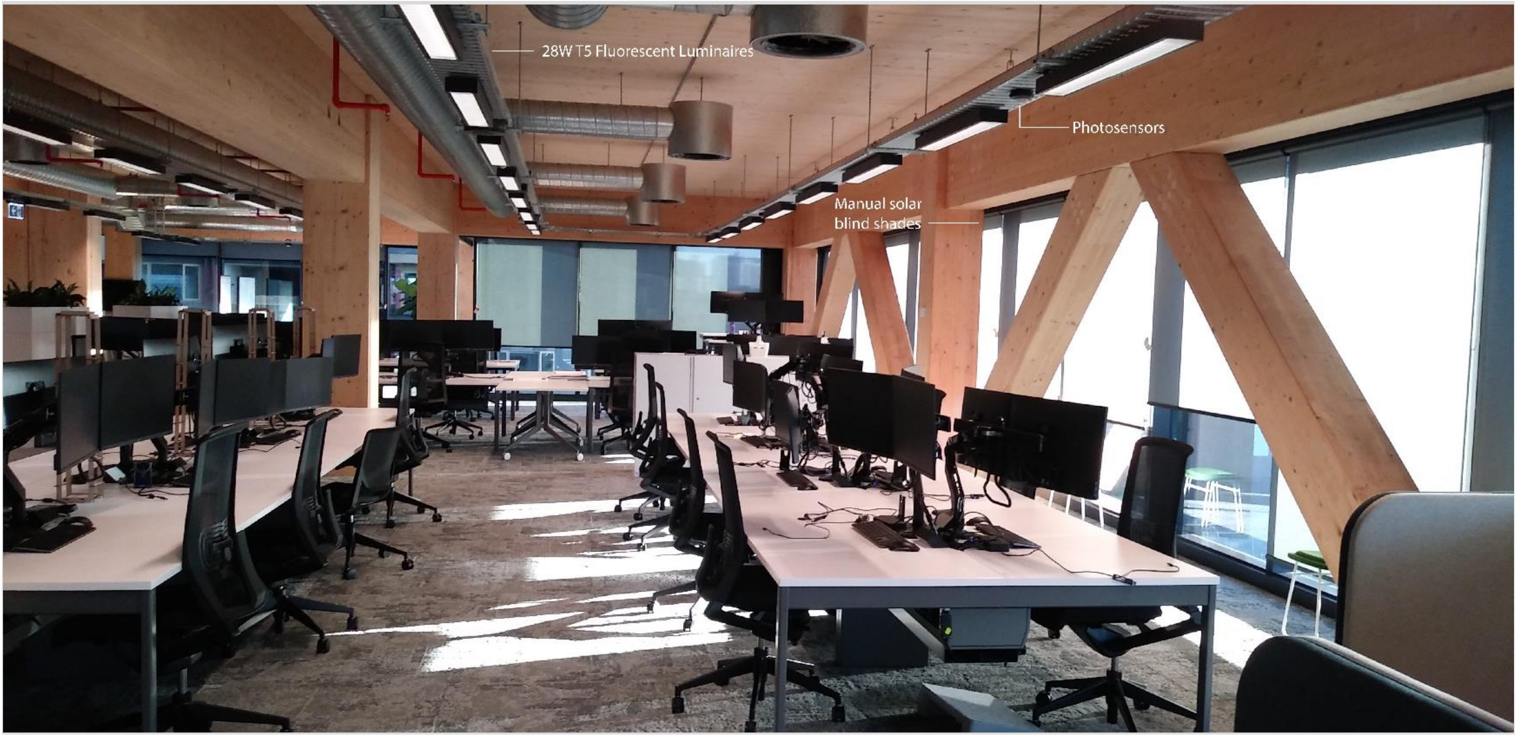
Integrating daylighting and lighting in practice

Lessons learned from international case studies



IEA SHC Task 61 / EBC Annex 77: Integrated Solutions for Daylighting and Electric Lighting

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The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is *"To enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50 % of low temperature heating and cooling demand by 2050."*

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- Solar District Heating (Tasks 7, 45, 55)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43, 57)
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- ➢ SHC Solar Academy
- ➢ Solar Heat Worldwide annual statistics report
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KEYWORDS

Daylighting; lighting; shading; lighting control; integrative lighting; field study.

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PREFACE

Lighting accounts for approximately 15 % of the global electric energy consumption and 5 % of greenhouse gas emissions. Growing economies, higher user demands for quality lighting and rebound effects as a result of low priced and more versatile electric lighting continuously still lead to an absolute increase of lighting energy consumption. More light is used, often less consciously.

Especially the electric lighting market but as well the façade, daylighting und building automation sectors have seen significant technological developments in the past decade. However these sectors still act mainly independent of each other, leaving out big potentials lying in a better technology and market integration. This integration is on the one hand beneficial to providing better user-centred lighting of indoor spaces. On the other hand it can contribute significantly to the reduction of worldwide electricity consumptions and C02-emissions, which is in line with several different governmental energy efficiency and sustainability targets.

IEA SHC Task 61 / EBC Annex 77 “Integrated Solutions for daylighting and electric lighting – From Component to system efficiency” therefore pursues the goal to support and foster the better integration of electric lighting and daylighting systems including lighting controls with a focus on the non-residential sector. This includes the following activities:

- Review relation between user perspective (needs/acceptance) and energy in the emerging age of “smart and connected lighting” for a relevant repertory of buildings.
- Consolidate findings in use cases and “personas” reflecting the behaviour of typical users.
- Based on a review of specifications concerning lighting quality, non-visual effects as well as ease of design, installation and use, provision of recommendations for energy regulations and building performance certificates.
- Assess and increase robustness of integrated daylight and electric lighting approaches technically, ecologically, and economically.
- Demonstrate and verify or reject concepts in lab studies and real use cases based on performance validation protocols.
- Develop integral photometric, user comfort and energy rating models (spectral, hourly) as pre-normative work linked to relevant bodies: CIE, CEN, ISO. Initialize standardization.
- Provide decision and design guidelines incorporating virtual reality sessions. Integrate approaches into wide spread lighting design software.
- Combine competencies: Bring companies from electric lighting and façade together in workshops and specific projects. Hereby support allocation of added value of integrated solutions in the market.

To achieve this goal, the work plan of IEA SHC Task 61 / EBC Annex 77 is organized according to the following four main subtasks, which are interconnected by a joint working group:

- Subtask A: User perspective and requirements
- Subtask B: Integration and optimization of daylight and electric lighting
- Subtask C: Design support for practitioners (Tools, Standards, Guidelines)
- Subtask D: Lab and field study performance tracking
- Joint Working Group: Evaluation tool & VR Decision Guide

Subtask D demonstrates and assesses, and either verify or reject, currently available and typically applied concepts for daylighting and electric lighting design and their integration to better understand how various integrated lighting systems and their control mechanisms behave with respect to several important parameters (e.g., energy use, thermal and visual environment, maintenance, adaptability to new requirements, etc.) and how building users respond to them. Work includes a comprehensive literature review of relevant research materials (in close collaboration with Subtask A.1), targeted medium-term experiments in several living laboratories, supplemented by short-term investigations of specific concepts or ideas in controlled research laboratory environments, as well as performance tracking through “real” field studies in recently completed or retrofitted buildings across selected building types in several of the participating countries. Case studies were selected in close collaboration with other Subtasks.

Subtask D project areas:

- D.1. Literature Survey: Quantifying Potential Energy Savings
- D.2. Monitoring Protocol
- D.3. Case Studies: Living Laboratories and Real Buildings
- D.4. Lessons Learned – Guidance to Decision Makers

EXECUTIVE SUMMARY

This report presents lessons learned from twenty-five worldwide real-life case studies implementing the integration of daylighting and electric lighting. The case studies were monitored with respect to energy use for lighting, visual performance, non-visual performance, and users' satisfaction. The monitoring is largely based on field measurements, but it is also complemented with simulations and calculations where needed.

The report is divided in two parts. The first part provides an overview of the case studies and the overall lessons learned. The second part provides factsheets for each of the case studies; the factsheets include details on the monitoring, results, and specific lessons learned.

Based on the lessons learned from the case studies, this report concludes that:

- The energy demand for lighting is drastically reduced thanks to the combined effect of more efficient light sources, advances in controls, and raised awareness in the integration of daylighting and electric lighting.
- Integrative lighting is currently driving the innovation in lighting technology and wider implementation is expected as knowledge in the field of non-visual requirements for lighting expands.
- However, the current integration of the integrative lighting concept with daylighting in practice is limited, which may result in significant energy rebound (increases).
- Daylighting integration is of utmost importance for achieving quality beyond energy savings.
- Integrated daylighting and electric lighting design is facing new challenges: questions connected with comfort and health are yet to be answered.

Contents

ABBREVIATIONS

ADF	Average Daylight Factor
ALFA	Adaptive Lighting for Alertness
CCT	Correlated Colour Temperature
CRI Ra	Correlated Rendering Index
CS	Circadian Stimulus
DA	Daylight Autonomy
DF	Daylight Factor
DF	Daylight Factor
DGI	Daylight Glare Index
DGP	Daylight Glare Probability
DHS	Daylight Harvesting System
EC	Electrochromic
Eh	Horizontal illuminance lx)
EML	Equivalent Melanopic Lux
ETFE	Ethylene tetrafluoroethylene
Ev	Vertical illuminance (lx)
HDR	High Dynamic Range
IOT	Internet of things
KSS	Karolinska Sleepiness Scale
LED	Light emitting diode
LENI	Lighting Energy Numerical Indicator (kWh/m^{2}y)
LPD	Lighting Power Density (W/m^2)
M&V	Monitoring and Verification
M/P	Melanopic over Photopic ratio
M-EDI	Melanopic – Equivalent Daylight Illuminance (lx)
PC	Personal computer
PMV	Predicted Mean Vote
POE	Post-Occupancy Evaluation
PPD	Predicted Percentage of Dissatisfied
sDA	Spatial Daylight Autonomy
SPD	Spectral Power Distribution
UGR	Unified Glare Rating

1 Introduction

Analysing case studies has the potential to teach and inspire, allowing practitioners to verify the actual performance of integrated solutions and to take informed decisions for new projects.

This report collates the results of extensively monitored real projects of integrated lighting and daylighting, termed here as case studies. Twenty-five case studies are included in this report. Most of the case studies are real life project, while a few consist of living lab experiments or laboratory studies. In respect to space type, these are associated with the non-residential sector, with an over-representation of offices. Case studies also include healthcare, retail, and a residence for the elderly. Geographically, these case studies are spread across five continents. These case studies bring together various proposals of different solutions towards achieving project goals connected with energy and lighting quality. Each case study has a different design objective, which is pursued with a different solution. The monitoring of these case studies follows a framework proposed by [place holder for T61 D.2]; with each case study adopting a different tool for monitoring, depending on specific design goals.

The first part of this report illustrates the collection of case studies, which is followed by overarching lessons learned from the monitoring. Finally, the case-study reports are provided in Appendix to this document, in the form of factsheets. The factsheets here are short reports aimed at a wider audience; readers interested in more information can refer to the citation list provided at the end of each factsheet.

1.1.1 Objectives

The objectives of this report are to:

- Illustrate selected case studies where daylighting and electric lighting are integrated in an energy-efficient user-centred fashion,
- analyse the results from the case studies, and
- draw relevant conclusions for lighting designers and related professional groups, as well as building users engaged in the design process

The report is intended to provide effective guidelines to industry members, designers, users and other decision makers involved in designing integrated lighting systems and control strategies, by suggesting what works and what does not; based on experiences from the consolidated research of Subtask D, e.g. through specific recommendations and suggestions.

2 Overview of the case studies

The collection of case studies is the result of the joint effort of IEA SHC Task 61 experts, and their monitoring teams around the globe. Task 61 was launched in February 2018 and the monitoring of case studies was planned to start during the second part of 2019. In the original plans, the monitoring was supposed to include only occupied real-buildings or living laboratories; and the monitoring should have lasted around one year per case study. Additionally, the monitoring should have been performed on-site only, and should also have included results of user-surveys. However, due to the covid-19 pandemic, many of the monitored buildings experienced a strict lockdown since February 2020, which prevented access to both, the occupants, and the monitoring teams. Despite such circumstances, the monitoring teams have made great efforts to deliver robust results despite drastic changes in the methodological approach to monitoring.

Given the above circumstances, the final monitoring of case studies presented here includes field monitoring completed with simulations, shorter monitoring, or monitoring with only informal user surveys. Details on the monitoring process are provided in each factsheet.

The case studies present a very heterogeneous set of projects. Instead of imposing a unified monitoring protocol to achieve highly comparable results at the expense of diversity, such heterogeneity was purposefully implemented by proposing a set of monitoring techniques as a toolbox for participants to choose from, according to the differing means available to them, the accessibility of the building and the characteristics of the specific case study considered.

As a result, this set of case studies presents a plurality of examples with a constant focus on the comfort of users and the energetic consequences of differing designs, retrofits, and control choices. The practitioner is thus encouraged to select examples most relevant to her or his problem, be it in terms of monitoring techniques, of metrics to compute, or of lessons to learn.

2.1 List of case studies

Twenty-five case studies were monitored during the Task 61 activities. The case studies cover a large span of climates and geographical position, both in longitude – from 123° W to 153° East – and in latitude – from 50° N to 27° S, and climates (Figure 1).

