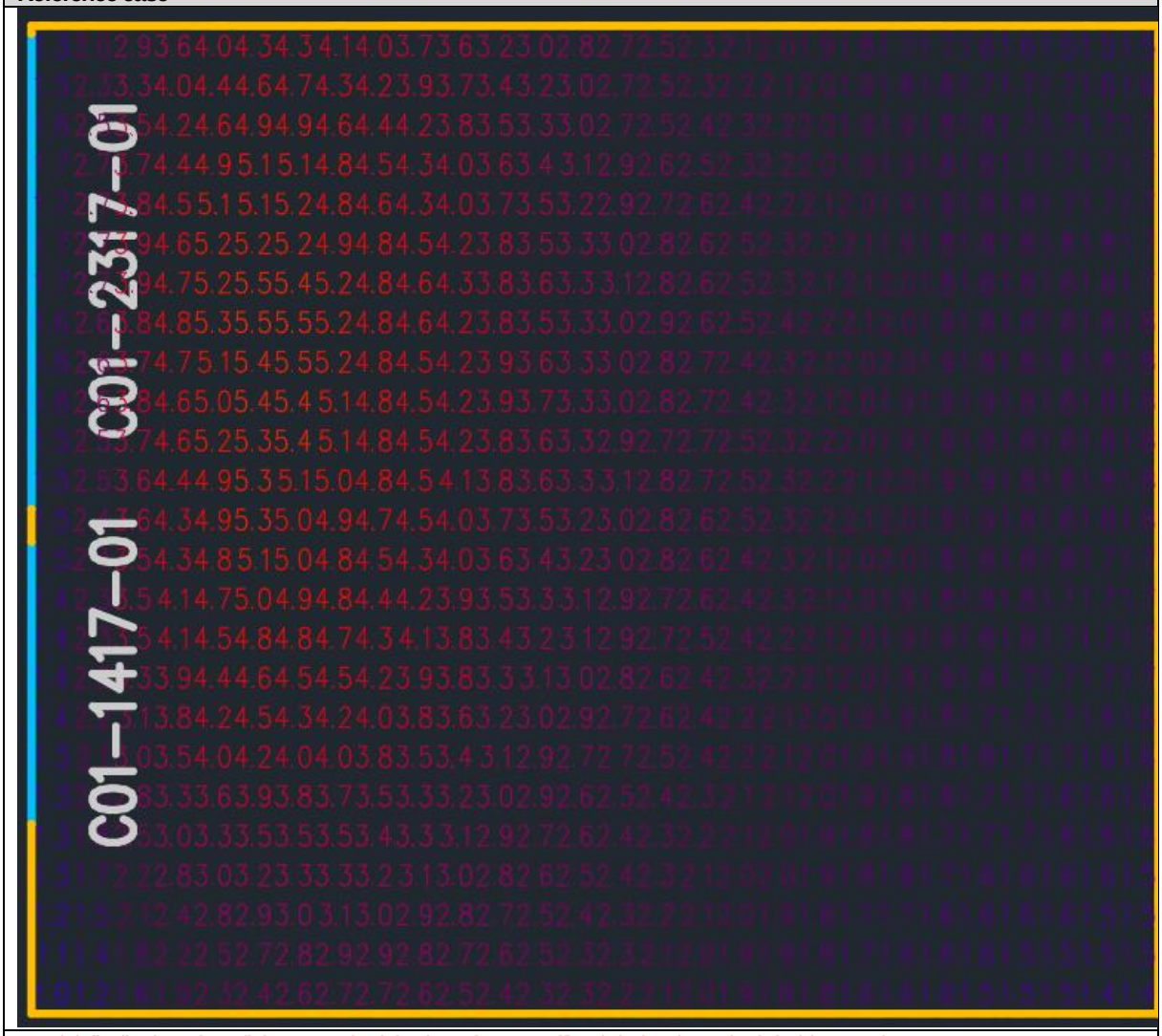
- Modeling utilizes planar modeling based on AutoCAD, resulting in inflexible operation.
- Reflection interfaces within a room can only be assigned a simple reflectance value (incapable of describing diffuse transmission phenomena).
- The transmittance of interior windows is limited to fixed preset options (does not support BSDF) or the use of certified material parameters (manufacturer-recommended); flexible customization is not possible.
- Project location support is limited to Chinese cities.
- It cannot import annual climate data files (e.g., EPW).
- Window shading systems cannot be added.
- Measurement points cannot be flexibly arranged (e.g., the distance from a measurement point to a wall cannot be set).

Results Office

	Metric	Reference case
Daylight Factor (CIE overcast sky)	**DF min**	0.85 %
	DF mx	8.46 %
	DF avg	2.76 %
	% area with at least 2% DF	NA
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	NA
	$ASE_{1000,250h}$	NA
	% area with at least 50% $UDI_{100\text{-}3000}$	NA
	$F_{DGP=0.40,exceed}$, view 1	NA
	$F_{DGP=0.40,exceed}$, view 2	NA
	$F_{DGP=0.40,exceed}$, view 3	NA
	$F_{DGP=0.40,exceed}$, view 4	NA
Circadian lighting	**mEDI**	NA
Electric lighting	**Annual energy demand for electric lighting**	NA
	Operating hours	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA
	Cooling	NA
	Ventilation	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA
	Cooling	NA
	Ventilation	NA

Example graphical output:

Reference case



Spatial distribution of Daylight Factor (DF) for the reference office (window is on the left side, West)

Results Hall

	Metric	Reference case
Daylight Factor (CIE overcast sky)	**DF min**	2.90 %
	DF mx	9.20 %
	DF avg	6.85 %
	% area with at least 2% DF	NA
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	NA
	$ASE_{1000,250h}$	NA
	% area with at least 50% $UDI_{100\text{-}3000}$	NA
	$F_{DGP=0.40,exceed}$, view 1	NA
	$F_{DGP=0.40,exceed}$, view 2	NA
	$F_{DGP=0.40,exceed}$, view 3	NA
	$F_{DGP=0.40,exceed}$, view 4	NA
Circadian lighting	**mEDI**	NA
Electric lighting	**Annual energy demand for electric lighting**	NA
	Operating hours	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA
	Cooling	NA
	Ventilation	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA
	Cooling	NA
	Ventilation	NA

Example graphical output:

Reference case



Spatial distribution of Daylight Factor (DF) for the reference hall (skylights facing North)

Radiance

Simulation run by:

- Greg Ward, January 2026
- David Geisler-Moroder, March 2026

Software and hardware:

- Radiance, version 6.1a (latest HEAD)
- Timestep calculations: backwards ray-tracing to compute flux transfer matrices in 20-band spectral calculations.
- 3-phase matrix method (same 20 bands) with **gensdaymtx** MF:4 sky created from EPW file for daytime hours (8-17) only.
- 3-phase method with direct-only matrix used for ASE calc.
- Spectral data for glazing was incorporated in all calcs.
- Simulation settings:
    - **rfluxmtx** -ab 3 -ad 8192 -lw 1e-6 -cs 20 *(sky-window flux transfer D matrix)*
    - **rfluxmtx** -ab 5 -ad 102400 -lw 1e-7 -cs 20 -I+ *(work-plane sensor to window V matrix)*
    - **rfluxmtx** -cs 20 -I+ -ab 1 -ad 100000 -lw 1e-7 *(direct-only for ASE)*
- Ray-tracing step for D matrix was 25 minutes on 13 cores (2024 Apple Mac mini M4pro). V matrix took 32 minutes on 4 cores of 2012 MacBook Pro. ASE run was a few minutes on one core of 2012 MacBook Pro. *(M4pro is about 2.5x faster per core compared to 2012 Intel.)*
- The only time-consuming matrix calcs were multiplying the 20-component 2306x3650 annual daylight matrix against the 145x2306 daylight matrix, which took 27 seconds on one core of M4pro.

General comments:

- Nearly all calculations used manual scripting, although some could have been optimized using frads and pyRadiance tools
- No effort was made to compute daylight factors and related metrics
- All simulations were run using 20 spectral components over visible wavelength range
- Daytime operating hours were assumed to be 7 days/week from 8-18 hours, for 4015 hours total

Description of alternative context for office: Blinds down in afternoon

- External sensor control algorithm was replaced with simple afternoon-down algorithm for window blinds, using same +75° blind angle independent of weather tape

Results Office

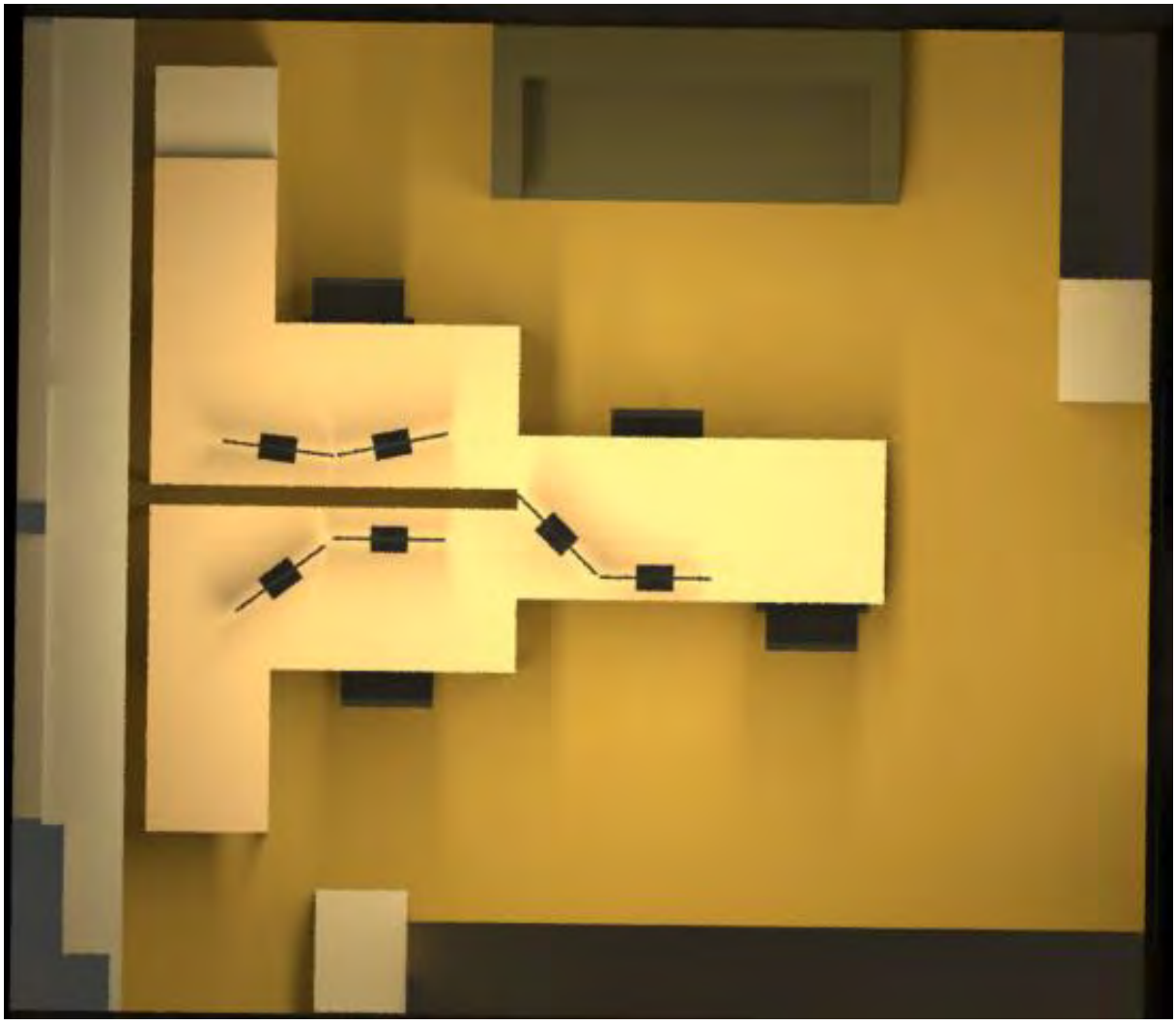
	Metric	Reference case	Context blinds down afternoon
Daylight Factor (CIE overcast sky)	DF min	1.1%	DF with blinds: 0.06%
	DF mx	11.1%	DF with blinds: 0.40%
	DF avg	3.8%	DF with blinds: 0.17%
	% area with at least 2% DF	71.4%	DF with blinds: 0.0%
Daylight metrics based on annual results	$sDA_{300,50\%}$	78.6%	5.3%
	$ASE_{1000,250h}$	53.4%	53.4%
	% area with at least 50% $UDI_{100\text{-}3000}$	78.6%	0%
	$F_{DGP=0.40,exceed}$ for view 1	0.3%	0%
	$F_{DGP=0.40,exceed}$ for view 2	1.1%	0%
Circadian lighting*	mEDI (vw1) (vw2) = mlux/1.10	121 lx 117 lx	121 lx 117 lx
Electric lighting	Annual electricity use for electric lighting	282 kWh / yr	439 kWh / yr
	Operating hours	2267 h	2932 h
	Heating	N/A	N/A
	Cooling	N/A	N/A

