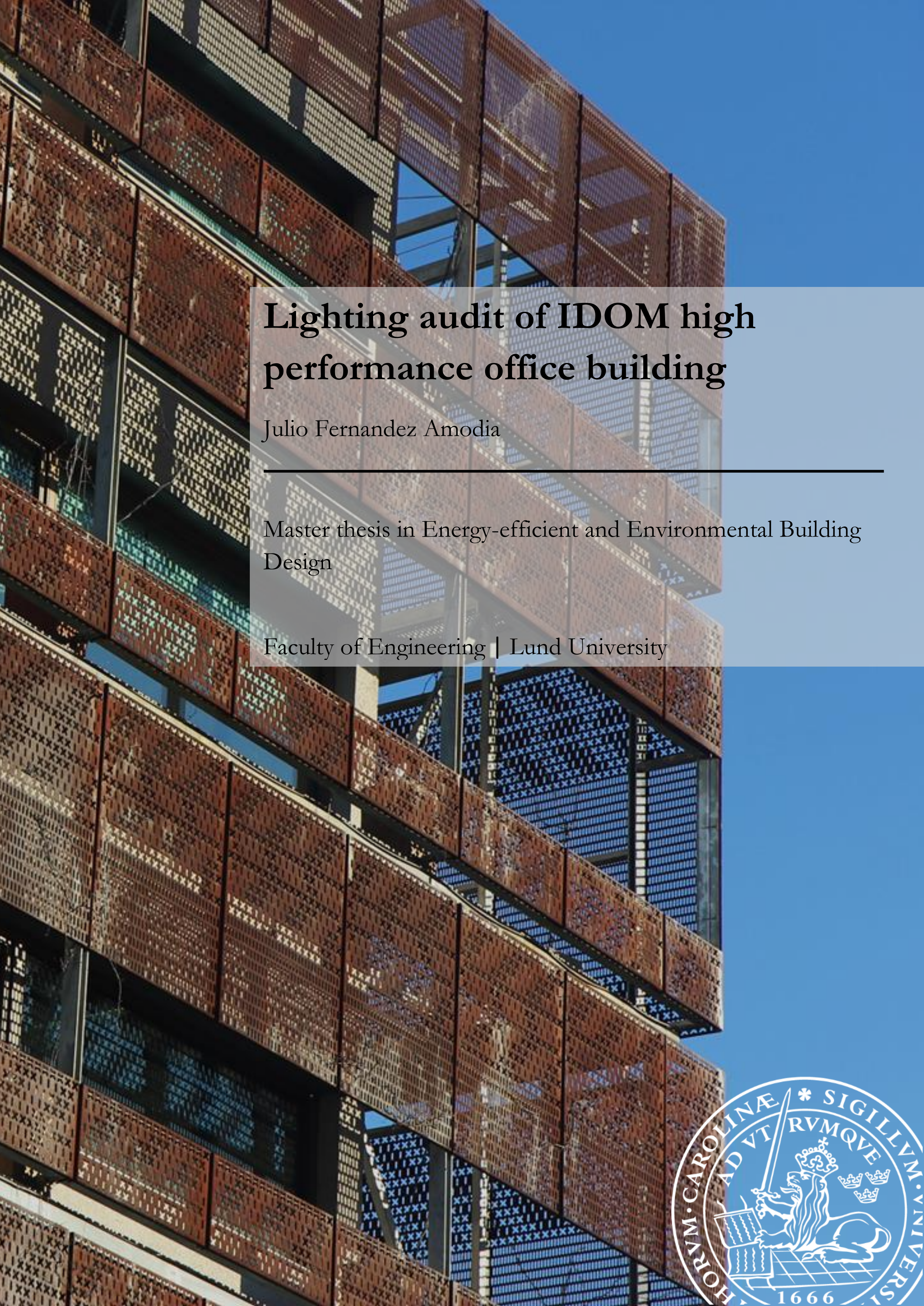

Lighting audit of IDOM high performance office building

Julio Fernandez Amodia

Master thesis in Energy-efficient and Environmental Building Design

Faculty of Engineering | Lund University

This thesis is the result of the collaboration between two institutions, on one hand Lund University and on the other hand IDOM consultancy company. Both provide valuable assets to enrich this document.

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behavior and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Examiner: Niko Gentile (Architecture and Built Environment)

Supervisor: Marie-Claude Dubois (Architecture and Built Environment), Iason Bournas (Architecture and Built Environment)

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IDOM Company

IDOM is a multi-national corporation which provides consulting, engineering, and architecture services in Spain and internationally.

From 1957 to the present day, IDOM has gradually developed into a multidisciplinary group in which more than 3,000 people work, distributed in 34 offices located in seventeen countries and five continents, having served more than 12,000 clients and carrying out 30,000 projects in 123 countries.

The Headquarter of the company is in Madrid and IDOM building, which was completed in 2010, is a benchmark for sustainable buildings in Spain. It is a high-performance facility with a thermally activated building structure (TABS), combined with a night evaporative hydraulic cooling. Its final energy use is extremely low compared to similar buildings. Additionally, natural lighting was a key parameter in the whole architectural design, avoiding both glare issues and unpleasant direct solar radiation.

Since the ownership of the firm is distributed among the members that compose it, IDOM is part of the ecosystem of "employee-owned companies", this characteristic makes it unique in Spain.

Supervisors: Sergio Arús Gutierrez, Antonio Villanueva Peñalver (Building Physics, Architecture)

Abstract

People in industrialized countries spend most of their time indoors. In this respect, a pleasant indoor environment is therefore very important, and daylight plays a fundamental role in this matter.

A good lighting design in offices has proved to improve the worker's wellbeing and increase their productivity. It has become an important part of the early stages of the building design. Simultaneously, lighting audit methodologies and techniques have evolved in the past few years.

This master's thesis presents a study of daylighting and lighting conditions at the IDOM headquarters located in Madrid, Spain. Several tools such as field measurements with a luxmeter and colorimeter, a questionnaire and daylight simulations with Honeybee were performed. A step-by-step documentation was developed to create a workflow that could be used for future lighting evaluations.

Overall, the audit shows that most workers were satisfied with the lighting conditions in the office. User on level one reported similar scores to those on level four. In contrast, users close to the core were less satisfied with the lighting conditions, the uniformity of light distribution and views while users with workspaces close to the window experienced over lighting due to the high daylight illumination. Other correlations linked the uniformity and light satisfaction, and glare from fixtures with low uniformity, which might be an indicator of too directional electrical light sources and a low-lit background.

Daylight simulations were conducted for three representative spaces on the fourth floor (open office, cell office and meeting room). The results of these simulations and the subjective assessment indicate similar outcomes.

It was also observed that shading devices affect the annual daylight simulations to a great extent. However, it is difficult to measure the extent of the impact since the shades are controlled by the users.

Lastly, the study conducted shows that a good daylight design improves the overall energy performance and reduces the consumption of electric lighting by almost fifty percent when daylight is considered.

Acknowledgement

I thank my supervisor Marie-Claude Dubois for her help and guidance and my thesis co-supervisor Iason Bournas for his patience and constructive feedback throughout the whole thesis. His support has proved to be invaluable and has increased my understanding of daylighting simulations.

I also extend my gratitude to IDOM, in particular to Sergio Arús Gutierrez and Antonio Villanueva Peñalver, who assisted me during my stay at IDOM. They clearly provided a great opportunity to work in a great company and environment. Their expertise in the sustainability field coupled with their comments and recommendations have been important to my education.

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Finally, I thank my classmates and other former students who contributed in different ways with their suggestions and support.

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Abbreviations

Daylight:

ASE	Annual sunlight exposure (hours)
BSDF	Bidirectional Scattering Distribution Function
CBDM	Climate-based daylight modelling
CFS	Complex Fenestration Systems
DA	Daylight autonomy (%)
DDM	Dynamic daylight metrics
DF	Daylight factor (%)
DF_a	Average daylight factor (%)
DF_{median}	Median daylight factor (%)
DGI	Daylight Glare Index
DGP	Daylight glare probability (%)
GUI	Graphical User Interface
HDR	High Dynamic Range
PS	Perforated screen
SC	Sky component
sDA	Spatial daylight autonomy (%)
Tvis	Visible transmittance (%)
UDI	Useful daylight illuminance (%)
VSC	Vertical Sky Component (%)
WWR	Window-to-Wall Ratio (%)

Definitions

Vertical Sky Component (VSC, %): *Measure of the amount of visible sky from a given point. It is expressed as a percentage. It is the ratio of the illuminance at a given point due to the light received directly from an overcast sky to the illuminance on an unobstructed outside plane under the same sky (CIE standard overcast sky).*

Annual Sunlight Exposure (ASE, hours): The fraction or percentage of the horizontal work plane that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year over a specified daily schedule with all operable shading devices retracted (IES LM-83-12).

CIE Standard Overcast Sky: A CIE mathematically defined standard sky, where the sun is fully obscured and there is no indication of its position (Tregenza & Wilson, 2011). Alternatively, the meteorological condition of clouds completely obscuring all the sky, which is characterized by the luminance at the zenith being three times brighter than at the horizon (DeKay & Brown, 2001).

Climate-based Daylight Modelling (CBDM): Climate-based daylight modelling (CBDM) is the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological datasets. Climate-based modelling delivers predictions of absolute quantities (e.g. illuminance) that are dependent both on the locale (i.e. geographically-specific climate data is used) and the building orientation (i.e. the illumination effect of the sun and non-overcast sky conditions are included), in addition to the building's composition and configuration (John Mardaljevic).

Daylight Factor (DF, %): The ratio of the illuminance at a point on a given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution, to the simultaneously measured illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, excluding the contribution of direct sunlight to both illuminances (CEN-TC169, 2015).

Daylight Glare Probability (DGP, %): A glare prediction index. A function of the vertical eye illuminance, the glare source luminance, its solid angle and its position index (Wienold & Christoffersen, 2006).

Daylight Glare Index (DGI,%): A value for predicting the presence of glare as a result of daylight entering an area. The glare index is affected by the size and relative position of fenestration, orientation to the sun, sky luminance, and interior luminance (Illustrated Dictionary of Architecture, 2012).

Illuminance (lux): Illuminance is the measure of the amount of light received on the surface. It is typically expressed in lux (lm/m2) (Velux).

Illuminance Uniformity (Uo): *Ratio between the minimum and average illuminance in a space or on a desk surface.*

Luminance (Cd/m²): Luminance is the measure of the amount of light reflected or emitted from a surface. It is typically expressed in cd/m² (Velux).

Respondent: Person answering the questionnaire.

Spatial Daylight Autonomy (sDA, %): A measure of daylight illuminance sufficiency for a given area, reporting a percentage of floor area that exceeds a specified illuminance (e.g., 300 lux) for a specified percentage of the analysis period (IES LM-83-12).

Useful Daylight Illuminance (UDI, %): Fraction of the time in a year when indoor horizontal daylight illuminance at a given point is within a given range, normally 100-3000 lux (Nabil & Mardaljevic, 2005).

Bidirectional Scattering Distribution Function (BSDF): *Stands for bidirectional scattering distribution function. Essentially, it is a mathematical function that determines the probability that a specific ray of light will be reflected (scattered) at a given angle.*

High Dynamic Range (HDR): Is a technique used in imaging to reproduce a greater dynamic range of luminosity than what is possible with standard digital imaging techniques. HDR images can record and represent a greater range of luminance levels than can be achieved using more traditional methods, such as many real-world scenes containing very bright, direct sunlight to extreme shade. This is often achieved by capturing and then combining several different, narrower range, exposures of the same subject matter (Wikipedia).

Ambient bounces (-ab)[1]: *Maximum number of diffuse bounces computed by the indirect calculation. A value of zero implies no indirect calculation.*

Ambient division (-ad): *Number of initial sampling rays sent from each ambient point into the hemisphere to determine the indirect incident light. The error in the Monte Carlo calculation of indirect illuminance will be inversely proportional to the square root of this number. A value of zero implies no indirect calculation.*
The Ambient divisions and super-samples parameters can be used to help reduce "noise" in a calculation. By setting these options higher more rays will be tested when calculating an ambient value for a point.

Ambient super-samples (-as): *The number of extra rays that will be used to sample areas in the divided hemisphere that appear to have high variance. Ambient super sampling should usually be set to about one half or one quarter of the Ambient division's parameter. Super-samples are applied only to the ambient divisions which show a significant change.*

Ambient resolution (-ar): *This number will determine the maximum density of ambient values used in interpolation. Error will start to increase on surfaces spaced closer than the scene size divided by the ambient resolution. The maximum ambient value density is the scene*

[1] For more information regarding Radiance settings please consult:
https://www.radiance-online.org/community/workshops/2011-berkeley-ca/presentations/day1/JM_AmbientCalculation.pdf

size times the ambient accuracy (see the Ambient Accuracy [-aa] parameter below) divided by the ambient resolution.

Ambient accuracy (-aa): *Maximum error (expressed as a fraction) permitted in the indirect irradiance interpolation. You should normally use a value between 1 and 0.1, with lower values giving the best accuracy. A value of zero gives no interpolation.*

Limit weight (-lw): *This parameter limits the rays' weight in the scene.*

Limit reflection (-lr): *This parameter limits the specular reflections in the surfaces.*

Transmittance (Tn)[2]: *Measured ratio of light at normal incidence. The percentage of visible light that is transmitted through the glass. The VLT is measured in the 380-780nm wavelength range perpendicular to the surface. The higher the percentage the more daylight. Also known as Tv, Tvis, LT and VT. This value is supplied by the manufacture company.*

Transmissivity (tn): *Ratio of the total light that passes through the glass. This value is used as input in "trans" and "glass" material definitions.*

Software

Some definitions about the software used in this thesis are provided below:

Radiance: Suite of tools for performing lighting simulation. It includes a renderer as well as many other tools for measuring the simulated light levels. It uses ray tracing to perform all lighting calculations, accelerated by the use of an octree data structure. Radiance often serves as the underlying simulation engine for many other packages[3] (Wikipedia).

Daysim: *Daylighting analysis software that calculates the annual daylight availability in buildings based on the Radiance backway raytracer. It calculates a series of climate-based daylight metrics including daylight autonomy (DA) and useful daylight illuminance (UDI). Furthermore, DAYSIM can calculate the daylight glare probability (DGP) for glare assessments.*

Rhino3d: is a commercial 3D computer graphics and computer-aided design (CAD) application software. Rhinoceros geometry is based on the NURBS mathematical model, which focuses on producing mathematically precise representation of curves and freeform surfaces in computer graphics (Wikipedia).

Grasshopper3d: Grasshopper is a visual programming language and environment that runs within the Rhinoceros 3D computer-aided design application. Advanced uses of this tool include parametric modelling for lighting performance analysis for eco-friendly architecture

[2] More information available: https://www.iesve.com/support/ve/knowledgebase_faq/faq/1282
https://floyd.lbl.gov/radiance/refer/Notes/rpict_options.html

[3] Other programmes such as Honeybee, Design Builder, Diva or Sefaira among other, use Radiance engine to perform lighting simulations.

and building energy consumption. It also favors the medium in which Ladybug and Honeybee is presented (Wikipedia).

V-ray[4]: *Rendering engine that uses global illumination algorithms, including path tracing, photon mapping, irradiance maps and directly computed global illumination.*

Design Builder: *EnergyPlus based software tool used for energy, carbon, lighting and comfort measurement and control. DesignBuilder is developed to ease up the building simulation process.*

Honeybee[5]: *Plug-in connecting Grasshopper to EnergyPlus, Radiance, Daysim and OpenStudio for building energy and daylighting simulation. The Honeybee project intends to make many of the features of these simulation tools available in a parametric way.*

Ladybug[5]: *Plug-in to import standard EnergyPlus Weather files (*epw) into Grasshopper and provides a variety of 3D interactive graphics/metrics, including: Sun-path, wind-rose, radiation-roses, radiation analysis, shadow studies, and view analysis.*

[4] In this thesis it is used as part of Rhino, as a render plug-in.

[5] Honeybee and Ladybug are ultimately python code libraries components to create, run and visualize the results of daylight (radiance), energy analysis (OpenStudio), and environmental analysis. They are also Open Source software and can be customized based on the user needs.

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1 Introduction

Daylighting as a strategy in building design has been a fundamental aspect in architecture for thousands of years. It is believed that, as far back as in the ancient Egyptian time, around 3100 BC, some buildings were shaped with daylighting in consideration (Dubois et al., 2019). Before the introduction of electrical lighting, buildings relied on daylight to illuminate interior spaces. The Egyptians used daylight control to temper the heat of their extreme climate, by lattice and screens with different size openings to allow for daylight penetrating into the space. In Rome, buildings were designed around courtyards surrounded by living space to maximize available daylight. European Renaissance masters revered light as both a practical and aesthetic design tool while Baroque style used indirect light to create mystery and intrigue in building. However, as electric lighting sources and technologies improved, daylight took a back seat in building design.

Today, encouraged by updated building codes, new energy regulations, and a renewed emphasis on sustainability, architects, building owners, and lighting designers are once again embracing daylight as a practical, aesthetic, resilient and symbolic element of good building design. Several studies have proved the importance of daylighting and its effectiveness on people’s health, well-being and performance (Vischer, 2008).

In order to establish a good visual environment with natural illumination, a wide range of codes and standards have been devised along with voluntary environmental certification systems such as e.g. LEED, BREEAM, etc. These codes, standards and systems provide a series of minimum requirements for daylight availability in regularly occupied spaces. This has resulted in an increasing demand for specialists in this field, leading to the rise of a variety of modeling techniques and approaches. Availability of advanced measuring and computer simulation tools and advanced daylight metrics has led to an exponential increase in the user frequency of daylight simulation tools during the last 20 years (Dubois et al., 2019).

The present study aims to provide an updated and verifiable monitoring workflow that could serve as a guide for future lighting evaluations and design decisions in the early design phase.

1.1 Objectives and research questions

The subject of this study, IDOM headquarters in Madrid, awarded for being among the first of its kind in Spain, when the built environment was obsolete and with scarce knowledge about its climate impact. In addition to this, special attention was attributed to the daylight aspects since its conception, avoiding both glare issues and overheating caused by direct solar radiation.

Therefore, the focus of this audit is to document the existing lighting conditions through different tools: subjective assessment, field measurements, daylight simulation of both static (daylight factor) and dynamic daylight metrics (daylight autonomy, probability of glare), and to propose a workflow that could be adopted for future daylighting and electric lighting integrated assessments in an attempt to answer the following research questions:

-Is it feasible the solely use of the same evaluation method for every building regardless its uniqueness?

-How to decide which simulation software is more appropriate in every situation?

-How much could influence in the annual metrics the impact of shading devices?

-To what extent the floor level influences daylight in a low-density area?

-How much electricity can be saved when using a harvesting daylight system?

-Is it possible to evaluate the importance of the different building features and quantify its impact?

-How to decide between one type of roller blind or another in depend which situation?

Literature review

Several studies and guidelines about daylighting evaluation have been written in the past few years. However, it is hard to find a generic paper that covers most aspects of daylight assessment. Instead, information from different sources was integrated. The literature review primarily focuses on protocols in generic lighting audits, check lists, and questionnaire evaluations.

In order to define the thesis boundaries, diverse articles about, rules of thumb, questionnaires, software comparison, solar screens, shading and case studies of renovations were consulted. Lack of information on simulation of complex fenestration systems and perforated screen facades, such as the one in this office building was one of the main issues.

General overview

Lighting simulation is increasingly becoming a substitute to traditional verification techniques based on e.g. physical scale models or full-scale measurements. It is expected that lighting simulation usage will increase as a result of newer, complex construction codes and the certifications requiring sophisticated ways to demonstrate compliance. As a consequence, architecture and engineering students become familiar with computer modelling and simulations during their education.

A general overview about the state-of-the-art lighting simulation context was proposed by Ochoa et al. (2012). His paper covers the main challenges that daylight simulations address nowadays.

The complexity in representing occupancy and user interaction with different control elements, such as blinds, movable shades, sensors and switches, was one of the main challenges. Easy availability of standard material libraries and models that translate geometry provided by CAD systems were some of the other important concerns raised by Ochoa et al.

(2012). The need for exploring the potential of using HDR imaging to characterize reflectivity and transmission functions of complex fenestration systems was also highlighted in this study.

It was seen from the literature (Reinhart and Andersen, 2006) that a minimum accuracy between measurements and simulation of a built space remains around 20%. Acquiring reliable measurements of reflectivity from surroundings is very difficult as well as replicating sky conditions. These are two of the major sources of errors in simulations.

Other papers with general content were found and are worth discussing. The monitoring protocol task 50 written by Gentile et al., (2016) is an attempt to develop a standard monitoring procedure with the aim of supporting both expert and non-expert monitoring in retrofit assessments. This model proposed qualitative and quantitative assessments. Task 50 intended to demonstrate different lighting retrofit strategies in non-residential buildings through best practice and cost-effective solutions.

This paper revealed some interesting aspects of the light that should be considered when evaluating the visual comfort within a space.

Gentile et al., (2016) make reference to several articles from other authors in Task 50 monitoring protocol. Some authors argued that although the daylight factor is simple to measure, it is not a very comprehensive metric for daylight. Instead illuminance values around the equinox and solstice are found more effective measurements for monitoring (Mardaljevic et al., 2009).

In this article is stressed the ambiguity of some aspects that occurs during lighting evaluations. For example, it is found that the color appearance is a matter of psychology, of aesthetics and of what is considered to be natural. Thus, many factors could affect the preference of a warmer or colder light color. In some cases, a cooler light color appearance is generally preferred in warm climates, whereas in cold climates a warmer light color appearance is preferred. It is also worth noting how illuminance ratios are not always a revealing measure when assessing directionality. Some exceptions occur for side-lit interior conditions, where the tolerance of non-uniform illuminance become greater than the case of an electric lighting lit space.

In this report, the importance of the view out was also highlighted as one of the main functions of windows. Windows with a view of natural surroundings have proved to act as micro restorative environments, especially in offices as is the case in this master’s thesis. This micro restorative environment contribute to increase work performance and job satisfaction (Kaplan, 2001). It is also crucial to assess the access to the view when shading devices are used, where darker fabrics with high openness factor achieve higher clarity scores than light colored fabrics (Konstantzos et al., 2015). To conclude some recommendations for a good view out are proposed in this monitoring protocol. The view should have a width larger than 28◦ and a view distance larger than 20 m and include a minimum of two layers. It should also allow the viewer to judge the time of day, the weather conditions, support spatial orientation and allow connection to nature (Hellinga and Hordijk, 2014).

Software comparison

The traditional design methods are gradually being replaced by new performance-based methods in which simulation tools are used to support decision making. One of the first research studies was focused on ways to optimizes computation time in daylight simulations; This study introduced the different software available at the time and their capabilities.

Ghobad, (2018) addressed this question on an article written for a conference about daylight and energy simulation workflow. This paper focused on programs that can perform both energy and daylight simulations, such as DesignBuilder, DIVA for Rhino, Honeybee for Grasshopper and Insight360 for Revit. Although these programs use the same simulation engines, they generated different results due to different simulation workflows, default inputs, and user-defined inputs through the graphic user interface (GUI).

The pros and cons of these tools are extensively discussed by Ghobad, and some substantial conclusions can be drawn from this paper. While Design Builder is a more integrated tool, where one single geometry and material definition is needed, other programs require separate models. For example, DIVA relies on two separate models, one for energy and another one for daylight. This has the benefit that the energy model could be simplified with fewer details than the daylight model. When it comes to assign materials, DesignBuilder allows the user to pick predefined materials from an extensive library of templates, as well as customize or create new materials. In DIVA materials have to be selected independently from a predefined list for both energy and daylighting simulations, where adding customized materials demands scripting (writing a descriptor in text form) is the only option. On the other hand, Honeybee provides an extensive library and allows to create customized materials without scripting knowledge. Insight360 provides an extensive list of predefined materials, but there is no possibility to customized materials through its GUI (Graphic User Interface) and advanced scripting knowledge in Revit is required.

In case of annual simulations, the option of picking single sensor points is an advantage, since this type of simulation requires less time as compared to point-in-time calculations. In this respect, DesignBuilder does not allow to pick specific sensor locations and only few adjustments about the desired height of nodes, grid size and grid offset from walls is possible.

In contrast, Diva and Honeybee provide broader possibilities: They allow multiple analysis grids, specific daylight sensor locations and vector directions. Insight360 has a different approach on this matter; it only permits to choose a "Level" from the Revit model or the whole building and the analysis grid dimensions are fixed to one foot for point-in-time simulations and two feet for annual simulations.

Ghobad (2018) found another limitation in DesignBuilder and Insight 360. He stated that these two programs present the results per zone and it is not possible to access the illuminance data for specific analysis nodes to either plot or correlate these values with the floor plan. In contrast, DIVA and Honeybee are very flexible in terms of graphic display; they allow plotting node values on floor plans while providing access to the data modified through "Math" functions in Grasshopper and allow the user to export the results to another software if needed.

The computation time also varies from one software to another. Since Insight360 is a cloud-based program, simulation might take more time depending on the cloud traffic. On the other hand, DesignBuilder, DIVA and Honeybee return similar computing times and they also use the same basic simulation algorithm, Radiance in this case. The energy functions of these programs are not being included since is not within the scope of this thesis.