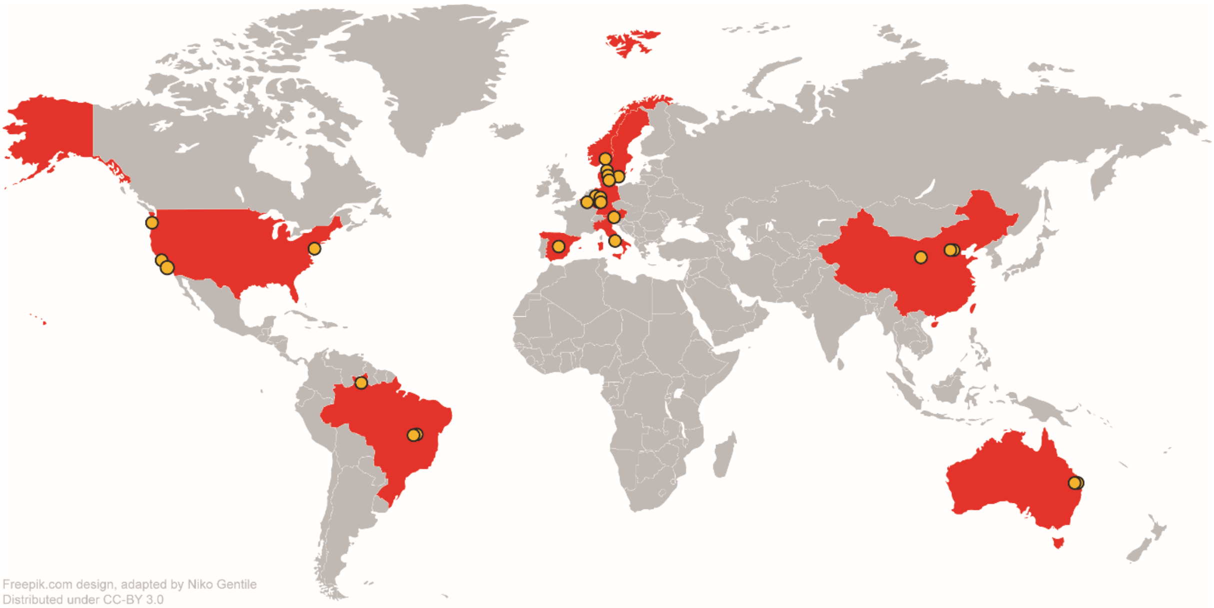


Figure 1. Geographical distribution of the twenty-five case studies in IEA SHC Task 61 Subtask D.

Nineteen of the case studies included real occupied buildings, while six consisted of living lab or mock-up spaces. Most case studies are office or office-like buildings (twenty), although several of such case studies also include the monitoring of common areas like meeting rooms, halls, etc. Three spaces can be considered residential, as they consist of elderly home, rehabilitation, or psychiatric hospital for long stays. Finally, the last two case studies consist of a retail space (furniture shop) and a sport venue (the national aquatic centre of Bejing built for the 2008 Summer Olympics) (Table 1).

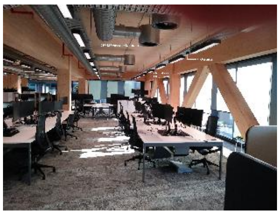
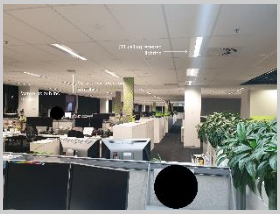
Table 1 provides a summary with short identification (ID) name for each case study. The ID will be used throughout the text to refer to the case study.

Table 1. Case studies and space type.

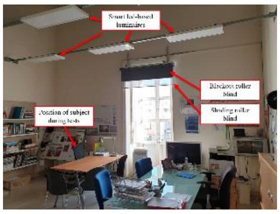
n.	City	Country	ID	Space type
01	Aldrans	Austria	AT Bartenbach	office - mixed
02	Brisbane	Australia	AU Aurecon	office - open plan
03	Brisbane	Australia	AU Aecom	office - open plan
04	Brussels	Belgium	BE Stephenson	health care, residence
05	Brasilia	Brazil	BR MME	office - mixed
06	Boa Vista	Brazil	BR ForumSoPinto	office - mixed
07	Brasilia	Brazil	BR UniBrasilia	office - mixed
08	Beijing	China	CH CABR	office - mixed
09	Beijing	China	CH NAC	sport venue
10	Xining	China	CH BankChina	office - mixed
11	Slagelse	Denmark	DK PsychiatricH	health care
12	Aarhus	Denmark	DK Navitas	office - mixed
13	Vikaergaarden	Denmark	DK Rehab	health care
14	Stuttgart	Germany	DE IBP_LED	office - two occupants (living lab)
15	Stuttgart	Germany	DE IBP_Daylight	office - two occupants (living lab)
16	Lüdenscheid	Germany	DE DIAL	office - mixed
17	Kaarst	Germany	DE IKEAKaarst	retail
18	Aversa	Italy	IT AbaziaSanLorenzo	office - single occupant (living lab)
19	Oslo	Norway	NO Norconsult	office - single occupant (living lab)
20	Madrid	Spain	ES IDOM	office - open plan
21	Lund	Sweden	SE TheSpark	office - mixed
22	Portland, OR	USA	US PortlandEC	office - mixed
23	Oakland, CA	USA	US DualZoneShade	office - mixed (field and living lab)
24	New York City, NY	USA	US NewYorkCity	office - multi-occupant (living lab)
25	San Francisco, CA	USA	US SoSanFrancisco	office - mixed

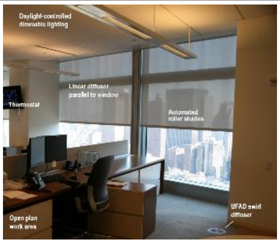
The range of integrated solutions that were adopted in the monitored projects is quite vast. A list of the main solutions is provided in Table 2. Although all case studies include some form of integration, the designs focused more on either daylighting or electric lighting for some projects. In such cases, there is a quite homogenous distribution between case studies with higher focus on daylighting solutions and focus on electric lighting solutions.

Table 2. Summary of the main solutions adopted in the monitored case studies

ID		Solutions
AT Bartenbach		Combined top and side openings for deep daylight penetration; external stating daylight deflecting louvres; LED with reflectors controlled with integrative lighting, daylight harvesting, presence sensing, and individually a.
AU Aurecon		Highly glazed building; T5 and LED daylight harvesting and presence sensing with override via remote control; manual roller blinds.
AU Aecom		Timber building with generous sidelit windows; T5 and LED with occupancy sensors; manual roller blinds.
BE Stephenson		Daylit rooms tested for different lighting scenarios: dim electrical lighting including workplane photopic illuminance and non-visual melanopic vertical illuminance.
BR MME		Fully glazed facades with brise soleil and solar control films; high-efficiency T5 (103 lm/W) with daylight harvesting and central management of target illuminance.
BR ForumSoPinto		Passive solar strategies. Daylight and static shading. Orientation and depth of building. Films in windows for solar radiation protection; LED T8 replacement tubes at 6500 K.
BR UniBrasilia		External horizontal brise soleil, solar control films, curtains; efficient T5 fluorescent tubes with manual control.

ID		Solutions
CH CABR		Horizontal blinds, tubular daylighting system; LED lighting with POE, absence sensing, daylight harvesting, scene control.
CH NAC		Transparent ETFE inflatable pillows for daylight; high power LED with different scenes (depending on sport) and dimming possibilities.
CH BankChina		Sidelight windows; IoT connected LED lighting system, integrative lighting, daylight harvesting, occupancy sensing, scene control (meeting rooms.).
DK PsychiatricH		Large windows providing ADF = 2-3%; LED lighting with different intensity and CCT during day and night, with manual switch on-off.
DK Navitas		Denmark' largest low-energy commercial buildings. Shading consists of black, manually operated, perforated interior roller blinds with 50% openings. T5 4000 K and manually operated desk lamps; luminaires grouped in zones with daylight harvesting close to windows and occupancy detection; manual setting of target illuminance via room control panel.
DK Rehab		Large windows; integrative lighting with daily schedule and three manual scenes ("light therapy", "night care", "calming").
DE IBP_LED		Dual-zone façade; traditional windows with automatic venetian blinds (lower part); micro-optical structure with LED above windows; zoning of direct-indirect luminaires with daylight harvesting.
DE IBP_Daylight		Dual-zone façade daylight area: traditional windows with automatic venetian blinds (lower), micro-optical structure in plexiglass (upper); zoning of direct-indirect luminaires with daylight harvesting.

ID		Solutions
DE DIAL		Automatic shading and lighting with manual override; highly controllable and customizable at individual level via PC interface.
DE IKEAKaarst		Windows in exhibition space; LED lighting with daylight harvesting; integrative lighting.
IT AbaziaSanLorenzo		Double manually controlled roller shade (semi-transparent and blackout); manually controlled LED pendant with 7-steps dimming and 3-steps CCT tuning. Remote controls for shading and lighting available at desk.
NO Norconsult		Sidelight windows with venetian blinds, horizontal daylight pipe for deeper part of room; LED with daylight harvesting.
ES IDOM		Double skin microperforated façade and roller shades; T5 pendants with open loop daylight harvesting.
SE TheSpark		Highly glazed building with automatic roller shades; integrative LED panels lighting system with manual override, including manual dimmer.
US PortlandEC		Electrochromic glazing with dynamic change of tint (manually override), indoor venetian blinds (kept open during test phase); fluorescent pendant with manual on-off and occupancy sensing.
US DualZoneShade		Dual-zone solar control (more daylight from upper zone, glare-free and open view out from lower zone). Inverted curved, horizontal louvres above (auto with manual override), manual transparent film roller shade below; Dimmable T8 pendant with daylight harvesting set-point 300 lx.

ID		Solutions
US NewYorkCity		High resolution lighting systems with individually addressable, direct-indirect LED luminaires, separate dimming control of up-versus down-light output, and setpoint tuning, occupancy, scheduling and daylighting control. Automated shading control.
US SoSanFrancisco		Project optimized with M&V in a mock-up; automated roller shades; individually addressable, indirect-direct pendant LEDs with daylight harvesting and relay shut-off.

2.2 Monitoring process

The case studies were monitored in respect to four aspects, as defined in the report [place holder for T61 D.2] energy, visual, non-visual, and user. The framework proposed in [place holder for T61 D.2] provides guide for conducting building purpose-oriented monitoring protocol in real integrated project. Therefore, each case study was monitored with a unique protocol. Some of the case studies introduced cutting-edge tools for monitoring, e.g. use of wearable devices or ceiling mounted luminance cameras. Therefore, the actual monitoring of case studies (D.3) informed the monitoring framework (D.2) in a continuous feed-back feed-forward process (Figure 2). The final framework of [place holder for T61 D.2] is thus a result of this process.

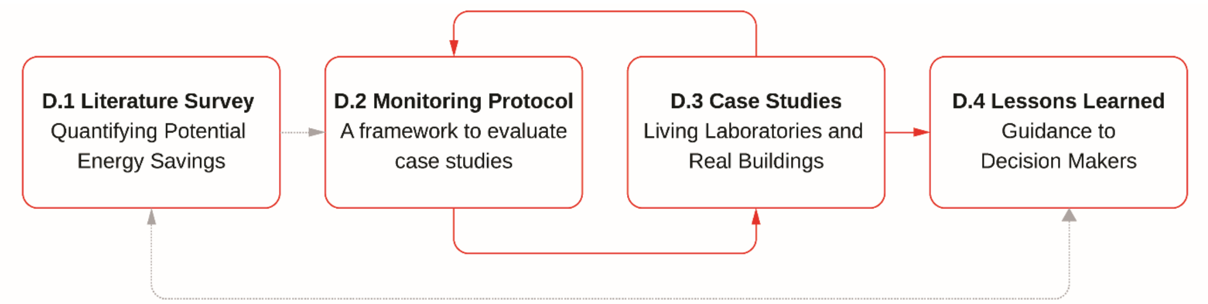


Figure 2. Case studies in the context of IEA SHC Task 61 Subtask D activities.

The monitoring teams primarily defined the initial goals (or ambition) of their case study project – in coherence with the framework and designed a purpose-oriented protocol for specific case studies later. The protocol stressed on aspects relative to the initial goals, by adopting more robust monitoring tools for those aspects. For example, projects aiming at a sensitive reduction of energy loads for lighting preferred to directly meter the lighting use; while projects with different aims, especially when metering was possible only with great difficulty, adopted calculation methods for evaluating lighting energy use.

Irrespective of the adopted tools, the monitoring teams planned to monitor each of the four aspects. However, strict lockdowns in many countries forced some of the field evaluations to be skipped. These were replaced by calibrated computer simulations, usually based on the field data collected to that date, or by a qualitative evaluation, the latter being the case for the non-visual aspect in some of the case studies (

Table 3).

Table 3. Monitored aspects and relative tools for the case studies.