Annual electricity use for HVAC (zonal level)	Ventilation	N/A	N/A
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	Heating	N/A	N/A
	Cooling	N/A	N/A
	Ventilation	N/A	N/A

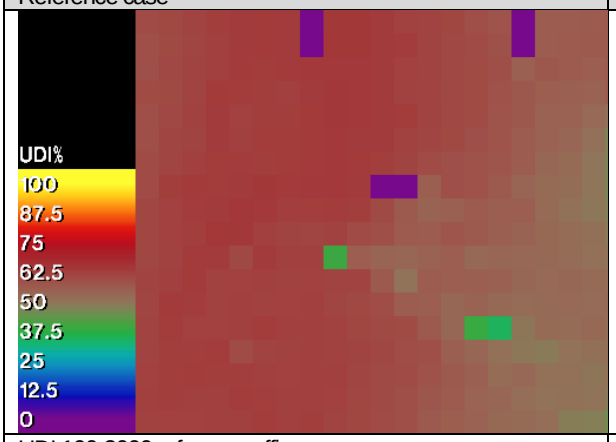
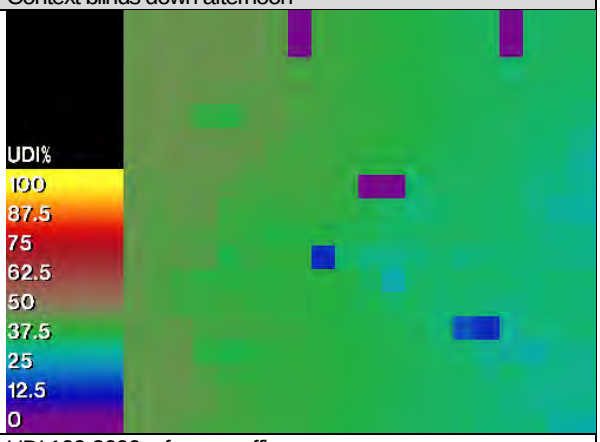
*Electric lights only @ 100%, though 50% level achieves target work-plane illuminance

Example graphical output:

I chose to plot UDI (% of year in 100-3000 lux range) over work plane, since the summary statistic does not reflect the overall similarity between the designed control condition and the afternoon blinds condition.
This is the plan view that roughly corresponds to the work-plane array, which contains 21x18 positions:



Plan view of office space at night, west window on the left.

Reference case	Context blinds down afternoon
	
UDI 100-3000 reference office (window is on the left side, West)	UDI 100-3000 reference office (window is on the left side, West)

Comments on the simulation for “office”:

- The sensor grid is aligned to the X and Y axes, though the building is slightly askew. I only noticed this issue towards the end of my analysis.
- A few dark spots in work plane analysis correspond to points that ended up in arms of sofa and back of chair.
- Lighting electric usage was based on control condition that maintained 625 lux over work plane using simulated proxy sensor in ceiling and masked to desk area.
- The spectra for the glazing and luminaire were manually added on top of the Radiance model provided
- Rather than simulating actual work-plane sensors, which would be impractical in a real space, we simulated a ceiling-mounted sensor masked to the desk area as a proxy for work-plane illuminance to control electric light dimming level.
- Electricity use assumes lossless dimming down to 10%, then stays at this level until 0% dimming is indicated, when it switches off.
- Lighting operating hours taken as time where dim level is non-zero.

Results Hall

	Metric	Reference case	Context
Daylight Factor (CIE overcast sky)	**DF min**	N/A	N/A
	DF mx	N/A	N/A
	DF avg	N/A	N/A
	% area with at least 2% DF	N/A	N/A
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	100%	N/A
	$ASE_{1000,250h}$	99.7%	N/A
	% area with at least 50% $UDI_{100\text{-}3000}$	81.3%	N/A
	$F_{DGP=0.40,exceed}$, East	0%	N/A
	$F_{DGP=0.40,exceed}$, North	8.9%	N/A
	$F_{DGP=0.40,exceed}$, South	0%	N/A
	$F_{DGP=0.40,exceed}$, West	0%	N/A
Circadian lighting	**mEDI @ 100% lvl**	143.0 lx	N/A
Electric lighting	**Annual energy demand for electric lighting**	770.3 kWh	N/A
	Operating hours	823 hr	N/A
Annual electricity use for HVAC (zonal level)	**Heating**	N/A	N/A
	Cooling	N/A	N/A
	Ventilation	N/A	N/A
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	N/A	N/A
	Cooling	N/A	N/A
	Ventilation	N/A	N/A

Relux

Adam Bladowski, Gdańsk University of Technology, Poland

Simulation run by:

- Adam Bladowski, 21 Sept 2025

Software and hardware:

- Relux, version 2025.1.8.0
  - Average Indirect Fraction
  - Sky models: CIE Overcast (for DF), Perez sky with EPW (for annual)
  - Timestep: hourly
  - Occupied hours: 08:00–18:00
- CPU: Intel(R) Core (TM) i7-7700HQ CPU @ 2.80GHz (2.81 GHz)
- RAM: 16,0 GB
- GPU: Nvidia GForce GTX 1070

General comments on the simulation, deviations from the templates, other:

- The geometric model, originally provided in Rhino's .3dm format, was not directly supported by Relux. To ensure compatibility, the file was first converted to .obj using Rhino and subsequently imported into Blender. With the aid of Blender CAD, the geometry was prepared and exported in .ifc format. However, during the import process, Relux classified the model as fitout elements rather than as architectural structures, which led to erroneous behavior in the simulation environment. To resolve this issue and enable accurate analysis, the architectural walls were reconstructed manually within Relux, while the fitout components were incorporated from the converted .obj model.

Description of alternative context for office:

- NA

Description of alternative context for factory hall:

- NA

Results Office

	Metric	Reference case	Context
Daylight Factor (CIE overcast sky)	**DF min**	0%	NA
	DF mx	7.33%	NA
	DF avg	1.51%	NA
	% area with at least 2% DF	72,73%	NA
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	NA	NA
	$ASE_{1000,250h}$	NA	NA
	% area with at least 50% $UDI_{100\text{-}3000}$	NA	NA
	$F_{DGP=0.40,exceed}$ for view 1	NA	NA
	$F_{DGP=0.40,exceed}$ for view 2	NA	NA
Circadian lighting	**mEDI**	216 lx	NA
Electric lighting	**Annual electricity use for electric lighting**	NA	NA
	Operating hours	NA	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

TRNSYS 18

Luigi Tufano, Giovanni Ciampi, University of Campania, Italy

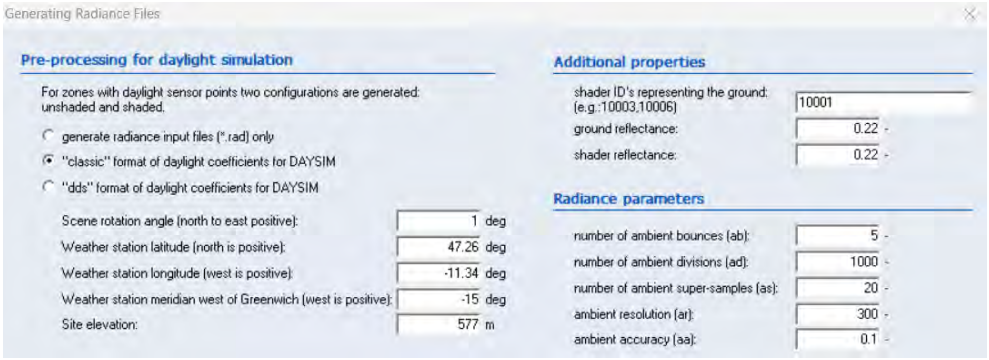
Simulation run by:

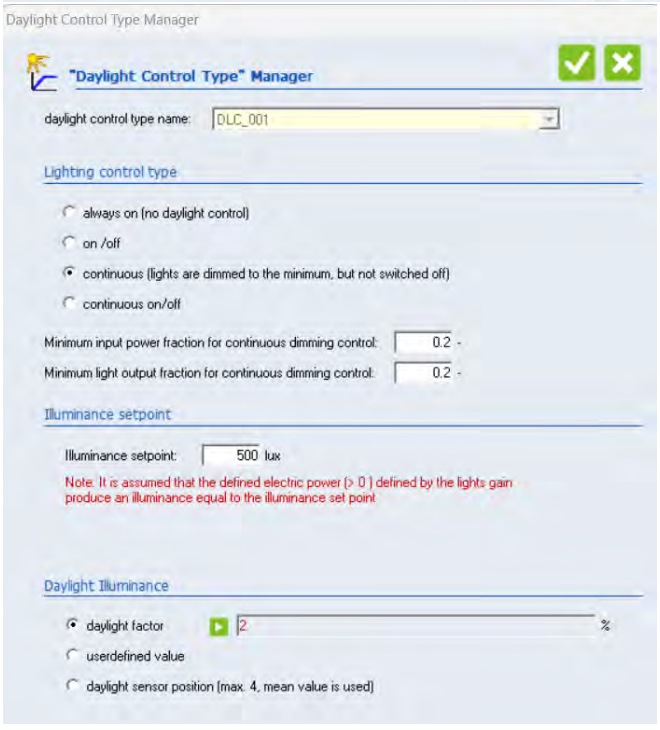
- Luigi Tufano, Giovanni Ciampi, November 4, 2025

Software and hardware:

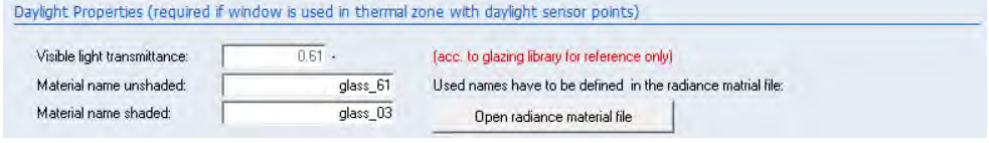
Reference case “office”:

- TRNSYS: 18.05.0001, version 6.0.0.15
- Timestep calculations: 1 hour, from 0:00 January 1st to 24:00 December 31st
- Simulation settings:
  TRNBuild





Daylight modes of thermal zone → Shading control for daylight sensor points → “userdefined control” equal to 1
Airodes → External shad. factor, Shading control: integrated radiation control acc. to window type → input from Simulation Studio (0 = Lamelle +00, 1 = Lamelle +75)
Window → “Bauing_ILM_Lamelle.dat”