As can be seen, each tool offers special features for daylighting and energy. However, none of them provide a user-friendly process for integrated daylighting and energy analysis.

Apart from the simulation time, the setting time must also be taken into consideration, so that the software can complete simulation and feedback work with few inputs. This point is essential in the early stage. A tool to accomplish simple simulations is needed for architects to be able to analyze different alternatives that can be compared with a meta-model[6] at a later stage.

Other relevant studies use different approaches to address the software selection issue. Han et al., (2018) established a criterion to evaluate multiple aspects of the software alternatives. This rating is based on the tools' interoperability, simulation results and functions.

Some of the criteria in this approach established that the software must be architect-friendly, should complete simulation and feedback work with a few inputs, support parametric analysis and allow comparison of multiple alternatives. Among these four criteria, the first and second one must be fulfilled while criterion three and four are considered optional. Han et al., (2018) differentiate between the early stage and late stage analysis tools from a more professional viewpoint, since more than 40% of energy-saving capacities come from earlier stage design decisions.

One of the popular reasons to lean towards one software or another are the available templates, which consist of a building library that includes several specific types of buildings and permit a quick simulation with few inputs.

A good building performance simulation (BPS) tool is needed to maintain the continuity of the design process and the possibility to compare multiple alternatives. However, most people only want a simulation result and the amount of energy saving. Therefore, a practical and suitable BPS tool requires a rapid calculation speed to support the architects' work. On the contrary an advanced simulation technique coupled with an optimizer tends to be a time-consuming strategy.

BPS tools can be divided in two categories: physical and statistical calculation models. The first tend to be very accurate, while the second is based on calculations obtained with experience values and predictions, which improves the calculation speed, but may yield only a rough estimation. The disadvantage of the statistical model is that it loses its effect when the default variable parameters change as it breaks its association.

[6] A meta-model is a method that involves analysis of input and output relationships in order to establish a mathematical relationship (algorithm) that is easy and fast to compute.

Aksamija (2018) discusses different methods and workflow for integrating parametric design with building performance analysis procedures. A case study building was used to test and evaluate the workflows, interoperability, modeling strategies and results. The tools used in this study are divided into BIM (Insight360, Sefaira) and non-BIM (Ladybug, Honeybee). Three different building performance aspects were analyzed for each workflow: energy analysis, solar radiation analysis and daylighting.

It is concluded that the framework applied to Rhino, Grasshopper, Ladybug and Honeybee offers a lot of options and customization. However, the lack of BIM integration in this framework is a drawback, which means that designers may use it for conceptual and schematic design but will migrate to a BIM-based software for the development phases. Insight360 is a relatively new tool and the functionality of the tool has its limits. On the other hand, Sefaira offers a more customizable and accurate tool, which integrates into the BIM environment.

Rules of thumb

In the quest to investigate the IDOM building's daylight performance a preliminary study based on rules-of-thumb was carried out. These basic rules are very useful and simple to use during the schematic design phase. They are capable to relate a design quantity of interest to one or several design parameters. The main interest is that they are easy to learn and offer quick advice regarding key design parameters without slowing down the design process. In an audit scenario, as such as this thesis, they are a great indicator of the daylight design deficits, they can be considered as simple indicators that emphasize critical points.

Reinhart and LoVerso (2010) found that many of these rules differ in their exact formulation from one source to another, and there is no standard establishing these rules accurately. Another explanation might be that rules-of-thumb tend to be purely empirical. Reinhart and LoVerso (2010) critically reviewed several of these rules and tested their validity comparing them with a series of Radiance simulation.

A highly useful rule-of-thumb to identify building zones with high daylighting potential is the daylight feasibility test. This rule offers a quick test to identify which zones within a building can potentially be daylit or not. In this context a zone consists of a series of spaces in a building with similar characteristics. Some key parameters that influence this daylight characteristics are facade orientation and external obstructions, such as surrounding landscape or buildings, and the daylight factor needed in the space.

The study suggests that when the zone's effective aperture (percentages of the window with no obstruction) is larger than a certain threshold, called feasibility factor (DFF), then the zone has a high potential for daylighting and merits a more comprehensive daylighting analysis. This test can effectively inform fundamental programing decision such as where to locate zones with a high need of daylighting within a building from the earliest design stages.

How satisfactory the daylight within a space ends up being, is further dependent on the specific lighting requirements as well as daylight uniformity. Daylight quantity and uniformity both depend on interior space dimensions and surface reflectance's. Reinhart and LoVerso (2010) emphasized the efforts made by researchers to supplement the Daylight

Factor (DF) alternatives, such as climate-based metrics. But DF still plays a main role in the current norms and guidelines since it still is the most widespread daylight metric.

A previous study mentioned in the article (Reinhart, 2010 via Christoph F. Reinhart and LoVerso, 2010) validates the following relationship between the depth of the daylit area and the window-head-height (H). This rule stablishes that when a space does not require the use of a shading device, this ratio range can increase up to 2.5H, if a shading device is required then a ratio of 2H should be used. It is important to remember that the exact ratio for a particular space is largely influenced by the glazing type and target illuminance.

Reinhart and LoVerso (2010) also found a strong correlation between daylight feasibility and average DF calculated with Radiance, with a coefficient of determination R^2 of 0.87.

The resulting equation that links these two metrics, is especially useful when neither the mean reflectance, nor the window heights are known, as is the case when the daylight feasibility study is applied.

$$WWR > \frac{DFF}{\tau vis} \times \frac{90°}{\theta} \sim \frac{0.088 \times DF}{\tau vis} \times \frac{90°}{\theta}$$

This equation also stablishes a minimum WWR criterion that can be used from the earliest design stages onwards.

It is worth notice that the relationship between the obstruction angle (θ) and the window head height (H) predicts that daylight becomes negligible for heavily obstructed facades.

Reinhart and LoVerso (2010) organizes these rules in a design sequence for diffuse daylight. In step 1, he analyses site conditions and programming needs, step 2 covers the daylight feasibility test, step 3 room portions and step 4 the required glazing area. Each of these steps uses a rule-of-thumb. Predictions from this sequence tends to be slightly more conservative than Radiance simulations, allowing for some safety margin within the analysis

In this study Reinhart and LoVerso (2010) also noted that, when used in isolation, this sequence results in oversized windows since the daylight factor approach favors a "more the better" attitude towards light. Therefore, these rules should be combined with other metrics that also take into account different aspects such as direct sunlight, local climate, facade orientation and movable shading devices. In sunny climates, such as the one in Madrid, on the South and West unobstructed facades, the results of this sequence become largely irrelevant as overheating and glare concerns will determine the overall facade design.

In the article, it is also pointed out that interior obstructions, such as partitions in a landscape office, can reduce the annual amount of light available beyond the obstructions. This aspect should also be considered in future studies.

Another interesting outcome is the high correlation between Lynes' formula results when compared with Radiance simulations. Reinhart and LoVerso (2010) suggest that this formula could be used as a powerful quality control test for computer models and validations.

Other studies about rules-of-thumb were further reviewed such as Goia's (2016) about optimal WWR in European climates.

He studied the optimal window-to-wall-ratio (WWR) in different European climates in relation to an office building characterized by the use of best available technologies for building envelope components and installations. The optimal WWR is the one that minimizes the sum of energy use for heating, cooling and lighting on annual basis.

Goia (2016) emphasized the impact of the facade on the energy balance in a building, specially the balance between glazing and opaque areas. The selection of materials and components with appropriate thermal and optical properties greatly influences all aspects of the total energy balance when the building envelope is used to control the indoor environment.

The optimization of the facade configuration is not a straightforward problem: measures to minimize one aspect (e.g. the energy use for heating), often have a negative impact on the others (e.g. energy use for cooling and electric lighting). The optimal solution is thus the best compromise of different possibilities and needs to be found by means of an integrated (thermal and lighting) approach.

Among all aspects involved in the design of a facade system, the WWR is a parameter that has a deep impact on both the energy balance and architectural appearance of the construction. The "transparency" of a building is often determined during the very first stage of the design process and will not be subject to later changes, thus, the selection of an appropriate WWR value is crucial and should be made carefully.

In this article Goia (2016) claims that most previous studies regarding WWR do not account for solar shading devices on their calculations, which would introduce higher energy savings potential. Other aspects that might be relevant for the facade configuration in a global optimization procedure (e.g. costs, environmental impact and aesthetics) are not considered in this research. The aim of Goia's research is to provide a robust "rule-of-thumb" for practitioners, and the study is focused on value ranges rather than a single WWR value, which would also promote its use in the early design stage to compare different design alternatives.

One of the important questions in this study was to determine to what extent is the optimal WWR value sensitive to a change in design parameters such as compactness (evaluated by means of the Surface Area over Volume ratio, SA:V), HVAC efficiency (evaluated by means of the Seasonal Coefficient of Performance, SCOP) and efficacy of electric lighting (evaluated by means of the luminous efficacy, measured in lumens per Watts). Best practice and standardized inputs values were chosen for occupancy and ventilation schedules, internal loads, temperature and illuminance set points.

A total of 20 simulations per orientation were carried out in Goia's study, five different WWR values are calculated ranging from 20 to 80% (20, 35, 50, 65, 80%). These values were interpolated afterwards covering the whole range. In order to develop a reliable tool for different scenarios, a sensitivity analysis was performed. The outcomes of this analysis were later used to determine the WWR ranges.

It should also be noted that the room depth (5.4m) was kept constant. This fact definitely influences the results of the analysis, since it is well known that energy and environmental performance of a building is affected by the geometrical relation between the facade and depth of the space behind the facade. The deeper the building, the lower the influence of the facade configurations, among which the WWR parameter.

The optimal WWR values were investigated in four different climates (weather data from Oslo, Frankfurt, Rome and Athens was used), evenly distributed across Europe so that could represent the most common conditions of the continent at different latitudes.

The outcome of the analysis for different electric lighting efficiency is very similar regardless the location and orientation, showing that more efficient installation determines a move towards lower values of the optimal WWR due to a lower impact of the artificial lighting energy use in the total energy balance.

This study also revealed that total energy can be non-linearly dependent on the WWR and that, when taking one entry of the energy balance at a time without considering the total picture, one might develop a non-optimal configuration.

When shading devices are required (South facades), the maximum DA is not obtained in combination with the largest WWR. Instead the highest values were obtained with WWR around 0.5. This fact can be explained considering the combined effect of WWR and the shading devices.

It was found that in cold dominated or temperate climates, the adoption of a wrong WWR is less critical than in warm climates, where the influence of WWR on cooling loads is important. In cold climates the highest increase in energy use for the south-facing facade is derived from a low WWR, even highly transparent facade solutions seem to be acceptable and energy-efficient. East and West-facing facades in cold climates are those where a non-optimal transparent percentage causes the lowest increase in energy use (as low as 5%).

The impact of the WWR increase as the location moves towards South, with Rome and Athens showing very similar values. Aided with an appropriate activation of shading systems, the South-facing facade is not the most critical one, even if very large glazed surfaces are used. In contrast the energy balance of the East-facing facade, immediately followed by the West- and North-facing facade, is the most sensitive to the non-optimal WWR, with a potential increase in total energy use up to 25%.

Some limitations arise from this study, the investigation was carried out on a highly insulated building envelope equipped with dynamic shading system. Results are therefore valid only under these conditions. Secondly, only one particular type of office building was investigated, where the plan layout had a central corridor with cell office rooms on both the sides. However, the type of office building chosen as case-study in this research is among those with the minimum room depth, and thus where the influence of the facade on the energy and environmental performance of the building is highest. This characteristic was chosen on purpose so that the impact of the WWR configuration could be assessed under the most relevant conditions.

Goia (2016) concludes that more transparent building envelopes are recommended moving toward colder climates if all variables are considered (heating, cooling and lighting energy use). This outcome is also confirmed by the fact that for almost all locations (excluding Oslo), the North exposed facade is the one where the optimal WWR has the highest impact. Finally, it is worth noting that the research outcome shows that the facade configuration (WWR in this case) has a lower impact on the total energy use of the building when compared to previous studies. This is because the efficiency of the entire construction has improved in the last few decades, and its impact on the overall energy use becomes more limited.

Shading systems

Current modeling guidelines are often focus on the potential for daylighting rather than the real performance.

In the quest for a more realistic results, Gilani et al., (2016) conduct a comparison between two different occupants' behavior (OB) models, one static case and another stochastic. This paper study the use of dynamic blinds and its impact in the overall energy use (heating, cooling and electrical lighting) in different WWR scenarios.
The study was carried out for a single room with one window and interior blinds. It is located in Ottawa and is only focus on the South orientation, as it is considered the most critical in terms of solar heat gains and daylighting.

The result of this study indicates that there is a deviation between the conventional and stochastic OB modeling approach predicting the energy and daylight performance. The OB modeling approaches yielded different optimal design regarding energy consumption.

Gilani et al., (2016) demonstrates that larger windows cause higher blind occlusion rates under the stochastic approach, especially for a window with higher visual transmittance. The increase in blind occlusion rates reduces the view and connection to outdoors, despite designers' expectation that larger windows provide better views.

The stochastic occupants' behaviour cases result in higher heating loads than the blind open static cases, due to higher blind occlusion rates and the resulting lower solar gains. However, the cooling loads are lower with the stochastic OB cases than the static ones.

This paper (Gilani et al., 2016) concludes that representing occupants interactions with building components using dynamic occupants models, is imperative for simulation supported design and code compliance to provide more accurate predicted building performance and near optimal design decisions.

Questionnaire

There are very few validated POEs (post occupancy evaluations) specifically focused on building illumination. Most studies cover a much wider spectrum of aspects. Very few POEs are seriously evaluated as such, and a standard method or questionnaire cannot be identified. Thus, one must be careful selecting which questions are specific to a building feature and which are common to all conditions.

Task 21 POE served as a guideline for this thesis questionnaire; it is a document presented as a manual where the main aspects of a subjective daylight evaluation are covered. The whole physical environment is also considered such as noise and thermal conditions, as it might influence the user experience.

The proposed questionnaire is meant to get the user's opinion of the work environment integrated over time, as a rule of thumb the author recommends a minimum of one month adaptation prior to answering the questionnaire. Moreover, a minimum of 10 to 15 respondents should answer the questionnaire. Other suggestions include the employment of homogeneous groups (similar age, background, etc.…) as a more reliable way to detect the real differences instead of mixing all kinds of persons in the same study.

It is remarkable that some of the reviewed articles were discarded due to their technicality level, as they are written in way, generally, only comprehensible and accessible for professionals and specialists that have been working in the field for several years. This way discriminates students who are willing to learn or began in the field.
Some of the more accessible and comprehensible literature that was found during this study has been listed below:
IEA SHC Task 50 Monitoring protocol for lighting and daylighting retrofits
IEA SHC Task 50 Energy audit and inspection procedures
Daylighting and Lighting Under a Nordic Sky

These documents have been used as reference for the lighting audit process of IDOM headquarters.

2 Methods

This thesis presents a step-by-step evaluation of the fundamental aspects of day/lighting design.

The collection of available data was considered one of the main first steps. From this information, it was possible to establish the base of the study and guarantee relation to reality.

The thesis covers a lighting audit where few alternative solutions are also tested. Therefore both, open loop and close loop workflow in some cases are used. The document is divided in four main chapters as shown in Figure 2.1, which includes:

1. A subjective assessment, where the author and user's perception are considered a key element, as their visual comfort is the ultimate objective.

2. A calibration section, where the model is checked through physical measurements with luxmeters.

3. A series of simulations to obtain a broader overview of the building performance.

4. An interpretation of the simulation results and conclusions of the audit.

5. If any improvement is proposed, in a retrofit or a new project, then a closed loop would be conducted as shown in Figure 2.2.

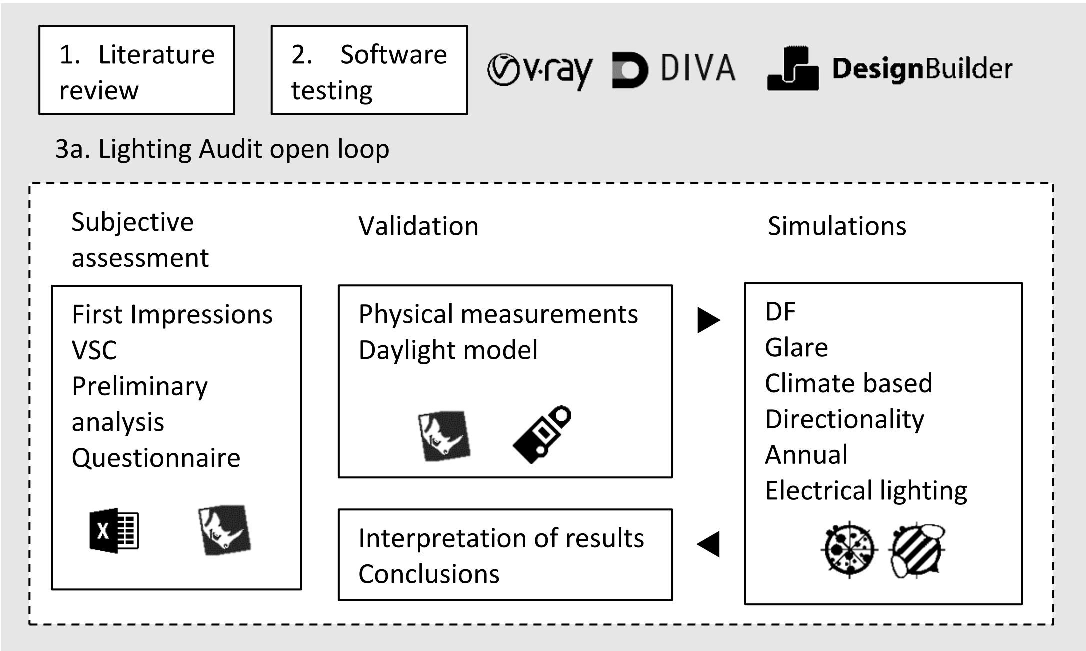


Figure 2.1 Open loop workflow.

If this is the case, one extra section would be added following the interpretation of results, a feasibility study. This will test if the proposal meets the requirements, if not, the process starts iteratively and a new set of inputs is needed.

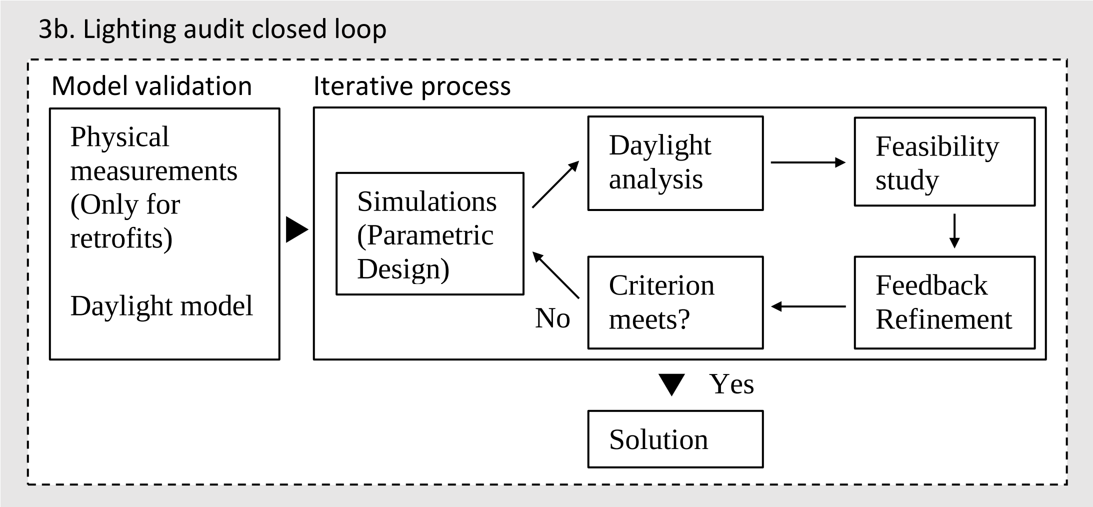


Figure 2.2 Closed loop workflow.

Whenever the criterion is fulfilled (building regulation, certifications, client demands, etc.…), then the loop stops, and the implementation of the solution starts.

2.1 Software review

As part of the thesis, the search for time saving solutions and new workflows to evaluate daylighting became a priority from the beginning.

Typical simulation programs are often complex for architects to use during the early design stages, resulting in building performance analysis being performed at later stages. However, the most critical design decisions (e.g. decisions regarding orientation, building massing, window sizes, etc.) are made at the conceptual stage of a project (Bazjanac, 2008). Based on this, a series of programs were developed over time. In this chapter, some of the main features of different programs will be discussed, outlining advantages and disadvantages from a daylighting simulation perspective.

HB and Diva provide more interaction with the user and allows for optimization and genetic algorithms (Han et al., 2018). While DB has a more explicit user interface, which guides the user by providing default values which limits its usage to basic calculations for environmental certifications (BREEAM, LEED, etc.). Diva is a more stable solution than HB, but as a counterpart, it is less flexible and does not allow to modify its code for possible changes[7].

It is also worth mention than among all them, HB is the only one which is freely available. This fact coupled with its flexibility and active online community decided the author to lean

[7] For a more in-depth review please consult: https://www.ashrae.org/File%20Library/Conferences/Specialty%20Conferences/2018%20Building%20Performance%20Analysis%20Conference%20and%20SimBuild/Papers/C053.pdf

for this tool. This web-based community guarantees that the software is updated and that there is continuity in this ever-changing society.

Some reflections about Ladybug and HB tools are summarized below:

Essentially, Ladybug and Honeybee have been designed to be somewhat intentionally difficult to use. While this may seem counter intuitive, the rationale behind this decision is that often with these types of software, users do not fully understand what is happening 'under the hood'. This means that often incorrect input parameters are entered, resulting in meaningless results. By allowing access to individual tools (components), users are forced to understand how they work before a result is returned. Furthermore, it affords users the possibility to customize their script, hence the notion of tool vs toolkit. It is basically the programming equivalent of a breathalyzer before you can drive ("Ladybug & Honeybee," 2016).

A fourth program called V-Ray[8], which is intended as a photorealistic rendering tool, was also analyzed. The last version provides a lighting analysis tool yet not verified by the author. Its potential as a commercial tool can be tested for displaying improvements in terms of interior design daylight performance, layout configuration or material selection. Interesting as a complement, but in any case, as a substitute of the previously mentioned tools.

[8] For more information regarding V-Ray lighting analysis please refer to: https://docs.chaosgroup.com/display/VNFR/Lighting+Analysis

2.2 First impresions

A walkthrough review of the whole building followed by a photographic documentation of the most representative elements, such as skylights, light wells, materials, windows among other, constituted an appropriate starting point.

Secondly, a subjective assessment through questionnaire to the building inhabitants was carried out. This provided information about the way daylight and lighting is perceived at different workstations resulting in a broad overview of the existing building's lighting conditions.

Some of the main insights from outside are its apparent simplicity, the use of humble and honest materials and its human scale, resulting in a very pleasant looking building that does not compete with its surroundings, but instead integrates in this delicate frontier between the countryside and the city.

From the inside, it has the capability to transport to another dimension, where nature is considered of a great importance. The entrance floor stands out for its biophilic design. This level is not focused on optimizing the space, but on providing a very pleasant transitory environment, surrounded by a garden full of fountains and water that could remind those of Islamic palaces where the water plays a main role. Despite being on the ground level and surrounded by several roads, this entrance is designed in such a way that one completely forgets about these hustles but feels emerged in this natural and peaceful space.

Figure 2.3 Perforated screen facade, entrance floor biophilic design, humble materials use.

Above the entrance level, are found the offices. The more permanent space is oriented towards the mountains, while the temporary office spaces are located towards the city of Madrid. The materials use in the interior are again very simple and natural, wood slats in the ceiling, visible bricks in the walls, white stucco in others, and dark vinyl flooring as shown in Figure 2.3.

2.3 Preliminary analysis

In order to identify the daylight design problems, a series of rules of thumb (Tregenza, 1998) were tested independently of any simulation result or previous measurements. Some of the aspects that were analysed are: window-head-height to room depth ratio and window-to-wall area ratio, also considering the surroundings, climate, shading features, shape, and orientation.

2.3.1 Window-to-wall ratio

Based on study by Goia (2016), the optimal WWR for office buildings in Athens can be extrapolated to the climate conditions in Madrid, as both belong to the same climate zone based on Köppen-Geiger classification: Csa, and both have similar latitude 37.9° N and 40.4° N respectively.

Table 1 WWR study based on Goia (2016) recommendations.

Orientation	*South*	*North*	*West*	*East*	*U-value/ W/m^2K*	*Ppl internal gains/ W/m^2*
Optimal WWR/%	20-30	35-40	30-35	30-35	0.7	11
IDOM WWR/%	22	68	30	16	1.1	22[9]

Table 1 values shows the optimal WWR[10] for a high-performance building office in Athens accounting for all the subsequent implications, including energy balance and daylight availability. These ratios when compared with the measured ones[11] retrieve acceptable values in the South and West facades. Larger differences are found in the North facade, where larger heat losses could be expected. However, in this particular case, where the panoramic views on this side are of great value, summed up to the expected internal heat gains in the open office, are enough reasons to justify this gap (Hellinga, 2013). On the other hand, Goia's study is located in a virtually non-obstructed context, while IDOM office building is in an urban context, where residential buildings are located very close to the East facade. This situation could be the reason behind this low WWR in order to keep the privacy on both sides, sum up to the fact that the East side is merely for transitional use.