ID	ENERGY	VISUAL	NON-VISUAL	USER
AT Bartenbach	Measured LENI	Illuminance, presence, dimming level (longitudinal); DF, DA (simulated), HDR for DGP	CCT, Ev, EML, M/P (measured for daylight, electric lighting, mix)	Questionnaires to occupants (appreciation, perception)
AU Aurecon	-	HDR at individual level via calibrated smartphone for DGP and DGI, cylindrical illuminance via low cost distributed sensors (longitudinal)	M/P via measured SPD	Questionnaire to occupants (preference, glare)
AU Aecom	-	HDR at individual level via calibrated smartphone for DGP and DGI, cylindrical illuminance via low cost distributed sensors (longitudinal)	M/P via measured SPD	Questionnaire to occupants (preference, satisfaction, glare)
BE Stephenson	Simulated LENI	DF, sDA, Spatial Glare Distribution (calibrated Climate Studio simulations)	EML, M/P, CS (calibrated ALFA simulations); use of personas	Discussion with personnel
BR MME	LENI calculated (long term), measured baseline + intervention (short term for checking energy savings)	Horizontal illuminances, DF, view out, HDR for directionality, luminance for contrast	EML via illuminance meter method	Questionnaires to occupants
BR ForumSoPinto	LENI calculated	Measured illuminances, Simulated sDA, ASE, UDI, view out	EML via illuminance meter method	Questionnaires to occupants
BR UniBrasilia	LENI and LPD simulated via Design Builder)	Measured horizontal, vertical, cylindrical illuminance, view out, HDR for directionality; simulated DF, Annual DGP.	EML via illuminance meter method	Questionnaires to occupants
CH CABR	Measured LENI, LPD	Measured illuminances, ADF, U_0, SPD, CCT, CRI	Qualitative	Questionnaires to staff
CH NAC	Calculated LPD and energy use	Measured horizontal and vertical illuminances, UGR, CCT, CRI	Qualitative	Informal chats
CH BankChina	Total energy use (kWh), LENI calculated	Measured illuminances, ADF, U_0, SPD, CCT, CRI, Stroboscopic	Qualitative	Informal chats

ID	ENERGY	VISUAL	NON-VISUAL	USER
		ratio, UGR, spot luminance		
DK PsychiatricH	Calculated LENI based on field power data and schedule	Horizontal illuminance, HDR for DGP and UGR, SPD, CCT, CRI Ra	Measured M-EDI, CS	Interviews with staff
DK Navitas	Energy use for selected days	DF, illuminance (logged), HDR	Measured M-EDI, CS	Interviews with occupants
DK Rehab	LENI calculated, DIALux simulations based on monitored data	Measured illuminances	Measured M-EDI, CS, Pattern of light intake with wearable sensors	Semi-structured interviews
DE IBP_LED	Installed power (W/m^2 100 lx)	Measured illuminances	Qualitative	Within-subjects surveys
DE IBP_Daylight	Energy use (kWh)	Measured illuminances	Qualitative	Within-subjects surveys
DE DIAL	-	Design values	-	Informal chats
DE IKEAKaarst	Calculated LENI based on measured usage pattern	DF, DA, cylindrical illuminance, DGP, view out	M/P ratios (calibrated ALFA simulations)	Questionnaires to visitors; interviews, and survey to employees
IT AbaziaSanLorenzo	Measured power for different scenarios	Measured horizontal and vertical illuminances, occupancy (longitudinal); SPD, CCT, view out, shade properties	EML, M/P, M-EDI (measured for daylight, electric lighting, mix)	Interviews with occupants
NO Norconsult	Measured LENI	Measured and simulated illuminances (horizontal and vertical)	Qualitative	Questionnaires with occupants
ES IDOM	Simulated LENI via Daysim	Measured DF, reflectance, simulated sDA, UDI, DGP	M/P ratios (calibrated Lark simulations)	Questionnaires with occupants
SE TheSpark	Calculated LENI based on measured usage pattern	DF,SPD, vertical illuminance	M/P ratios (calibrated ALFA simulations), Pattern of light intake with wearable sensors	KSS sleeping scale, interviews
US PortlandEC	LENI measured, SHGC, U-Value, measured solar irradiance	EC optical properties, EC tint status, blinds position, HDR for DGP	M/P daylight-driven for different times and EC tints, (measured via HDR)	Questionnaires to occupants
US DualZoneShade	Measured energy for lighting and cooling	Shades properties, measured illuminances, lighting energy, HDR for DGP	Qualitative	Questionnaires to occupants
US NewYorkCity	Measured LENI	Measured illuminances (longitudinal), lighting energy, HDR for DGP	Qualitative	Questionnaires to occupants, PPD/PMV for thermal comfort
US SoSanFrancisco	LPD for different scenarios	Measured illuminances (longitudinal), lighting energy, HDR for DGP	Qualitative	Interviews with the facility management

3 Lessons learned

This chapter summarises the lessons learned from the twenty-five case studies as presented in the attached factsheets, §6 The case studies. The lessons learned were first analysed together and then grouped in categories, corresponding to the following subchapters.

Figure 3. Word cloud generated from the twenty-five factsheets presented in this report.

3.1 Dramatic reduction of energy demand

For the selected case studies, wise combinations of daylighting strategies, controls, and more efficient light sources enabled reductions in energy demand for lighting by a factor of four compared with current installations. Indeed, the energy demand for lighting was around 5 kWh/m²y for many of the office case studies, independent of the type of office (single occupant or open plan) (Table 4). This is a striking improvement compared to the roughly 20 kWh/m²y found in most current installations and is much lower than the benchmarks provided by EN15193-1:2017.

Energy demand for lighting is much closer to current benchmarks for case studies relying on traditional light sources (16.84 kWh/m²y for recessed fluorescent T5 at the BR ForumSoPinto), or newer light sources with higher efficacy, like the LED T8 replacement lamps used at the BR MME which achieved 17.23 kWh/m²y. Nevertheless, the opportunities for energy saving in integrated design go well beyond the mere switching to LED. The case study of the office in US NewYorkCity with 9.79 kWh/m²y for 12.2 m deep perimeter zones showed that 41-59% of savings were attributable to re-lamping from fluorescent T5 to LED, but as much as 27-51% savings was due to proper (re)commissioning (setpoint tuning), and 8-14% to control strategies (occupancy sensing and daylight harvesting). Part of the CN CABR monitored rooms were equipped with T5; a hypothetic switch to LED would have lowered the energy demand roughly from 6 kWh/m²y to 5 kWh/m²y. Possibly, most of the savings were already achieved with daylight integration (side windows and tubular skylighting systems). This is a clear indication that re-lamping alone is not sufficient to exploit the energy saving potential of lighting systems. Integration must include controls and it should go along with a careful design, as well as a proper commissioning and recommissioning.

The energy benefits of integration are found also in spaces different than offices. For example, in the retail sector, the Living Room department of DE IKEAKaarst achieved a 50% of reduction in lighting energy (comparing actual use of 40.3 kWh/m²y to the EN15193-1:2017 benchmark of 78.1 kWh/m²y). For health care, the solutions proposed at DK PsychiatricH hospital allowed a 34% reduction in energy demand from 8.20 kWh/m²y to 5.40 kWh/m²y. However, integrated projects should be well-thought and designed to achieve such performances. For two cases, the Home Decoration department of DE IKEAKaarst did use more energy than the benchmark (84.0 kWh/m²y) since extra electric lighting was used to illuminate products despite there being plenty of daylight. In addition, given the particularity of the case study, inefficient halogen spotlights were used because of their high colour rendering. In DK PsychiatricH, the existing lighting system, which consists of efficient LED, results in 60.5%

more energy use than the benchmark because no control is implemented (daylight harvesting and occupancy sensing).

Indeed, much energy can be saved by using shading and lighting controls if those are correctly commissioned and fine-tuned. Open-loop daylight harvesting performed well in the ES IDOM (4.90 kWh/m^2y with fluorescent light sources, i.e. 79% energy saving compared to EN15193-1:2017 benchmark) and the US SoSanFrancisco case studies. A closed-loop daylight harvesting system reduced by 9% the global energy demand in the BR MME case study. In US SoSanFrancisco, the open-loop outperformed the closed-loop daylight harvesting strategy, achieving appropriate dimming for respectively 70% and 56% of the time. The open-loop strategy allowed a reduction of LPD from 5.5 W/m^2 to only 1.4 W/m^2 for a 300 lux set-point, i.e. 74% of reduction in LPD, with peak values of only 0.005 W/m^2. It is worth mentioning that successful stories with control included careful commissioning; for example, the US SoSanFrancisco case reports on an advanced strategy for self-commissioning and a period of M&V where several adjustments were made. Commissioning, monitoring, and verification is of utmost importance for controls. For example, the photosensors of daylight harvesting systems should be correctly positioned as direct sunlight on the photosensor compromises the calibration (NO Norconsult).

Good daylight design fully exploits the energy saving potential of controls, by maximizing daylight penetration and minimizing discomfort from glare or the like. In the AT Bartenbach case study, for example, tilted and vertical openings, the latter combined with static daylight deflecting louvres and movable glare protection screens, provided DF > 3.5% at any location of an open plan office and virtually no glare occurrences. As a result, the occupants acted very limitedly on the shading and lighting systems. Those were equipped with a complex occupancy sensing and daylight harvesting, which lowered the energy demand for lighting from 16.50 kWh/m^2y with no control to an astonishing 3.65 kWh/m^2y. In the DE IBP_Daylight, the use of a micro-optical light redirecting structure on top of the windows allowed daylight to reach the deeper part of the rooms without causing discomfort; the use of daylight harvesting resulted thus highly beneficial, and it could cut by roughly 50% the energy demand for lighting compared to a reference case with traditional openings only. The horizontal tubular daylight system used in the NO Norconsult case study has a similar scope – providing daylight deeper in the room – and achieved around 35% energy use compared to a reference case with traditional sidelit window only, despite the issues with the photosensor. The adoption of electrochromic glazing reduced lighting energy use by 26% (from 9.37 kWh/m^2y to 5.96 kWh/m^2y) in the US PortlandEC case study, but also reduced heat gains from solar transmission from 28 W/m^2 to 3 W/m^2, with clear benefits on the building cooling loads and the occupants' thermal comfort. However, electrochromic glazing alone was found to be inadequate in controlling glare from the solar orb so in the US PortlandEC case study, occupants used venetian blinds to improve visual comfort.

The lighting and shading control systems at AT Bartenbach provided outstanding results relying on advanced hardware whose energy self-consumption 1.09 kWh/m^2y, that is roughly a third of the measured demand for lighting. While the introduction of controls was certainly beneficial for the AT Bartenbach, the energy self-consumption of controls should always be considered. For example, the standby power in the IT AbaziaSanLorenzo case study was 11 W, a third of the power demand for the most dimmed mode (≈ 30 W). If the daylighting design allows for very low lighting demand, standby may become the main reason for using energy. Introducing relay shutoff is a good practice to reduce standby power; over 50% of standby power use was saved using this technique in the US SoSanFrancisco case study.

Finally, when daylighting is correctly and abundantly provided, designers may consider harvesting energy even without using automatic controls and relying only on training and education of occupants. This is the case of IT AbaziaSanLorenzo, where a combination of training, education and good daylight provisions resulted in very limited use of electric lighting, often in dimmed mode, and high degree of occupant satisfaction. The IT AbaziaSanLorenzo case study may serve as inspiration for those projects where designers have limited options for integration.

Table 4. Energy (or power) use for lighting for the case studies.

Case study ID	Value	Notes
AT Bartenbach	3.65 kWh/m^2y	Measured annual lighting energy use
AU Aurecon	*n.a.*	-
AU Aecom	*n.a.*	-
BE Stephenson	5.8 -> 3.8 kWh/m^2y 7.7 -> 7.8 kWh/m^2y	Bedroom before -> after improvement Dining room before -> after improvement

Case study ID	Value	Notes
		Annual lighting energy use based on simulations for typical days
BR MME	17.23 kWh/m^{2}y	Calculated LENI
BR ForumSoPinto	16.80 kWh/m^{2}y (13.70 – 20.10) kWh/m^{2}y	Average calculated LENI (min - max) calculated LENI
BR UniBrasilia	109.00 kWh/m^{2}y	Simulated annual lighting energy use
CH CABR	6.15 kWh/m^{2}y	Measured LENI
CH NAC	174 W/m^2	LPD – Standard LPD for similar type of space is 290 W/m^2
CH BankChina	8.10 kWh/m^{2}y	Measured annual lighting energy use
DK PsychiatricH	8.20 - 13.10 - 5.40 kWh/m^{2}y	Standard (Danish standard) – Existing (measured) – proposed change (calculated)
DK Navitas	*n.a.*	-
DK Rehab	13.70 – 15.20 – 6.90 kWh/m^{2}y	Standard (Danish standard) – Existing (measured) – proposed change (calculated)
DE IBP_LED	5.75 W/m^2	LPD at 100 lx for both lighting and LED structure
DE IBP_Daylight	< 1 kWh/m^{2}y	Daily energy use for the entire office, in both clear and overcast sky conditions (estimated < 7 kWh/m^{2}y)
DE DIAL	*n.a.*	-
DE IKEAKaarst	40.30 – 41.30 kWh/m^{2}y 84.00 – 84.70 kWh/m^{2}y	“living room” with DHS – without DHS “home decoration” with DHS – without DHS.
IT AbaziaSanLorenzo	178.8 - 30.4 W	Measured power at different dimming settings. Electric lighting is almost never used after daylighting design
NO Norconsult	6.00 kWh/m^{2}y	Measured LENI
ES IDOM	4.90 kWh/m^{2}y	Simulated annual lighting energy used based on existing system and realistic occupancy schedules
SE TheSpark	22.43 kWh/m^{2}y	LENI calculated based on real measured output of luminaires.
US PortlandEC	5.96 kWh/m^{2}y	Measured annual lighting energy use
US DualZoneShade	20%	Measured energy saving for lighting and cooling of the automatic grey-grey shade vs reference roller shade (fluorescent DHS lighting)
US NewYorkCity	9.79 kWh/m^{2}y	Measured lighting energy use. Reference value: 45.83 kWh/m^{2}y (reference case), 12.2 m deep perimeter zone
US SoSanFrancisco	1.40 W/m^2	Measured average daytime LPD of commissioned daylighting controls (DHS system). Reference (no dimming): 5.49 W/m^2.

3.2 Integrative lighting: opportunities and challenges

“Integrative lighting” is the official term used by CIE, for lighting designed to produce positive psychological and physiological response in humans, which replaces what has been informally or commercially been termed “human-centric lighting”, “biocentric lighting”, or the like. Integrative lighting is normally used to elicit circadian responses: our sleep-wake cycles are regulated by lighting (and its absence), which serves to reset out biological clocks. At present, it is understood that circadian response depends on five factors: intensity of light, spectrum of light, duration of the exposure to light, time of the day, and history of light exposure. Since daylight has been the source of light through human evolution (and of other organisms), it can be claimed that daylight is the ideal time-giver. Thus, integrative lighting systems are typically systems that change their intensity and spectral power distribution through different times of the day and follow the natural variation of daylight (Figure 4). Normally, this is done according to pre-determined schedules.