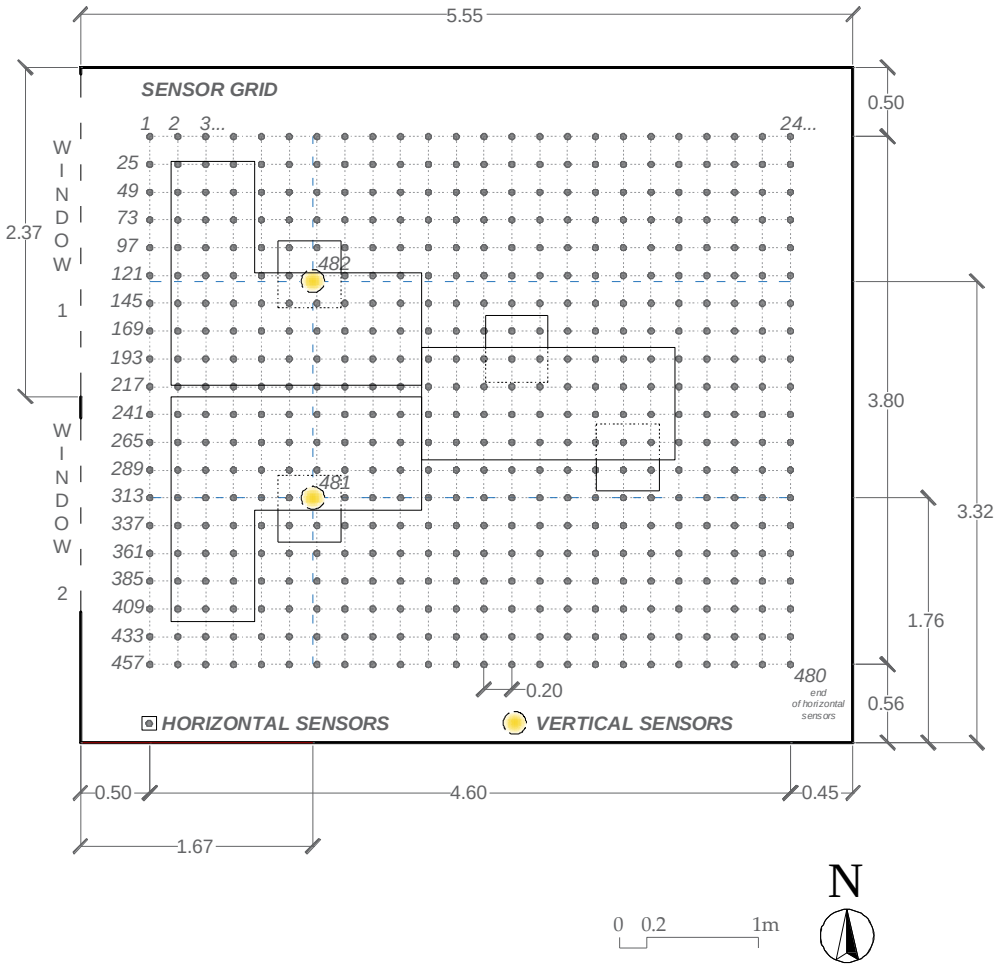
Absorption coefficient → Walls: 0.1312, Ceiling: 0.2816, Floor: 0.5992
Simulation Studio

Sky model: Perez 1999 Model
Spectral: 1) not available

- Total run time for annual simulation, general hardware description: 1hr 5min, on ASUS Vivobook 16x, AMD Ryzen 9 5900HX 3.30 GHz, 8-core CPU (16 threads), 16 GB RAM

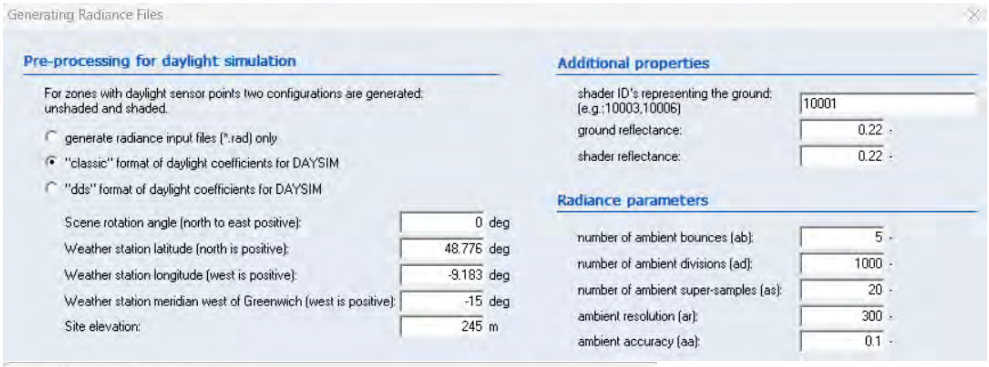
General comments on the simulation, deviations from the templates, other:

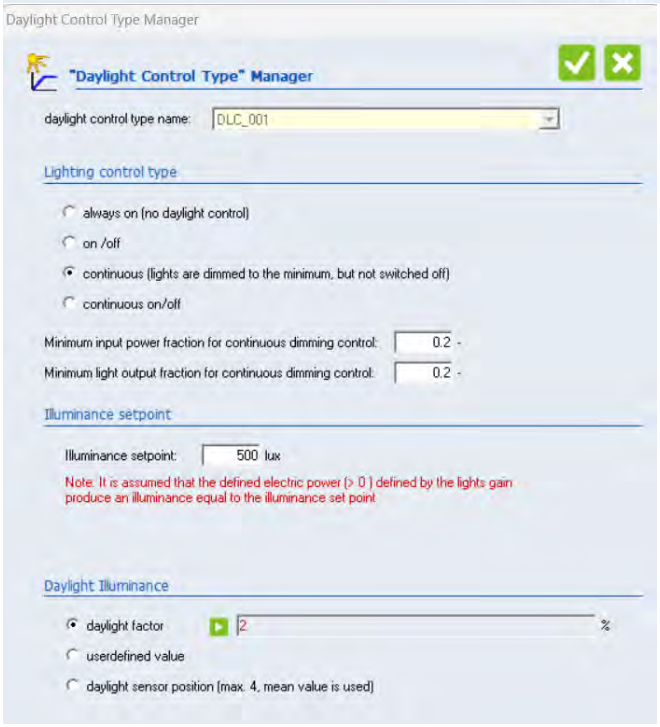
- The software does not permit including luminaries for photometric calculation; “lighting control type” is only utilized to manage the internal gains related to the artificial lighting system and to estimate the electric energy consumption linked to a fixed illuminance set point.
- Software reports the following indexes: DA_300 (%), CDA_300 (%), UDI_100_2000 (%), and DF (%) for each installed sensor; however, a file with the illuminance values hour by hour for each installed sensor is provided.
- The following daylight sensor grid was used in the simulation



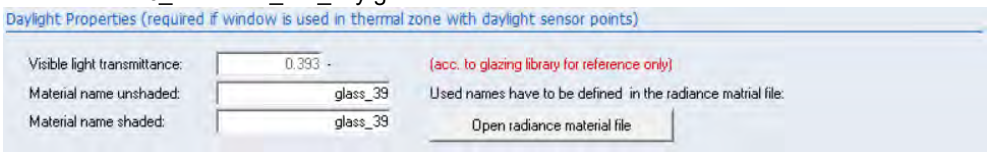
Reference case “hall”:

- TRNSYS: 18.05.0001, version 6.0.0.15
- Timestep calculations: 1 hour, from 0:00 January 1st to 24:00 December 31st
- Simulation settings:
  TRNBuild





Daylight modes of thermal zone → Shading control for daylight sensor points → "basic control"
Window → "T70_Reference_Hall_Skylight.dat"



Absorption coefficient → Walls: 0.54, Ceiling: 0.28, Floor: 0.80

Simulation Studio

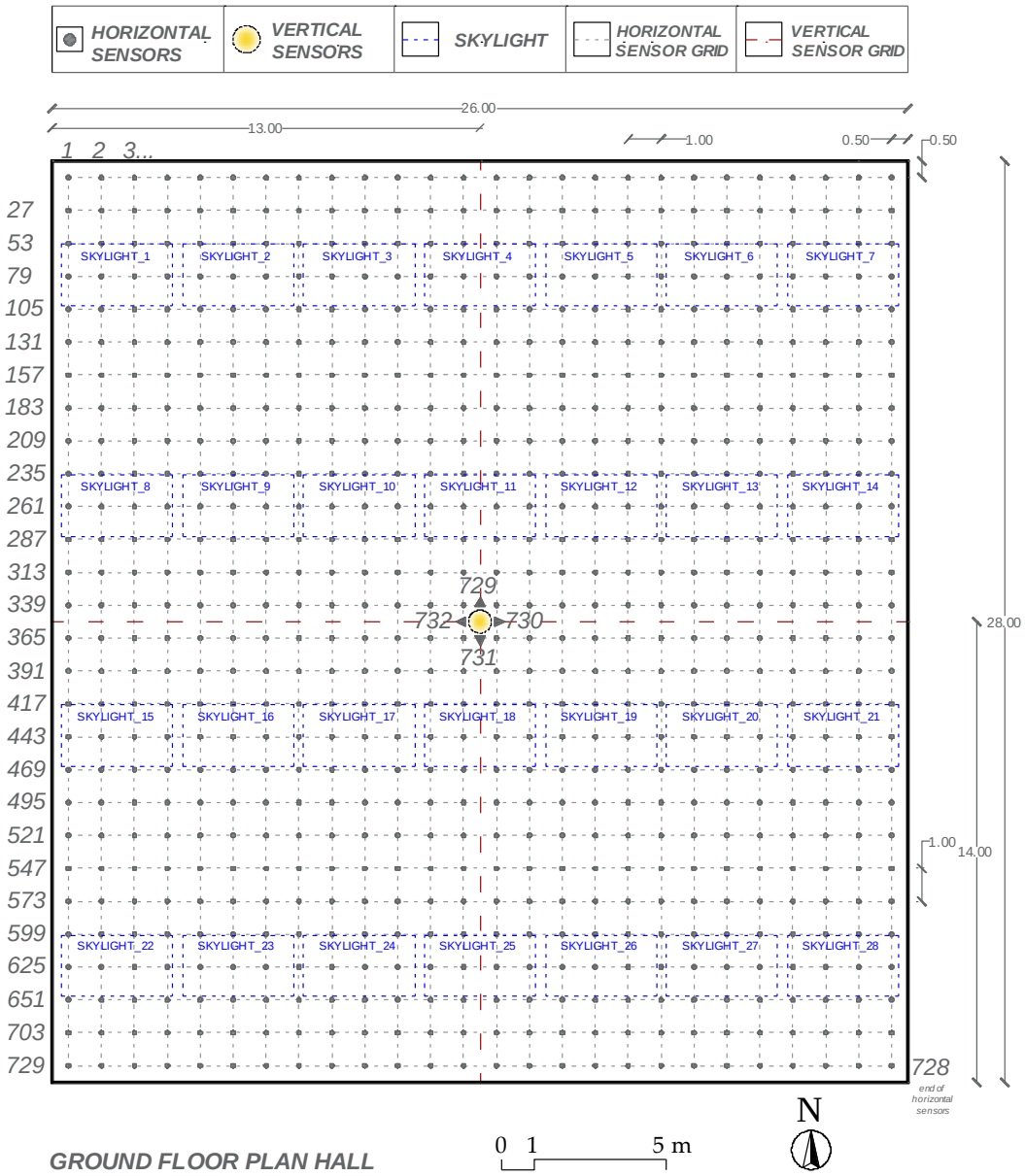
Sky model: Perez 1999 Model

Spectral: 1) not available

- Total run time for annual simulation, general hardware description: 1hr 25min, on ASUS Vivobook 16x, AMD Ryzen 9 5900HX 3.30 GHz, 8-core CPU (16 threads), 16 GB RAM

General comments on the simulation, deviations from the templates, other:

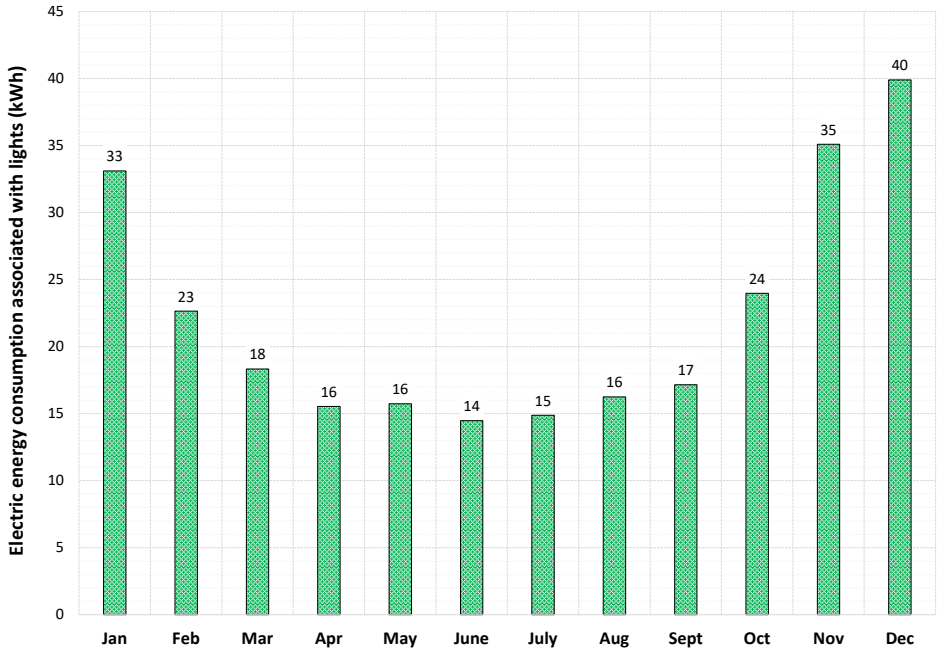
- The software does not permit including luminaries for photometric calculation; "lighting control type" is only utilized to manage the internal gains related to the artificial lighting system and to estimate the electric energy consumption linked to a fixed illuminance set point.
- Software reports the following indexes: DA_300 (%), CDA_300 (%), UDI_100_2000 (%), and DF (%) for each installed sensor; however, a file with the illuminance values hour by hour for each installed sensor is provided.
- The following daylight sensor grid was used in the simulation