2.3.2 Room depth

The rule regarding window-head-to room depth rule states that the maximum depth should not exceed 2.5 times the window head height[12] as shown in Figure 2.4 (C. F. Reinhart and LoVerso, 2010).

Since the window head is at 3m from the floor, the maximum room depth should be 7.5 m. Hence, the last 7.5 meters close to the core does not receive enough daylight and this area thus depend on electric lighting.

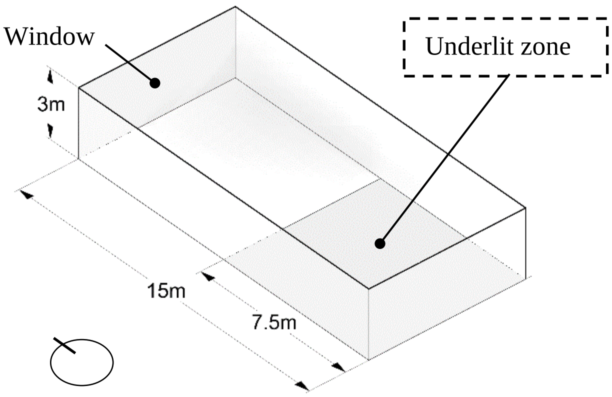


Figure 2.4 Room depth scheme.

[9] This value is obtain based on the typical open office plan [North oriented], counting the seats, multiplying this number by the average adult heat emission rate while doing office work seated [130W] from ASHRAE Handbook, and dividing this value by the occupied area.
[10] This thesis identifies WWR as the ration between the net transparent area and the total opaque area and not the ratio between the window surface (including the frame) and the total facade area.
[11] These values can be contrasted with the elevations plans in the appendix section. Please also note that the entrance floor has not been included in the WWR calculations, only the office area.
[12] Reinhart recommend $2*h_{window\text{-}head\text{-}height}$ if shading device is required and $2.5h_{window\text{-}head\text{-}height}$ if no shading device is required.

2.3.3 Layout function distribution

Another major point to consider is the space usage. In this case, the building serves as an office, and thus, its distribution is limited by daylight availability and solar heat gains constraints. Based on this, the service rooms and circulation core are placed in the most unfavorable daylit areas, where skylights (marked in grey) serve to bring daylight. The cellular offices and meeting rooms, which have fewer internal gains, are located towards South while the open office, which has a higher density of internal heat load is oriented towards North [see Figure 2.5].

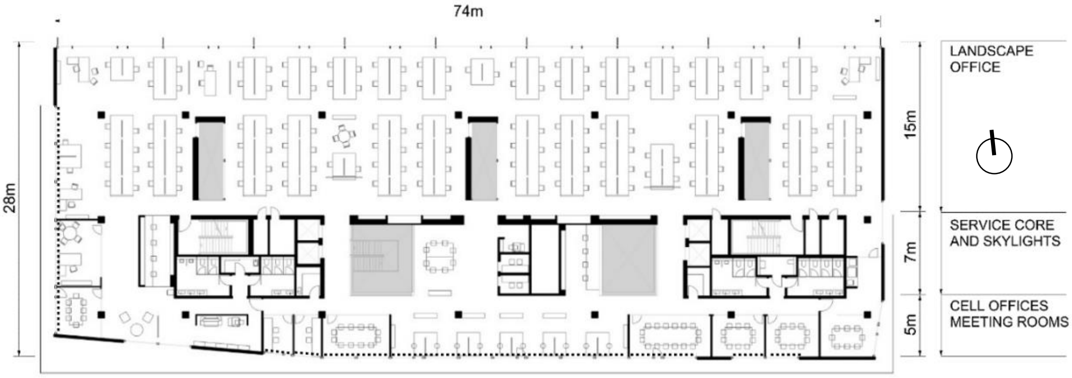


Figure 2.5 Typical floor layout with blinds marked in dash lines and skylights in solid grey.

This layout resulted in a very pleasant working environment since the open office is fully glazed and offers unobstructed views of Madrid's mountain range. It is also remarkable that the disposition of trees barely obstructs daylight, but instead provides much needed shade on the South facade [see Figure 2.6] which is extended with the use of climbing plants during summer.

Figure 2.6 South (left) and north (right) facades.

A double facade solution is applied to the South facade through perforated panels in order to mitigate the effect of solar gains and glare.

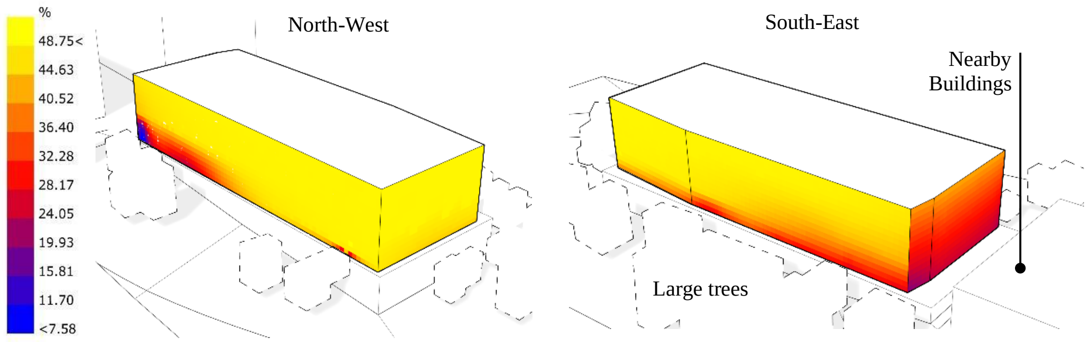


Figure 2.7 VSC in all four facades.

The effect of the surroundings is shown in the Vertical Sky Component (VSC) analysis, which determines the massing daylight potential. In Figure 2.7 it can be seen that the North is not as shaded as the South facade, and it also justifies the low WWR on the East facade, which is mostly a transition space and also favors privacy from the nearby buildings and the street.

2.4 Physical measures

The building was modeled according to the provided as-built drawings. Some updating modifications were made regarding furniture location and minor elements. All components that could affect daylight were considered. Furthermore, in-situ geometrical measurements were carried out in some cases.

The materials' surface reflectance was measured aided using a colorimeter[13] and post-processed with the color-picker online tool[14]. Every surface color was assessed three times. The color values obtained were later imported to color-picker tool to obtain the reflectance values and lastly averaged. The main specifications can be found in Table 2.

Table 2 Colorimeter specifications.

Accuracy	*Measurement*	*Technology*	*Color formats*
<1 ΔE[15] average on 2000 colors <0.3 ΔE average in inter-instrument agreement	4mm diameter area 40/0 measuring optics	Tri-stimulus XYZ sensor Full spectrum white LED's	CIE Lab LCH sRGB HEX

A similar procedure was carried out to measure the glazing transmissivity. Three illuminance measurements were collected with the lux meter positioned parallel to the window pane.

[13] Model Color Muse, for more information see https://colormuse.io/color-muse.html
[14] Available at https://www.jaloxa.eu/resources/radiance/colour_picker/index.shtml
[15] Delta E (ΔE) measures the amount of change in visual perception of two colors. A Delta E of 1 between two colors that are not touching each another is generally considered to be barely perceptible by the average human observer. From: http://www.colorwiki.com/wiki/Delta_E

Normal illuminance values were measured, inside and outside simultaneously; the ratio between them corresponds to the transmittance[16] (Tn). To obtain the transmissivity (tn), Tn could be simply multiplied by a linear scalar factor of 1.09 as a simplification of the original formula (Jacobs, 2014).

$$tn = \frac{\sqrt{0.8402528435 + 0.0072522239Tn^2} - 0.9166530661}{0.0036261119Tn} \sim tn = 1.09 \times Tn$$

The floor is dark gray with a glossy finish, whereas the walls are white. The ceiling is covered by wooden slats, which favors daylight penetration if compared with conventional solutions since it increases ceiling height.

The following table shows the measured values compared with the recommendations. The reflectance values were collected and compared with guideline recommendations[18] as shown in Table 3:

Table 3 Material surfaces reflectance's.

	Colour	*Measured reflectance*	*Recommendation*
Floor[17]	Dark grey	0.35	0.2-0.4
Visible slab ceiling	Dark grey	0.35	
Columns	Light grey	0.7	
Brick walls	Orange - red	0.45	0.5-0.8
Interior walls	White	0.8	0.5-0.8
Desk	White	0.75	0.2-0.7
Desk partitions	Cyan	0.4	0.2-0.7
Carpet	Cyan	0.4	0.2-0.4
Doors	Dark gray	0.35	0.2-0.7
Ceiling wood slats	Light brown	0.5	0.7-0.9
Aluminum mullions	Light grey	0.7	
Wood frame	Dark brown	0.35	
Fabric ducting	Light grey	0.8	
Acoustic ceiling boards	Grey	0.5	0.7-0.9
	Type	*Transmissivity*	
Interior glazing	Clear glass	0.8	
Exterior glazing		0.5	

[16] Transmittance is the measured ratio of light at normal incidence, whereas transmissivity is the ratio of the total light that passes through the glass.
[17] Please note that the floor is a non-lambertian surface and thus cannot be accurately measured with a colorimeter. To measure specular surfaces, advance optical equipment (spectrophotometer) is needed. However, to be able to perform the simulations and continue with the study a value of 0.35 from the colorimeter was used.
[18] Recommended values according to the European Standard EN 12464-1.

As can be noted from Table 3, in most cases the materials' reflectance matched the recommended values considered adequate in an office building, except for those used in the ceiling elements.

The sample areas chosen are intended to be the most representative, one typical open office on the North facade, a meeting room on the South facade and a cell office on the West facade. These spaces were selected since they cover different functions and daylight conditions, thereby representing the overall building lighting performance.

In order to validate the model, a series of illuminance measurements were undertaken. First, illuminance values from both luxmeters were calibrated under the same conditions and returned similar values. Two persons with luxmeter, on inside the building, and another one outside in an unshaded exterior location, worked together to obtain simultaneous measurements of the daylight level at every moment during an overcast sky condition. Every point was measured at 0.8m from the floor, three times and averaged to obtain more realistic values.

The previous measurements were carried out with the device model Urceri lux meter mt-912[19], its specifications are shown in Table 4:

Table 4 Luxmeter specifications.

Range	*Response time*	*Precision*
0~200,000 Lux	2 times/sec	± 3% rdg ± 8 dgt (10,000 lux)

For this task, a grid of points was defined, starting with a higher density of points in the areas close to the window and a lower density in the distant regions [see appendix Figure 0.1, Figure 0.2, Figure 0.3].

2.4.1 Simulation model

After gathering all the information, drawings and 3D models were built in Rhino. The model was subsequently optimized for daylight simulations. In this operation, all irrelevant details were excluded, and a simplified model was built to reduce computing time[20].

During the process, it was possible not only to produce a reliable 3D model, but also to understand how daylight behaves in space and relates with surroundings and the building inhabitants.

2.4.2 Simulation settings

Throughout the simulation, several tests were conducted. When testing the script, it is recommended to use low quality settings as it will reduce the simulation time considerably, but in return allows to check whether the inputs are correct, and everything is working just fine.

[19] https://www.urceri.com/mt-912-light-meter.html

[20] Please note that when the author refers to irrelevant details, this means only the details that does not affect daylighting quantitatively, like making desks as plane surface as well as the ceiling slats, this doesn't include frames, as they definitely influence daylight.

The next step corresponds to the interpretation of results, for this phase it is recommended to use medium quality simulation settings. This configuration allows to obtain some preliminary results, which could be used to make predictions and obtain first impressions.

Finally, in order to obtain more reliable results, high-quality settings were used. These values are considered as correct as far as the model is validated with reality. In most cases, high quality settings report higher values as the rays bounce more times over the surfaces, especially in the darkest parts of the building, hence its importance.

Table 5 presents the different settings used to perform the simulations:

Table 5 Radiance rendering settings.

Settings	*-ab*	*-ad*	*-as*	*-ar*[1]	*-aa*	*-lw*	*-lr*	*-ps*
Low quality	2	512	128	1448	0.25	0.05	4	1
Medium quality	3	2048	2048	1448	0.2	0.01	6	1
High quality	6	4096	4096	1448	0.1	0.005	8	1

The selected grid size was 1m for general simulations (entire floor) and 0.5 m for detailed room analysis (open office, meeting room and cell office).

2.5 Daylight model

In order to generate a model to run the simulations, the main external factors that could influence daylighting were considered. The model was divided in different parts as shown in the scheme [see Figure 2.8].

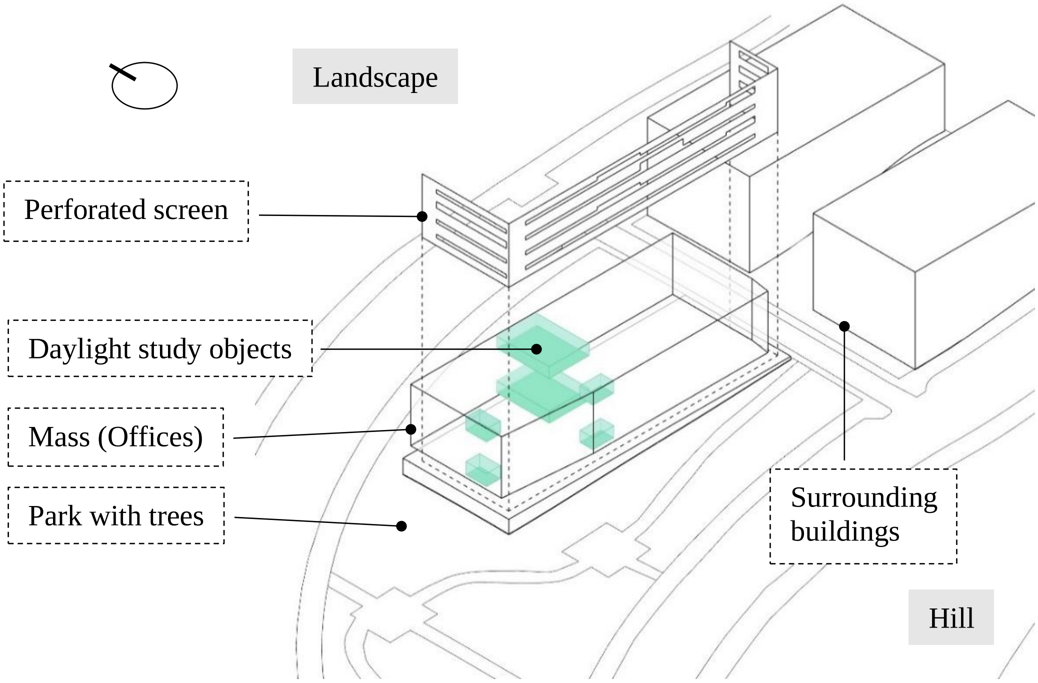


Figure 2.8 Daylight model scheme.

The way these elements were determined is explained in the following sections.

2.5.1 Topography

The location and surrounding topography were important considerations in the architectural design. The rectangular building is oriented with the longer sides facing North and South. On the East side there are several residential buildings that condition the facade configuration.

On the South, on the other side of the road, there is a small hill further away, which could affect to the daylighting at the back of the South oriented rooms.

Because of this favorable site, the Northern light from the sky can be entirely used in the open office. And the access to exterior views towards North is guaranteed [see Figure 2.9].

Figure 2.9 Panoramic window in open office.

2.5.2 Perforated screen

The perforated screen on the South facade is probably the most peculiar and complex element in the daylight model. This detail was studied carefully when modeling the building.

Some concepts must be considered prior to model it, to obtain the most accurate results possible.

Figure 2.10 Perforated screen detail.

In order to model the perforated panels, a simplified version was developed to reduce simulation time, always keeping in mind an acceptable error margin.

It is assumed, that because of the small perforation size, this difference would not significantly affect the accuracy of daylight calculation. Furthermore, this method will reduce simulation time considerably.

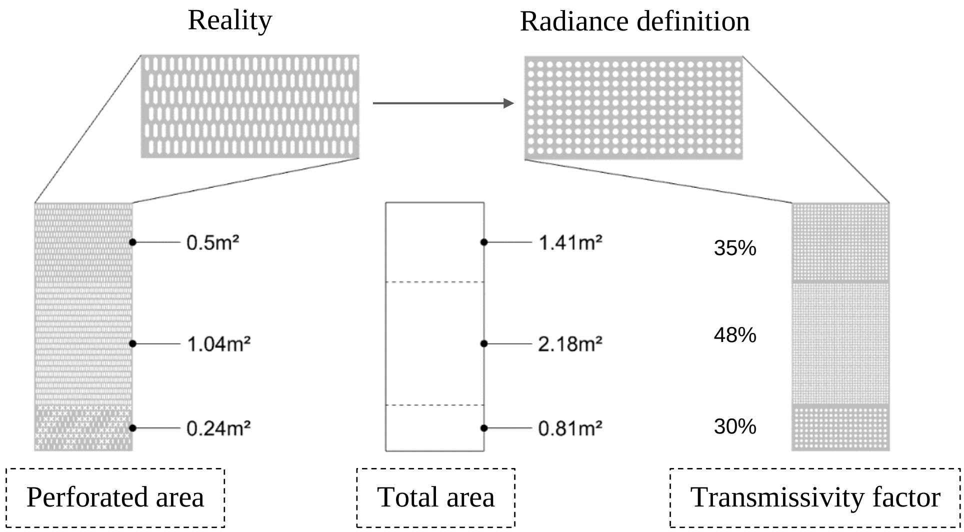


Figure 2.11 Microperforated panels Radiance definition.

To translate the real model to the Radiance definition a *cal format (Drakou et al., 2017) was used. This format allows transforming complex perforated panels into a more understandable structure [see Figure 2.11].

This structure consists of circular holes, where the ratio and distance between centers determined different transmissivity factor[21].

Some limitations were found regarding how the sunbeam's incidence angles affect the light transmitted to the office, especially in the annual simulations. This could affect the way calculations predict daylight transmitted into the space. This issue needs to be addressed by using a new software to define a bidirectional scattering distribution function (BSDF) file that could represent these variations, especially in cases where the panel thickness is disproportionately high compared to the hole size (McNeil, 2014).

2.5.3 Trees and surrounding buildings

Trees and surrounding elements were modeled as bounding boxes, so the space that these elements occupied is covered by a green translucent rectangular box, which mimics the leaves. As a limitation, this method could overestimate the effect of this feature.

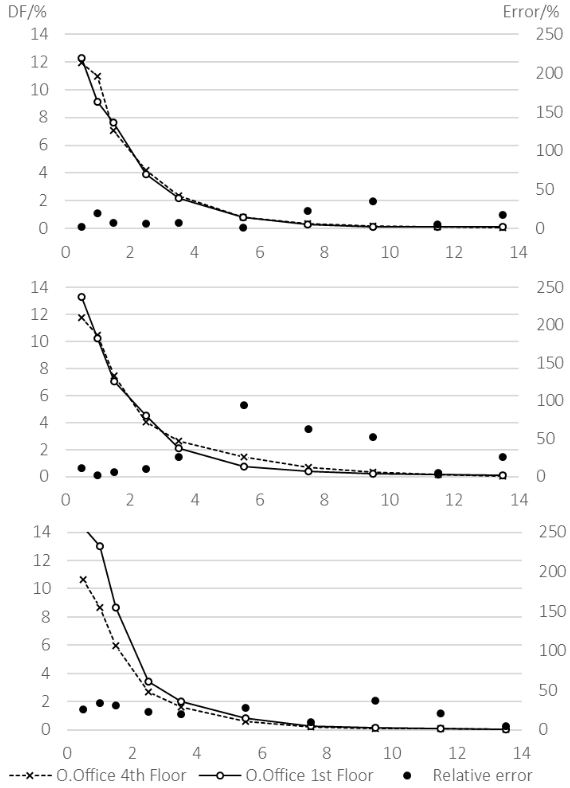
The dimension and location of such components were estimated by visual assessment and from aerial pictures in Google maps. Further studies with drones and photogrammetry methods could also be considered in order to improve the model accuracy, especially where the topography is of significant influence.

The reflectance values of the surrounding buildings correspond to a brick wall, with a reflectance of 0.35. On the other hand, the trees allow some light to go through. Jakubiec and

[21] Transmissivity factor determines how much light can go through the perforated metal panels in percentage. By this means the middle panel allows almost half of the light go through it.

Balakrishnan, (2015) guide to model trees in Radiance was used to define the trees' material properties. For annual simulations, a transparency schedule was applied to the deciduous trees, where they lost the leaves during the cold season.

2.5.4 Assumptions



After gathering all DF points values from the grid shown in appendix [Figure 0.1, Figure 0.2, Figure 0.3], agreement between the measurements on floors 4 and 1 was confirmed since they are spaces with the same size and configuration.

Based on this, in order to reduce the number of simulations, it is assumed that both floors will report similar outcomes and daylight levels.

Some differences in the open office values could be found due to the disposition of exterior fins on the North facade, as could be seen from Figure 2.6 (right picture) the fins location doesn't match between the first and fourth floors.

The relative error represents the absolute difference in percentage between two values located in the same sensor point.

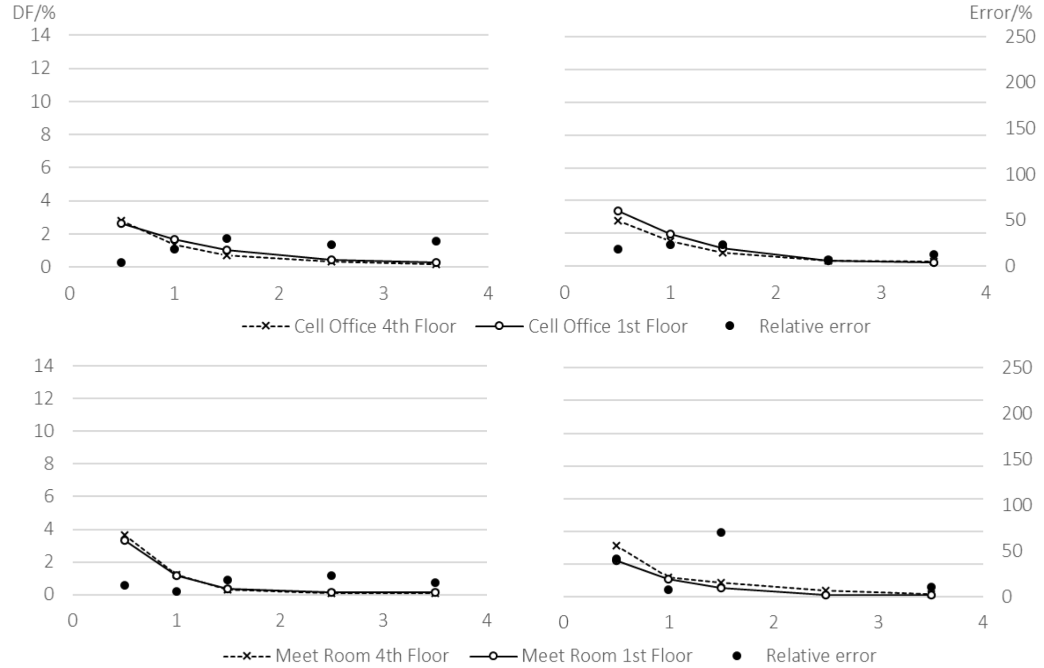


Figure 2.12 DF comparison between 4th and 1st floors.

2.5.5 Model validation

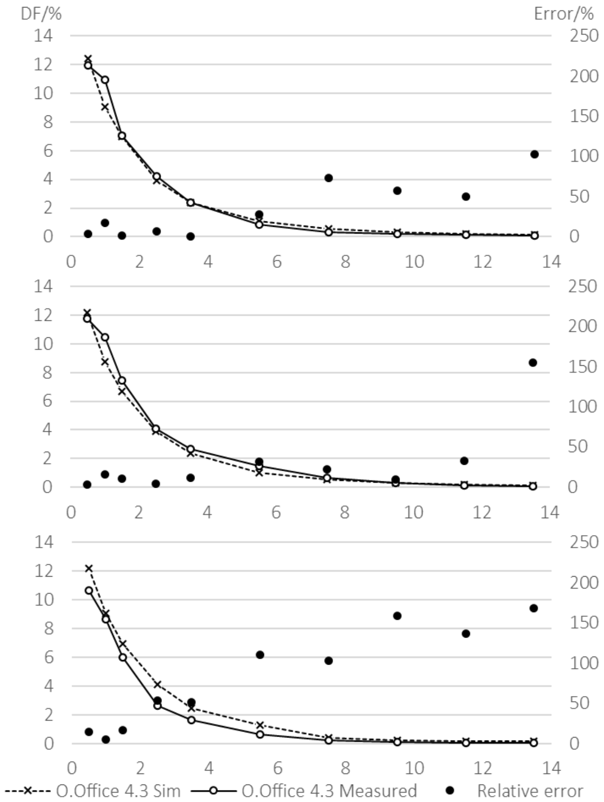


Figure 2.13 shows the resulting daylight factor values for each point on the 4th floor.