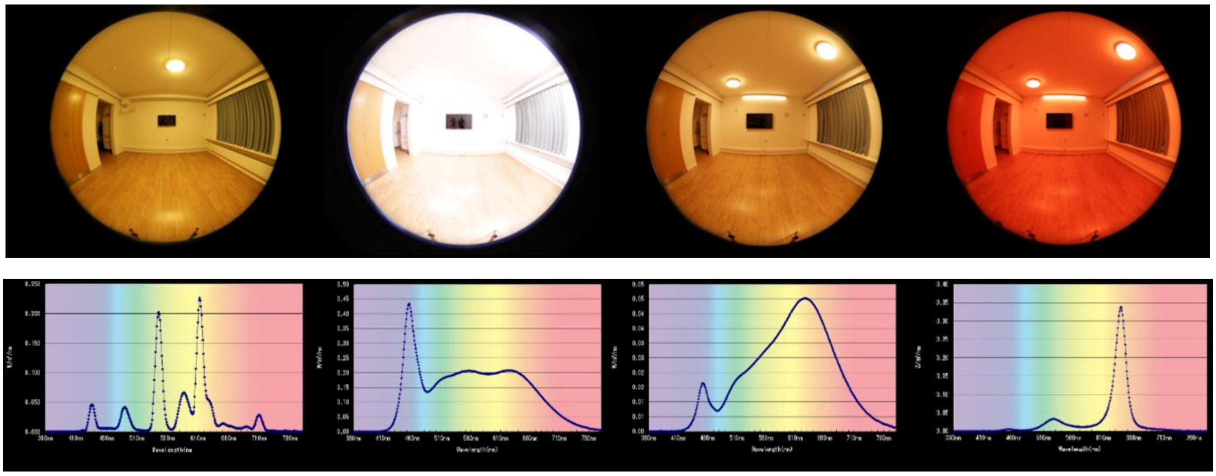


Figure 4. Example of integrative lighting. Photographs of the space under different lighting scenes (above) and their relative measured spectral power distribution (below). Pictures from the DK Rehab case study.

Ten out of the twenty-five case studies adopted integrative lighting as solution for integrated daylighting and electric lighting, which makes this a popular strategy in the collection. An interactive visualization of these systems is provided on the Task website:

- AT Bartenbach [placeholder for URL]
- IT AbaziaSanLorenzo [placeholder for URL]
- SE TheSpark [placeholder for URL]

The range of light intensity (measured in terms of delivered illuminance) and CCT was available for some of the electric lighting systems used in the case studies, see Table 5.

Table 5. Ranges of light intensity (expressed via measured illuminance at selected points) and CCT for the integrative electric lighting system of selected case studies. Ev = Vertical Illuminance at eye position, Eh = Horizontal illuminance at workspace.

Case study ID	**“Quantity of light”**		**CCT**	**Note**
	Unit	Value		
AT Bartenbach	Ev Eh	190 lx 500 lx	2174 ~ 4095 K	Measurements at Eh = 500 lx
CH CABR	Eh	*na*	3300 ~ 5300 K	
CH BankChina	Eh	127 ~ 615 lx	2939 ~ 5394 4225 ~ 6030 3616 ~ 5645 3497 ~ 5945	First row Eh and CCT refers to exemplary office, other CCT rows refer to other monitored spaces for which Eh is *na*
DK PsychiatricH	Eh	100 ~ 250 lx	1750 ~ 2700 K	
DK Rehab	Eh	47 ~ 430 lx	2700 ~ 5500 K	
DE DIAL	Eh	0 ~1200 lx 0 ~ 2000 lx 0 ~ 3000 lx	*na* ~ 6500 K	Range of illuminance depends on occupants’ choice
IT AbaziaSanLorenzo	Ev	15 ~ 351 lx	2200 ~ 4000 K	
SE TheSpark	Ev	640 ~ 1218 lx	2300 ~ 6200 K	

There is a wide variation of illuminance- and CCT range across cases. CCTs are higher for offices as compared to “residential” settings of psychiatric hospital and rehabilitation facility; where the highest CCT in the psychiatric hospital is just 2700 K. Offices are traditionally provided with lighting offering CCT in the range of 3000 – 4000 K, so, unsurprisingly, the integrative lighting ranges are not far from these values. Extreme values (2200 K or 6500 K) were not always appreciated by interviewed occupants in e.g. SE TheSpark.

Integrative lighting was adopted in different declinations. At AT Bartenbach, DE DIAL, CN BankChina, DE IKEAKaarst, DK Rehab, and SE TheSpark, the system changed dynamically in intensity and CCT with a predetermined schedule. As far as office spaces are concerned, the schedules include typically bright and high CCT light during the morning, which decrease in both intensity and CCT in the afternoon. Schedules can be more articulated for needs, like the rehabilitation facility DK Rehab. An example of schedule is provided in the interactive guide for AT Bartenbach [placeholder for URL], while for most of other cases the exact schedules were often unknown as they can be proprietary. In all above cases except at IKEAKaarst, the occupants were provided with manual override of controls, a solution that was highly appreciated. At AT Bartenbach and DE DIAL, despite the high level of automation provided ("*The user doesn't have to operate anything, the intelligent building serves the user*." DE DIAL), the manual override is expressly provided so that occupants can adapt their workplace to their own needs. In SE TheSpark, one occupant chose to adhere to a particular setting (Scene 4, lowest intensity and CCT), claiming that variation in settings was perceived irritating.

Lighting systems with a wise use of luminaires, are able to steer the quantity of light reaching the eye. In DK PsychiatricH, LED lighting were separated in two different circuits, one with three brighter LED downlights provided lighting through the day, while another with two more dimmed LED downlights provided lighting in the evening. This is a simpler solution which avoids automatically dimmable and tunable systems, while still reaching the "circadian target".

Nowadays, lighting technologies allow a much easier control and steering of luminaires, and there is a clear tendency to adopt integrative lighting in many new and retrofit projects. The prevalence of this solution in the list of case studies is a good indication. Technology seems mature enough to implement circadian lighting in practice, however, scientific understanding in the field of non-visual effects of light is still incomplete. Also, it is still difficult to design lighting systems that can balance both the visual and non-visual requirements. It is expected that the technology will evolve and adapt as more knowledge is acquired. Therefore, it is safe to predict that integrative lighting will drive innovation in lighting and in lighting control technology over the coming years.

In all the cases listed above, electric lighting was considered solely without daylight integration. However, daylight must also be included when checking circadian effectiveness of lighting systems. Daylight is, after all, the main regulator of our circadian clock. This brings to the question: can integration of daylighting support circadian potential? This question is discussed in the next subchapter.

3.2.1 Circadian potential of daylighting and lighting projects

Integrative lighting systems are usually designed such that electric lighting alone can support circadian response. However, it is worth verifying if daylight, as the ideal time-giver, can instead be used to support circadian response in indoor spaces. Table 6 provides target circadian metrics (EML, M/P, CS, M-EDI) according to current international standards and publications.

Table 6. Thresholds for circadian lighting design for EML, M-EDI and CS, recommended by WELL v2, Underwriter's Laboratory 24480 and Brown et al. 2021. Table adapted from Houser & Esposito (2021).

Standard or publication	Temporal pattern		Metric				Location
	Timing	Duration	CS	EML	M-EDI (lx)	Photopic ill. (lx)	
WELL v2.0 (1 point)	**9:00 -13:00** Ok lower levels after 20:00	≥ 4 hours	≥ 0.30 (EL)	≥ 150 (EL) ≥ 120 (EL*)	≥ 136 (EL) ≥ 109 (EL*)	N/A	Vertical et eye level
WELL v2.0 (3 points)	**9:00 -13:00** Ok lower levels after 20:00	≥ 4 hours	N/A	≥ 240 (EL) ≥ 180 (EL*)	≥ 218 (EL) ≥ 163 (EL*)	N/A	Vertical et eye level
UL 24480	**7:00 – 16:00**	≥ 2 hours, morning if not full period	≥ 0.30	Comply with WELL criteria listed above to	N/A	≥ 500	Vertical et eye level

Standard or publication	Temporal pattern		Metric				Location
	Timing	**Duration**	**CS**	**EML**	**M-EDI (lx)**	**Photopic ill. (lx)**	
				achieve 1 or 3 points			
	17:00 – 19:00	During full period	≤ 0.20	N/A	N/A	N/A	
	20:00 – 07:00	During full period	≤ 0.10	N/A	N/A	N/A	
Brown et al.	**6:00 – 19:00**	During full period			≥ 250		Vertical et eye level
	19:00 -22:00 (3 hours before bed)				≤ 10		
	22:00 - (Night-time)				≤ 1		

The melanopic over photopic ratio (M/P) is also commonly used to indicate the melanopic and photopic "content" of the spectral power distribution of a light source. The software ALFA provides the following thresholds for M/P ratios of light sources:

- M/P < 0.35 : a blue-depleted light source with calming effect
- 0.35 ≤ M/P ≤ 0.9 : A neutral light source, neither calming nor alerting
- M/P > 0.9 : a blue-enriched light source promoting alertness

In office spaces, light should promote alertness during mornings. At AT Bartenbach, electric lighting set at 5000 K delivered 138 EML at Eh = 500 lx, well below the 842 EML (Eh = 1647 lx) and 1588 EML (Eh = 901 lx) provided by midday daylighting during overcast and sunny sky day. The spectral composition of daylight is also such that the alerting effect of daylight is much stronger than that from electric lighting, with M/P equal to 0.946 (sunny), 0.935 (overcast), and 0.726 (electric lighting).

At SE TheSpark, electric lighting during nights could actually steer circadian response going from 1178 EML (M/P = 0.97) of the boost scene (6200 K, highest Eh) to 328 EML (M/P = 0.51) of the lounge scene, when set at lowest Eh at 2300 K. However, daylight during a clear sky day provided much stronger illumination, outdoing the effect of electric lighting (from 5803 EML, M/P = 1.00 to 4772 EML, M/P = 0.95 for the two scenes). The occupants self-reported an increased alertness during the morning, and the indirect proportionality between sleepiness with illuminance levels and CCT, as measured by wrist-worn light loggers, was quite evident. Although these findings suggest that integrative lighting can support circadian entrainment, the data is way too little – and the real life setting too uncontrolled – to make any major claim.

At DE IKEAKaarst, M/P ratios for mixed daylight and electric lighting (integrative lighting in the Home Decoration department) were measured during an afternoon at the beginning of March. They were constantly higher than 0.9 for views where daylight could reach. When integrative lighting also provided illumination, its contribution was small enough for any difference in the measured M/P ratios to be identified. Considering the levels of illumination provided by daylight alone, it can be argued that electric lighting in these offices may be used to steer circadian response through the day, only during some overcast days in winters.

During a day with partially overcast sky, the measured M-EDI in IT AbaziaSanLorenzo varied between 89 and 346 lx, at the eye of an office employee sitting 9:00 – 17:00 at the office, with M-EDI as high as 276 lx just before leaving the office at 17:00. The electric lighting system, which is designed to deliver 500 lx of photopic illuminance at the desk, could reach M-EDI higher than 100 lx only at its highest intensity level with CCT at 2700 K and 4000 K settings.

The system installed in DK PsychiatricH provided target values of both CS and M-EDI during night time, in both the "day" and "night" settings. However, the electric lighting could not provide sufficient circadian contribution during the day if daylight was not included; as CS was always lower than 0.1 and M-EDI lower than 50 lx for any of the settings and tested views. Similar numbers were found for the integrative lighting system at DK Rehab; however, in this case, a "light therapy" setting, delivering 5500 K and Eh = 430 lx, was able to reach CS > 0.3 and M-EDI > 200 lx without daylight (Figure 5). In this case, there was also some evidence that the integrative lighting system improved the sleep-wake cycles of patients, although the evidence could not be conclusive, given the limitations of the study.

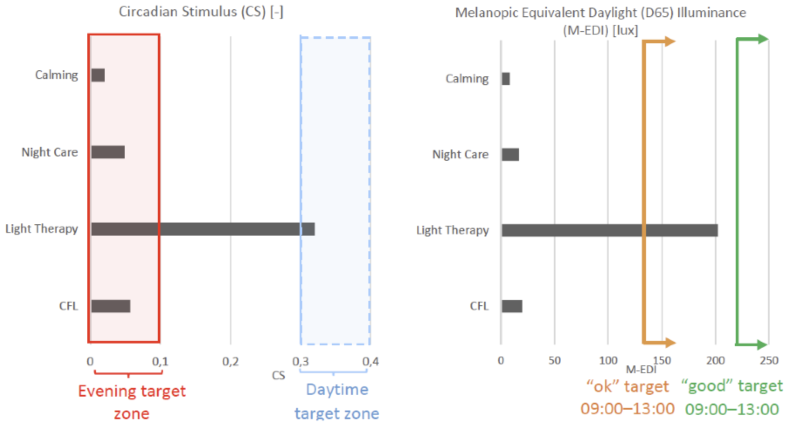


Figure 5. Measured CS and M-EDI and their relative benchmarks. Case study: DK Rehab.

CS and M-EDI measurements for daylight only performed at working stations at DK Navitas were on close to target for the central hours of the day during the January, 21st; a quite impressive result, considering day length and available daylight Aarhus (56.16°N, 10.22°E) at that time of the year. CS and M-EDI increase substantially when light from VDT is accounted. This must be considered in future design, as office work is today conducted almost exclusively in front of screens.

A well-balanced circadian lighting design should guarantee high M-EDI, CS, EML, or M/P during daytime, but should also lower levels of lighting while approaching evening, see Table 6. This is easier to be achieved in office spaces, which are occupied typically until 17:00, but harder in residence-like spaces. In the elderly residence BE Stephenson, for example, target values were critical to be achieved during early mornings and evenings. Daylighting provided low stimulation in the bedroom during the morning (CS = 0.02, 12 EML), and excessive stimulation during evenings at the dining room (CS = 0.23, 120 EML). The evening case suggests that providing more daylight is not always the correct solution towards designing circadian lighting, just as is the case for traditional "visual" lighting design. The integrated design should also consider the need of shading daylight at times, so as to achieve the circadian goals.

Shading devices are designed to increase visual comfort, e.g. reducing glare, but this may conflict with non-visual requirements. Densely woven roller shades minimized discomfort glare, but, potentially, generated lower circadian stimuli than venetian blinds in US DualZoneShade and US NewYorkCity.