GROUND FLOOR PLAN HALL

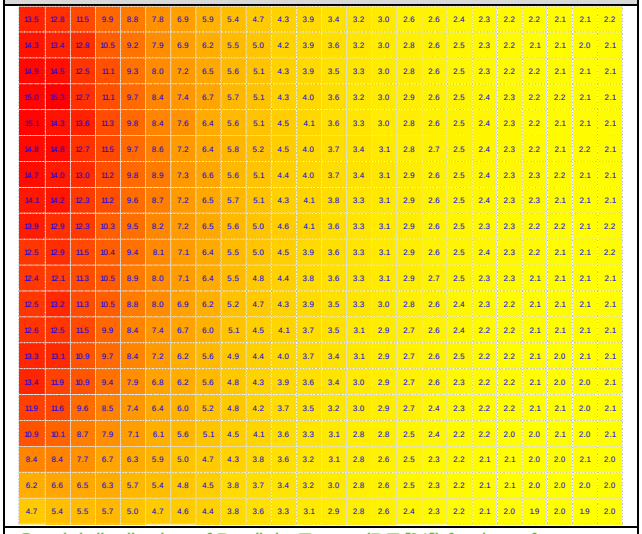
Results Office

Electric lighting	**Annual electricity use for electric lighting**	267 kWh / yr
	Operating hours	3285 h
Annual thermal energy demand (zonal level)	**Heating**	2096 kWh / yr
	Cooling	1668 kWh / yr



Daylight Factor (DF) distribution

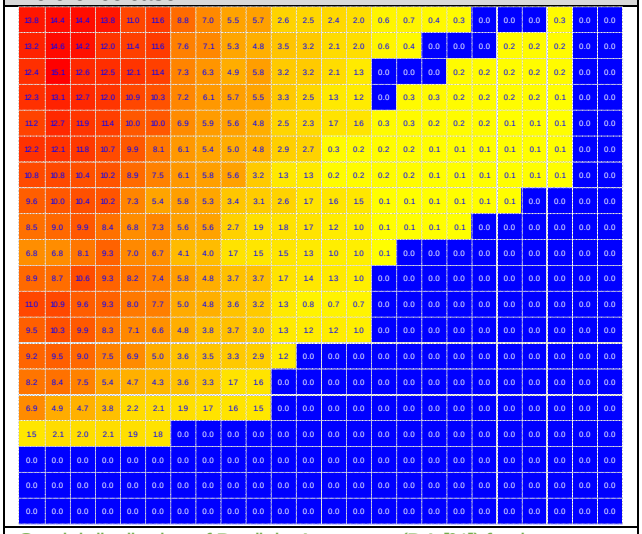
Reference case



Spatial distribution of Daylight Factor (DF [%]) for the reference office (window is on the left side, West)

Daylight Autonomy (DA) distribution

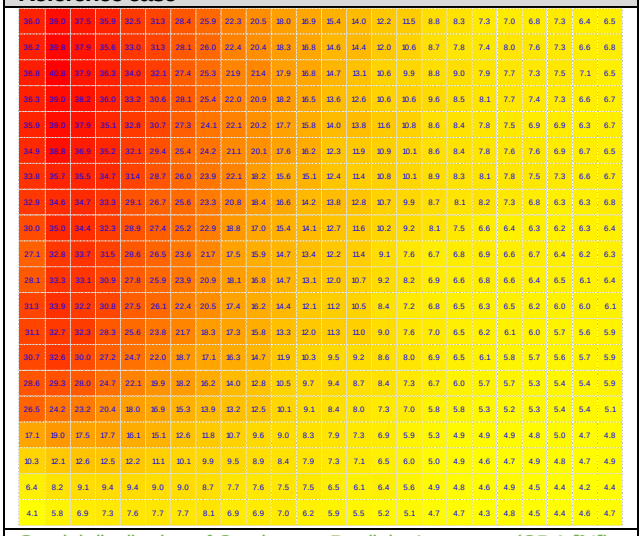
Reference case



Spatial distribution of Daylight Autonomy (DA [%]) for the reference office (window is on the left side, West)

Continuous Daylight Autonomy (CDA) distribution

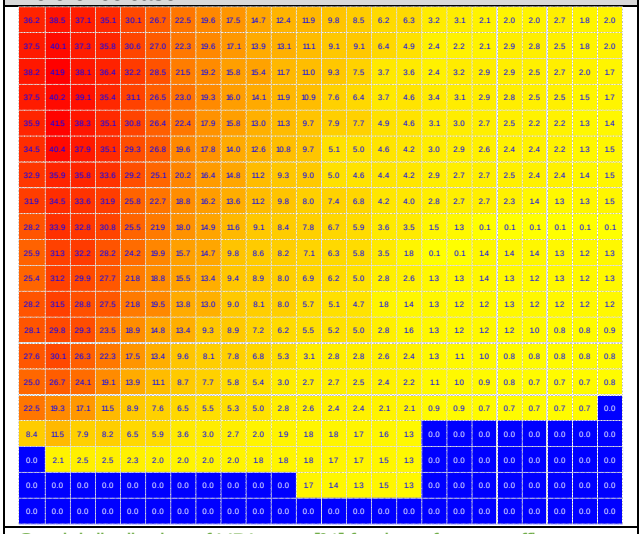
Reference case



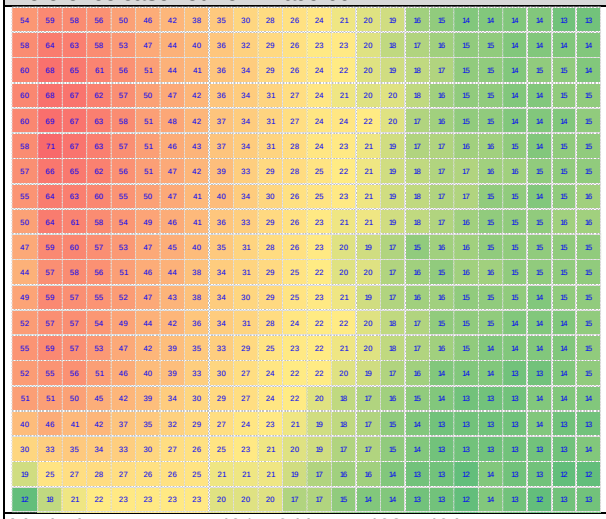
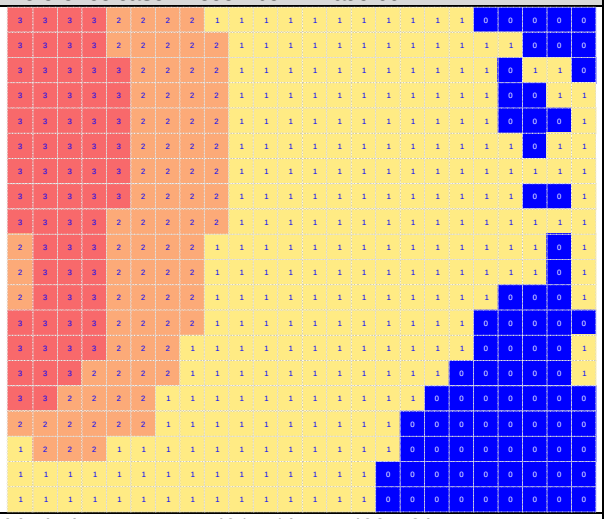
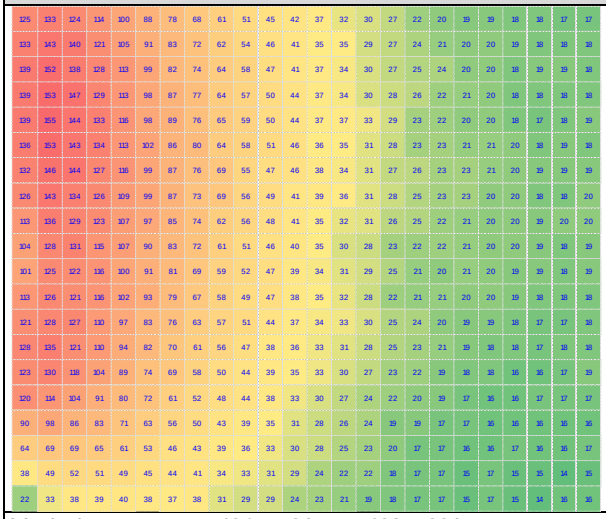
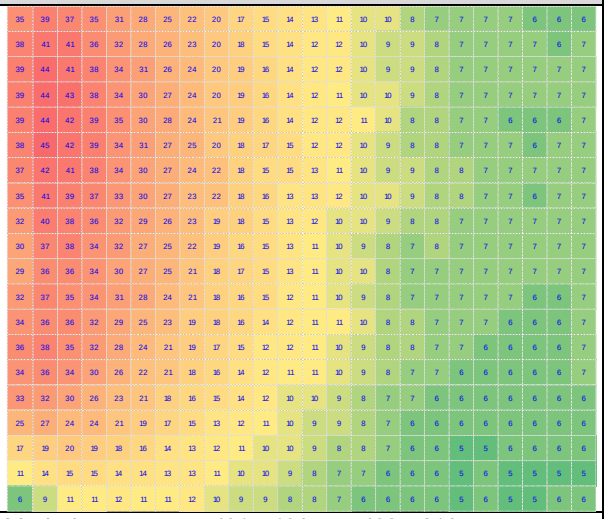
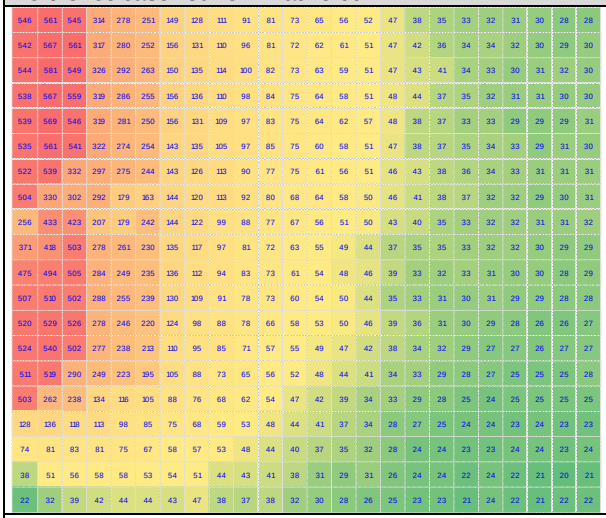
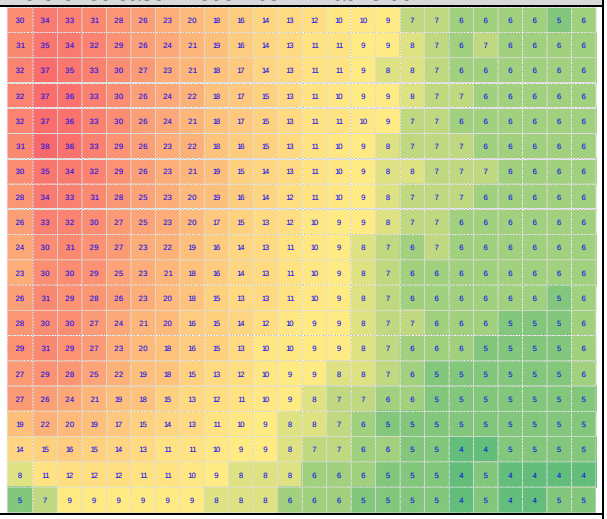
Spatial distribution of Continuous Daylight Autonomy (CDA [%]) for the reference office (window is on the left side, West)

$UDI_{100\text{-}2000}$ distribution

Reference case



Spatial distribution of $UDI_{100\text{-}2000}$ [%] for the reference office (window is on the left side, West)