In this figure, the measured and simulated values are compared. It can be noticed how the relative error is inversely proportional to the daylight level. The weaker lit regions report higher errors, especially when they are below 1% DF. One explanation could be that for the points closer to the core, a higher portion of daylight is from the reflected component or from the skylight coming from the horizon. Both light components may be affected by uncertainties in the input.

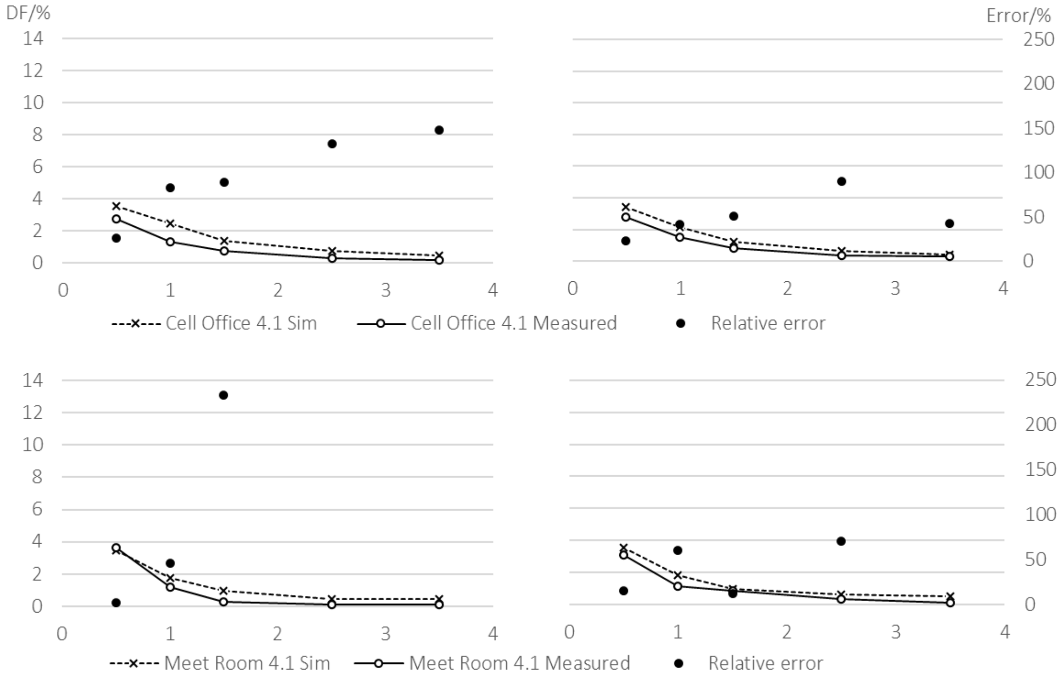


Figure 2.13 DF comparison between simulated and measured values.

2.6 Building features

In order to understand how the different elements in the building affect daylight a cull selection with daylight factor simulations was performed. This makes possible to quantify to what extent these elements affect daylight factor in three different room types (open office, meeting room and cellular office) and orientation.

This comparison helps to identify the hierarchy among features with respect to different configurations. For example, if some features are removed from the simulation, some certain elements become more important than others. Simultaneously, it is possible to appreciate how the computing time is reduced when some elements are removed from the scene and thereby determine whether they are relevant to the overall daylight performance.

Furthermore, this type of sensitive analysis makes possible to identify the daylight design weaknesses and how to improve them.

2.7 Directionality

Shadows play an important role for the perception of spatial structures and perspective, and for general orientation. Good shadow conditions are created through an appropriate mix of diffuse (non-directional) and direct light. This ensures a gradual transition from dark to light areas.

In order to evaluate a broader user experience, a study about directionality was also included in the audit. This metric considers not only the horizontal light level, but the light incidence in all directions, trying to mimic a human head. This simulation is performed at two different levels, one at 1.2m above the floor, emulating a person sitting, and another one at 1.6m for standing position as described in the European Standards EN 12464-1[22].

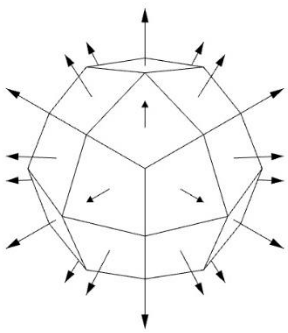


Figure 2.14 Vector-to-scalar scheme.

To carry out the vector-to-scalar directionality simulation, a polyhedral form, close to the one of a sphere of 120mm diameter was used. In this case this shape returns 24 evenly distributed sensor points as shown in Figure 2.14.
The value of the vector illuminance, Ev, is the difference between the highest illuminance at the surface of the sphere, E(max), and the illuminance measured at the opposite side, E(-max). The scalar illuminance, Es, is defined as the mean illuminance at the surface of the sphere.
This simulation was performed under overcast sky conditions (Dubois et al., 2016).'

[22] https://glamox.com/gsx/en-12464

2.8 Annual simulation

In order to calculate the electric light bills and see which portion of the space is well lit for most of the year, an annual simulation is required. Some important facts to consider before performing this kind of simulation includes:

Occupancy schedule provides information about occupancy assumptions for different building types. In this case, standard office working hours were used, from 9:00 to 17:00, where most of the workers are in the office.
Dynamic shading device system composed of moveable elements that work within an algorithm. Two control systems are generally used, manually controlled shading and automatic shading.
Illuminance threshold sets the limit from which the shading system is on. In this case the shading set point was >1000 lux for partially open state and >2000 lux for fully closed state. These limits are based on reports of occupant preferences and behavior in daylit offices with user-operated shading devices, as described in previous studies, see Nabil and Mardaljevic, (2005).
Shading group. The sensor points are divided in groups, normally one per orientation. For this case, there is only two groups for roller blinds in the South and West orientations.
Shading sensor. A list of test points that generally coincide with the occupants' sitting position. It is assumed that when the limit is exceeded the roller blinds go down.

The roller blinds were modeled in Rhino and added into the Honeybee as a translucent material surfaces ("trans" function in Radiance) with the following settings[23]:

Table 6 Roller blind assumptions.

Reflectance	*Diffuse transmission*[24]	*Specular transmission*[25]	*Specular reflection*	*Roughness*
0.8	0.12	0.03	0	0.01

These settings correspond to a white fabric roller provided by Bandalux, similar to the ones installed in the building.

Figure 2.5 shows the location of the roller blinds in the fourth floor marked as dash lines in the South and West facades.

A sensitivity analysis where a wide range of roller blinds were simulated and compared was essential to understand the effect of these elements in the overall daylight performance. Two metrics were evaluated DGP and DGI making possible to discard the options that could produce disturbing glare. The following table was used to rate the glare by level of tolerance:

[23] For more information regarding trans materials, please refer to: https://www.schorsch.com/en/software/rayfront/manual/transdef.html
[24] Fraction of light that passes all the way through the surface diffusely.
[25] Fraction of light transmitted as a beam, that is, the fraction of light not diffusely scattered.

Subjective rating	*DGP range*	*SGI range*
Imperceptible glare	<0.35	>18
Perceptible glare	0.35-0.4	18-24
Disturbing glare	0.4-0.45	24-31
Intolerable glare	>0.45	>31

In search for alternatives, several roller blinds were compared by using the DesignExplorer online tool. A total of twelve different fabric options divided in three color ranges (white, pebble and slate) and four different openness factors (OP 1, 3, 5, 10%) were investigated. The optical properties of these elements are described in Table 7:

Table 7 Fabric roller blinds optical properties provided by the manufacture Bandalux.

	White[26]				*Pebble*				*Slate*			
Openness factor (OP)	1%	3%	5%	10%	1%	3%	5%	10%	1%	3%	5%	10%
Visual transmittance (VLT)	13%	15%	15%	22%	3%	5%	5%	14%	2%	3%	5%	12%
Diffuse Reflectance (Rv)	83%	80%	78%	73%	36%	35%	33%	33%	14%	14%	13%	13%

2.9 Electric lighting system

One aim of this audit was to evaluate the efficiency of the electrical lighting system and compare the results with the simulations. This procedure could also be carried out for a new building design, where some luminaire systems would be tested, and an integrated lighting solution could be developed.

The main lighting control strategy used in the building is the dimming control through sensors, which automatically regulates the electrical lighting level until an adequate illuminance is obtained.

In this case the author assumed an automatic dimming system that is only on during the working hours. Other control systems such as always on or absence detection are also be proposed and compared thereafter. The lamps models used in this project are the following:

- Tubular fluorescent TL5 HE 2x28W/840[27]
- Compact fluorescent PL-C 2x26w/840/4p[28]

[26] The roller blind specifications for the model use in this building are marked in grey.
[27] For more technical aspects consult: https://www.assets.signify.com/is/content/PhilipsLighting/fp927926584055-pss-es_es
[28] For more technical aspects consult: https://www.assets.signify.com/is/content/PhilipsLighting/fp927907384002-pss-global

As it is not always possible to find the exact same luminaire as *ies files used in the simulation program, lighting systems with similar specifications were used to perform the simulations. *The photometric diagrams of each luminaire can be found in the appendix [see Figure 0.29 Luminaire photometric distribution (see tubular lamp left, compact lamp right).*

Figure 0.30Figure 0.31.].

External limitations on gathered field measurements were encountered due to inaccessible building at the time of performing this part of the study, consequently previously recorded data about lighting fixtures was used. Otherwise, the *ies lamp files would have been validated with the real illuminance values. It should also be noted that the simulation only considered the lamps and not the entire luminaire, which could be the source of important overestimation.

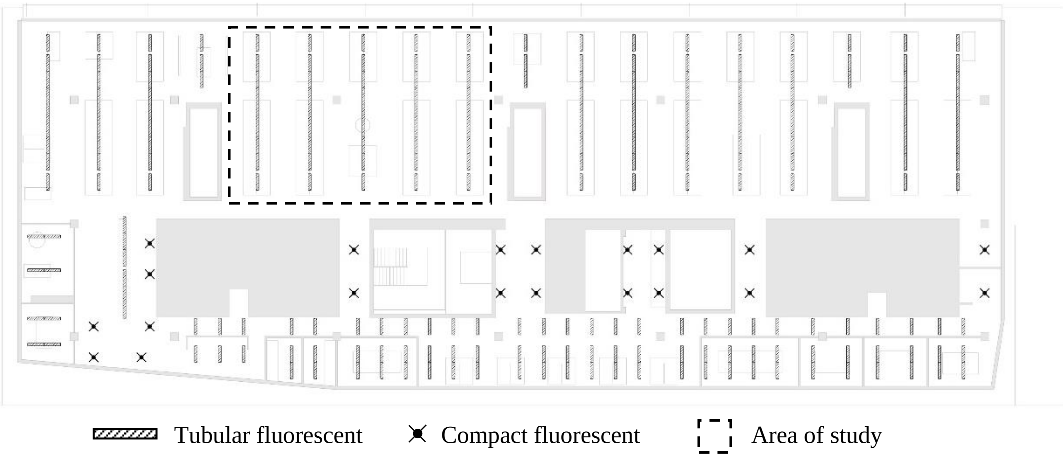


Figure 2.15 Luminaries location.

To carry out the detailed electrical lighting simulation a representative area in the open office was chosen, marked in dashed lines in Figure 2.15. In this case, a 0.5m grid subdivided in four lighting control groups was considered. This control groups were based on their distance from the facade.

The electric lighting system was set to keep a level of 500 lux[29] on the theoretical sensors, following the recommendations from ASHRAE, which are distributed all over the working space in the open office.

[29] For more information regarding recommended values for various activities please consult: https://www.engineeringtoolbox.com/light-level-rooms-d_708.html

2.10 Subjective lighting evaluation

The first part of the study consisted of a subjective assessment by a questionnaire. The selected questions were aimed to set a base to support some of the simulation outcomes. Some of the variables of this evaluation include daylight availability, glare control, lighting preferences, light levels, color rendering, color temperature, directionality, user's control, etc.

In this evaluation a total of 15 individuals were chosen according to their sitting position and background (professionals aware about daylighting). The intention was to pick the workplaces which could provide a reliable picture and help to compare the results. According to this, a variety of locations on the open office on floors 1 and 4 were chosen, where some of them were located next to the window looking towards one direction or its opposite, while others were located close to the building core.

The time and day were selected according to the frequency of sky conditions[30]. The most typical sky condition for Madrid is a sunny sky [see Figure 2.16].

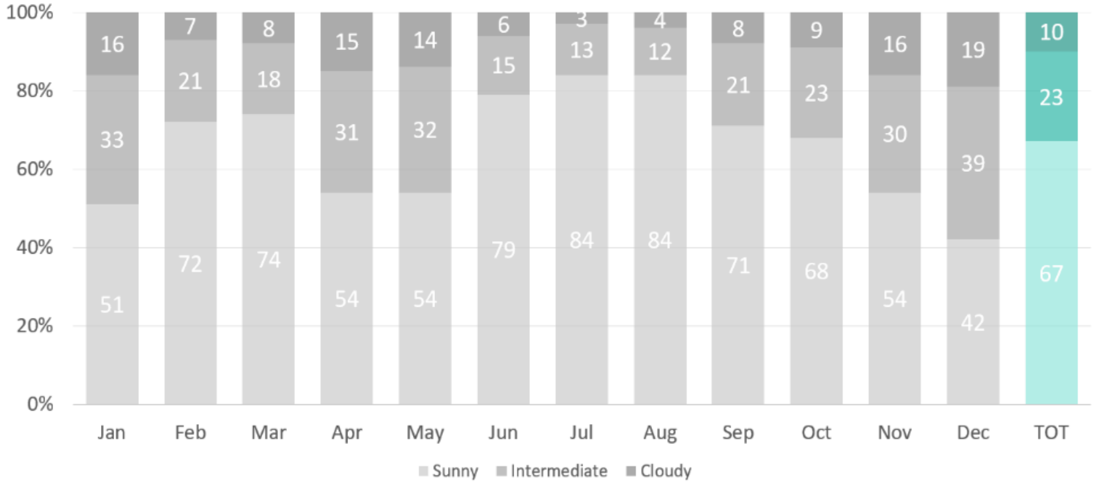


Figure 2.16 Sky type frequency.

Please see the questionnaire evaluation example in the following subchapter.

[30] Data from http://www.satel-light.com/indexs.htm.

Questionnaire

Dear Sir/Madam

This questionnaire is part of a master thesis research where light quality at the workspace will be evaluated. Lighting plays an important role in guaranteeing a healthy work environment and reducing energy consumption.
At the end of the questionnaire you will find a space for additional comments you might wish to provide. Please fill out the paper while seated at your work desk and answer the questionnaire before an hour from the delivered time.

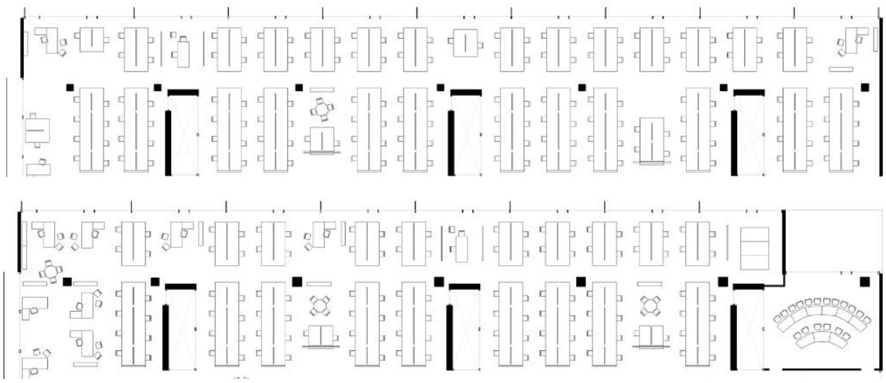
Floor N____ Date__________ Delivered time __________

Age □ <20 □ 21-30 □ 31-40 □ 41-50 □ 51-60 □ >60 Gender □M/ □F

Please mark with an V where are you sitting and your gaze direction:

4th Floor

1St Floor



1. How would you rate the origin of the light source at your workplace?
Daylight □ □ □ □ □ □ □ Electric light

2. If you could choose, would you prefer more
Daylight □ □ □ □ □ □ □ Electric light

3. The light satisfaction in your workplace is
Very high □ □ □ □ □ □ □ Very low

4. Is light effectively distributed?
Very uniform □ □ □ □ □ □ □ High contrast

5. How do you rate the overall light level on your desk?
Too lit □ □ □ □ □ □ □ Too dark

6. Do you experience any reflections at your workplace?
Yes, very much □ □ □ □ □ □ □ Not at all
If yes, specify where: □ Computer work □ Paperwork

7. In general, are you visually bothered by glare from the light fixtures?

Yes, very much ☐ ☐ ☐ ☐ ☐ ☐ ☐ Not at all

8. In general, are you visually bothered by glare from sunlight?
Yes, very much ☐ ☐ ☐ ☐ ☐ ☐ ☐ Not at all

9. Do you experience any level of reflected glare from
☐ Wall ☐ Floor ☐ Desktop ☐ Window ☐ None of the previous
If yes, specify the source: ☐ Sunlight ☐ Electric light

10. How do you rate the appearance of the room under electric lighting?
Too cold ☐ ☐ ☐ ☐ ☐ ☐ ☐ Too warm

11. How would you rate the object's colours under the artificial light?
Vivid ☐ ☐ ☐ ☐ ☐ ☐ ☐ Mild

12. How do you rate the access to exterior views at your workplace?
Very high ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very low

13. Do you consider you need control over the light level at your workplace?
Yes, very much ☐ ☐ ☐ ☐ ☐ ☐ ☐ Not at all
If yes, would you: ☐ Lower the intensity ☐ Increase the intensity

14. How do you distinguish shapes and contours under the light clearly?
Sharp ☐ ☐ ☐ ☐ ☐ ☐ ☐ Blur

15. Your visual concentration at the workplace is
Very high ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very low

16. Do you experience any or several of the following disorders?
☐ Eye fatigue ☐Headache ☐Distraction ☐ Blur vision ☐Other________

17. Overall, your ambience satisfaction is
Very high ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very low

18. Do you use any visual aids (e.g. glasses, contact lenses…)?
Please specified ______________
How often? Always ☐ ☐ ☐ ☐ ☐ ☐ ☐ Never

19. Do you experience any of the following discomforts in the work environment
☐ Cold ☐ Hot ☐ Air draft ☐ Moisture ☐ Odours ☐ Dust ☐ Exhaust air ☐ Noise

20. Would you propose any changes in the lighting design, if yes, please briefly describe in the remaining space.

3 Results

3.1 Daylight availability

In this chapter, the lighting quantity and quality indoors are analyzed. A good indicator in the first stages is the daylight factor. This metric represents the ratio between the natural light level outside and inside as measured simultaneously. It is the maximum daylight availability in the worst-case scenario, that is, an overcast sky. From this analysis it was possible to obtain some first impressions. In this section [see Figure 3.1], it can be seen that the first six meters from the window have a DF >1%[31]. This figure also shows how the window height affects

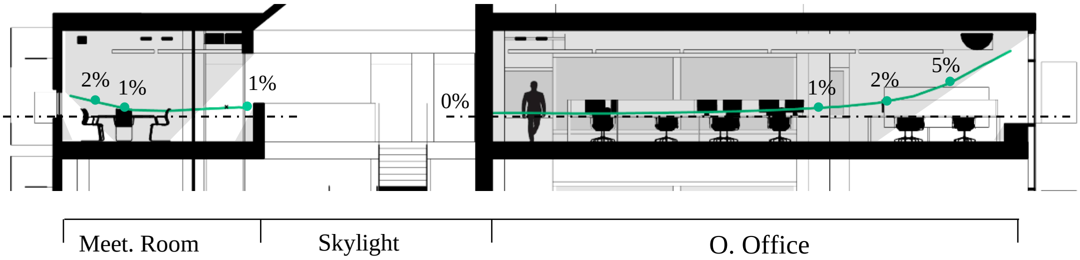


Figure 3.1 DF section.

daylight penetration on the South (left side in the section).
The window height is much lower than the North side, and thus the daylight does not reach far, and its reduction rate is higher. However, the depth in these two spaces varies considerably. Meanwhile, the meeting room is about 4m deep, while the open office has a depth which is about four times this value. This fact justifies the different window heights (0.64 m in the meeting room and 2.6 m in the open office).
Figure 3.2 shows the isocurves for a series of representative DF values.

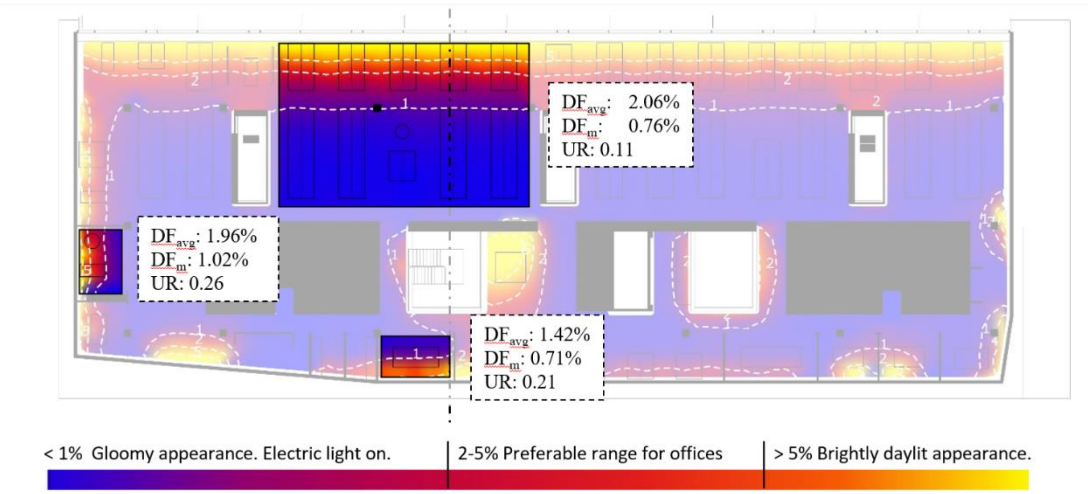


Figure 3.2 Daylight factor 4th floor.

[31] The 0% DF matches with the work-plane height, in this case 80cm.

From Figure 3.2 it can be read that the daylight levels in the open office regions close to the window there is a brightly appearance which in some cases could lead to users discomfort as it is conclude in the questionnaire section.

Areas under 1% DF far from the window are dependent on electric lighting and the workers seated in this area would probably experience a low daylit environment, poor color rendering, glare from fixtures, cold light temperature light, which are attributes matching with the votes shown in the questionnaire results.

It should also be mentioned that the skylights contribute to illuminate the core, bringing a feeling of relief into the space, which also helps to enhance its appearance. In some cases, the skylights mitigate the psychological impact of the electric lighting, which could lead to chronic discomfort, stress, and lower performance among others (Aries et al., 2015).

The study rooms were further analyzed, in order to obtain a more detailed investigation and results. Therefore, in this detailed evaluation, corridors and other service spaces were neglected in the average (DF_a), median (DF_m) and uniformity ratio (UR) calculations.

Apart from that, only the sensor points located 0.5m from the windows and walls will be considered, to neglect the extreme values.

The open office [see Figure 3.2] obtained a very low uniformity and a high average DF[32] when compared with the median value, and a very low uniformity. This is due to the size and depth of this room. The contrast between the values in the perimeter and the core is considerable.

The fact that the North facade is unobstructed, and it is possible to enjoy the views from almost any point in the office, contributes to reduce these drawbacks.

[32] Please note how all three DF simulation for the different rooms use the same reference legend.

3.2 Building features

In this sensitivity analysis certain elements are removed from the daylight factor simulation, one at a time, and its impact is compared with the reference case.

The reference case corresponds to the initial configuration where all the elements are considered as the set up used in this document to carry out the simulations[33].