During daytime, daylight seems superior to electric lighting system since it provides a naturally blue-enriched lighting and it is freely delivered with high level of illuminances. During late afternoon, circadian stimulus from daylight may be excessive, if the targets in Table 6 are to be met. But currently there are no advanced solutions for daylight control with respect to circadian requirements. Glazing and shadings are still designed for visual requirements only. While electric lighting has seen a real development towards circadian lighting, this cannot be said for daylighting solutions.

During heavily overcast winter days, especially at high latitudes, integrative lighting might successfully compensate for the lack of daylight. However, the lighting system should deliver high level of illumination, typically higher than what is normally required by traditional visual lighting design (e.g. 500 lx on the working space). This brings to the next question: are there any energy concerns for integrative lighting? The question is discussed in the next subchapter.

3.2.2 Risk for energy rebound with integrative lighting

The lighting energy demand in this collection of case studies was generally very low, around 5 kWh/m². This was achieved with a combination of good integration of daylight with controls, and a wide adoption of efficient LED light sources. The design of projects in this collection was based on traditional lighting design principles, where the visual requirements of occupants are considered; typically, this translates to providing adequate illuminance on the horizontal task plane (e.g., 500 lx for offices). However, this may not be sufficient towards satisfying their non-visual requirements. Figure 6 illustrates the measured photopic and melanopic stimuli for two electric lighting settings at AT Bartenbach. The lighting design of this office space targets visual requirements, with Eh = 500 lx on the desk. This results in Ev = 190 lx at eye position, which is barely 138 EML for the blue-enriched lighting provided by the electric lighting system, well below the 180 EML requirement given by WELL v2.0 for integrated daylighting and lighting systems, and below even the WELL v2.0 requirement for 1 credit in case of electric lighting only.

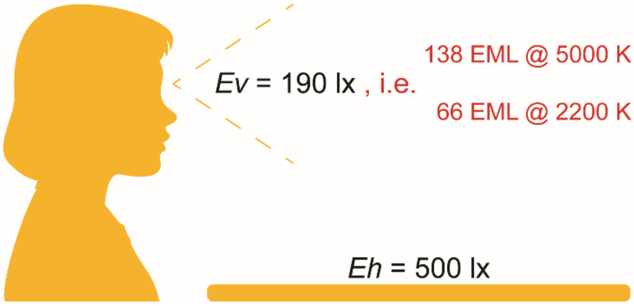


Figure 6. Horizontal (Eh), vertical (Ev) photopic illuminance, and Equivalent Melanopic Lux measured for two electric lighting settings at AT Bartenbach case study. Design adapted from abstract vector created by macrovector - www.freepik.com

One solution could be to adopt light sources with even higher blue components, but this would result in very high CCT, probably above 6500 K, which is usually discouraged. The alternative is to provide more illuminance on the vertical plane by:

- design lighting so that lighting is more homogenously distributed between the vertical and horizontal plane, or
- increase the luminous flux from luminaires.

The latter choice seems to be more common, according to this collection of case studies. In the hypothesis of a direct proportionality between absorbed power for lighting, Eh, Ev, and EML, this would mean that Eh should be raised to 870 lx for reaching 240 EML at 5000 K, which is necessary in order to achieve 3 credits for electric lighting in WELL v2.0. In other terms, this corresponds to a 74% increase in absorbed power, if daylight is not included in the design.

At BE Stephenson, in addition to changing light sources, the horizontal plane illuminance was raised from 12 to 357 lx to achieve non-visual targets in the morning. While whether the initial 12 lx was sufficient even from the perspective of visual requirements is worth discussing, it is undeniable that illumination was largely increased for non-visual requirements. At DK Rehab, the “light therapy” setting could achieve daytime non-visual targets by delivering Eh of 430 lx, as compared to Eh of 300 lx recommended for that type of space. None of the light settings of IT AbaziaSanLorenzo reached daytime M-EDI ≥ 250 lx, since the system was designed to deliver Eh of 500 lx on the task area. Assuming again a direct proportionality between Eh and M-EDI, the lighting system should deliver Eh of at least 658, lx to reach a 250lx M-EDI, and this would happen for the sole 4000 K full luminous output setting.

These hypotheses are confirmed by the SE TheSpark case study, which is instead a project aiming at non-visual requirements from the beginning. In this case, horizontal illuminances as high as 1300 lx were measured on the task area for some of the settings. While the system could effectively reach non-visual targets, the calculated LENI was as high 22.43 kWh/m²y, slightly above the present benchmark, and well above the energy performance levels of many of the other case studies. It should also be noted, that the LED lighting used in this project had a relatively low luminous efficacy, of about 88 lm/W, as compared to the ordinary luminous efficacy of current commercial LED modules at about 100-120 lm/W. Low efficacy of LED modules for integrative lighting was also observed in other case studies, e.g. 76 lm/W for IT AbaziaSanLorenzo. One hypothesis is that producers of integrative lighting systems focus more on spectral power distribution of the light source, somewhat at the expense of energy efficiency. Also, red-shifted lighting with low CCT is intrinsically less efficient than blue-enriched lighting, which could also explain an overall lower luminous efficacy. However, the case studies did not provide evidence to support this claim.

In conclusion, the risk of energy rebound linked to a wider large-scale adoption of integrative lighting is quite evident. In retrofit projects, this rebound could potentially offset any gain from the adoption of efficient LED light sources. The energy rebound is arguably linked to the fact that circadian lighting design is still an evolving discipline, and the risk could be minimized over the next years, given the following:

- standards shift their design focus from horizontal, to both horizontal and vertical planes, so that visual and non-visual requirements are balanced in the most energy efficient way;
- designers are sufficiently trained to understand the often conflicting requirements for visual and non-visual lighting design, for different space and use typologies;
- designers are provided with tools, e.g. software, capable of handling circadian lighting design, for both daylighting and electric lighting, so that lighting systems can be sized with daylight harvesting even for non-visual requirements;
- manufacturers improve light sources, both spectrally and energetically.

3.3 Daylighting and view out

3.3.1 Quality of view out

View out is a huge (and free) attribute towards improving lighting quality and user wellbeing. The occupant surveys suggest that view out plays a key role in the determining the quality of the integrated project. Appropriateness of the view out is evaluated in both “quantitative” and “qualitative” terms. Occupants seem to care about both these aspects, of how much they can see and what they can see. However, there were few systematic evaluations of view between case studies, supporting the idea that robust methods for view evaluation are still missing. The procedure provided by EN17037:2018 possibly represents the only standardized method for evaluating view, in this selection of case studies.

The aesthetic value of a view must be factored-in with view-quality. At DE IKEAKaarst, shop visitors have spontaneously reported that the view out contributed towards improving the shop’s atmosphere; while some complained about its quality, claiming that a parking lot was a bad choice of view since more beautiful options were available around the building. At BR ForumSoPinto, application of solar control film drastically reduced the glazing’s visual transmittance, which certainly impacted the daylight provision, but had also some effects on the view out. Two-third of occupants were either neutral or did not appreciate the view out, despite the generous opening size. In such cases, it is possible that the view out did not offer a variety of layers as defined by EN17037:2018, but the alternative, that solar films altered the naturalness of the view out, is also a possibility. According to US PortlandEC, it seems that occupants are concerned about reduction in daylight when using electrochromic (EC) glazing, but they do appreciate EC as it allows for view out. Interestingly, the monitoring team could not integrate darkest tint in the automatic switching options, since it was least appreciated by the occupants.

The quality of view can also improve a visual environment. View out seemed to be one of the determinants for occupants’ satisfaction with daylight in the BR MME case study. In some cases, view out can even reduce complaints for glare, like for BR MME (Figure 7), BR UniBrasilia, US Oakland, or US PortlandEC.

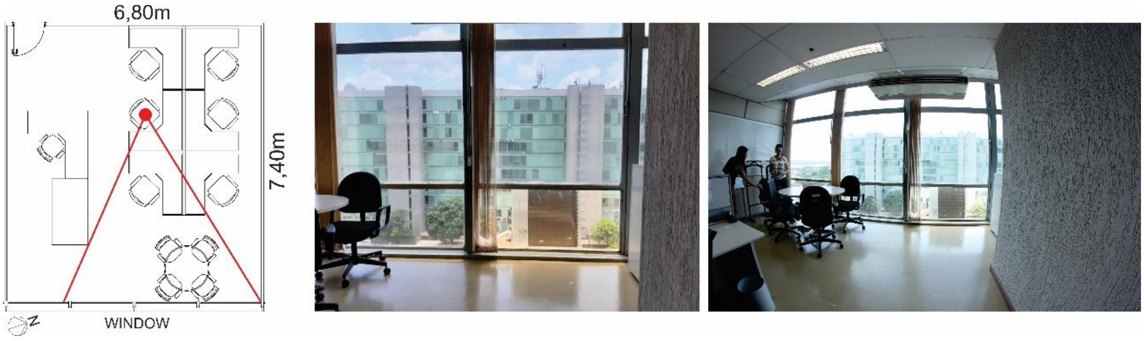


Figure 7. Evaluation of the view out for BR MME.

While the aesthetic value of a view depends on the context in which the building is located, the overall quality of the view also depends on the size of opening, and the relative position of occupants.

In some cases, this is just impractical, like in older buildings with thick walls, e.g. IT AbaziaSanLorenzo. In such cases, even sight angles were dramatically reduced due to the presence of thick walls, but occupants did appreciate what was qualitatively possible to see. In this case, the quality of view out was rated as “minimum” according to EN17037, but it raises questions on the appropriateness of the ranking criteria for such historical buildings.

In other cases, increasing the view towards the outside brings along additional issues, such as privacy, over-illumination, and excessive solar gains or thermal losses. This merits careful planning coupled with use of shading devices.

3.3.2 Internal shadings

The case studies provided some interesting solutions shich deal with the interplay between illumination needs and view out. In AU Aecom, over two-third of occupants were satisfied with their view provided by large windows and individually controllable shadings, and even larger appreciation (80%) was found for BR MME. US NewYorkCity, US DualZoneShade, and US PortlandEC used automated shade or window controls to preserve view and daylight, while controlling glare. The internal shading elements can complement and help to make effective all the “macro” strategies in the buildings (orientation, form, external protection) or even compensate when these macro strategies did not work so well. At ES IDOM – a building immersed in a nice naturalistic context, shadings were rarely used despite the large openings, since the façade was oriented towards the north. Occupants were happy to be able to see the sky, which somewhat connected to the general concept of view out. Given the above, development of advanced solutions for internal shading devices or glazing is very welcome.

Efficient shading elements are important, especially in hot climates, where the challenge is to retain view while also protecting from both solar gains and glare. The BR ForumSoPinto is one such example – while the original design protected from direct solar radiation, dark control films were added for privacy issues, which drastically reduced the daylight levels. The case of ES IDOM also demonstrates such an issue, with internal roller shades that compensate insufficient solar protection from micro-perforated facades. The US DualZoneShade showed significant improvements in term of admission of daylight and access to view out, but also higher cooling loads when compared to traditional venetian blinds.

3.3.3 Multi-zone shadings

The dual role of openings – providing illumination and connecting to the outdoors – is well recognized. Unsurprisingly, at least three case studies directly addressed this aspect by using a dual-zone shading approach. This approach consists of vertically dividing the opening in two parts. The lower part set nearly at eye height, is used for both: illumination and view out, and consists typically of regular fenestration systems. The upper part serves for illumination only, mostly for the deeper parts of the room, and it may consists of different technological solutions. In US DualZoneShade, the lower part of large openings was provided with manual roller shades, while the upper part had automatic curved louvres, which optimized light redirection in the room (Figure 8). Survey responses indicated that the system provided a more comfortable and higher quality visual environment (i.e., less glare, more view) compared to the existing vertical blinds. More occupants appreciated the view with this new system. However, occupants seated deeper in the room reported lower satisfaction with the view, since their view was blocked by louvres in the upper part, and by walls in the lower part. The two solutions tested at IBP Fraunhofer in Stuttgart, DE IBP_LED and DE IBP_Daylight, used a similar Dual Zone approach designed in two different ways. In the first case, upper lighting was provided by micro-optical structures illuminated by LEDs, aimed mostly at reducing contrasts, while, in the second, upper lighting was provided by daylight filtering through a Plexiglas panel. In both cases, the lower part of the opening consisted of a traditional window with automatic venetian blinds, whereas the upper part had an applied innovation. Although specific surveys on view out were not conducted, the occupants indicated that they appreciated the atmosphere in the two test rooms more, as compared to an identical room with traditional windows only. Finally, the side windows of AT Bartenbach are provided with external static deflecting louvres on the highest part of the window, a solution which provides extra illumination from an opening located higher up, which also serves the function of redirecting incident daylight towards the deeper parts of the room.

Figure 8. Indoor (left) and outdoor (right) view of the dual-zone shades at US DualZoneShade, Oakland, CA.

3.3.4 Bringing daylight deep in the space

Traditional side-openings may not provide sufficient daylighting in deeper spaces. To address this, a multi-zone shadings approach with top openings is capable of supporting deeper daylight penetration. Skylight is another possible solution for bringing daylight deeper into spaces. It has also been illustrated that this can be enhanced with external louvres (AT Bartenbach), where a tilted top-lighting with internal glare protection was able to guarantee daylight factor higher than 3% along the whole room depth (6.5 m) (Figure 9), resulting in a Daylight Autonomy at 500 lx of 82%. The atrium of DE DIAL is provided with skylights, which when combined with peripheral sidelight windows at the floor plan, guarantees daylight provision in the whole space: at the perimeter as well as at the core of the building.