Reference case - June 21st at 9:00	Reference case - December 21st at 9:00
	
Vertical sensors → n. 481 = 34 lux; n. 482 = 40 lux;	Vertical sensors → n. 481 = 1 lux; n. 482 = 2 lux;
Reference case - June 21st at 12:00	**Reference case - December 21st at 12:00**
	
Vertical sensors → n. 481 = 56 lux; n. 482 = 66 lux;	Vertical sensors → n. 481 = 18 lux; n. 482 = 21 lux;
Reference case - June 21st at 15:00	**Reference case - December 21st at 15:00**
	
Vertical sensors → n. 481 = 87 lux; n. 482 = 106 lux;	Vertical sensors → n. 481 = 15 lux; n. 482 = 19 lux;

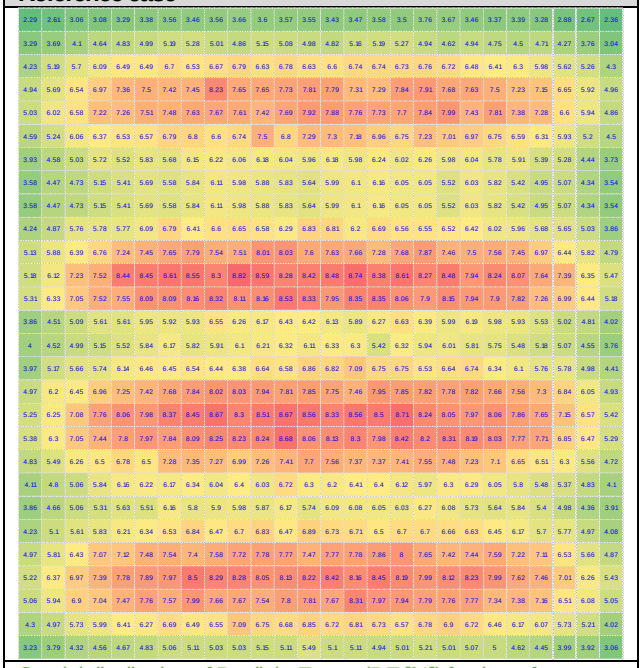
Results Hall

Electric lighting	**Annual electricity use for electric lighting**	2361 kWh / yr
	Operating hours	3650 h
Annual thermal energy demand (zonal level)	**Heating**	134044 kWh / yr
	Cooling	16982 kWh / yr



Daylight Factor (DF) distribution

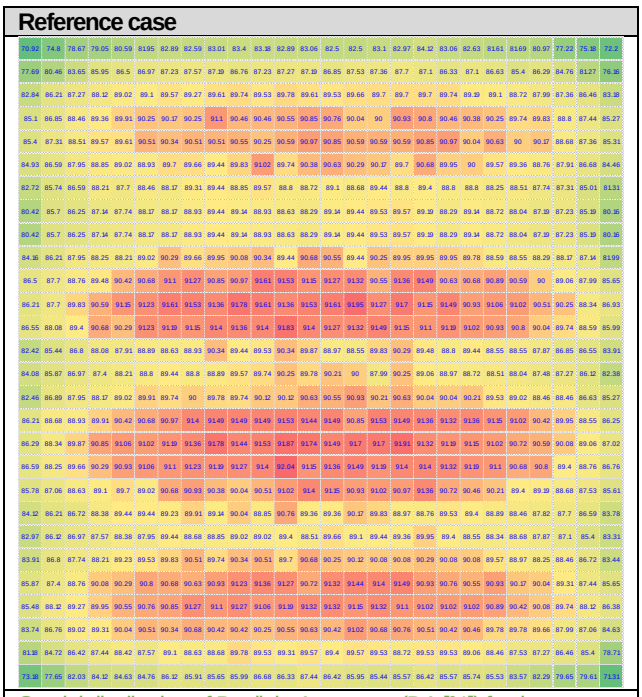
Reference case



Spatial distribution of Daylight Factor (DF [%]) for the reference office (window is on the left side, West)

Daylight Autonomy (DA) distribution

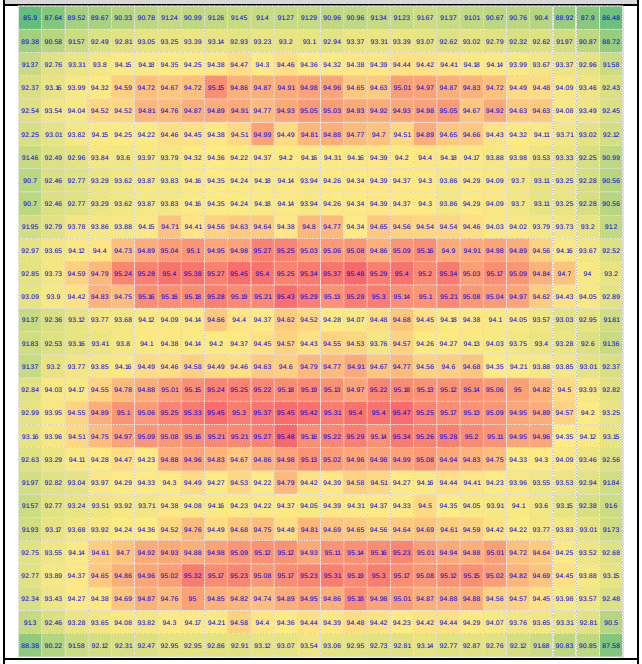
Reference case



Spatial distribution of Daylight Autonomy (DA [%]) for the reference office (window is on the left side, West)

Continuous Daylight Autonomy (CDA) distribution

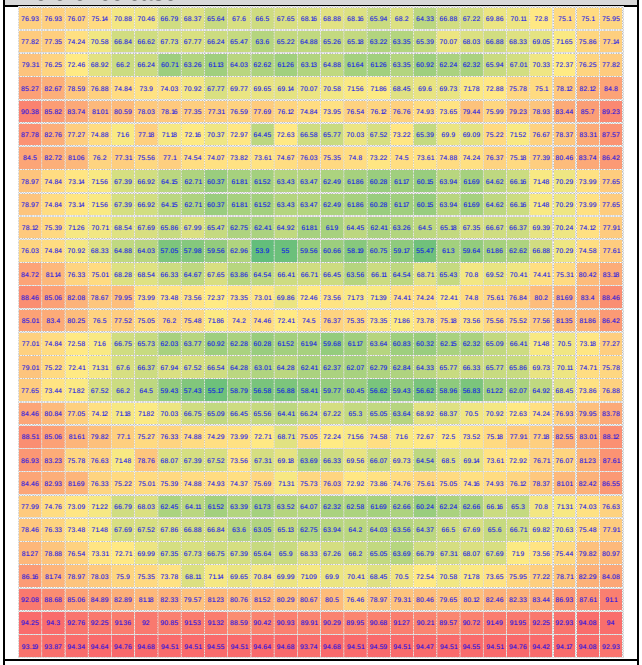
Reference case



Spatial distribution of Continuous Daylight Autonomy (CDA [%]) for the reference office (window is on the left side, West)

$UDI_{100\text{-}2000}$ distribution

Reference case



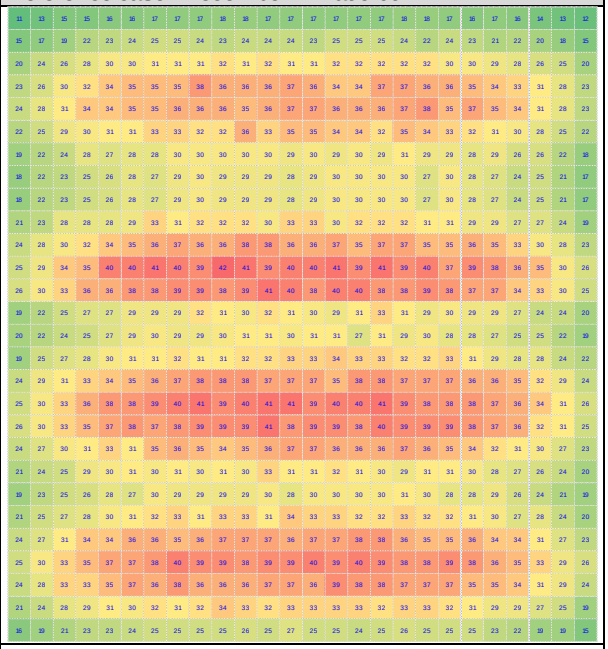
Spatial distribution of $UDI_{100\text{-}2000}$ [%] for the reference office (window is on the left side, West)

Reference case - June 21st at 9:00



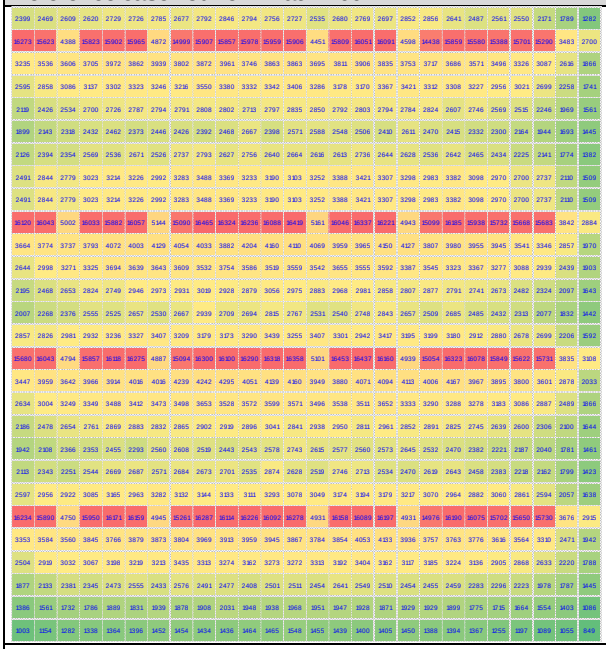
Vertical sensors → n. 729 = 1265 lux; n. 730 = 1176 lux; n. 731 = 1077 lux; n. 732 = 962 lux

Reference case - December 21st at 9:00



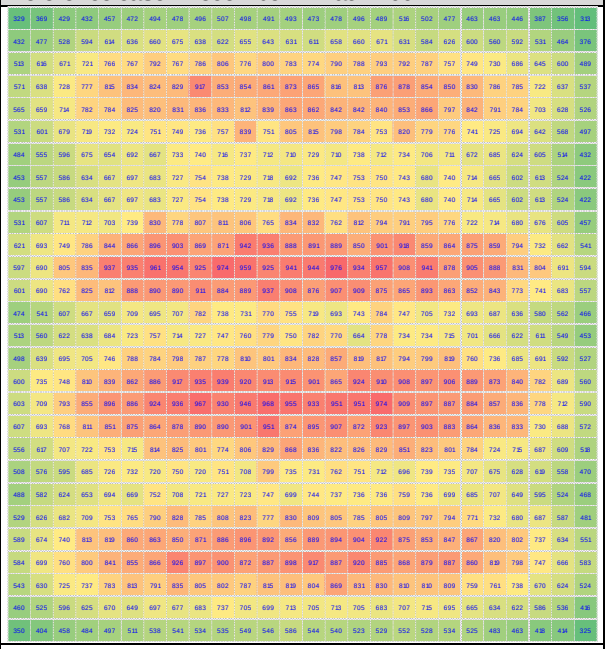
Vertical sensors → n. 729 = 20 lux; n. 730 = 14 lux; n. 731 = 14 lux; n. 732 = 13 lux