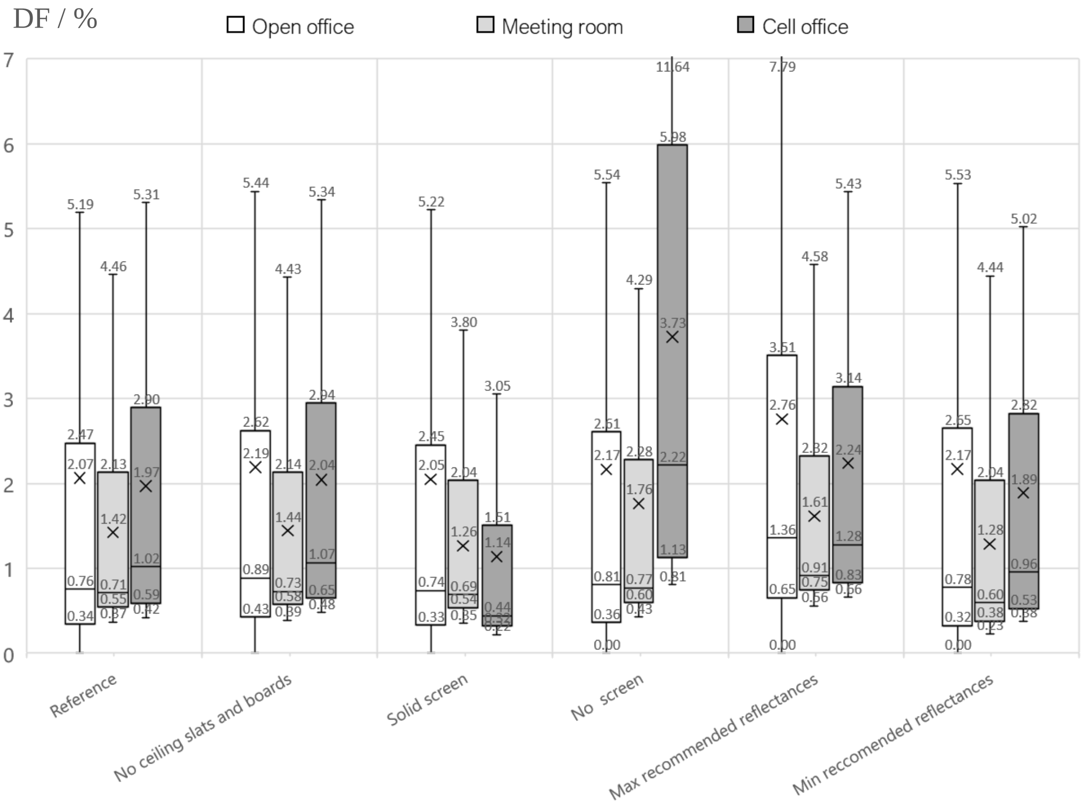


Figure 3.3 Building lighting features comparison.

From Figure 3.3 it can be observed that if ceiling wood slats and acoustic boards are removed from the calculation, any drastic change occurs. Because the DF metric is mostly affected by the zenithal light from an overcast sky, reflections from the ceiling are unlikely to have a strong effect on the simulations. Thus, no big differences were expected when removing details at the ceiling level.

Instead if perforations in the solar screen panels were neglected, DF values in the ceiling room (West) decreased considerably, where almost half of the window is covered by this element as shown in Figure 3.6. This feature strongly affects the daylight performance in this room, where very comfortable levels were achieved in the previous stage.

On the other hand, when the perforated screen panels are completely removed from the equation, very high daylight levels are found. Especially in the cell office, where could lead

[33] The X corresponds to DF average and the horizontal bar to DF median.

to disturbing glare. This can help to conceive these elements' importance, especially in rooms with high exposure to direct solar radiation.

When maximum recommended reflectance values [see Table 3] are used, then the maximum and median values rise considerably in all three rooms. The effect this feature has in the open office DF levels is remarkable. The median DF increases from 0.8 to 1.4% and the minimum from 0.3 to 0.7%, which considerably affects the daylight uniformity, one of the main characteristics of a well-lit space. It should be mentioned that these maximum reflectance values are applied to all elements in the ceiling, so this includes the ceiling wood slats and the acoustic boards. Instead, when minimum recommended reflectance values are used then the values remain alike to the ones obtained in the reference case.

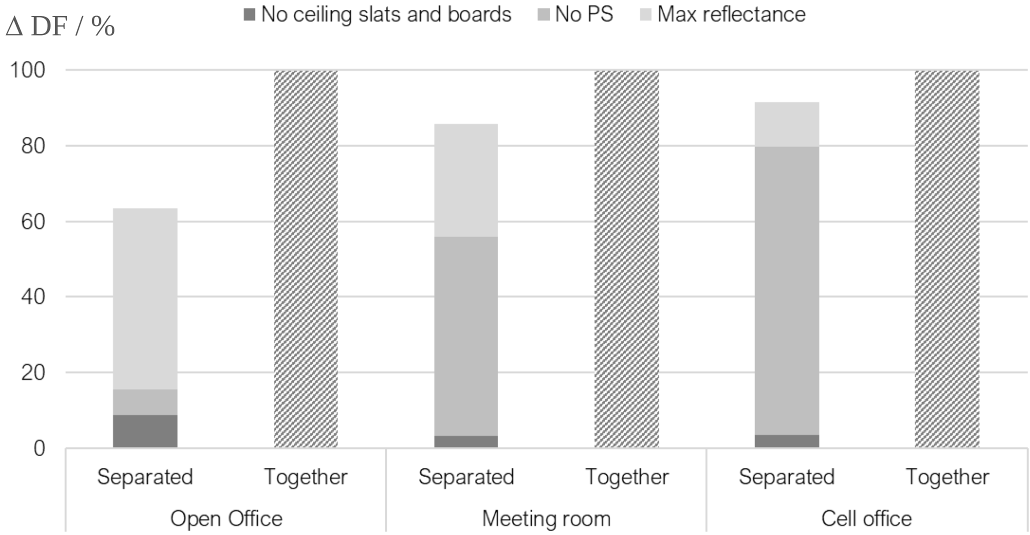


Figure 3.4 Features synergies in the different rooms.

Figure 3.4 represents the cumulative daylight factor difference with the reference case in percentage. It can be seen which elements gain more importance than others. In the open office case, the use maximum reflectance surfaces represent the biggest difference.
On the other hand, in the meeting room and cell office the effect of the perforated screen is of great importance, especially in these orientations where direct sunlight protection is needed.

When these elements are removed together it can be appreciated the effect is boosted, especially in the open office room, thus the ceiling elements and the maximum reflectance's are interfering each other, and this affects to a great extent in the daylight performance.

Please also note that this sensitivity analysis was carry out under overcast sky conditions (only daylight factor metric was assessed) due to time constraints, an annual climate-based simulation would have retrieved more realistic and revealing results.

Figure 3.5 Maximum recommended reflectance's daylight contribution.

Figure 3.5 shows the difference between the back of the open office, in the reference case (left picture) and the case with the maximum reflectance's in the ceiling (right picture) on the daylight levels.

The area close to the core in the open office retrieved very low DF lowering the uniformity in the whole room. Instead, when using light colors in the ceiling it can be seen how the task level appears considerably brighter than the current case and thus the uniformity in the room improves.

3.3 Photorealistic rendering

Some of the above comments are confirmed in the following photorealistic renderings produced with V-Ray [see Figure 3.6]. Also note that some of these renderings are performed when glare occurs. This explains the high contrast. In practice, this scenario would not happen since a shading device would be used. These renders were performed intentionally as raw as possible (no electrical light or shading blinds) to appreciate daylight behavior in the space.

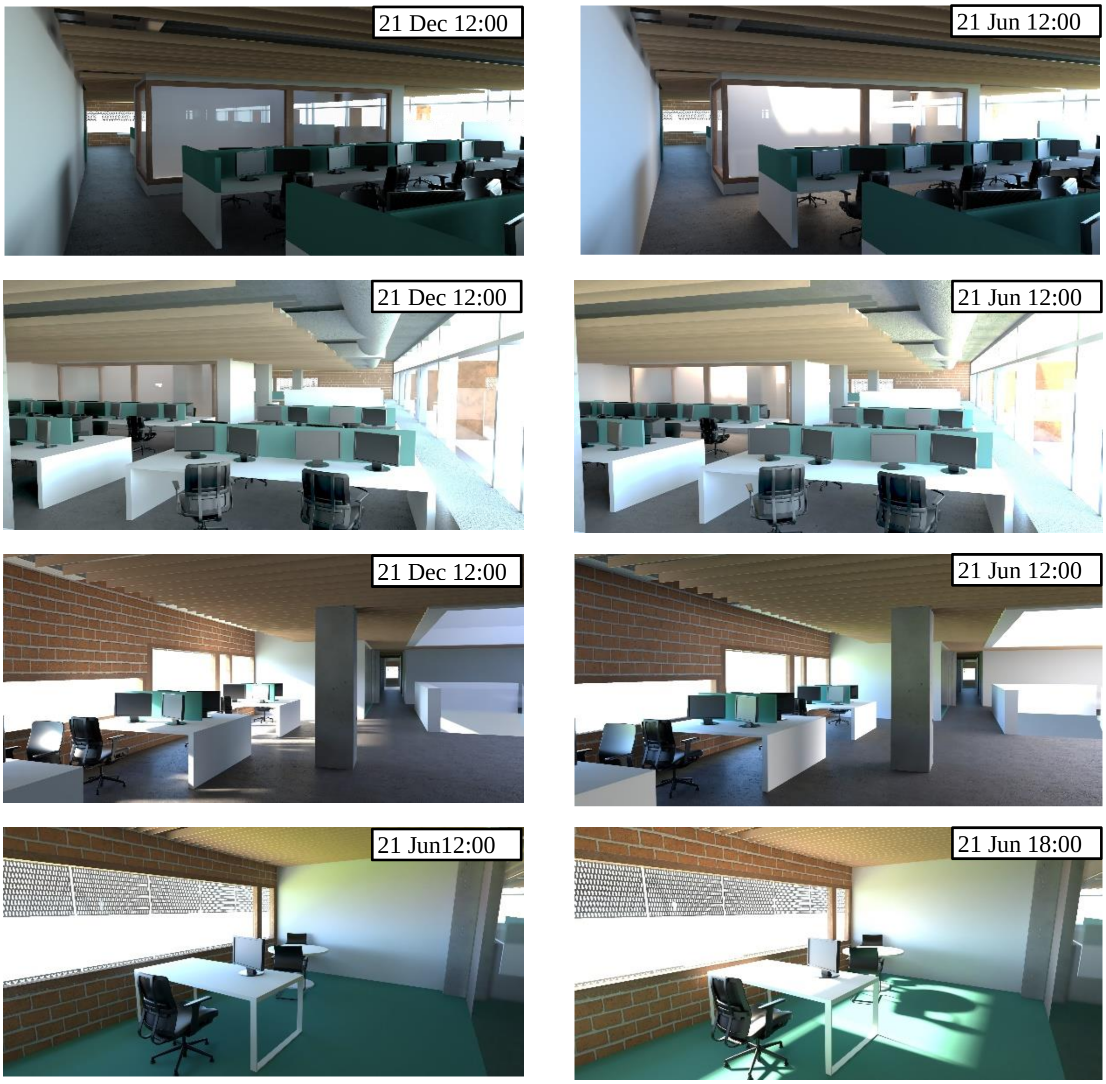


Figure 3.6 Photorealistic renderings.

It can also be observed the exponential daylight decay from the facade in the open office, and the effect of the skylight and the lightwell when the sun angle is vertical (21 Jun 12:00). It is important to point out that these images are only based on daylight under a sunny sky condition and do not have any other light source added, therefore they might differ with reality in this aspect.

3.4 Glare assessment

With the objective to calculate the magnitude of solar glare issues in the study zones, the temporary use rooms, such as meeting rooms, were removed from the assessment. Based on this, only the cell office and four open office positions were studied, two in the South and two in the North, each one looking in a different direction [please refer to appendix Figure 0.4 *DGP Open office South window looking West.*

Figure 0.5 DGP Open office South window looking West with blindsFigure 0.6- Figure 0.15].[34]

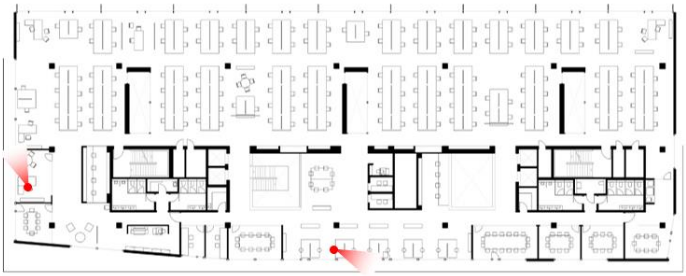


Figure 3.7 DGP study positions and gaze direction.

It was intended to pick the worst-case scenarios all year round. Consequently, the cell office and one position in the open office located on the South facade were selected as the most critical as shown in Figure 3.7. These two cases were analyzed further with image-based simulations.

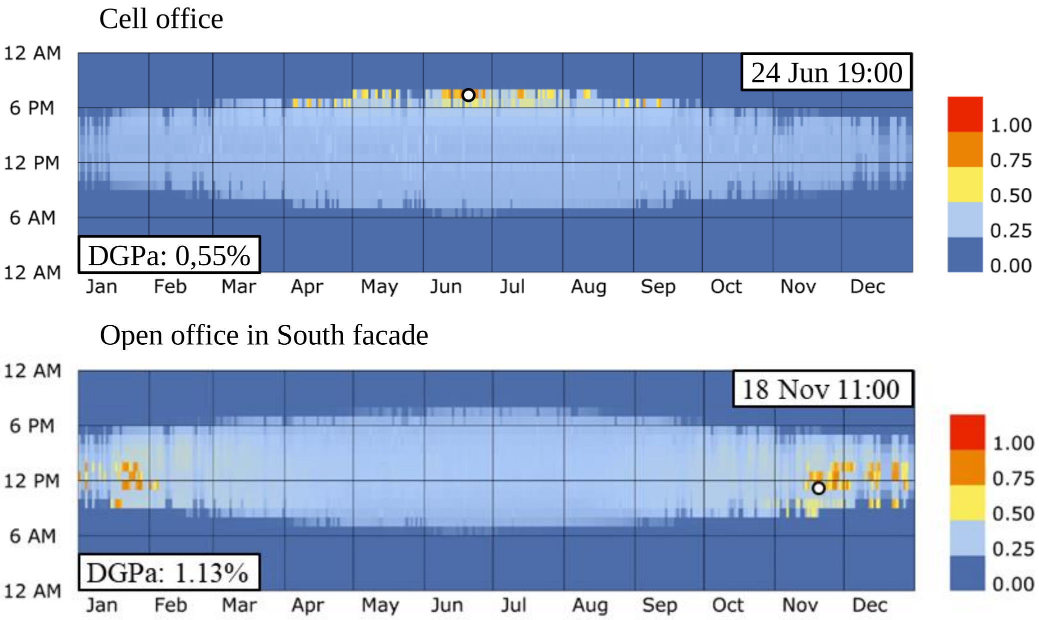


Figure 3.8 Annual glare probability in two critical locations.

Figure 3.8 shows the annual glare probability in the cell office and open office in South facade, the yellow and orange areas indicate intolerable glare and thus should be studied. The hour whit the highest probability is presented in the upper right corner on each annual profile.

[34] The DGP annual represent the percentage of hours above 45% glare probability in a year from a certain position.

Based on this it was intended to pick these hours in order to perform the image-based glare simulations.

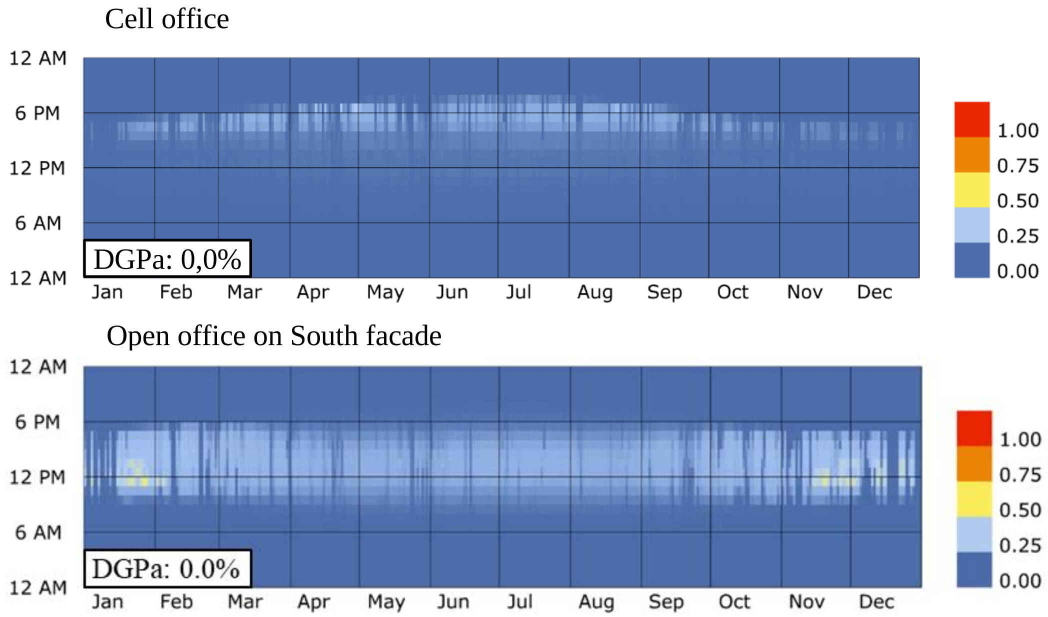


Figure 3.9 Annual glare probability with roller blinds.

A very efficient way to remove the direct glare and still benefit from daylight are roller blinds. These translucent elements allow some diffuse light to go through while blocking the direct sunbeams. Many of these devices have been used in this project in the South and West windows. Once used, these blinds removed most glare risk as shown in Figure 3.9.

The effect can be seen in Figure 3.10 which shows the fisheye view[35] 1.2m from floor trying to emulate the eyes position looking at the computer screen. The glare risk from the cell office position on the most critical day of the year without protection is 100%, once the blinds were added, this probability was reduced to 34%, which is in the range “imperceptible”[36].

In the open office on the South facade the risk appears to be lower on the critical hour from the annual DGP. However, it can also be seen how this risk is reduced from 0.27 to 0.18.

[35] The fisheye lens is the closest perspective to a human eye and has the capability to capture a broad luminance distribution.
[36] Please note how the perforated screen is projected in the indoor roller blinds.

It should also be mentioned that some of the times when glare occurs are outside the working time (8:00 to 19:00), so the probability of glare risk is reduced.

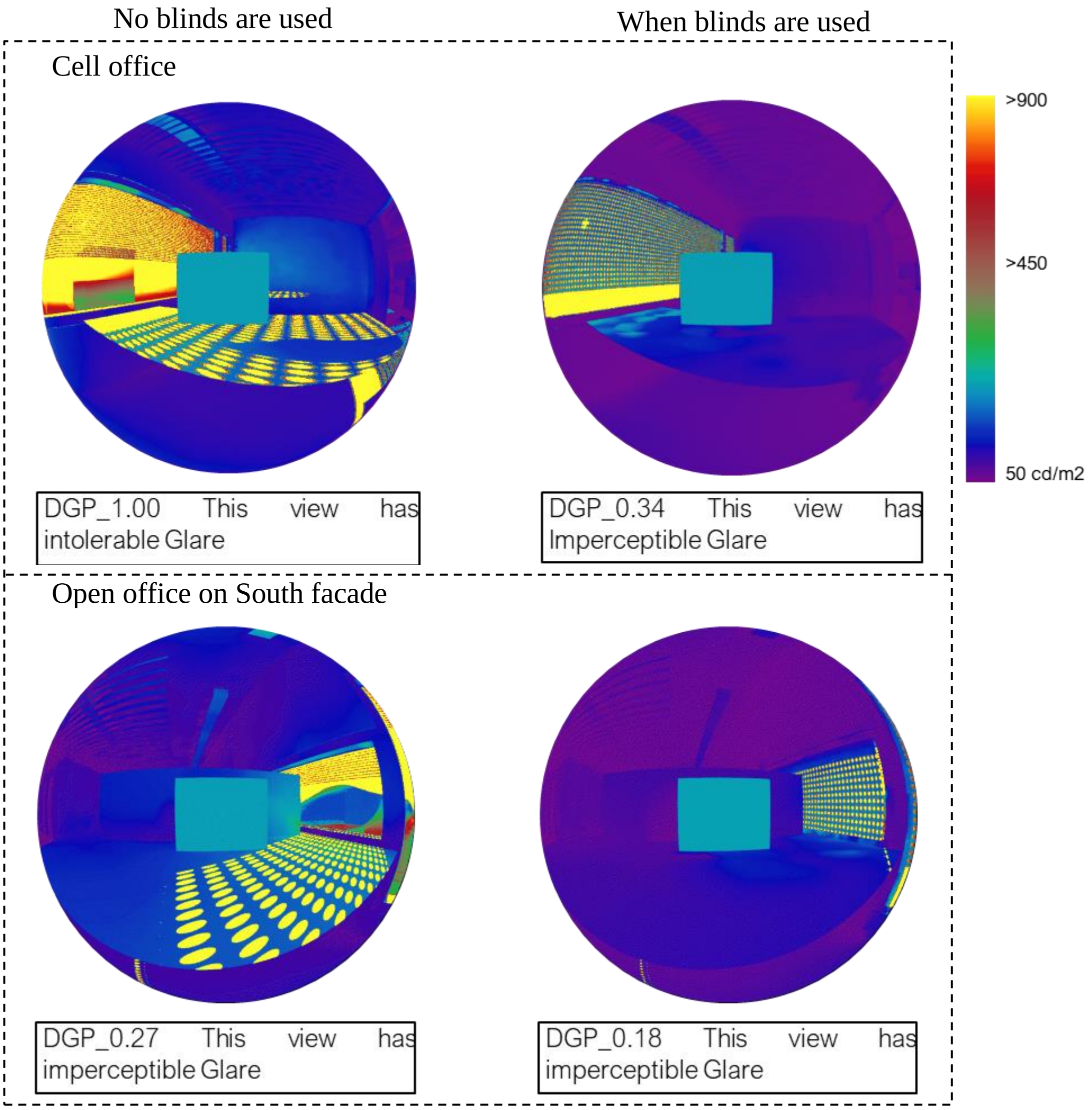


Figure 3.10 Image-based glare study on critical hours.

3.5 Directionality

Figure 3.11 shows where the sensor points were located. In the open office, some of these sensors were distributed close to the window and some others farther away. In the cell office and meeting rooms, one single sensor was placed in the middle of the room.

According to CIBSE (1984), a vector-to-scalar illuminance ratio of 3 is very strong and 0.5 is very weak, thus, something in between corresponds to the ideal ratio (Dubois et al., 2019).

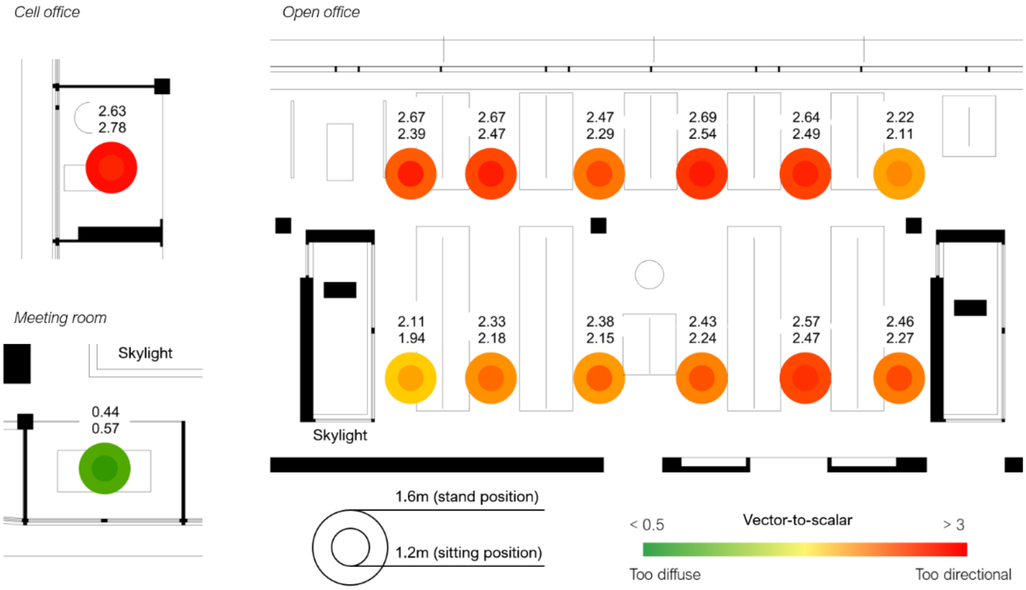


Figure 3.11 Vector-to-scalar directionality in the three target rooms.

Vector-to-scalar illuminance ratios seems to present very similar values in most positions, between 2-3, this means that the perceived directionality is strong for both, seated and stand positions.

From Figure 3.11 it can be seen how the sitting position has higher directionality than the standing position. In some extreme cases this could lead to perceive harsh shadows in this height, especially in positions close to the windows.

The directionality of the light in the open office brings illumination all the way to the core and hits the walls which enhance the space and its uniformity, while providing a feeling of amplitude. This can also explain why some of the points close to the core are slightly more diffuse than the points close to the facade.

It is also noticeable how the lowest are found in the positions close to the skylights. This is own to the fact that the daylight comes from two different sources. So thus, these two daylight sources in opposite directions counteract, removing the directionality in this room.

3.6 Climate Based Daylight Modelling (CBDM)

With the objective of obtaining a wide overview of the daylighting performance of the building a series of climate-based simulation are required. This type of simulation reveals how the building responds to the seasonal aspects of daylight.