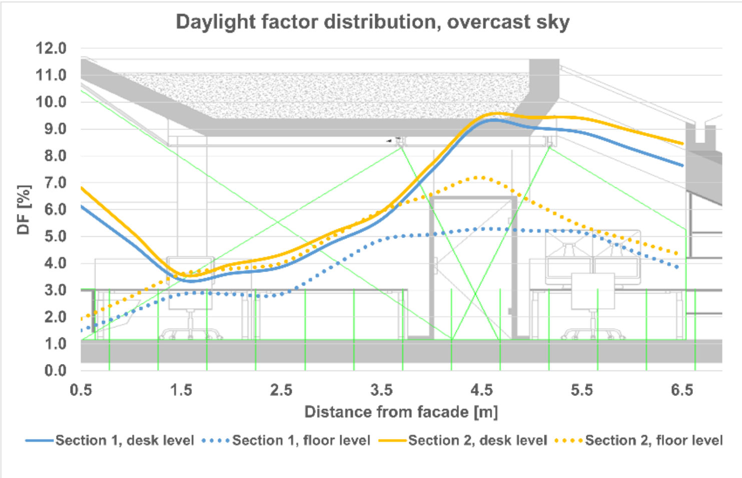


Figure 9. Daylight Factor is kept high across the room thanks to a wise combination of vertical and horizontal openings (AT Bartenbach).

Tubular daylighting systems can also support daylight penetration. At CN CABR, vertical pipes brought daylight at the center of a large conference room, which was also provided with sidelit windows on two sides, protected by horizontal blinds. The solution resulted in 0.73 average daylight factor and high uniformity (U_0 = 0.4). As vertical pipes might be difficult to implement in real buildings, NO Norconsult used a horizontal solution, with a straight pipe facing south. The pipe carried daylight in the deepest part of a two-occupants office room, guaranteeing almost identical daylight illuminance level for the sitting position close to the window as the one located in deepest part of the room. The solution, combined with a daylight harvesting, contributed significantly towards lowering the lighting energy use.

3.4 User at the centre

The lighting and daylighting projects must be designed, keeping the user at the centre. DE DIAL and AT Bartenbach are examples of user-centered design, where the system is designed with high granularity; and individual preferences are considered via individually adjustable settings. It is well-known that occupants prefer to have control over environmental cues, so it is perhaps unsurprisingly that this theme is recurring in the case studies.

In the two Australian case studies (AU Aurecon and AU AECOM), manual control were given for shading after redesign, and this resulted in very high appreciation of the systems, *in retrospect*. Allowing control and override increases occupant satisfaction, whereas not allowing control or override can increase dissatisfaction and friction; as is evident in US PortlandEC, SE TheSpark, DK PsychiatricH, or BR MME. Therefore, solutions should include automation to reach the energy requirements, but also manual override to minimize dissatisfaction and, eventually, sabotage. For example, US PortlandEC includes an automatic change of tints for the electrochromic glazing, but this includes only the clearer tints; and the darker tints can only be manually selected by the occupant. Monitoring showed that the dark tint was rarely chosen, and occupants were largely satisfied with the system.

Clearly, a wide adoption of manual override control creates conflicting interests: whether the focus should be on energy savings, or on user override at any cost? For example, at DK Navitas the illuminance set points were increased by some occupants. One solution to reduce these conflicting interests would be by raising awareness among occupants. At IT AbaziaSanLorenzo, the occupants were informed on the functioning of lighting and shading systems, as well as the implications of their energy-unaware behaviors. At IT AbaziaSanLorenzo, the occupants were informed on the functioning of lighting and shading, as well as on the implication of energy unaware behaviors. This resulted in a very limited use of electric lighting, a maximization of daylighting, and high satisfaction, despite the system being fully manual.

Occupant’s training and education is of outmost importance, even beyond energy saving goals. The growing possibility with lighting and shading allows for a wide range of setting possibilities at the user’s end: switching, dimming, tuning color, opening, or moving shadings, etc. As a results, occupants may a) have difficulties in understanding overwhelming control interfaces with many settings, and b) may not understand why so many options are provided. With respect to control interfaces, DK PsychiatricH was provided with a relatively simple switch interface, but without labels, making it confusing to use. More intuitive was the digital interface proposed by DE DIAL. In this case, icons described quite clearly how pressing each button would affect the lighting and shading. In some cases, a manual override is provided, which however is not readily available to the occupant. At BR MME, the lighting system is overridden by a complex switching interface located at corridor; but occupants are asked to submit a request to the building management for changing lighting settings. This kind of approach distances an integrated project from an occupant. Even if a manual override is provided, this creates the problem of “ownership”, and the occupant does not feel at the center anymore. On the contrary, IT AbaziaSanLorenzo and AU Aurecon offer hand-held remote controllers, readily available to the occupant. In the latter case of AU Aurecon, the controllers are provided with various buttons and text, possibly making the interface less tangible in respect to the one proposed in DE DIAL.

In conclusion, manual controls and overrides are appreciated and wisely used, if the system is accessible to a user. To increase the accessibility of these systems, designers are requested to train and inform users on their functioning. Additionally, there is a strong need for higher *availability* and *tangibility* of control interface. This is the only way for designers to guarantee optimal performance from the integrated systems.

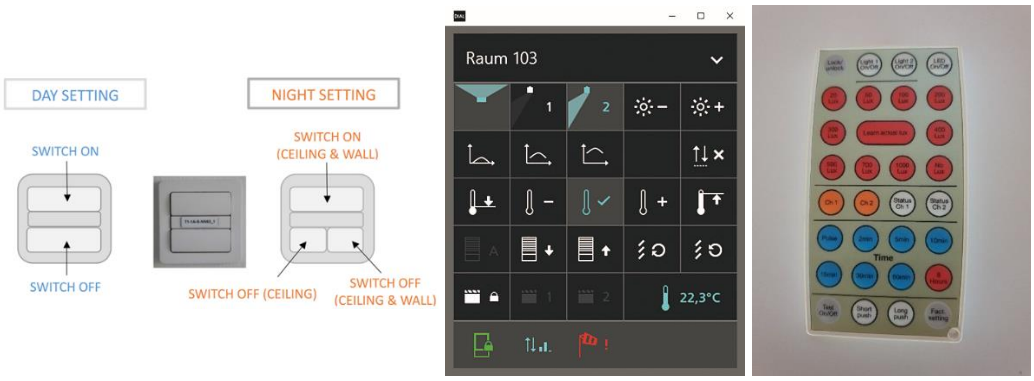


Figure 10. Control interfaces used at (left to right): DK PsychiatricH, DE DIAL, AU Aurecon.

Putting a user at the center also means explaining, as to why some of the solutions are adopted. For example, just installing integrative lighting does not guarantee the system's user-centeredness; people should also know what integrative lighting is, and also the benefits of adopting them. This would increase acceptance and reduce complaints (SE TheSpark).

Finally, keeping a user at the center also means potentially re-commissioning systems following occupants' feedback. For example, system recommissioning to incorporate a slower shift between lighting scenes is recommended at DK Rehab, while slow dimming which allows adaptation is one of the strengths of DE DIAL. This brings us to the following lesson learned: concerning the importance of planning for monitoring and verification (M&V), and, eventually, recommissioning.

3.5 M&V and recommissioning are keys for success

There are no such things like a perfectly integrated design; and each project has its own story, its own requirements, its own shortcomings, and its own solutions; even in this collection of case studies. Since solutions are new and unique, each project is prone to errors at the beginning. This collection of case studies teaches that M&V is key towards improving and optimizing a project.

The US SoSanFrancisco is a case study heavily based on the importance of M&V. The design team relied on a rich set of sources to inform the design. They collected data from full-scale mockups (Figure 11), conducted observations, had weekly collaborative meetings with all the stakeholders involved in the project and with domain experts. They developed a new control system for lighting but optimized it on a trial-and-error process before going to the final design. They used a similar approach for the design of the shades. They managed to reduce the average daily LPD (6 am to 6 pm) from 5.52 W/m^2 (no controls) to 1.4 W/m^2. The proof-of-concept was not just applied to the real building, rather they planned for follow up monitoring in the real building. The real application informed further decisions. For example, a traditional dimmable LED system was chosen over an integrative system, as daylight provision was deemed sufficient to provide enough circadian stimulus. Occupants were trained to the new system before occupancy. The facility management was invited to receive feedback from occupants, which translated to further fine tuning of the lighting and shading system. All in all, the design did not stop at procurement and construction. The design was meticulously updated with feedback even after occupancy, generating a virtual circle of M&V and improvement, which resulted in a real exemplary integrated project.

Figure 11. The mockup used at US SoSanFrancisco to fine-tune the final integrated design for the actual building.

It is common to deliver projects without M&V plans; a potentially efficient integrated system at BR MME failed in reaching design goals, since there was a lack of appropriate technical support, in addition to poor user-training. IN contrast, CN CABR provided a similar system that delivered a much higher performance, since they had in-house technical staff, who could implement changes to the system over time. Similarly, although not expressively mentioned, the project at AT Bartenbach showed an all-round outstanding performance for all the tested aspects (energy, visual, non-visual, and user perspective); this project has in-house expertise in lighting and daylighting, which most likely contributed to a continuously improving process of the project. One way to minimize the need to recommissioning is, of course, good commissioning. This is actualized with an informed design and proper training of stakeholders. The US NewYorkCity included an educational series with interactive sessions aimed at training design professionals, owners, installers, and facility manager. The project was a real success in terms of both energy saving and occupants' appreciation (e.g., only sixteen requests in one year to override automatic shades), and it is safe enough to bestow part of the success to the educational series.

The monitoring of case studies shows also that Post-Occupancy Evaluations helps identify scopes of improvement, even in the best conceived projects. At DK PsychiatricH and DK Rehab, the poor tangibility of controls emerged only during POE. During the initial visit to DE IKEAKaarst, the monitoring team found a DHS sensor taped, as it lost its calibration after furniture re-arrangement, and caused failures in scheduling human-centric lighting system in their home department. Both issues were eventually investigated and solved by the building management. The two Australian case studies adopted manual shading devices after complaints on the automatic ones.

4 Discussion

Taken all together, these lessons learned provide an understanding of the present status of integrated daylighting and lighting design, while also offering an indication of what could be the way forward in this field. This chapter discusses such aspects and their implications for future designs.

4.1 What is driving innovation in lighting technology?

The answer is health and well-being. Alertness and sleep quality are affected by spectral composition and intensity of light over the course of the day and night. Integrative lighting is possibly the most significant innovation in this domain in recent years. Also, views to the outdoors support human health, and views can serve restorative functions. Perhaps unsurprisingly, view out was considered in many of the case studies. In both areas, the body of knowledge is growing, and innovation will follow.

4.2 What are the new innovations in lighting technology?

4.2.1 Lighting

The case studies provided an overview of what can be the lighting of tomorrow. “High resolution” control over LED lighting includes fixture by fixture control (spatially resolved), individual controls, spectral and intensity control versus time, dimmable intensity control are the keywords today. These type of controls are becoming increasingly common with the market uptake of LEDs, possibly due to much lower incremental cost for dimming compared to fluorescent lighting.

Spectral control (integrative lighting) involves change from CCT of 4000-6300K in morning hours (e.g., 8:00 to 12:00) to 2300-2700K (e.g., 16:00 to 19:00 am), indicatively. Intensity control may involve change from 950-1500 lx in the morning to 300-500 lx for all other hours in offices, indicatively. Future systems may focus more on the SPD of light sources, rather than CCT only, for better circadian optimization. Non-visual requirements also call for a higher illumination at eye position. Future systems should deal with the risk of energy rebound by using high performance LEDs, and must optimize integrated daylight and lighting design towards supporting both, the visual and non-visual requirements.

4.2.2 Daylighting

In these case studies, we observed only incremental changes in design strategies and technologies for shading, solar control and daylight-redirection. Stark changes were not evident in the way these systems are designed in supporting health-related requirements, e.g., intensity control of daylight vs time of day. This provides a scope for future innovation.

The most interesting daylighting solutions are perhaps those showing ways to increase daylight across larger portions of the floor-space: horizontal and vertical tubular skylights (CN CABR and NO Norconsult), wise placement of skylight (AT Bartenbach), or subdivision of windows with dedicated areas for illumination and view-out (DE IBP_LED, DE IBP_Daylight, US DualZoneShade).

Despite the incremental changes in technology, aspects of daylighting and view out are increasingly valued in projects. These aspects have now emancipated from the domain of office buildings design, and have merged with the domain of spaces dominated by electric-lighting, such as the retail sector (DE IKEAKaarst).

4.2.3 Integration of daylighting and electric lighting

Granular and individual controls are certainly innovative. Personal control may be achieved via mobile phone app (e.g. DE DIAL) or it could be combined with central control. Given the new range of possibilities for controlling lighting and shading, the control interface may become quite complicated (DE DIAL, AU Aurecon). More work should be devoted in the development of interface usability.

There is no clear evidence of the need for bidirectional communication between daylight and electric lighting control systems, e.g. via common communication protocols. Integrated solutions seemed to work fine as long as the design and planning of daylighting and electric lighting is integrated, i.e. if there is communication between professionals, and if M&V plans are implemented.

There is instead a clear gap in the integration of daylighting with electric lighting, when designing a circadian lighting system. New knowledge and software tools may be able to improve the designs, so that the integrated projects may be able to optimize daylighting with electric lighting, to guarantee the visual and non-visual requirements, and also lower the energy use.

4.3 Towards a definition of integration

The inclusion in the collection of case studies implied that each case study attempted provision of both daylighting and electric lighting in an integrated manner. The meaning of "integration", however, was interpreted differently in different projects.

In recent past, integration was interpreted as energy saving, typically by lowering electric lighting loads to their minimum while maximizing daylight provision. Such integrated projects supported good visibility and not much more, in a mere "photometric" perspective. These designs were based on few photometric requirements, typically horizontal illuminances and, at most, luminance ratios or contrasts. This approach of the recent past is rarely seen in this collection of case studies. Instead, health and comfort questions related to lighting – alertness, sleep quality, views to the outdoors – prevail in the collection, and those questions arguably are – and will be – the drivers of innovation in (day)lighting technology. Health and comfort questions suggest that integration must go beyond visibility, and an integrated project must also address psychobiological questions. In addition, some case studies demonstrate that integration, with their extreme daylight exploitation, brings up other questions besides lighting: thermal comfort, heating, and cooling loads should also be included in the big picture.