Reference case - June 21st at 12:00

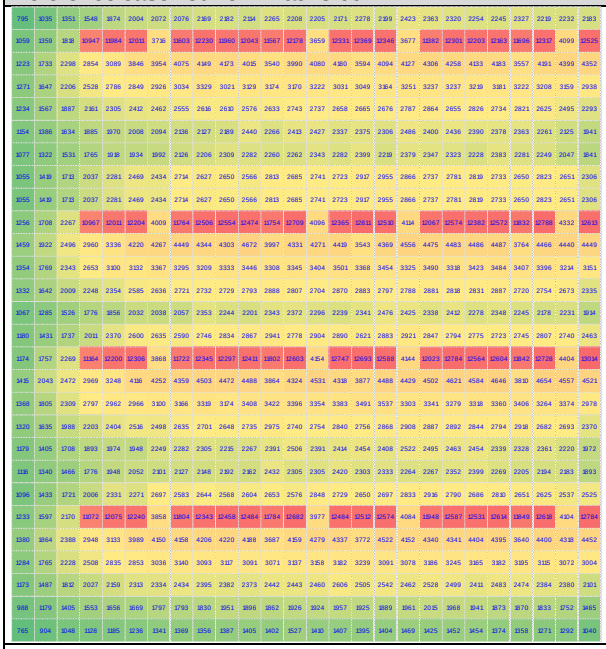
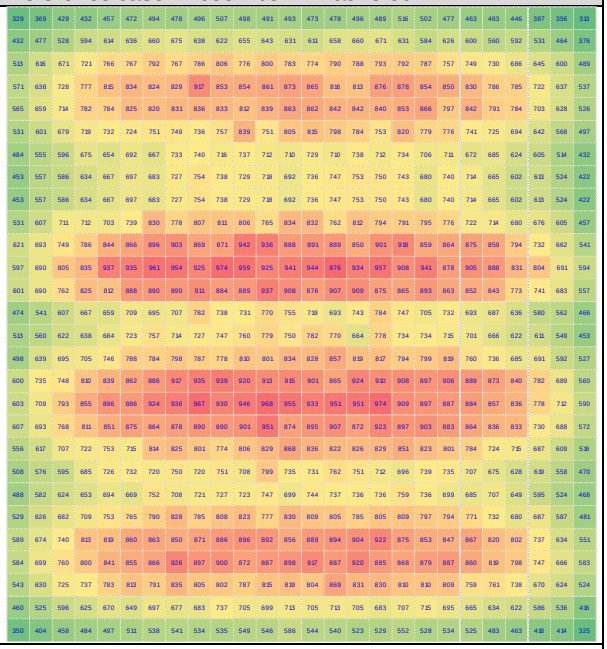


Vertical sensors → n. 729 = 1427 lux; n. 730 = 1502 lux; n. 731 = 2038 lux; n. 732 = 1401 lux

Reference case - December 21st at 12:00



Vertical sensors → n. 729 = 448 lux; n. 730 = 332 lux; n. 731 = 389 lux; n. 732 = 318 lux

Reference case - June 21st at 15:00	Reference case - December 21st at 15:00
	
Vertical sensors → n. 729 = 1350 lux; n. 730 = 1216 lux; n. 731 = 1622 lux; n. 732 = 1429 lux	Vertical sensors → n. 729 = 307 lux; n. 730 = 219 lux; n. 731 = 303 lux; n. 732 = 285 lux

Unreal Engine 4

Michelangelo Scorpio, Revsen Ozdemir, University of Campania, Italy

simulation run by:

- Michelangelo Scorpio and Revsen Ozdemir, July 1, 2025

Software and hardware:

- Unreal Engine 4
- Simulations performed from 9 to 17, with a timestep of one hour, on June 21, 2025
- Simulation settings: Default settings
- Sky model: SunSky UE4 actor
- Spectral: not available

General comments on the simulation, deviations from the templates, other:

- Software does not support annual simulations and metrics based on annual simulations
- Software does not support spectral simulations; all surfaces were modelled spectrally neutral with RGB values
- Software does not support a calculation grid; therefore, only 20 calculation points uniformly distributed in the space were considered for the horizontal illuminance
- The software is not intended for circadian, electrical or thermal simulations
- Shading systems are modelled as objects on the external side of the window, blocking sunlight
- Daylight was simulated using the SunSky UE4 actor as suggested in Hegazy et al. [1]
- Artificial light was simulated using the method proposed by Scorpio et al. [2]
- Luminance values were obtained using the "pixel inspector" function

Description of alternative context for office: Context "Aversa"

- Location: Aversa (Latitude: 40.9853° N, Longitude: 14.1989° E, Time Zone: +1 (CET), +2 (CEST in summer), Elevation: 39m)
- Orientation: the building model has been rotated by 25 degrees clockwise relative to the geographic north

Description of alternative context for factory hall: Context "Aversa"

- Location: Aversa (Latitude: 40.9853° N, Longitude: 14.1989° E, Time Zone: +1 (CET), +2 (CEST in summer), Elevation: 39m)
- Orientation: the same as the reference industry hall

References:

[1] Hegazy, M.; Yasufuku, K.; Hirokazu, A. Validating Game Engines as a Quantitative Daylighting Simulation Tool. In Proceedings of the Projections - Proceedings of the 26th International Conference of the Association for Computer-Aided Architectural Design Research in Asia, CAADRIA 2021; 2021; Vol. 2, pp. 285–294.

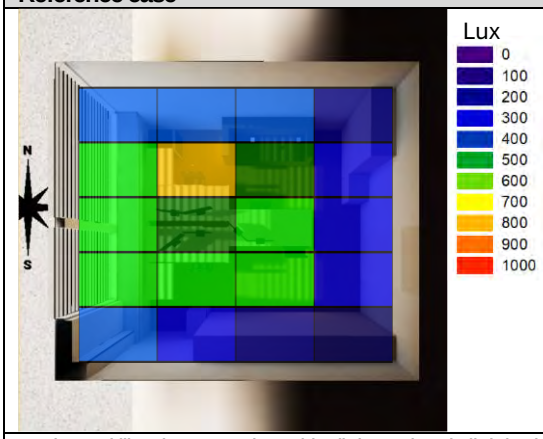
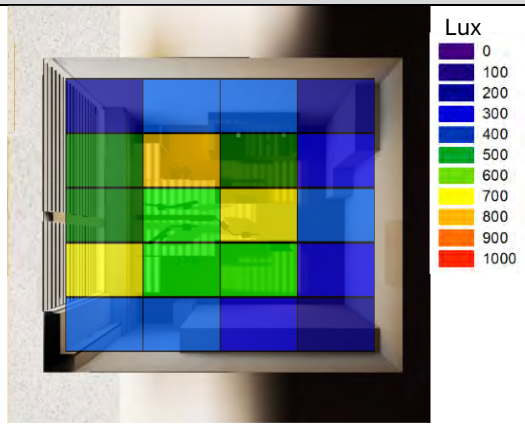
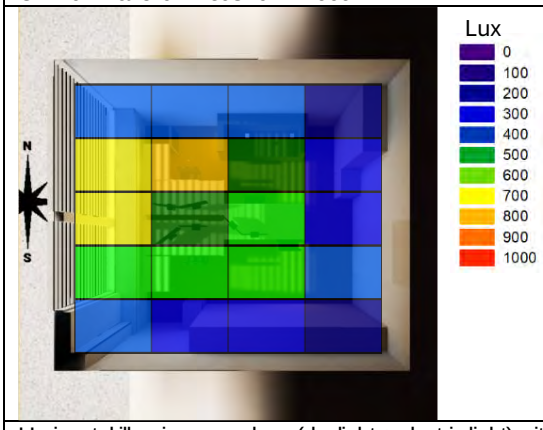
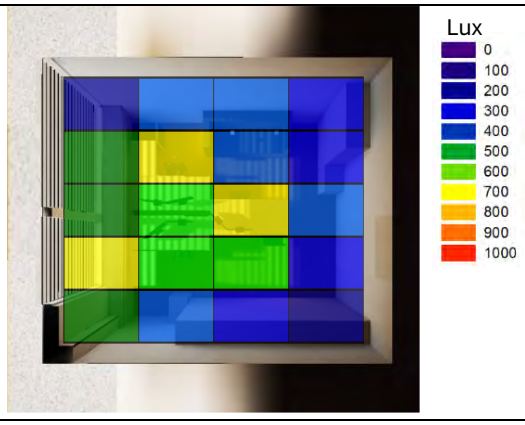
[2] Scorpio, M.; Laffi, R.; Teimoorzadeh, A.; Ciampi, G.; Masullo, M.; Sibilio, S. A Calibration Methodology for Light Sources Aimed at Using Immersive Virtual Reality Game Engine as a Tool for Lighting Design in Buildings. Journal of Building Engineering 2022, 48, 103998, doi:10.1016/j.jobe.2022.103998.

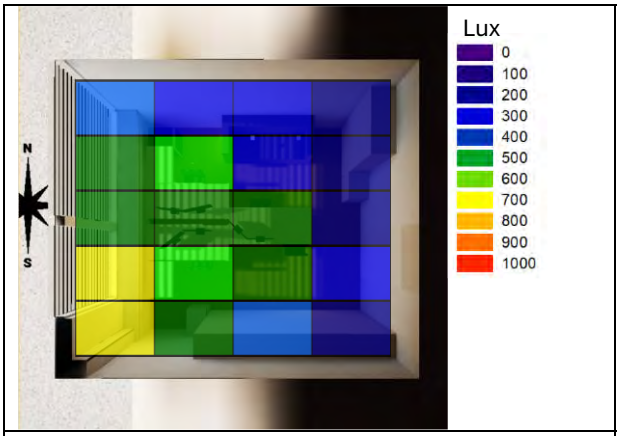
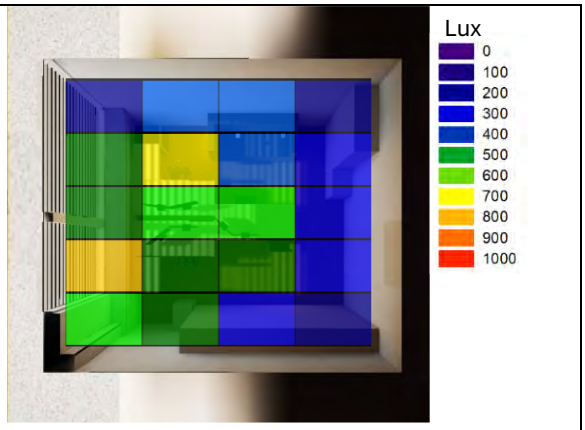
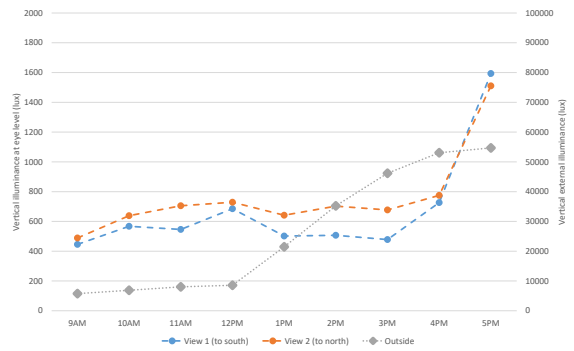
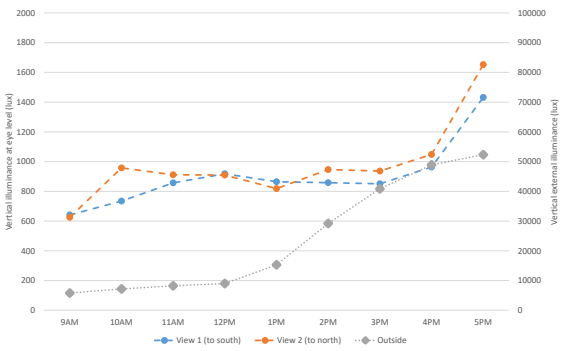
Results Office

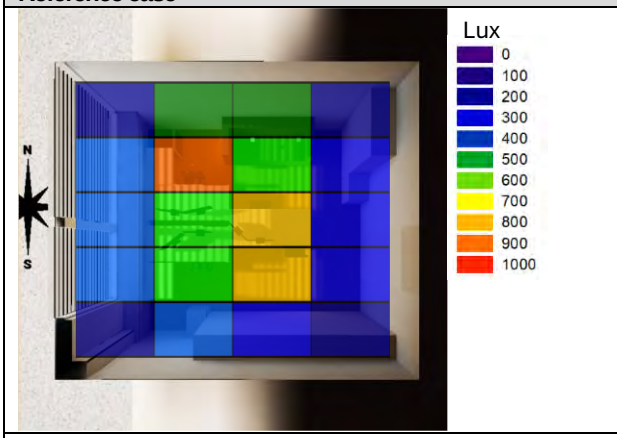
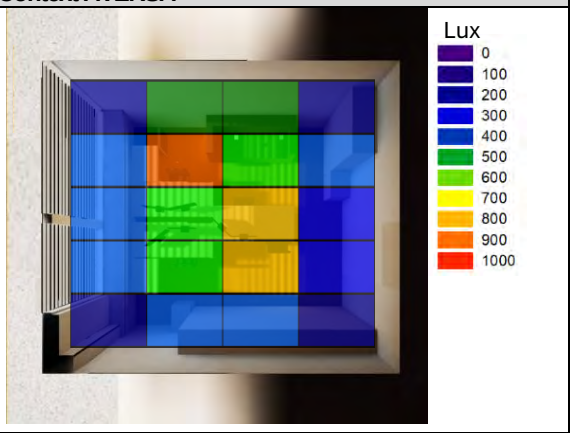
	Metric	Reference case	Context Aversa
Daylight Factor (CIE overcast sky)	**DF min**	NA	NA
	DF mx	NA	NA
	DF avg	NA	NA
	% area with at least 2% DF	NA	NA
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	NA	NA
	$ASE_{1000,250h}$	NA	NA
	% area with at least 50% $UDI_{100\text{-}3000}$	NA	NA
	$F_{DGP=0.40,exceed}$ for view 1	NA	NA
	$F_{DGP=0.40,exceed}$ for view 2	NA	NA