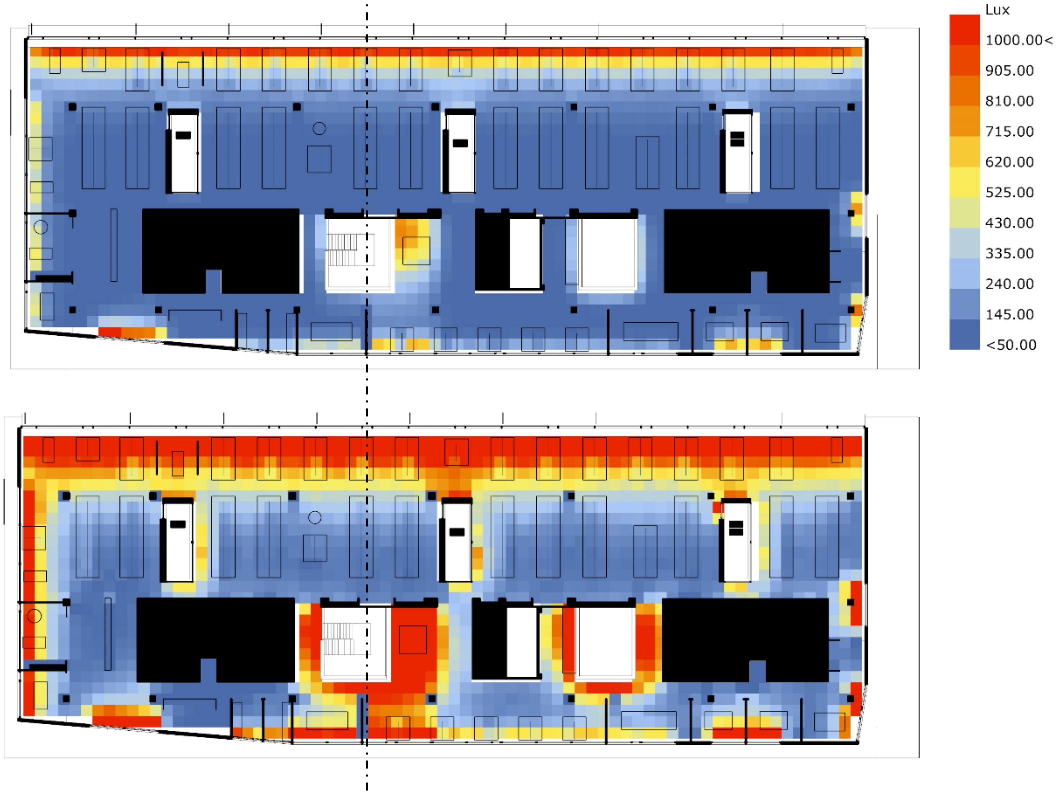
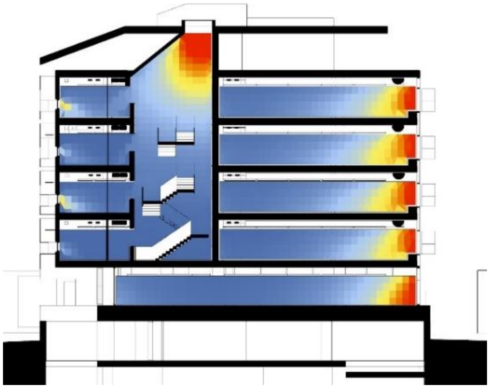


Figure 3.12 Grid based illuminance simulation on 21 December (above) and 21 June (below) at 12:00.

The previous Figure 3.12[37] show two key dates, the winter and summer solstice[38], this correspond to the worst and the best day in terms of potential daylight. It can be seen how, even in the worst daylight condition [see Figure 3.12 above] the illuminance level is still quite acceptable in the perimetral workplaces, but it cannot be guaranteed in the core. In the Figure 3.12 below, it is noticeable the effect of the skylights, converting this core a highly daylit space.

[37] Please note how the core has not been included in the simulation in order to reduce simulation time. It appears mark as a black solid.
[38] A sky from the weather file were used to perform this grid analysis.



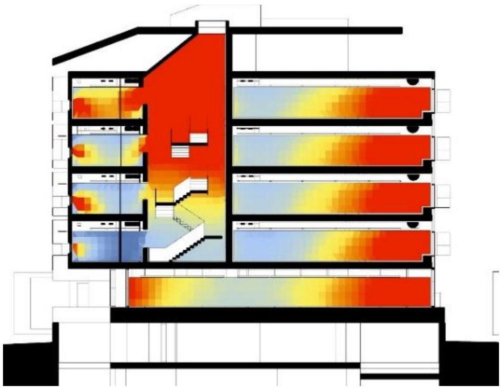


Figure 3.13 Illuminance section.

A similar situation could be seen in the sections [see Figure 3.13], they represent the same dates[39] than the previous situation. Again, it can be seen the effect of the skylights, and how the daylight dimmers as reaches the lower levels.

3.6.1 Annual simulation

In this chapter simulation results of annual illuminance distribution in the fourth floor are discussed. The main outcomes comprise Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), Continuous Daylight Autonomy (CDA) and Spatial Daylight Autonomy (sDA).

Furthermore, from this type of simulation is possible to calculate the dynamic shading schedule and the light control systems, so to integrate electrical light within the overall lighting design.

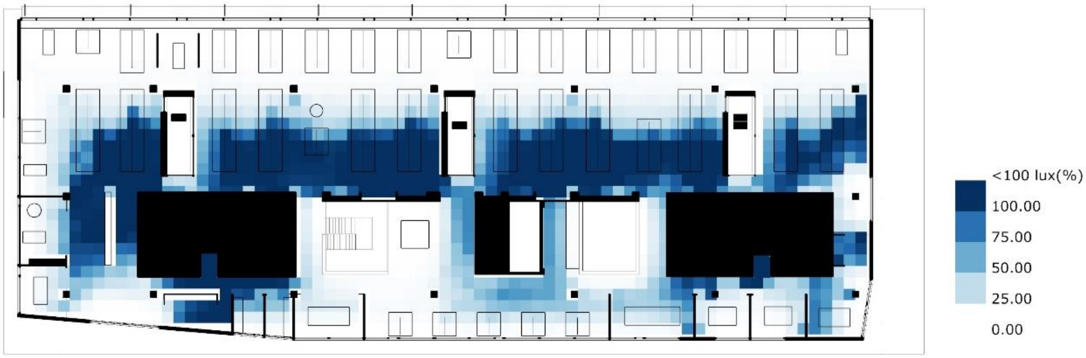


Figure 3.14 UDI <100 lux.

[39] The sections and floor plans use the same legend, from 50 to 1000 lux.

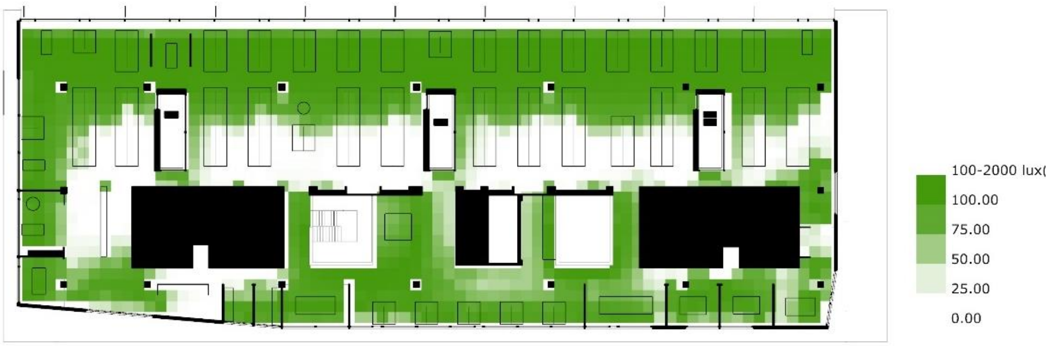


Figure 3.15 UDI 100-2000 lux.

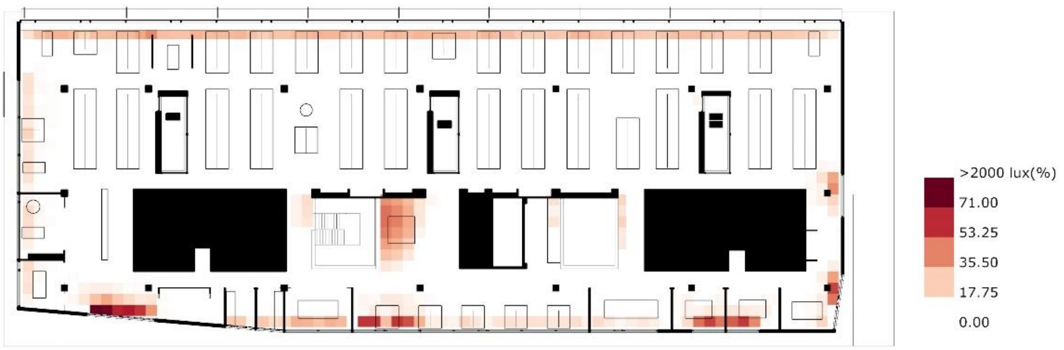


Figure 3.16 UDI >2000 lux.

The previous figures show the useful daylight autonomy for three different conditions, below 100 lux [see Figure 3.14], it is considering a poor daylit space marked in deep blue. On the other hand it can be appreciated the high population of cells between 100-2000lux [see Figure 3.15], which is consider useful daylight as a high portion of the floor plan area is colored green.

Lately, Figure 3.16 shows the points that overpass the 2000 lux threshold, which could lead to glare and over lit issues. Note how the maximum in this last figure only reaches 71%.
For this evaluation it is also considered the effect of the roller blinds in the daylight performance[40].

Figure 3.17 Daylight autonomy with no blinds (left) and blinds (right) in the meeting room.

[40] Please note how all the daylight autonomy analysis share the same legend, where yellow corresponds to 100% DA and dark blue to 0%.

Figure 3.17 shows the daylight autonomy in the meeting room under two conditions. On the left side of the figure, the blinds are not being considered, while in the right one, the effect of the blinds is included. It can be observed how shading devices are affecting the annual daylight performance.

If this phenomenon is further analysed [see Figure 3.18], it is possible to appreciate how the values above 2000 lux threshold almost disappear with the use of blinds and how the range below 100 lux and between 100-2000 lux increases.

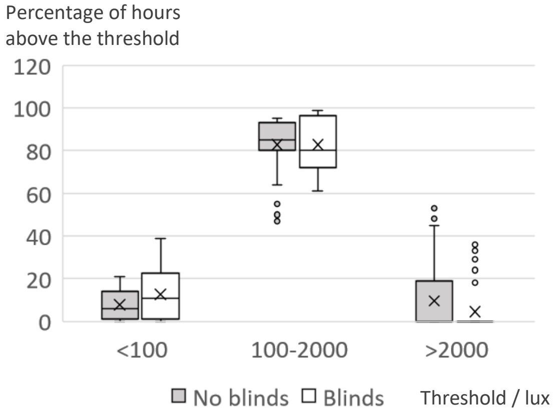


Figure 3.18 UDI frequency distribution in meeting room.

As can be seen from Figure 3.19 the shading schedule shows that the blinds are never used fully down as the sensors are located where the workers are supposed to be seated, and it is never immediately close to the window. In this case the disturbing southern light can be easily removed by just bringing down the blinds halfway since it is more vertical than the Western daylight.

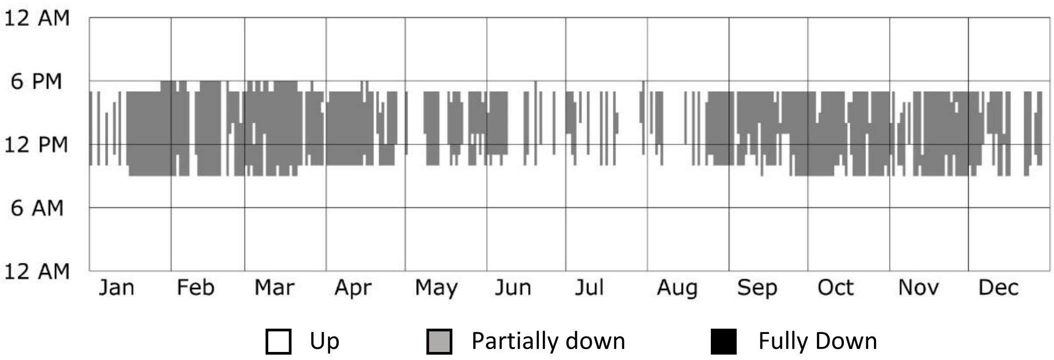


Figure 3.19 Meeting room roller blinds annual profile.

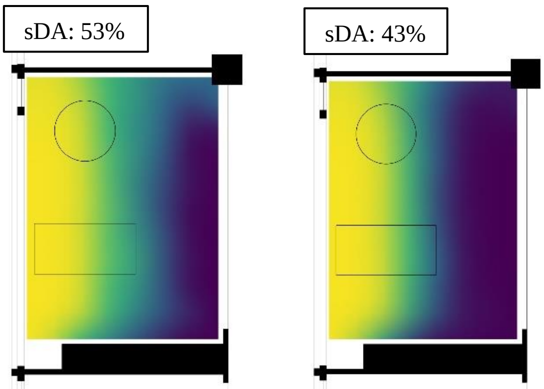


Figure 3.20 Daylight autonomy with no blinds (left) and blinds (right) in the cell office.

On the contrary, the cell office is not affected as much as the meeting room by the blinds as can be seen in Figure 3.20, most likely due to the active hours of the roller blinds since the West oriented rooms received less hours of daylight as shown in Figure 3.21. The roller blinds in this case are used fully down only during some hours when the sunlight is more horizontal, and during summer, only partially down blinds are used as it is enough to remove the disturbing light.

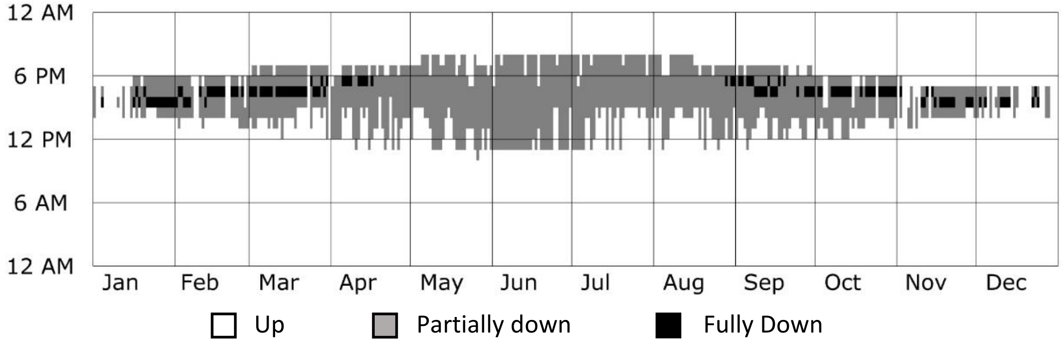


Figure 3.21 Cell office roller blinds annual profile.

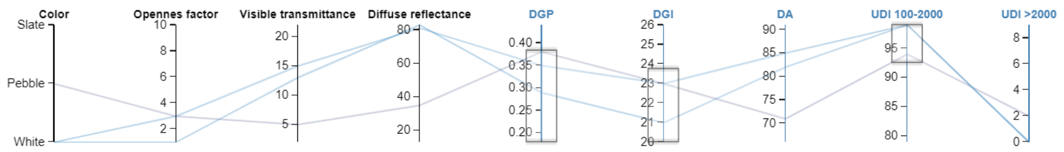
Figure 3.22 demonstrates how the blinds remove some disturbing direct sunlight (> 2000 lux), and as a result the autonomous range (100-2000 lux) increases.

Figure 3.22 UDI frequency distribution in cell office.

It can be concluded that some well-lit area is lost, but on behalf of a more comfortable space with no glare issues or overheated spaces.

Finally, it should also be mentioned that even though the daylight levels are lower when roller blinds are used, this calculation is based on human behaviour assumptions, thus these predictions could lead to discrepancies with reality and uncertainties (Konis and Selkowitz, 2017). Furthermore, most of the rooms where blinds are located have a temporary use. This results in blinds left in a fixed position most of the time, until the room is occupied again.

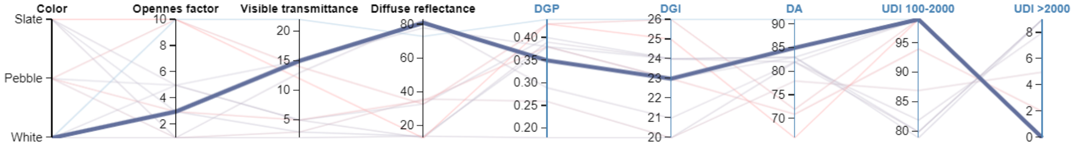
Different alternatives of roller blinds from Bandalux manufacture were tested. For this study, a workplace on the South facade was selected since it is more likely that glare will be experienced on this facade during working hours. The inputs of this study are marked in bold black while the outputs are in bold blue. Several metrics were analysed in order to have a broader perspective on the roller blinds' performance. Metrics such as DGP have more weight and were filtered first with a threshold of <0.4, then DGI with a threshold of <24 and finally, an UDI range of 100-2000 lux.



Color	Opennes factor	Visible transm...	Diffuse reflect...	DGP	DGI	DA	UDI 100-2000	UDI >2000	Rating
Pebble	3	5	35	0.38	23	71	94	2	0
White	1	13	83	0.29	21	82	99	0	0
White	3	15	81	0.35	23	85	99	0	0

Figure 3.23 Blinds rollers filtered selection.

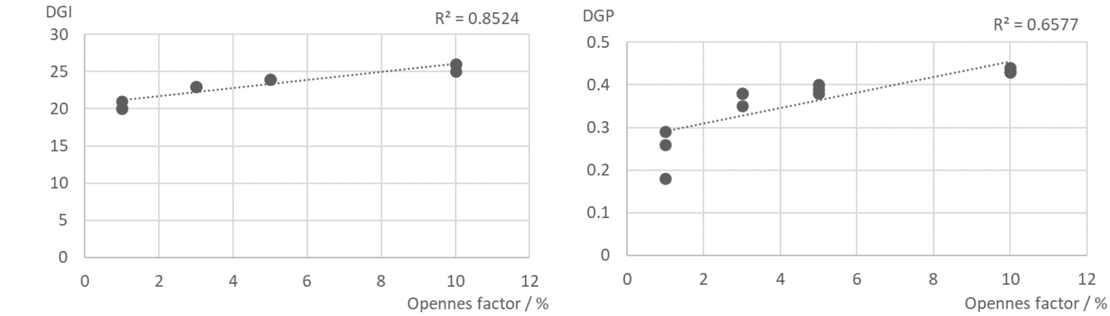
Three different options met the requirements as shown in Figure 3.23, and from those, the one with the highest daylight autonomy was selected as optimum for the south facade[41].



Color	Opennes factor	Visible transm...	Diffuse reflect...	DGP	DGI	DA	UDI 100-2000	UDI >2000	Rating
Pebble	1	3	36	0.26	20	78	87	5	0
Pebble	3	5	35	0.38	23	71	94	2	0
Pebble	5	5	33	0.4	24	83	80	9	0
Pebble	10	14	33	0.43	26	72	99	0	0
Slate	1	2	14	0.18	20	82	80	9	0
Slate	3	3	14	0.38	23	83	79	9	0
Slate	5	5	13	0.39	24	82	82	8	0
Slate	10	12	13	0.43	25	66	99	0	0
White	1	13	83	0.29	21	82	99	0	0
White	3	15	81	0.35	23	85	99	0	0
White	5	15	78	0.38	24	83	99	0	0
White	10	22	73	0.44	26	91	99	0	0

Figure 3.24 Inputs and outputs in Design Explorer.

It is worth to notice that the glare assessment was carried out when the daylight glare probability was 100% and no roller blinds were used, so it was possible to assess the performance under the worst-case scenario possible. Some interesting correlations arise from this comparison study.



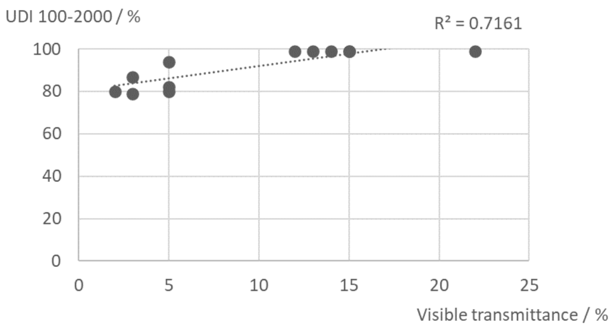


Figure 3.25 Roller blinds analysis correlations.

The openness factor seems to be highly linked to the glare probability (rs = 0.95, p = 9.09E-07) and glare index (rs = 0.99, p = 1.2E-09), since the holes between the fabric fibres might allow some sunlight to pass through. Moreover, the visible transmittance has a considerably effect on the useful daylight illuminance (rs = 0.86, p = 5.76E-04), although the UDI>2000 would also increase unless a smaller openness factor is used. It was also found the color of the fabric was not related to glare as anticipated. Clear and grey colors performed better when useful daylight illuminance was lower than 2000 lux. Also note that this analysis is only certain for blinds oriented towards South, other orientations will retrieve different optimal blinds properties.

[41] The Design Explorer study is accessible from the following link: https://bit.ly/2YLrMXe

3.7 Electric light

The electric system was designed in such a way that the corridors received a considerably lower lighting level than the workplaces, values ranging between 150-200 lux are common as can be seen in Figure 3.26.

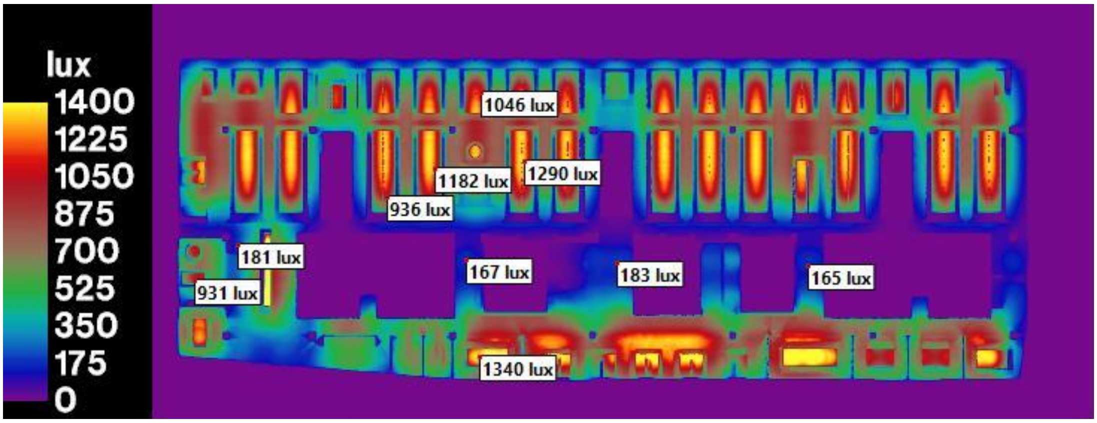


Figure 3.26 Electrical light illuminance levels 4th floor.

It can also be appreciated that the workplaces yield much higher values, in some cases even higher that the recommendations (500 lux for normal office work), which could cause overlit working areas as suggested for some answers in the questionnaire. Other reasons for this high illuminance levels could be due to the density of devices in the middle areas of the open office, where several light fixtures overlap, which increase the illuminance values in those points.

This supports the fact that the values on the extremes are slightly lower. Similar situation occurs in the meeting room where very high levels are retrieved when the luminous flux overlap.

The open office case is further assessed in a more detailed study.

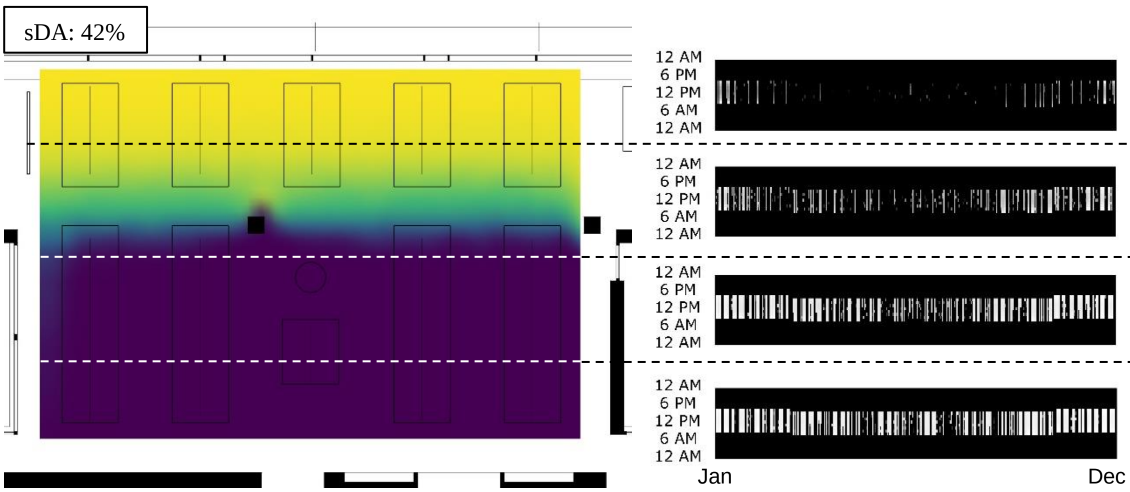


Figure 3.27 Open office DA and daylight control system annual dimmer values profiles.

In this scenario, a daylight harvesting control system is used, as could be appreciated in Figure 3.27. The closer to the core the more electrical light is needed, in contrast with the first luminaires group, where is barely required.