So, today, integration moved:

a) from a strict "photometric" definition to a wider "spectral" one;
b) from "allowing visibility" to "allow for visibility, well-being, comfort and restoration" e.g., via quality views;
c) from a "space-centred approach" to a "user-centred approach", where lighting is designed for the individual (e.g., it is more and more common to measure lighting vertically at eye position) rather than for the workspace, typically with grid-based measurements;
d) from "decreasing energy for lighting" to "decreasing the overall energy use for lighting, heating, and cooling, while increasing visual and thermal comfort".

Therefore, integration can then be defined today as "*the combined use of daylighting and lighting (and their controls) to increase visibility, well-being, comfort, and restoration of individuals, while saving energy in buildings*".

The implications of this wider definition are that designers should be equipped with new tools and methodologies to address all the design goals of integrated projects.

5 Conclusions

This report presented the monitoring of twenty-five case studies consisting of integrated daylighting and lighting projects. The case studies were monitored under a common framework. Several overall lessons learned were presented in this document. The report concludes that:

- The energy demand for lighting is drastically reducing thanks to the combined effect of more efficient light sources, advances in controls, and raised awareness about the integration of daylighting and electric lighting. Annual lighting energy use as low as 3-4 kWh/m^{2}y are now possible with wide adoption and current technology. Recommissioning and M&V are central to achieve the energy results.
- Integrative lighting is currently driving the innovation in lighting technology and its wider implementation is expected as knowledge in the field of non-visual requirement for lighting expands. With the endless advancements in LED technology, when controls have reached previously unprecedented capabilities, electric lighting will be able to support non-visual requirements when daylight cannot suffice.
- However, integrative lighting is currently little integrated with daylighting in practice. There is a lack of tools and knowledge for designers to implement daylight in integrative lighting schemes.
- Consequently, integrative lighting may result in significant energy rebound. Integrative lighting is often designed disregarding daylight; electric lighting loads increase to reach appropriate lighting levels at eye during daytime, when daylight is more available.
- Daylighting integration is of outmost importance for achieving quality beyond energy saving. View out has been proven of primary relevance for occupants' satisfaction with the project.
- Integrated design is facing new challenges: from aspects of energy and visibility, questions like comfort and health need now to be answered. The design of the integrated project is more and more tailored on the individual needs, rather than only on the space use.

6 The case studies

Lighting at the heart of an integrated building control system

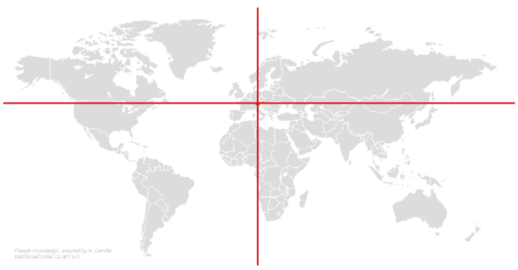
Integrated lighting solutions enable biologically active lighting in the glare-free Living Lab in the Bartenbach R&D building

In the Bartenbach R&D building a high level of daylight integration is realized while maintaining glare and heat protection. In combination with workstation-zoned LED lighting with color temperature and intensity control adapted to the time of day, the occupants experience a lighting environment that provides both visual comfort and biologically activating effects satisfying individual preferences. To exploit the energy effects of integral concepts, the heating and ventilation trades are also controlled in addition to the daylight and artificial lighting trades.

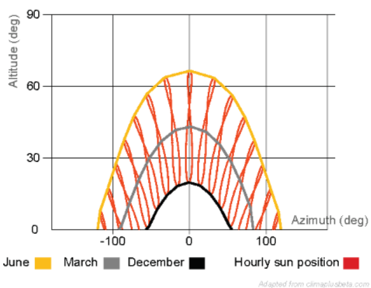
Figure 1. Careful daylighting design is integrated with CCT tuning at the Bartenbach headquarter in Aldrans, Austria.

The project

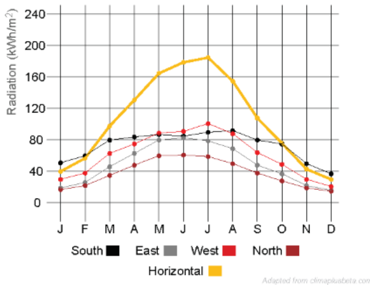
Upon entering the R&D office building of Bartenbach, the large, south facing windows together with north-oriented skylights are identified as prominent feature, ensuring a high daylight level in the office. 200 m² of office space are divided into an open-plan office, two individual offices and a meeting room (Fig. 2). To avoid disruptive effects of direct sunlight on the workplaces, external static daylight deflecting louvres are installed, the size and spacing of which were specially arranged and dimensioned for the geographical location of the building. The electrical lighting of the workplaces and transit zones is realized with a ceiling-integrated LED lighting system equipped with patented freeform surface reflectors developed by Bartenbach. With the artificial lighting, glare-free illumination of the workplaces is ensured by means of longitudinal glare control and asymmetrical beam characteristics. In addition, the luminaire arrangement provides uniform illumination of the workstations and prevents the user from shading the work surface. Via illuminance sensors and passive infrared sensors, the artificial light is automatically switched or



Location: Aldrans, Austria
47.24°, 11.46°



Sun path for
Aldrans, Austria



Global horizontal and vertical radiation for
Aldrans, Austria

IEA SHC Task 61 Subtask D

Monitored by **Sascha Hammes and David Geisler-Moroder**, Bartenbach
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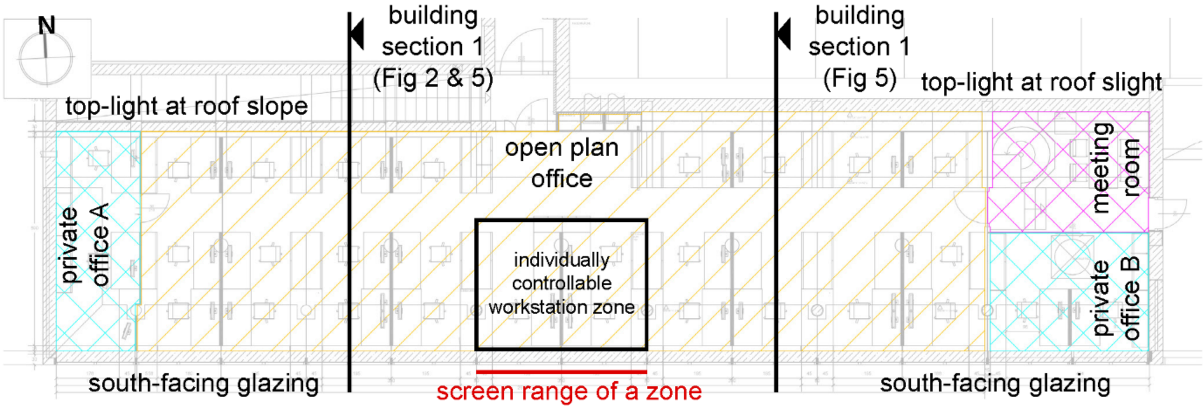

Figure 2. Floor plan of the Bartenbach R&D building.

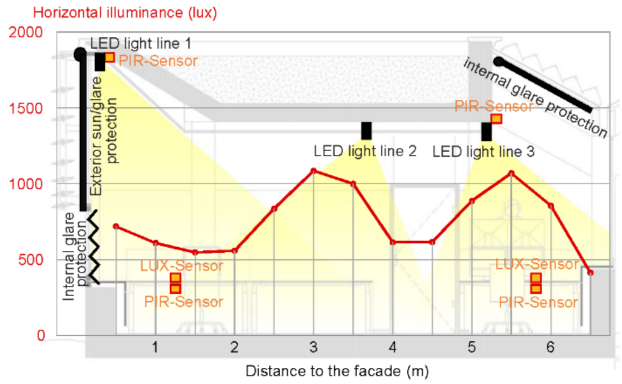

Figure 3. Position of light sensors, actuators, and maximum artificial illuminance. See Figure 2 for orientation of the office.

dimmed depending on the availability of daylight and presence. To follow individual lighting preferences, a zoning of daylight and artificial lighting systems is implemented in the open-plan office, in which the respective neighboring workplaces are interconnected to form workplace zones (Fig. 2).

To support the human circadian system, cold white light (5000 K) is used in the morning hours, which dynamically changes to warm white light (2200 K) and lower illuminance levels over the day following a predefined control curve. Figure 3 shows the maximum artificial illuminance levels depending on the room position, reachable in every color temperature between 2200 K and 5000 K. These high artificial illuminance levels allow individual preferences to be represented in the best possible way.

Monitoring

Measurement data from more than 80 sensors and the status information of the actuators are logged via the central Beckhoff building control system and converted into a data format that can be further processed. This includes, among other things, the illuminance and presence per workplace zone, information on the room climate and the dimming level of the lighting. Figure 3 shows a cross-section of the sensors and actuators relevant to lighting technology (viewing direction marked in Fig. 2). Depending on the measured variable, data acquisition is either based on a change of state or cyclically per minute. Long-term monitoring was started in March 2019. Due to the COVID-19, phases with reduced occupancy resulted. The field monitoring provides valuable insights, for additional evaluations computer simulations were performed. The building was first remodeled in Rhinoceros 3D and daylight simulations were made with Radiance through the Honeybee plugin. Among other things, daylight indicators such as daylight autonomy (DA) were evaluated. Here, an average daylight autonomy DA500 of 82 % resulted in relation to the normative minimum illuminance of 500 lx (reference time: 08:00-18:00, summertime not considered). Furthermore, potentials for increasing energy efficiency could be derived based on the collected data during post-occupancy evaluations. These findings on user-centered lighting and reduction of electric lighting demands have been published by Hammes et al. (2021a, 2021b).

Energy

The LED luminaires in the R&D office building have a connected power of 42.5 W each. Based on the logged status information for the artificial lighting system, the LENI was determined (Table 1). In relation to the normative minimum illuminance for office activities of 500 lx (EN12464-1), the office area of about 200 m² results in an energy demand per area of about 3.65 kWh/m²y. The low energy demand results from the high daylight autonomy. For the extensive sensor technology in the R&D building, including an Embedded PC as hardware for the integral building control, an energy demand of 1.09 kWh/m²y results. Without the

Table 1. LENI values: monitored and calculated benchmark.

	Monitored	Benchmark
LENI [kWh/m²y]	3.65	16.5

Table 2. Logged cumulative system interventions from Mar-Nov 2019, from 06:00-20:00.

Cumulative system interventions per year	South façade	North side
Daylight system	638	241
Artificial lighting system	315	676

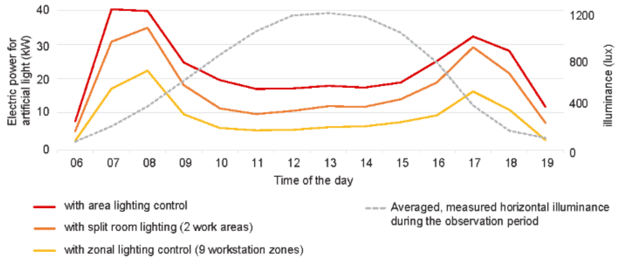

Figure 4. Comparison of the electric power for artificial light for different lighting zonings, supplemented by the averaged measured daylight-based illuminance values (data set from: 02.09. - 03.11.2020).

benefits of illuminance sensors, the benchmark energy demand per area would be about 16.5 kWh/m²y (calculated for electric light providing 500 lx when presence was detected). The influence of the daylight responsive control is therefore very important. Similar considerations apply to the influence of occupancy sensors on the energy demand of artificial lighting. The positive effects of the sensors on the energy demand therefore clearly outweigh the monitoring units' own energy demand. The users act rarely on the daylight and artificial lighting system, showing a high level of user satisfaction; however, number of interventions differs noticeably depending on the room zone (Table 2).

To test and evaluate different concepts, the effects of different room zoning were considered (control of the open-plan office as a whole; divided into 4 west-facing workstation zones and 5 east-facing workstation zones; 9 workstation zones; see Fig. 2). The results show that with greater user-centeredness, there is not only greater system acceptance, since it is possible to follow individual lighting preferences more closely, but also significant reduction of the energy demand (reduction by a factor of 2.6 from area lighting to control at the level of the workstation zones, cf. Fig. 4). In addition, data logging shows that little or no artificial lighting is required during daylight hours. The need for artificial light in the office therefore mainly occurs in the daytime marginal areas. As these times also show high user dynamics, the use of occupancy detection is of high importance in the Bartenbach R&D building to ensure energy-efficient operation.

Photometry

The office building is designed in such a way that daylight

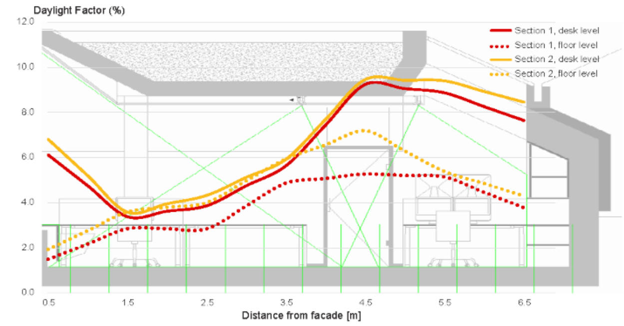

Figure 5. Distribution of Daylight Factor in the building section. Location of Section 1 and 2 is provided in Figure 2.

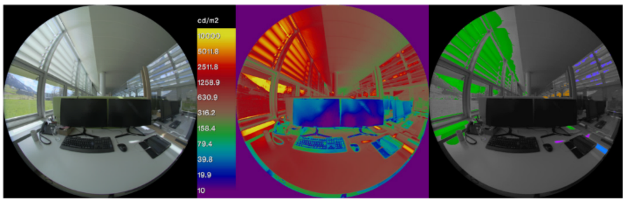

Figure 6. Representative workplace on April 8, 14:00 CEST, additional glare protection screens not activated: E_v = 2576lx, DGP = 0.316 („imperceptible glare"), maximum luminance: ca. 25.000 cd/m² in reflection at windowsill.