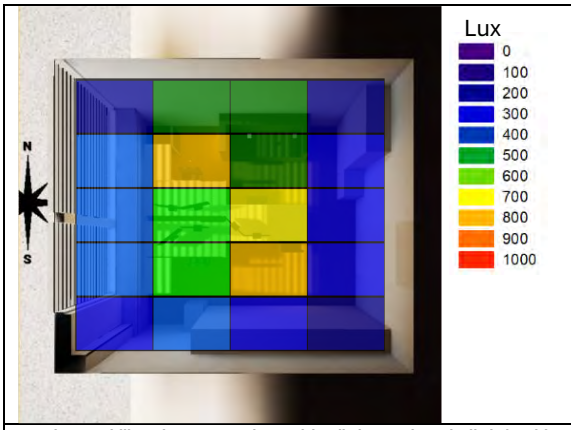
Circadian lighting	**mEDI**	NA	NA
Electric lighting	**Annual electricity use for electric lighting**	NA	NA
	Operating hours	NA	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

Example graphical output: global illuminance values distribution deduced from elaboration of UE4 luminance values

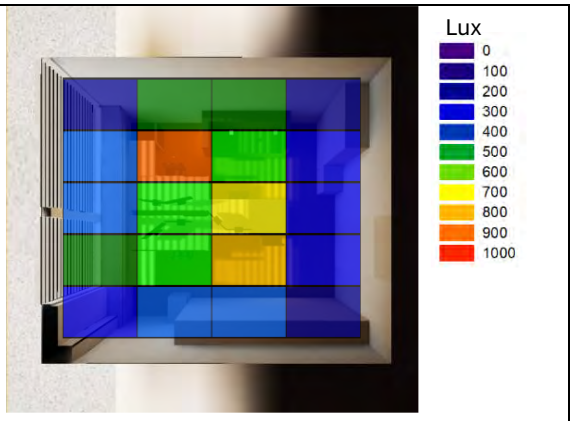
Reference case	**Context AVERSA**
	
Horizontal illuminance values (daylight + electric light) with shading open, at 9 am, for the reference office (window is on the left). UE4 luminaire luminous flux = 4000 lm	Horizontal illuminance values (daylight + electric light) with shading open, at 9 am, for the Aversa office (window is on the left). UE4 luminaire luminous flux = 5500 lm
	
Horizontal illuminance values (daylight + electric light) with shading open, at 12 pm, for the reference office (window is on the left) UE4 luminaire luminous flux = 3500 lm	Horizontal illuminance values (daylight + electric light) with shading open, at 12 pm, for the Aversa office (window is on the left). UE4 luminaire luminous flux = 4750 lm

	
Horizontal illuminance values (daylight + electric light) with shading open, at 4 pm, for the reference office (window is on the left) UE4 luminaire luminous flux = 1250 lm	Horizontal illuminance values (daylight + electric light) with shading open, at 4 pm, for the Aversa office (window is on the left). UE4 luminaire luminous flux = 4000 lm
	
Vertical daylight illuminance values for view 1 and view 2 with shading open, + electric lighting as well as vertical external illuminances for the reference office (window is on the left)	Vertical daylight illuminance values for view 1 and view 2 with shading open, + electric lighting as well as vertical external illuminances for the Aversa office (window is on the left)

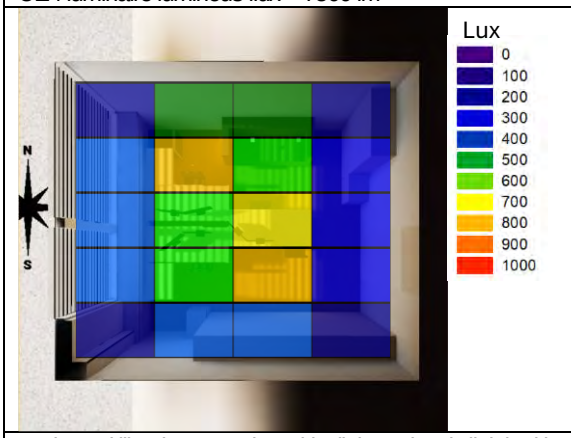
Reference case	**Context AVERSA**
	
Horizontal illuminance values (daylight + electric light) with shading closed, at 9 am, for the reference office (window is on the left). UE4 luminaire luminous flux = 8000 lm	Horizontal illuminance values (daylight + electric light) with shading closed, at 9 am, for the Aversa office (window is on the left). UE4 luminaire luminous flux = 8000 lm



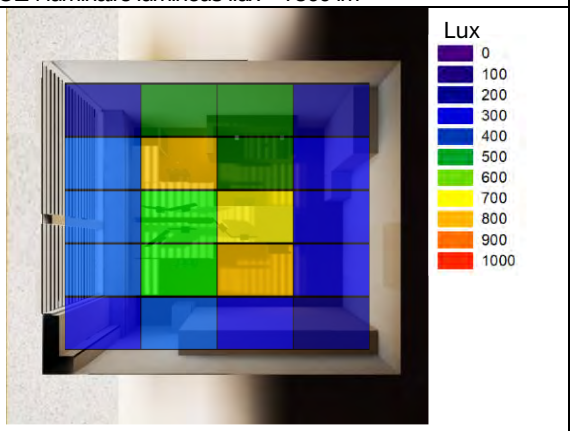
Horizontal illuminance values (daylight + electric light) with shading closed, at 12 pm, for the reference office (window is on the left)
UE4 luminaire luminous flux = 7500 lm



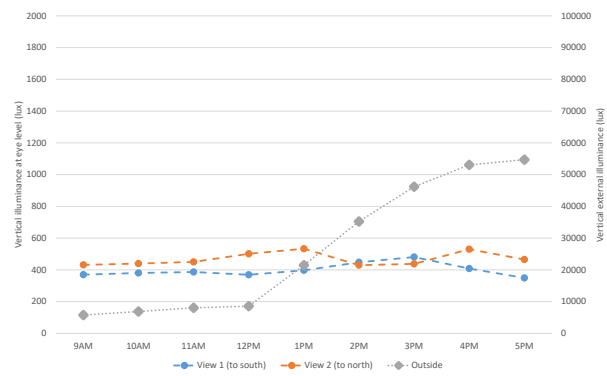
Horizontal illuminance values (daylight + electric light) with shading closed, at 12 pm, for the Aversa office (window is on the left).
UE4 luminaire luminous flux = 7500 lm



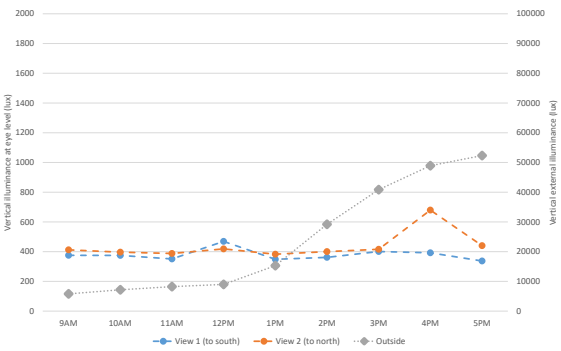
Horizontal illuminance values (daylight + electric light) with shading closed, at 4 pm, for the reference office (window is on the left)
UE4 luminaire luminous flux = 7500 lm



Horizontal illuminance values (daylight + electric light) with shading closed, at 12 pm, for the Aversa office (window is on the left).
UE4 luminaire luminous flux = 7250 lm



Vertical daylight illuminance values for view 1 and view 2 with shading closed + electric lighting, as well as vertical external illuminances for the reference office (window is on the left)



Vertical daylight illuminance values for view 1 and view 2 with shading closed + electric lighting, as well as vertical external illuminances for the Aversa office (window is on the left)



View of the office from the inside

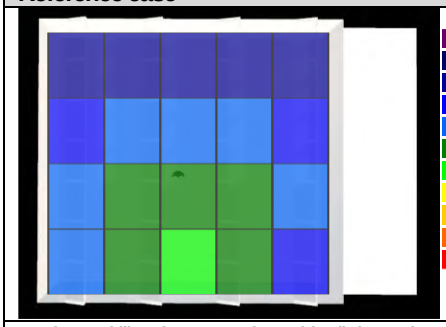
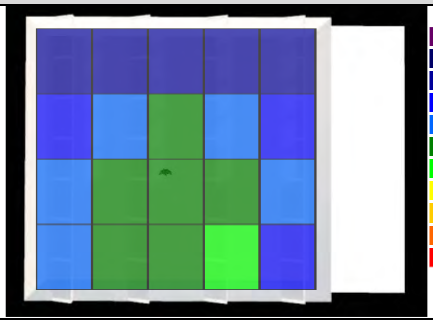
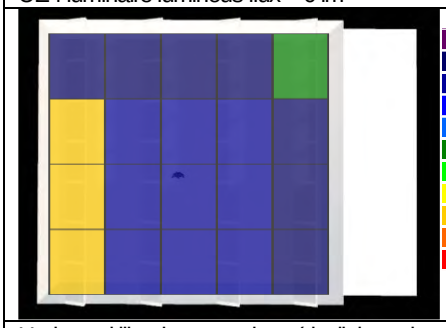
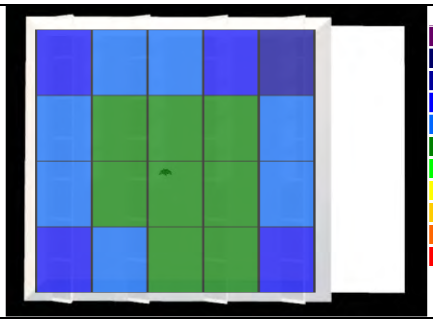
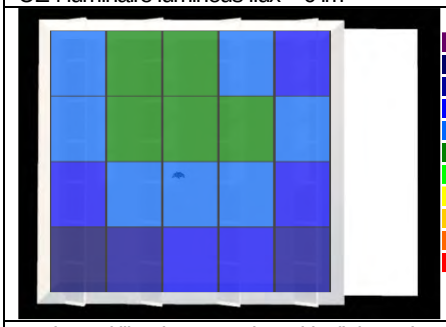
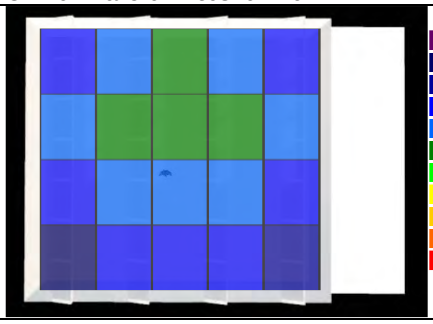
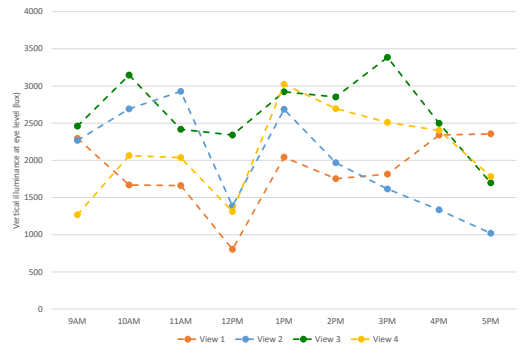
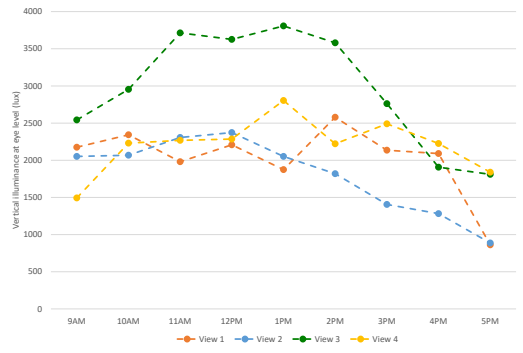
Specific comments on the simulation for the reference case and alternative context “office”:

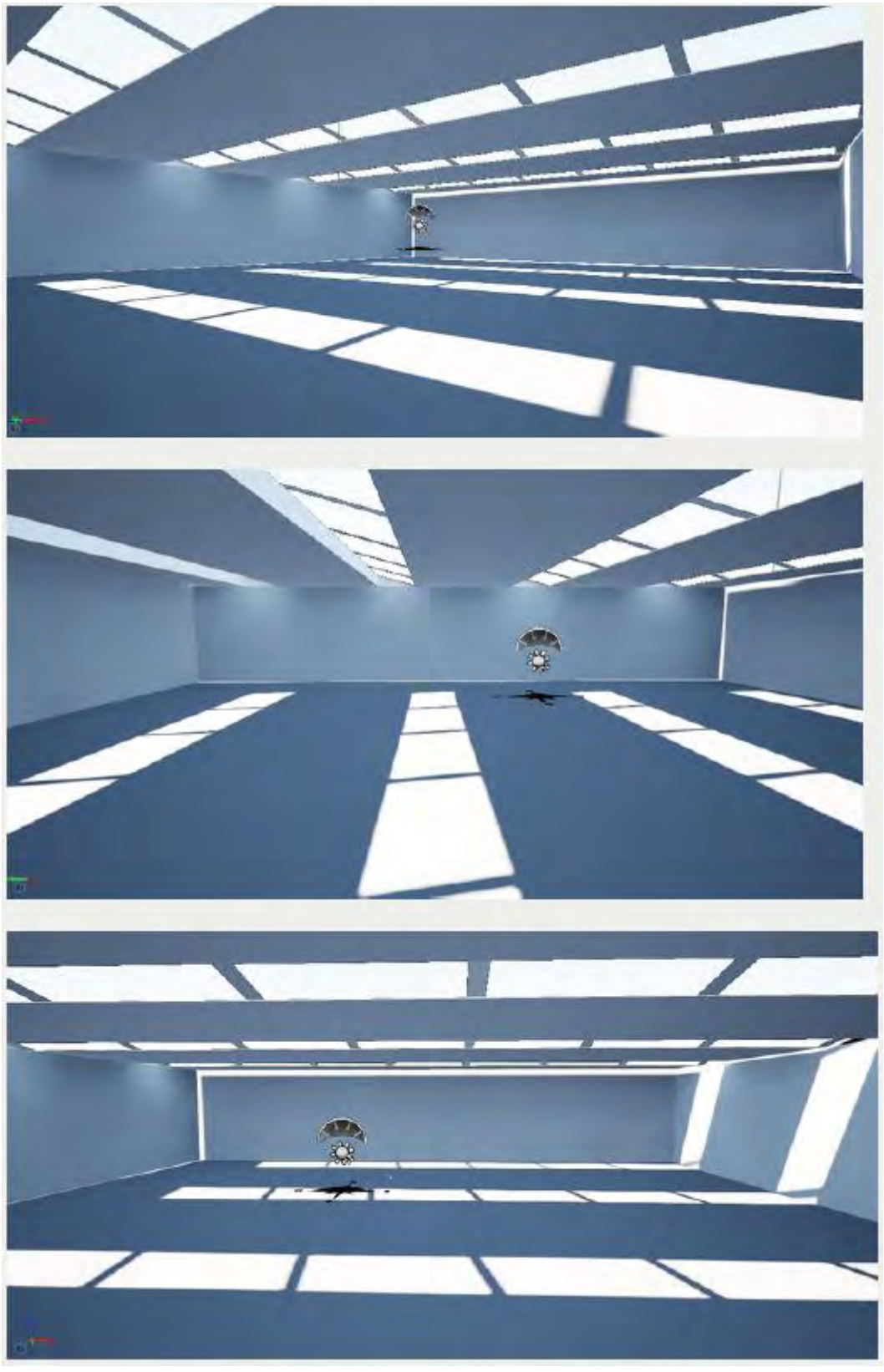
- The luminance values were read and stored individually for subsequent processing aimed at obtaining illuminance values and their representation in graphic form.
- The software does not allow the simulation of automatic electric lighting and shading control systems. Simulations were performed twice, once with open and once with closed venetian blinds. Accordingly, the luminaires' luminous flux was manually adjusted to complement the natural light and ensure an average horizontal illuminance of approximately 500 lux.
- The software provides daylight luminance values for a specific day of the year and hour of the day. The simulations were repeated eight times to determine the light distribution from 9:00 a.m. to 5:00 p.m. on June 21, 2025.
- The illuminance values were deduced from luminance values measured on a diffusing white surface positioned on each of the horizontal and vertical calculation points
- A vertical calculation point was considered on the external surface of the window to deduce the external daylight illuminance values
- Diffusing white surfaces were positioned vertically to simulate the user’s eye looking toward a specified direction

Results Hall

	Metric	Reference case	Context Aversa
Daylight Factor (CIE overcast sky)	**DF min**	NA	NA
	DF mx	NA	NA
	DF avg	NA	NA
	% area with at least 2% DF	NA	NA
Daylight metrics based on annual results	**$sDA_{300,50\%}$**	NA	NA
	$ASE_{1000,250h}$	NA	NA
	% area with at least 50% $UDI_{100\text{-}3000}$	NA	NA
	$F_{DGP=0.40,exceed}$, view 1	NA	NA
	$F_{DGP=0.40,exceed}$, view 2	NA	NA
	$F_{DGP=0.40,exceed}$, view 3	NA	NA
	$F_{DGP=0.40,exceed}$, view 4	NA	NA
Circadian lighting	**mEDI**	NA	NA
Electric lighting	**Annual energy demand for electric lighting**	NA	NA
	Operating hours	NA	NA
Annual electricity use for HVAC (zonal level)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA
Annual energy use for HVAC (zonal level, specify fuel – e.g., natural gas for heating)	**Heating**	NA	NA
	Cooling	NA	NA
	Ventilation	NA	NA

Example graphical output: global illuminance values distribution deduced from elaboration of UE4 luminance values

Reference case	Context AVERSA
	
Horizontal illuminance values (daylight + electric light) at 9 am, for the reference hall. UE4 luminaire luminous flux = 0 lm	Horizontal illuminance values (daylight + electric light) at 9 am, for the Aversa hall. UE4 luminaire luminous flux = 0 lm
	
Horizontal illuminance values (daylight + electric light) at 12 pm, for the reference hall. UE4 luminaire luminous flux = 0 lm	Horizontal illuminance values (daylight + electric light) at 12 pm, for the Aversa hall. UE4 luminaire luminous flux = 0 lm
	
Horizontal illuminance values (daylight + electric light) at 4 pm, for the reference hall. UE4 luminaire luminous flux = 0 lm	H orizontal illuminance values (daylight + electric light) at 9 am, for the Aversa hall. UE4 luminaire luminous flux = 0 lm
	
Vertical daylight illuminance values for view 1 to view 4, daylight + electric lighting for the reference hall.	Vertical daylight illuminance values for view 1 to view 4, daylight + electric lighting for the reference hall.



View of the office from the industry hall

Specific comments on the simulation for the reference case and alternative context “hall”:

- The luminance values were read and stored individually for subsequent processing aimed at obtaining illuminance values and their representation in graphic form.

- The software provides daylight luminance values for a specific day of the year and hour of the day. The simulations were repeated eight times to determine the light distribution from 9:00 a.m. to 5:00 p.m. on June 21, 2025.
- The illuminance values were deduced from luminance values measured on a diffusing white surface positioned on each of the horizontal and vertical calculation points
- A vertical calculation point was considered on the external surface of the window to deduce the external daylight illuminance values
- Diffusing white surfaces were positioned vertically to simulate the user's eye looking toward a specified direction

Appendix B: Questionnaire: VR in lighting design

This appendix presents the international questionnaire used to gather thorough understanding of the applications and consequences of virtual reality use for lighting design.

Parameter	Question	Option
Section I: Demographics and General VR Use	Please choose one of the alternatives:	I am a professional
		I am a student
	Nationality	
	Age	10-20
		20-30
		30-40
		40-50
		50-60
		Above 60
	Gender	Female
		Male
		I prefer not to inform
		Other
	Nature of your company or organization	Public sector
		Private sector
		Self-employee
		N/A
	What is your activity domain?	architecture
		urbanism
		lighting
		daylighting
		designing
		real estate
		building physics
		research
		internal designer
		landscape designer
		CAD/CAM designer
		other
	What is your current level of professional experience?	Less than 1 year
		1-5 years
		5-10 years
		10-20 years
		More than 20 years

	Definition of virtual reality Virtual reality (VR) is a simulated experience that employs pose tracking and 3D near-eye displays to give the user an immersive feel of a virtual world. Applications of virtual reality include entertainment (particularly video games), education (such as medical or military training) and business (such as virtual meetings). Other distinct types of VR-style technology include augmented reality and mixed reality, sometimes referred to as extended reality or XR, although definitions are currently changing due to the nascence of the industry.	
	Are you familiar with Virtual Reality (VR) technology?	Yes No
	What is your current level of experience in using VR?	Less than 1 year 1-2 3-4 More than 4 years My answer to previous question was negative
	If yes, how often do you use VR technology in your practice?	Daily Weekly Monthly Rarely Never My answer to previous question was negative
	Which VR applications/tools do you use most frequently in your practice? (multiple choices allowed)	Unity Unreal Lumion? https://sketchfab.com/ other (Specify)
	How would you rate your proficiency in using VR technology?	rate from 1 (novice) to 5 (expert)
	How have you learned to use VR in your practice? (multiple choices allowed)	Formal training Self-taught Colleagues/Peers Online tutorials/courses Other (Please specify)
Section II: VR Application in Practice	What purposes do you primarily use VR for in your work? (multiple choices allowed)	Conceptual design Detailed design Client presentations Collaboration with other team members Design reviews Create interactive installations Allow clients to experience different schemes before they are built Train designers Other (Please specify)

	How beneficial has the use of VR been in your practice?	Rate from 1 (not at all beneficial) to 5 (extremely beneficial)
	What challenges, if any, have you experienced when incorporating VR into your practice?	Financial Lack of training Lack of experience Hardware (pc or other running device) specifications Motion sickness Lacking HMD (head mounted display) Lacking specialists to create custom software Reluctance towards new technology Lack of time Other
	Have you observed any impact on client satisfaction or engagement due to using VR in your presentations?	Scale from 1 (No impact) to 6 (Yes, significantly)
	Do you believe that VR technology will become a standard tool in architectural design in the future?	Yes No Unsure No opinion
Section III: Complexity of VR Experiences	What is the complexity level of the VR experiences you typically create?	Basic (simple walkthroughs, static models) Intermediate (interactive models, basic environmental changes) Advanced (detailed environmental changes, simulations, multi-user) Not applicable
	What aspects of your VR experiences do clients engage with most?	Interactive features (e.g., opening doors, changing materials) Immersive environments (e.g., realistic lighting, weather conditions) Collaboration features (e.g., multi-user walkthroughs) Other (Please specify)
	Have you noticed a correlation between the complexity of the VR experience (1 level only walkthrough, 2 levels interaction like opening door, etc) and the final design decisions made by the client?	Yes No Unsure No opinion
Section IV: Lighting in VR	How often do you simulate natural and/or artificial lighting conditions in your VR experiences?	Always Often Sometimes Rarely Never

How do clients typically react to the changing lighting conditions in your VR experiences?	They notice and comment on it They don't usually comment Not sure I have never used VR for lighting
Do you believe that realistic lighting in VR can influence design decisions?	Yes No Unsure
The photometric accuracy in reproducing lighting distribution is important to use virtual reality for lighting.	Rate from 1 (Strongly Disagree) to 6 (Strongly Agree)
The aesthetical quality of the virtual environment is more important than light distribution accuracy.	Rate from 1 (Strongly Disagree) to 6 (Strongly Agree)
Using virtual reality, a plausible light environment is enough for lighting professionals.	Rate from 1 (Strongly Disagree) to 6 (Strongly Agree)
What aspects of lighting simulation in VR would you like to see improved? (open ended question)	
Virtual reality can replace traditional lighting simulation software.	Rate from 1 (Strongly Disagree) to 6 (Strongly Agree)
Virtual reality must be used in conjunction with traditional simulation systems.	Rate from 1 (Strongly Disagree) to 6 (Strongly Agree)