Different electrical lighting control methods were compared. Figure 3.28 shows the different possibilities of lighting controls, from this analysis, it is remarkable how having the lights always on during the occupancy hours implies more than double the energy use compared with situations for which daylight is harvested.

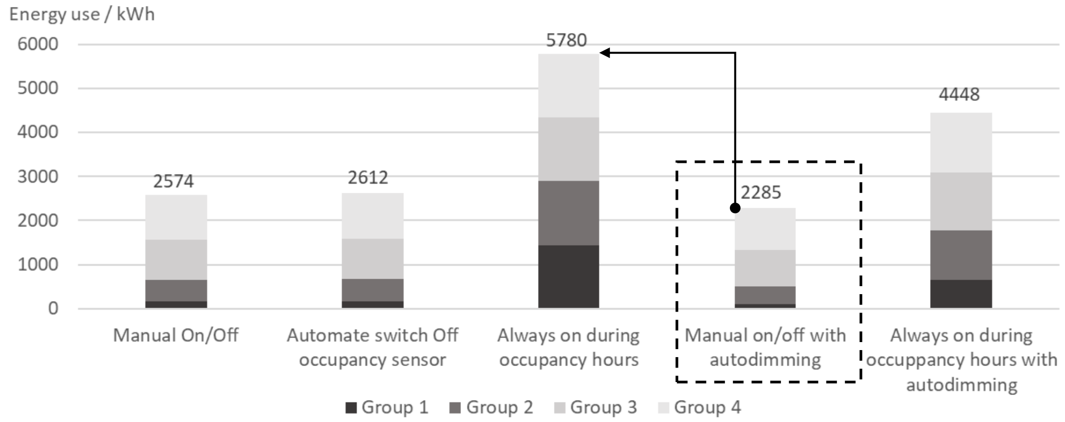


Figure 3.28 Electric lighting energy use control methods comparison.

Furthermore, group 4, which corresponds to the least daylit space, benefits a little from daylight, which results in significant savings throughout the year.

The manual on/off system is based on Reinhart's algorithm (Reinhart, 2004) and does not considers the inconvenience of switching on and off the system regularly, thus it could lead to overestimations.

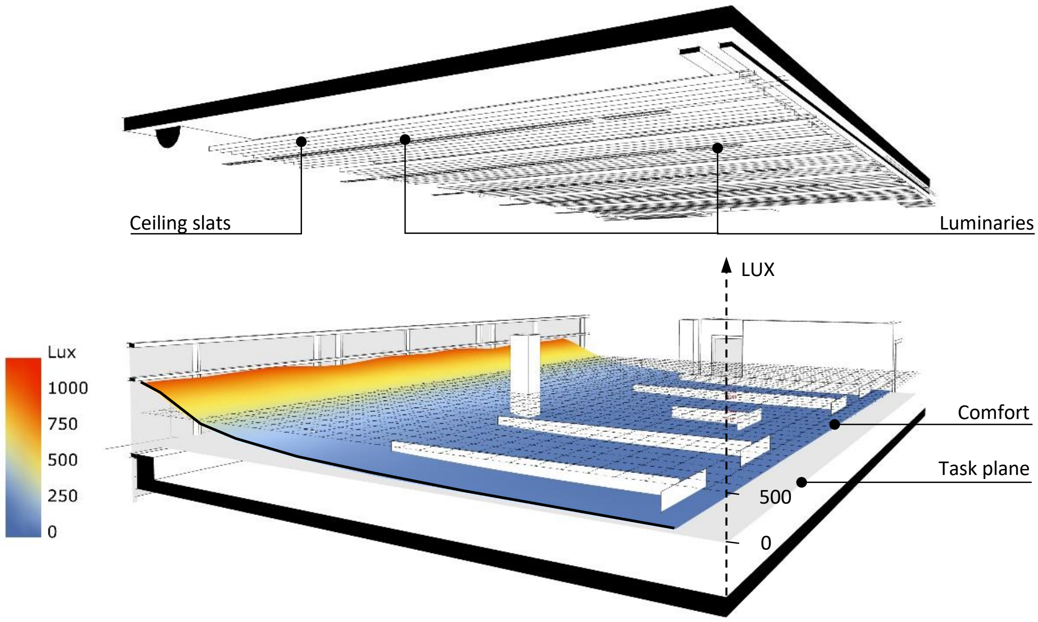


Figure 3.29 Open office annual average daylight.

The system used in IDOM open office appears marked in dash lines in Figure 3.28, and it is considered the most efficient harvesting strategy, with savings that represent more than 50% compared to a reference case where lights are always on during occupancy hours.

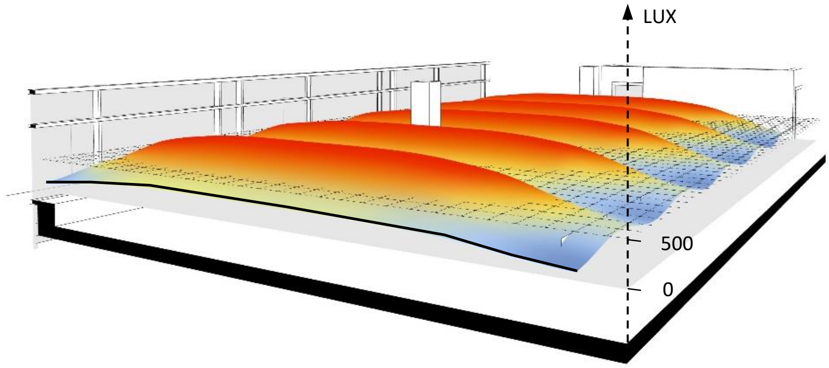


Figure 3.32 Open office illuminance level when luminaries are fully on.

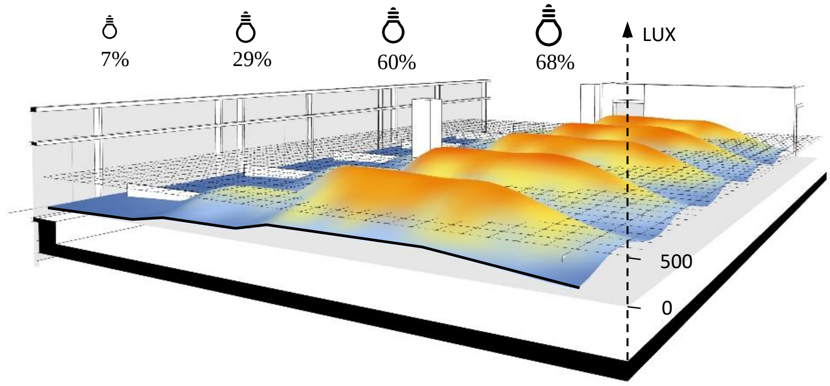


Figure 3.30 Open office illuminance level with dimmable lighting control system groups.

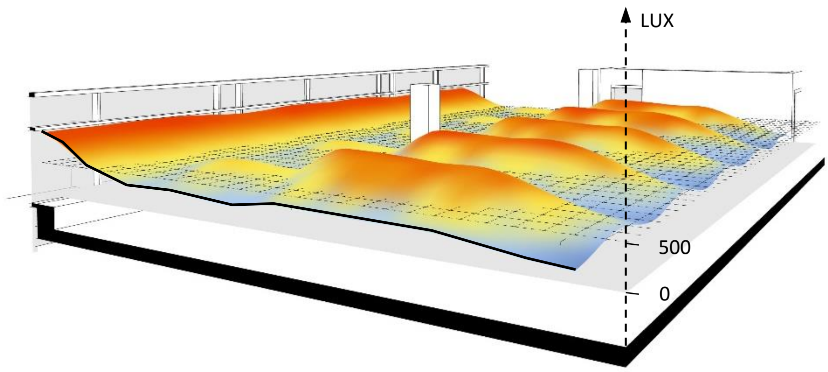


Figure 3.31 Open office daylight integrated system.

The previous figures present the different stages of the daylight integrated design in the open office.

Firstly, the daylight availability is studied through an annual daylight simulation. This step allows to obtain the average illuminance levels during the occupancy hours.

In order to reach an acceptable illuminance level in the darker areas, a dimmable lighting control system is added according to the daylight levels in the different regions, where the space closer to the facade only needs 7% of the total light capacity. In contrast, the region far from the facade requires about 68% of electrical light contribution and only 32% of daylight can be harvested as shown in Figure 3.30.

Overall, 59% of daylight is harvested, and only 41% of electricity is required in order to achieve a comfortable lit environment. Finally, the resulting mesh [see Figure 3.31] shows a more even illuminance level over the whole area.

3.8 Questionnaire

The interviewees were requested to fill the questionnaire within an hour from receiving it the Feb 27th at 12:30. After the collection of results, it was noticed that some of the questions were not well understood, such as satisfaction in the ambience and light satisfaction, which yield similar outcomes. The same was observed regarding glare from light fixtures or from sunlight, where most respondents answered similarly, indicating that they are not aware of the origin of glare.

The results in Figure 3.33 are shown as median values filtered by floor. A difference of two points between floors was considered significant. From this figure it is possible to make some observations.

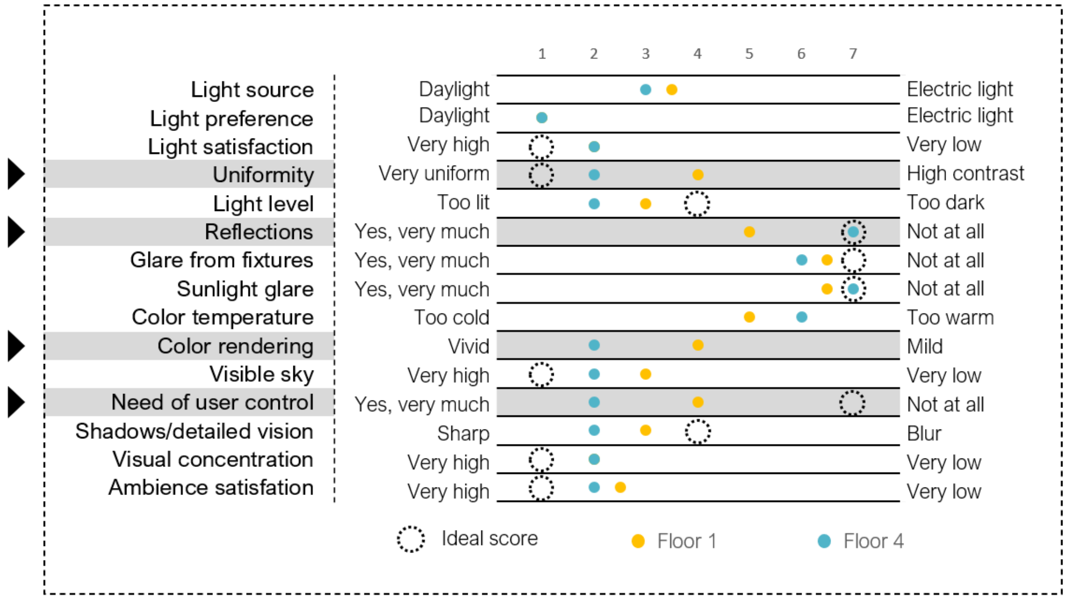


Figure 3.33 Questionnaire results filtered by floor.

Questionnaires from respondents on the 1st floor indicated lower uniformity levels, higher reflections, lower vivid colors and lower need of user control.

Otherwise, it can be note that the overall experience is very positive in the floor 4th and good in the floor 1, except for the need of user control, where it is found that in both cases a higher user control over light is claimed but for different reasons. In the first floor the respondents feel the need of increase the light intensity whereas in the 4th floor they want to reduce it [see appendix Figure 0.34 Questionnaire results in coloured gradient scores filtered by floor.

Figure 0.35Figure 0.36].

It can also be noticed that in this second chart the differences are more noticeable than the first chart filtered by floor. Which means that the floor factor is not as decisive for a comfortable and productive lighting environment in an unobstructed building condition.

The results that only show one point is due to the superposition of both series, so it means in both cases the collection of answers have the same score.

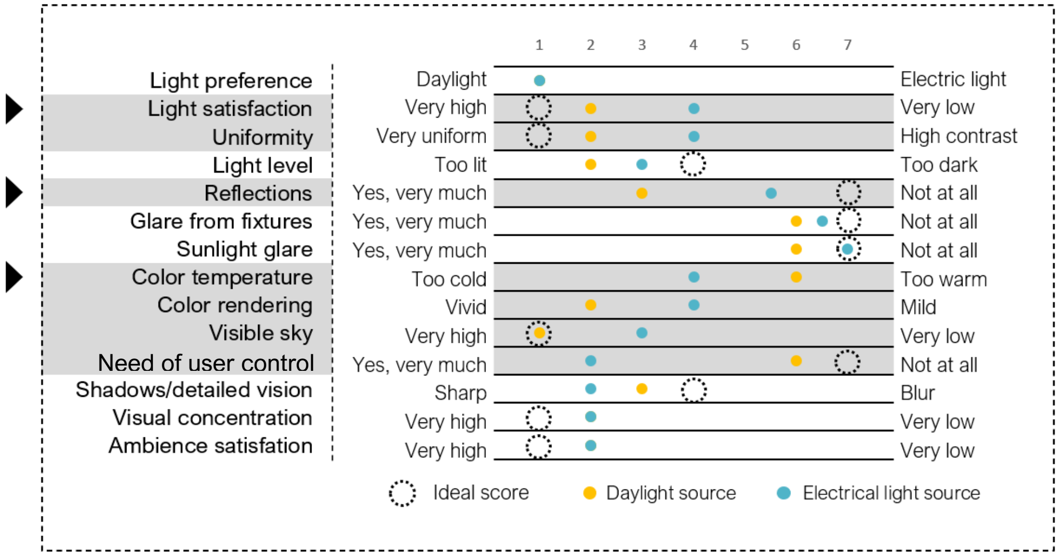


Figure 3.34 Questionnaire results filtered by light source.

Figure 3.34 shows that people sitting closer to the window (daylight source) complain about more reflections, and they suffer from glare and heat in extreme cases. Despite these complaints, they were satisfied concerning ambience, uniformity, and light level. The workers in this location also reported warm color temperature and vivid colors.

In contrast, workers located far from the window experience poor air quality and cold draught [see appendix Figure 0.37 Questionnaire results in coloured gradient filtered by light source.

Figure 0.38], which may also negatively affect their daylight quality evaluation, since they might be more susceptible to see light color temperature colder than it is. Furthermore, they claim a much higher need of control over the lighting fixtures and more disfunctions compared with the respondents sitting close to the window.

Overall, workers located close to the window are very satisfied, with the exception of some reflections. On the contrary, workers far from the window have a moderate opinion regarding lighting comfort.

A strong correlation between uniformity and light satisfaction was found. The Spearman correlation indicated that "uniformity" is strongly correlated with "light satisfaction" (rs = 0.79, p <0.0004).

This result again supports the importance of a uniformly lit space, thus the importance of highly reflectance materials, specially in the darkest areas.

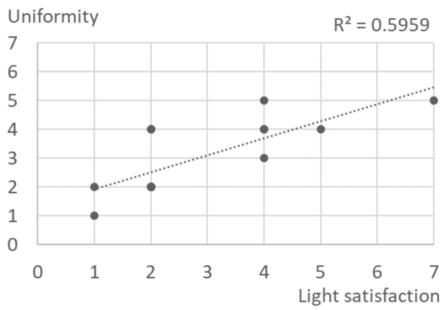


Figure 3.35 Questionnaire correlation.

Due to the limited number of participants, the questionnaire results must be interpreted with caution, but they could be used to obtain some impressions about the interior illumination without statistical significance in the results. It is also true that most participants were familiar with the lighting conditions in the open office, so this fact might also influence their answers since they are probably interpreted as general questions instead of the point in time situation.

It is worth mentioning that some of the characteristics analyzed in the questionnaire are relative and depends on personal preferences so there is no ideal score as aforementioned. That is the case of color temperature, which depends most likely on the climate conditions, where there is a preference for warm light colors in cold conditions and vice versa. User control is another factor where ideal condition mostly depend on personal preferences. Some suggestions from the users include the use of a warm task light that can also be locally controlled.

4 Conclusions

Integration between daylighting and operation of other building systems, and consideration of occupant perception and behaviour are important to obtain the maximum energy savings from daylighting and to support visual comfort, health, and productivity in the workplace.

Within this framework, this thesis presents the subjective and objective assessment of daylight conditions in an environmentally certified office building, IDOM headquarters, located in Madrid. This study involves questionnaires to the employees, in-situ measurements, and advanced lighting simulations. The main conclusions are summarized below

- It must be mentioned that every building evaluation should be treated individually, as every situation is different and, in some cases, some aspects require more attention while others would be irrelevant to the study. One important aspect is that the main evaluation set should be preserved from one building to the next. In this way, the knowledge about different buildings can be expanded and compared, apart from that the evaluation should be tailored for each building.

- Daylight simulations are an important part of a lighting audit. Hence, the choice of software becomes extremely important. The author found that customizable software like Honeybee and DIVA were more useful in situations that required an in-depth evaluation and adaptation to upcoming standards and regularizations since they allow more flexibility and post processing of results. However, programs like DesignBuilder, Sefaira, or Insight360 may provide a faster alternative for early design stage analysis.

- If the impact of shading devices is included in the annual metrics simulations, the occupants' behaviour can influence the results to a great extent. This might lead to inaccuracies, since many assumptions must be taken. Further studies in this area could improve the reliability of the results. If blinds or the fenestration are not properly modelled, energy consumption can be underestimated, and human benefits can be exaggerated in terms of a building's spatial daylight autonomy score.

- The use of high reflectance materials in the areas close to the core in the open office have the potential to improve the uniformity of light distribution substantially, as seen in the feature's sensitivity analysis.

- In places located in low density areas (urban periphery or rural areas) such as IDOM headquarters, the floor level has not been found to be crucial for a good daylight level. Eventually, the room depth is key in a well-lit space, especially if uniformity is considered. Consequently, respondents located close to the side windows report better conditions than those located in the deeper areas of the room.

- When measuring daylight in a real case, the values result lower when comparing with the simulation ones, which tend to be more optimistic. This is a curious fact; the main hypothesis is that the daylight model used in the simulations might miss some inputs or features (furniture).

- During the occupancy hours, a correct daylight design could provide large electric light savings, especially in those regions with low overcast sky frequency and long days.

- The right choice of shading device can be decisive to guarantee an appropriate indoor climate, especially for Southern latitudes. Interior shading for glare issues combined with exterior shading (double facade system) for thermal considerations could be a powerful combination primarily in the South and West facades where overheating occurs.

- Thermal impact of roller blinds should also be considered alongside visual comfort properties for a proper integrative solution. In this thesis the right choice of roller blinds has been based exclusively on the optical properties on the fabric. Further studies about the effect of the blinds on the thermal comfort and the view outdoors could be addressed in future studies.

Unexpected mobility limitations, due to a pandemic (COVID19) raised during the course of this thesis. As a result, field measurements and other evaluations were difficult to achieve as planned. The project thus mainly focuses on lighting simulations and outcome few measurements and answers from questionnaires.

Because of time constraints, the field measurements as well as the questionnaire correspond to a particular point in time and no further monitoring was carried out.

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Appendix

Figure 0.1 Open office sensor points grid.

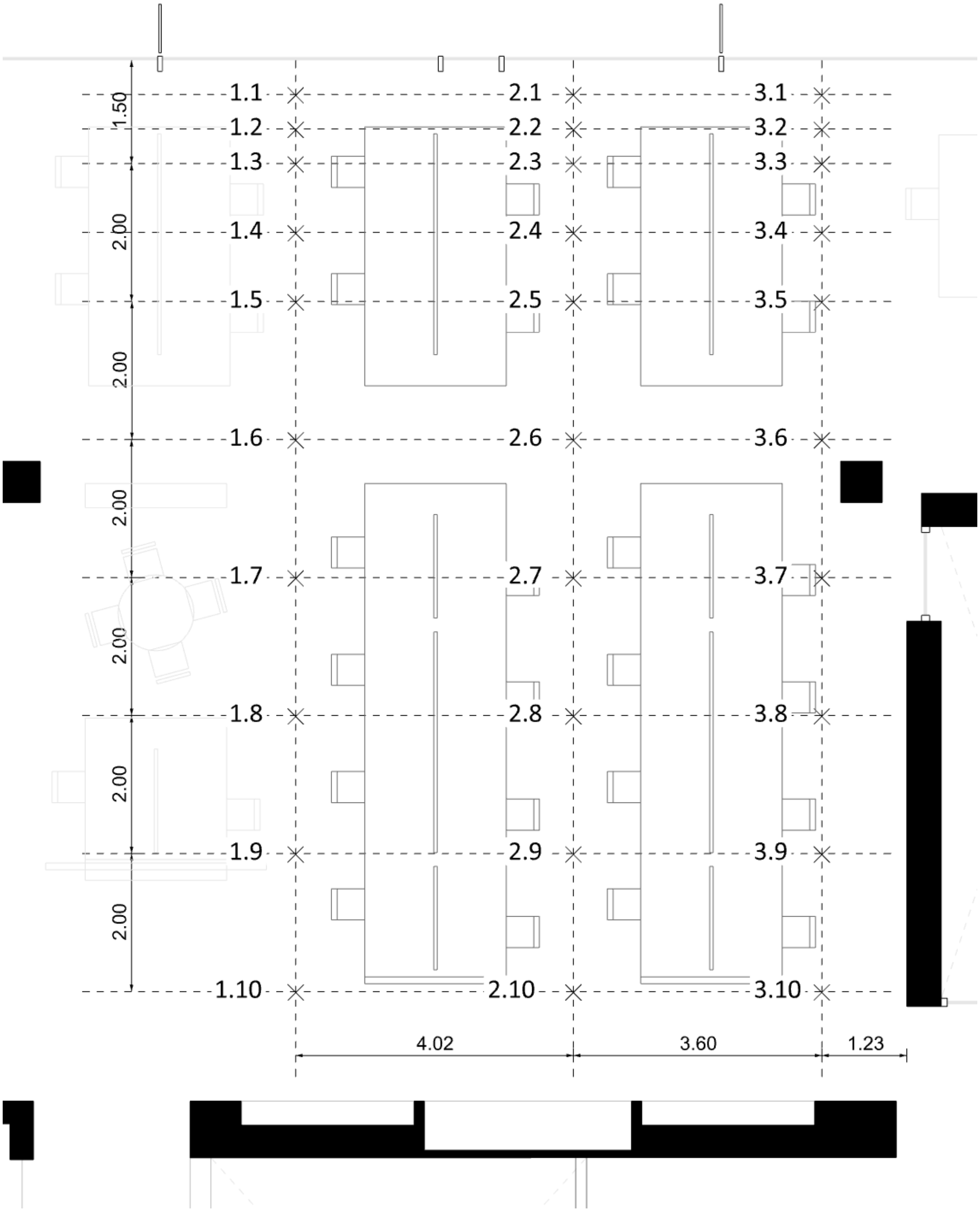


Figure 0.2 Meeting room sensor points grid.

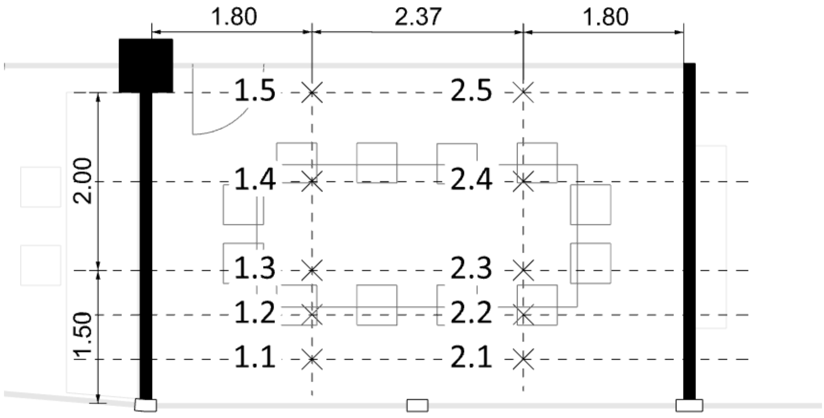


Figure 0.3 Cell office sensor points grid.

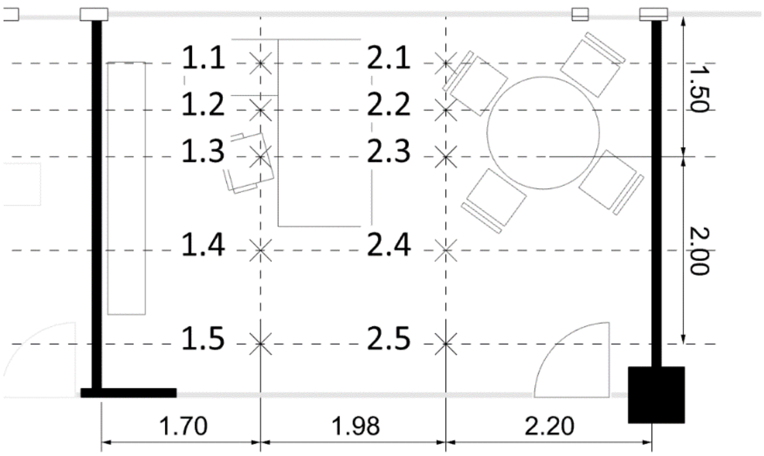


Figure 0.9 DGP study positions and gaze direction.

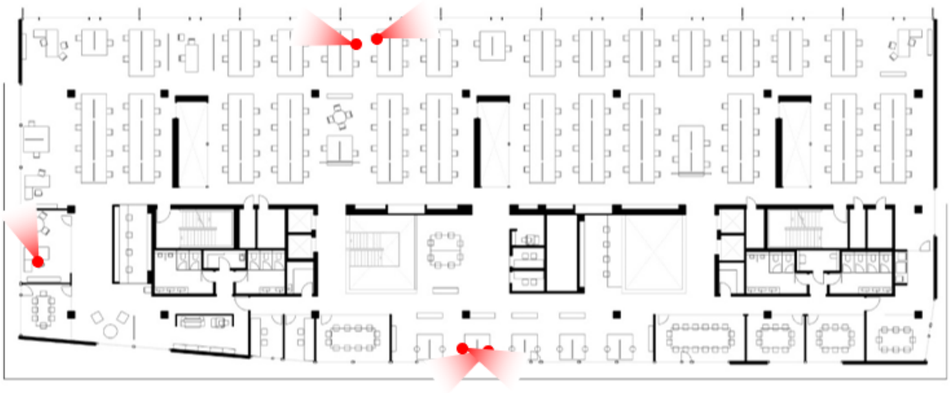


Figure 0.4 DGP Open office South window looking West.

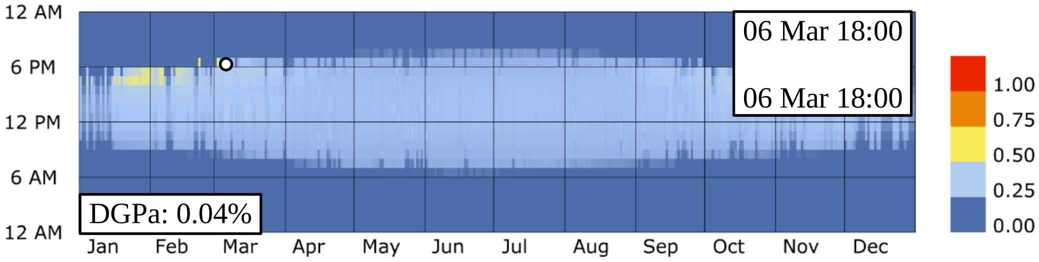


Figure 0.7 DGP Open office South window looking West with blinds

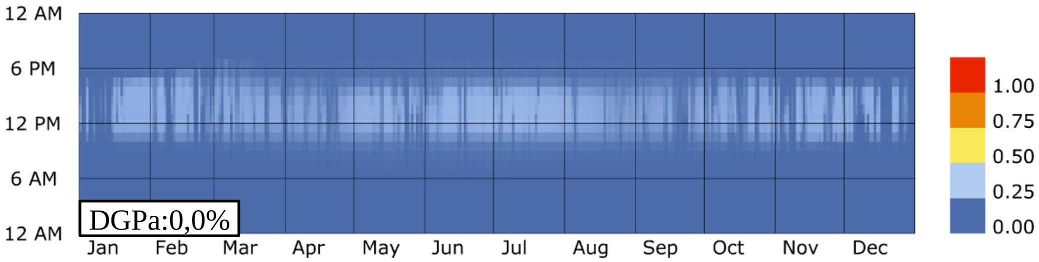


Figure 0.11 Image-based glare assessment (left blind off, right blind on)

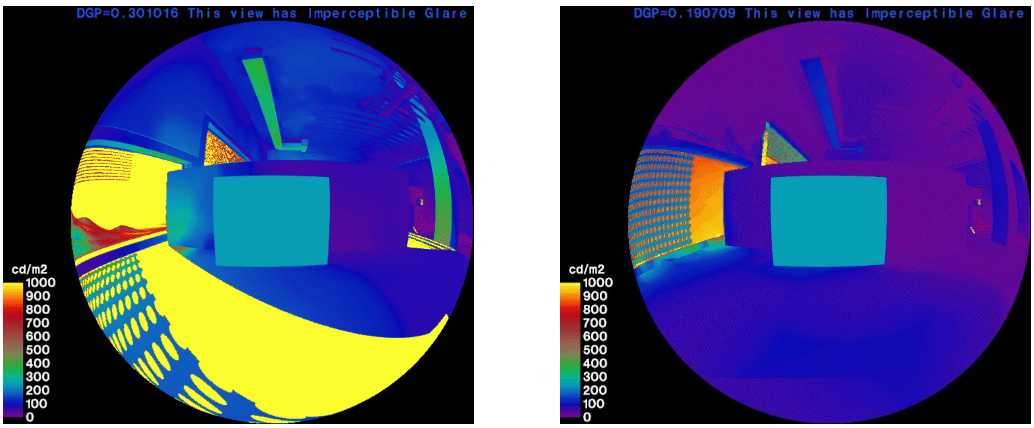


Figure 0.14 DGP Open office North window looking East.

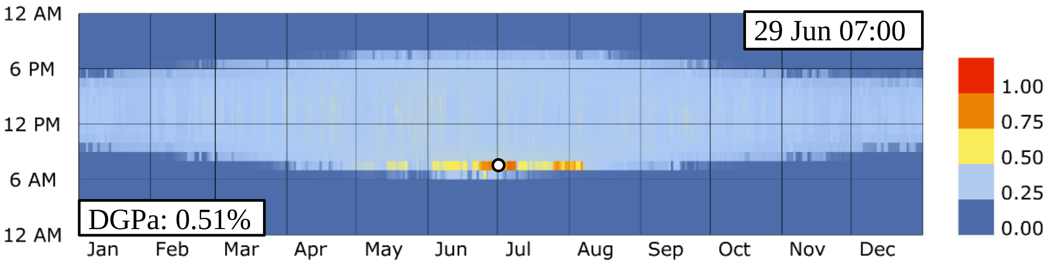


Figure 0.17 DGP Open office North window looking West.

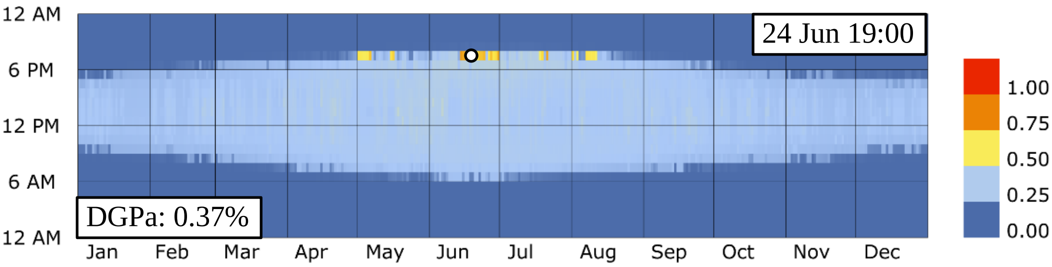


Figure 0.19 Image-based glare assessment (left looking east, right looking west).

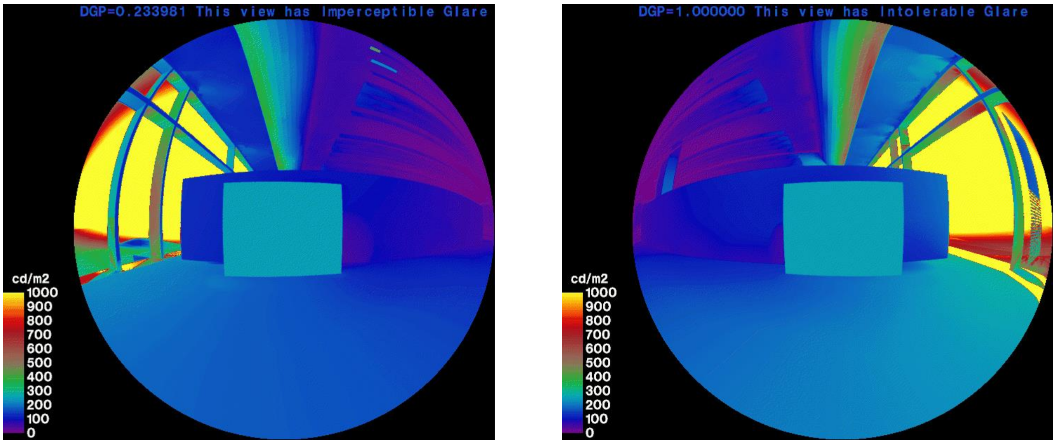


Figure 0.26 Building longitudinal section.

Figure 0.22 Building cross section.

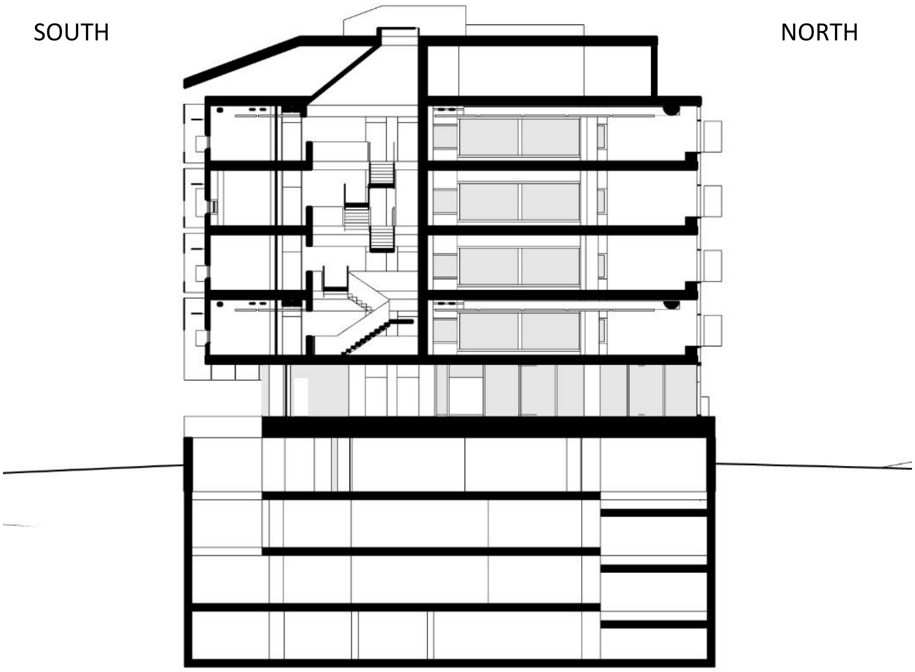


Figure 0.32 Ceiling plan where wooden slats, ducting and luminaries are shown.

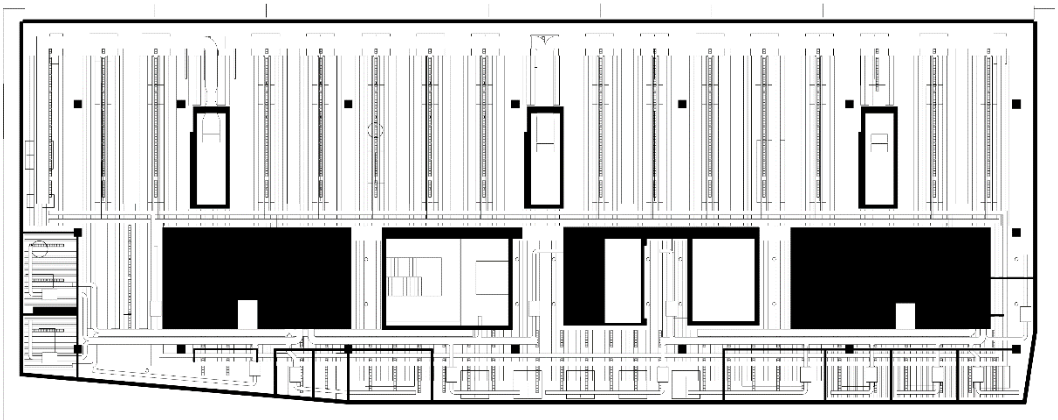


Figure 0.29 Luminaire photometric distribution (see tubular lamp left, compact lamp right).

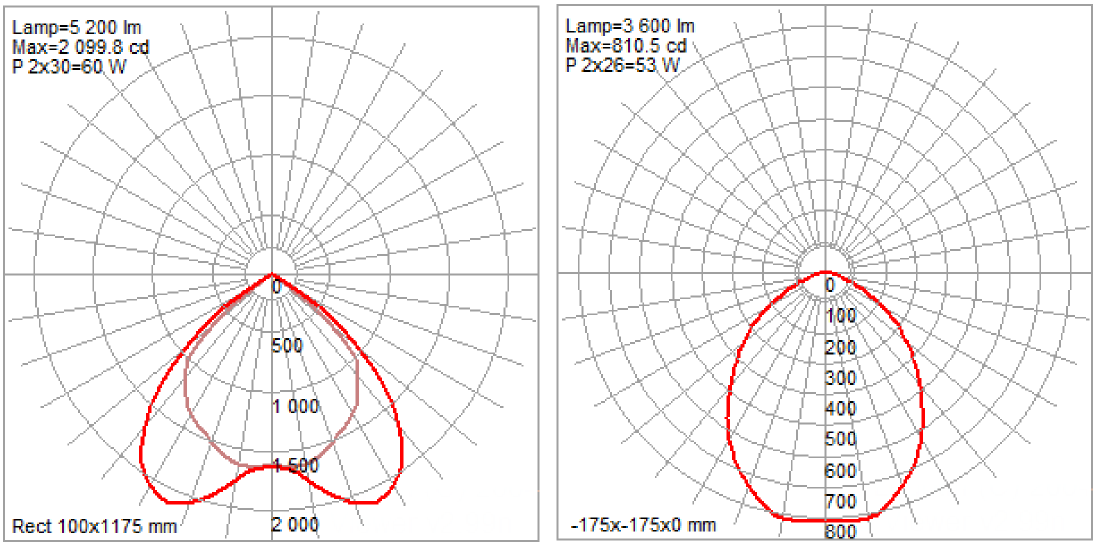
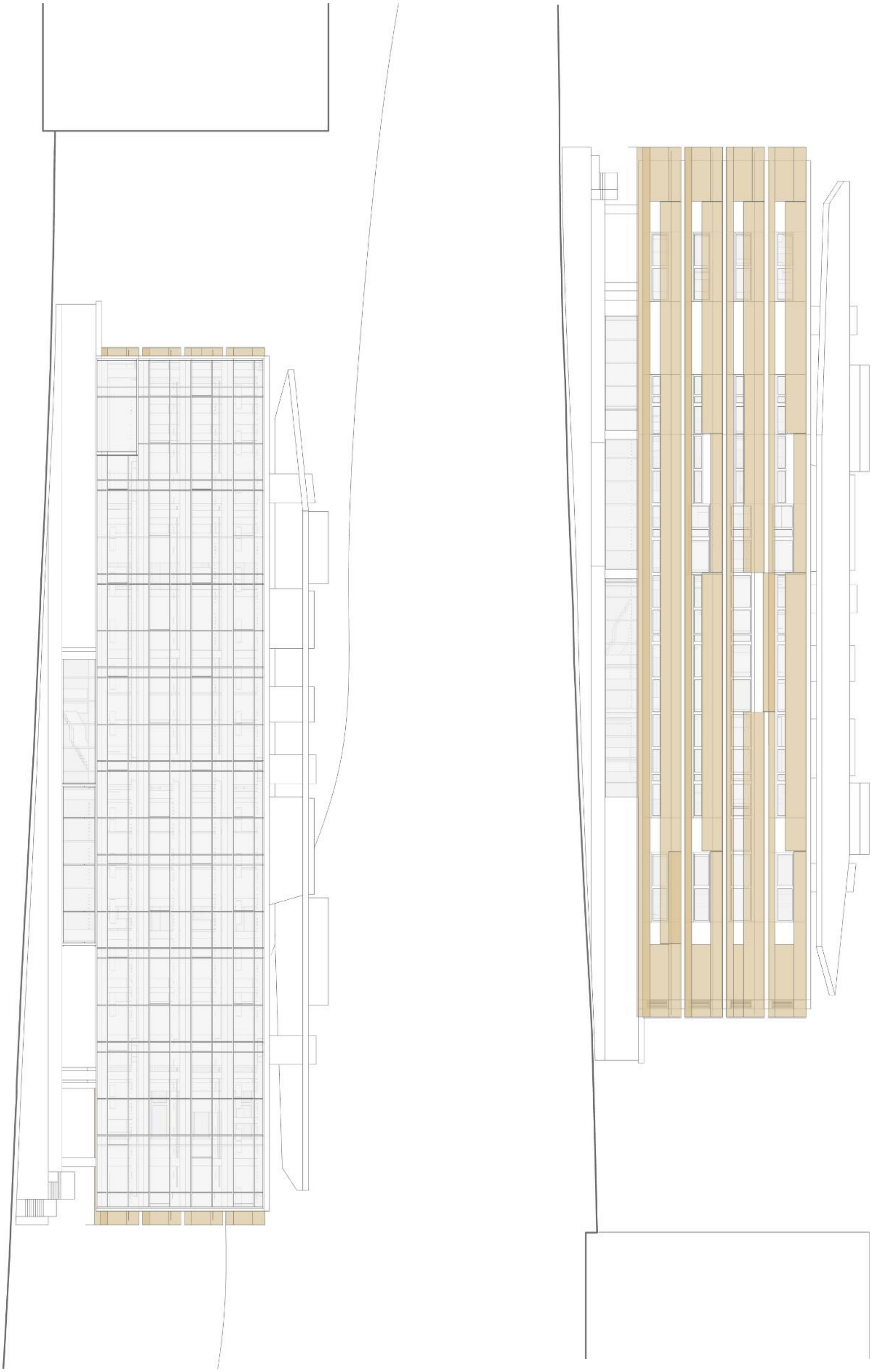


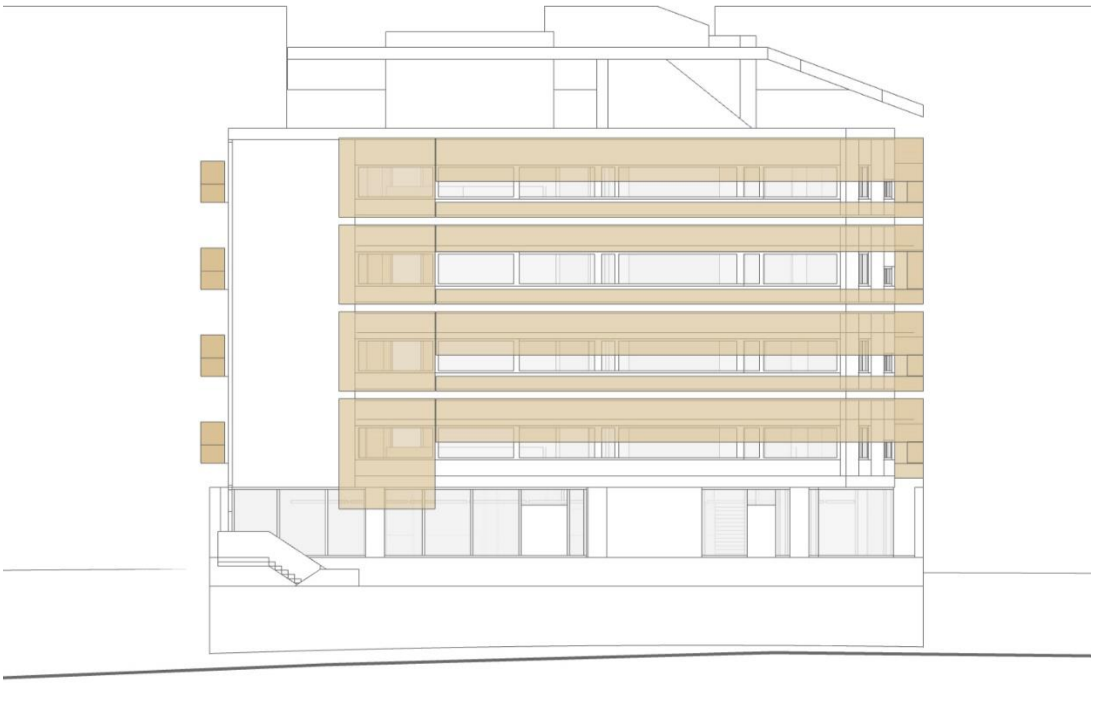
Figure 0.34 Questionnaire results in coloured gradient scores filtered by floor.

Floor	4	4	4	4	4	4	4	4	4	1	1	1	1	1	1
Light source	1	7	6	6	2	1	3	3	2	1	2	5	7	2	6
Light preference	6	1	2	1	5	1	2	1	1	1	2	2	1	1	1
Light satisfaction	4	7	4	4	2	1	2	2	2	1	2	2	5	2	4
Uniformity	3	5	4	5	2	1	2	2	2	2	4	2	4	4	4
Light level	1	1	4	3	2	1	2	2	1	2	2	3	5	3	5
Reflections	2	3	7	3	7	7	7	7	2	2	3	6	5	6	5
Reflection type	Vertical	Horizontal	None	Vertical	None	None	None	None	Vertical	Vertical	Vertical	None	Vertical	None	Vertical
Glare from fixtures	6	1	6	3	7	7	7	7	6	7	3	7	7	6	6
Sunlight glare	2	7	6	7	7	7	6	7	6	2	3	7	7	6	7
Indirect glare	Window	Desktop	None	Window	None	None	Window	None	None	Window	Window	None	None	None	None
Color temperature	6	2	6	3	6	6	4	4	6	6	4	3	5	5	6
Color rendering	2	1	4	4	2	1	3	4	2	4	4	3	5	3	4
Visible sky	1	2	4	3	1	1	2	2	1	1	4	7	3	2	3
User control	2	1	2	2	6	7	6	1	6	7	5	6	3	3	2
Intensity	Reduce	Reduce	None	Reduce	None	None	None	Rise	None	None	None	None	Rise	Rise	Rise
Shadows/ detail vision	3	2	2	3	1	1	2	1	2	4	4	1	3	3	3
Visual concentration	3	1	2	3	2	1	3	1	2	2	2	2	2	2	4
Disorder	Headache	Eye fatigue, Headache, Blur vision	Eye fatigue, Blur vision	Eye fatigue	None	None	Eye fatigue	Eye fatigue, Headache	None	Eye fatigue	Eye fatigue	None	Headache	None	None
Ambience satisfaction	5	5	2	2	1	1	2	1	2	1	3	2	5	2	4
Visual aid	None	Glasses	Glasses	None	Glasses	Glasses	None	Glasses	Glasses	None	Glasses	None	Glasses	None	Glasses
Discomfort	Hot	None	None	Exhaust air	None	None	None	Cold, Hot, Air draft	None	Exhaust air	None	Cold	Hot, Exhaust air	Hot	Exhaust air
Comments		Add task lights			Add warm temperature task lights			Add warm temperature task lights		Insufficient control in meeting rooms				Add task lights	

Figure 0.37 Questionnaire results in coloured gradient filtered by light source.

Light source	1	1	1	2	2	2	2	3	3	5	6	6	6	7	7
Light preference	1	1	6	1	2	1	5	1	2	2	1	1	2	1	1
Light satisfaction	1	1	4	2	2	2	2	2	2	2	4	4	4	5	7
Uniformity	2	1	3	4	4	2	2	2	2	2	4	5	4	4	5
Light level	2	1	1	3	2	1	2	2	2	3	5	3	4	5	1
Reflections	2	7	2	6	3	2	7	7	7	6	5	3	7	5	3
Reflection type	Vertical		Vertical		Vertical	Vertical					Vertical	Vertical		Vertical	Horizontal
Glare from fixtures	7	7	6	6	3	6	7	7	7	7	6	3	6	7	1
Sunlight glare	2	7	2	6	3	6	7	7	6	7	7	7	6	7	7
Indirect glare	Window		Window		Window				Window			Window			Desktop
Color temperature	6	6	6	5	4	6	6	4	4	3	6	3	6	5	2
Color rendering	4	1	2	3	4	2	2	4	3	3	4	4	4	5	1
Visible sky	1	1	1	2	4	1	1	2	2	7	3	3	4	3	2
User control	7	7	2	3	5	6	6	1	6	6	2	2	2	3	1
Intensity			Reduce	Rise				Rise			Rise	Reduce		Rise	Reduce
Shadows/detailed vision	4	1	3	3	4	2	1	1	2	1	3	3	2	3	2
Visual concentration	2	1	3	2	2	2	2	1	3	2	4	3	2	2	1
Disorder	Eye fatigue		Headache		Eye fatigue			Eye fatigue, Headache	Eye fatigue			Eye fatigue	Eye fatigue, Blur vision	Headache	Eye fatigue, Headache, Blur vision
Ambience satisfation	1	1	5	2	3	2	1	1	2	2	4	2	2	5	5
Visual aid		Glasses			Glasses	Glasses	Glasses	Glasses			Glasses		Glasses	Glasses	Glasses
Discomfort	Exhaust air		Hot	Hot				Cold, Hot, Air draft		Cold	Exhaust air	Exhaust air		Hot, Exhaust air	
Comments	Insufficient control in meeting rooms			Add task lights			Add warm temperature task lights	Add warm temperature task lights							Add task lights





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