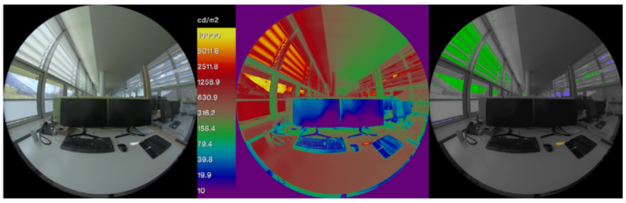

Figure 7. Representative workplace on April 8, 14:00 CEST, additional glare protection screens activated to block direct sunlight: E_v = 1898lx, DGP = 0.274 („imperceptible glare"), maximum luminance: ca. 15.000 cd/m² in bright cloud above mountain.

can be used with high efficiency, resulting in an average horizontal daylight illuminance at the workplace of over 1000 lx at lunchtime, averaged over the measurement period and across all workplaces. At the south-facing window workplaces, temporary daylight-based illuminance levels of more than 2000 lx result. To avoid disturbing effects such as glare, in addition to the external static lights, there are also external screens (south side) and internal screens (north side), which are controlled automatically with the option for manual override. The external screen on the south side is supplemented by an internal screen for the lower window area at table height that is controlled manually. Due to the high proportion of glazing in the office building, the transit zones are sufficiently illuminated with daylight between the morning and evening hours. The well daylit design results in an average daylight factor (DF) of 6 % at workstation level and of 4 % at floor level, providing sufficient illumination even under overcast skies (Fig. 5).

An evaluation of the luminance distribution at a representative workplace demonstrates the effectiveness of the installed shading systems. Even without activating the additional glare protection screens, the DGP of 0.316 predicts "imperceptible glare" (Fig.6). However, the high luminances in the reflection at the windowsill and from the uppermost part of the exterior louvers with the largest distance still can lead to visual discomfort and problems in the stable perception. In such situations the automatic control closes the exterior screen in the upper part just enough to block direct sunlight, the user can manually close the interior screens in the lower part to block out the reflections.

Fig.7 shows the resulting situation that provides a real human centered lighting situation: glare free (DGP = 0.274) and at the same time biologically active with a vertical illuminance at the eye of 1898 lx. This is confirmed by the high system acceptance and the low number of user interventions in the daylight shading system (cf. Tab. 2).

Lighting at the heart of an integrated building control system

Table 3. Measured Melanopic Lux (benchmark WELL v2: 180 EML for daylight and electric lighting).

	Daylight, sunny sky, April 16, 11:50 CEST	Daylight, overcast, April 19, 12:25 CEST	Electric light, 5000K @ 500 lx Eh	Electric light, 2200K @ 500 lx Eh
CCT	5451 K	5317 K	4095 K	2174 K
Ev	1647 lx	901 lx	190 lx	190 lx
EML	1558	842	138	66
M/P	0.946	0.935	0.726	0.347

Circadian potential

Due to the industry-specific dynamics regarding working hours, both longer working phases and working hours that lie before and after typical business hours can result. As a result, the standard use of space is from 06:00 to 20:00. This has a great influence on the well-being and productivity of building users, so daylight is also important as a regulator of circadian rhythms. Despite a high level of daylight integration, care was also taken to support the circadian rhythm of the employees through the dynamic intensity and color temperature control of the artificial light (5000 K to 2000 K), which is adapted to the time of day. The individual circadian phase was not considered for the color temperature control since zonal differences in color temperature in the open-plan architecture have a detrimental effect on visual comfort. To ensure a homogeneous appearance in the room, adjustment of the color temperature is only possible at room level. The spectral distribution was measured at the user viewpoint as shown in Fig. 6 and 7 for the different lighting situations. Table 3 shows the resulting photometric and melanopic illuminance and the derived M/P ratio. The broad range confirms the effectiveness of the human centered approach and its biological effectiveness.

"An office space that really implements Human Centric Lighting: high daylight doses in a glare-free environment"

User perspective

The high proportion of daylight combined with the user-centered design is also reflected in the perception of the lighting atmosphere. A voluntary user survey conducted in February 2016, in which 19 building users (17 male, 2 female, age: 20-60 years) participated, revealed a high level of satisfaction (Fig. 8). The uniform room illumination and high illuminance levels were recognized as such by the user respondents (bright = 95 %, uniform = 100 %). All respondents rated the lighting situation in the R&D building as very pleasant, orderly, calming, appropriate, and modern. In addition to the high proportion of daylight, the visual reference to the outside has a high relevance to

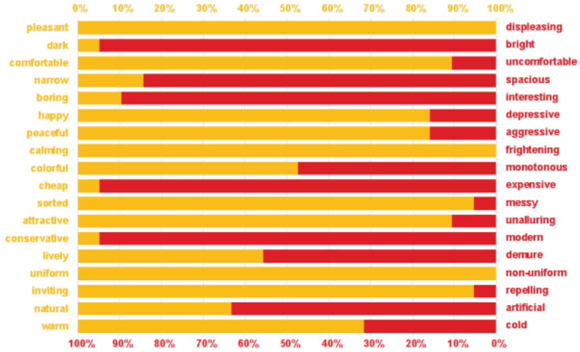

Figure 8. User survey on the lighting atmosphere in the R&D building.

user satisfaction. Another recent user survey on the R&D building and the building control system from November 2020, in which 16 building users participated, revealed that despite the high proportion of glazing, no glare occurs for the majority (approx. 80 %). This confirms the effectiveness of the glare protection concepts used. Furthermore, the control curve underlying the building control system proves to be very accurate, as the majority is satisfied with the illuminance on the work surface (approx. 80 %) and there is hardly any intervention in the automatic mode (approx. 90 %).

"In the integrated control heating and ventilation dance to the lighting's tune"

Lessons learned

By fulfilling individual lighting preferences with high illuminance levels and varying color temperatures, a positive impact on work performance and wellbeing is reached. The integrated Human-Centric-Lighting concept supports the circadian rhythms of the building occupants. The high daylight input and the use of lighting sensors for daylight-dependent artificial lighting adjustment allow to significantly reduce artificial lighting energy demands. With the ability to log and monitor a wide range of condition information in the building, post-occupancy evaluations can be used to account for user effects in the control logic that only occur after commissioning. This can reveal potential for reducing energy demand.

Further information

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Acknowledgements

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Evidence-based management to monitor and improve indoor lighting

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Queensland's first WELL platinum certified open plan office building with daylight responsive controls and active management team

Daylight responsive lighting controls, electrical lighting, user responses and the luminous conditions were evaluated in a Green Star and WELL platinum certified office building in Brisbane Australia. Combining smart technologies with POE surveys delivered practical solutions to mitigate issues of glare and improve individual control.

The project

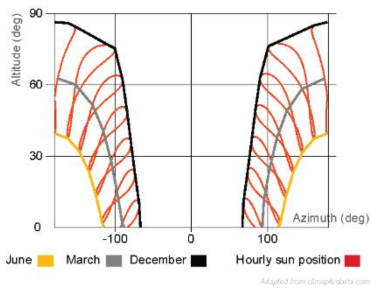
Aurecon Brisbane is the largest and tallest 9-storey engineered timber building in Australia (Fig. 1). It is a 6-Star accredited Green and WELL platinum certified commercial office building designed by Aurecon, Bates Smart and Woods Bagot. The open plan office adopts a unique nomadic work style for occupants to choose and change where they work in the office to enhance multi-disciplinary collaboration and company culture. As the anchor tenant, Aurecon monitors the indoor lighting environment using Post-Occupancy Evaluations (POEs) to fine-tune lighting energy efficiency, visual comfort, and occupant satisfaction. Using an integrated approach, daylight responsive ceiling mounted occupancy sensors and photosensors detect optimal daylighting levels, to offset linear LED luminaires via automated dimming control (Fig 2). Manually adjustable blind shades are used for glare control and to allow occupants individual controllability of daylighting levels.

Figure 1. Aurecon's open plan office located in Brisbane, Australia. Image sourced from: https://www.archdaily.com/906495/the-tallest-timber-tower-in-australia-opens-in-brisbane

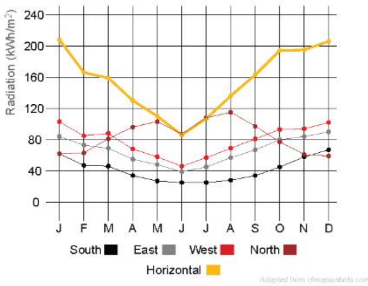
Monitoring

An initial site investigation was conducted in April 2019 and proceeded with a four-week period of data collection in May 2019 and subsequently in May 2021 across a 2-day period (approaching winter solstice). Data collection was carried out on levels 2 and 4. A POE framework

Location: Brisbane, Queensland, Australia
27° 27' 7.884" S, 153° 2' 1.95" E



Sun path for
Brisbane, Queensland, Australia



Global horizontal and vertical radiation for
Brisbane, Queensland, Australia

IEA SHC Task 61 Subtask D
Monitored by **Kieu Pham and Veronica Garcia-Hansen**
More info **Prof Veronica Garcia-Hansen,** Queensland University of Technology,
v.garciahansen@qut.edu.au

Figure 2. (Left) Inside the open plan office at Aurecon Brisbane. (Right) Hand-held remote presence sensor controller (Servodan 41-926) to override automated dimming or turn luminaires on-off.

was developed to collect objective and subjective measures about the indoor lighting environment (Fig. 3) Part of the framework was to develop methods and instruments specific to occupied end-user settings in large open plan office environments. In particular, HDR images were collected using an android mobile device and a micro fisheye lens and the indoor illuminance was measured using low-cost lux sensors. Surveys collected where carried out by Aurecon, as part of their evidence-based approach to fine-tuning lighting systems.

Energy

The electrical lighting system consists of 20W Linear LED luminaires fitted to suspended parabolic Beta louvres with DALI ballasts. Obtaining direct metering of the true energy usage was not possible during data collection. It was mentioned during our site investigation that the installation is still being fine-tuned to work in-line with daylight-linked systems (photosensors, occupancy sensors and manual blinds). This was to try to find the best balance between delivering energy efficient lighting and visually comfortable lighting to building occupants.

Photometry

Glazing facades in subtropical climates can become a source of glare for occupants. Glare assessments were carried out to evaluate potential glare sources from using a calibrated android mobile device with a micro fish-eye lens (see Fig.4.). Occupants working along the office perimeter were asked to evaluate their subjective lighting environment by using the device to capture HDR images of their field-of-view (typical viewing position facing their computer monitor screens) and to report whether they experienced glare in a short survey on the phone. Fig. 5 shows the glare results of four occupants reporting glare. The DGP values were well below the imperceptible range (0.35), however the DGI indicated noticeable to acceptable glare (range within 18-22 for the DGI). Whilst the HDR images were captured at a point-in-time, it is likely that the DGI values would exceed towards intolerable glare.

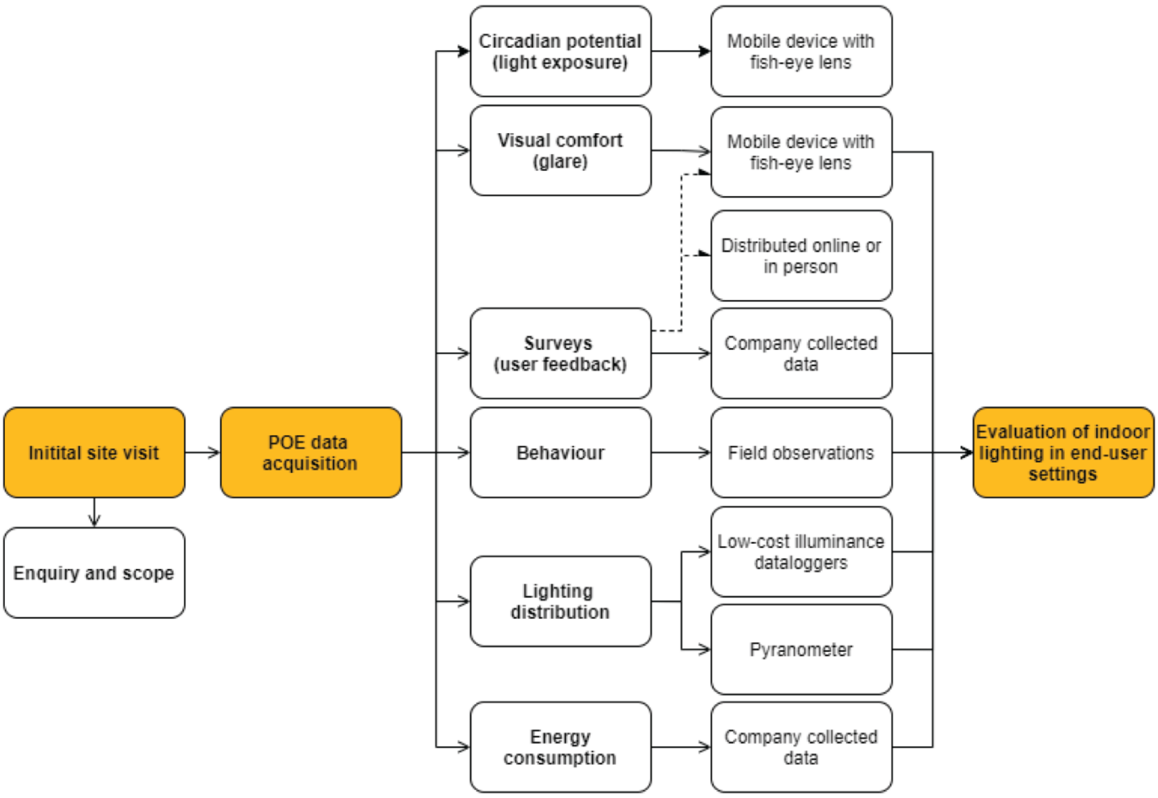


Figure 3. Post-occupancy (POE) framework to collect objective and subjective measures of the indoor lighting environment specific to occupied end-user settings in large open plan office environments.

Fig. 4. Calibrated mobile phone device with a micro fish-eye lens to capture HDR images at occupant workstations.

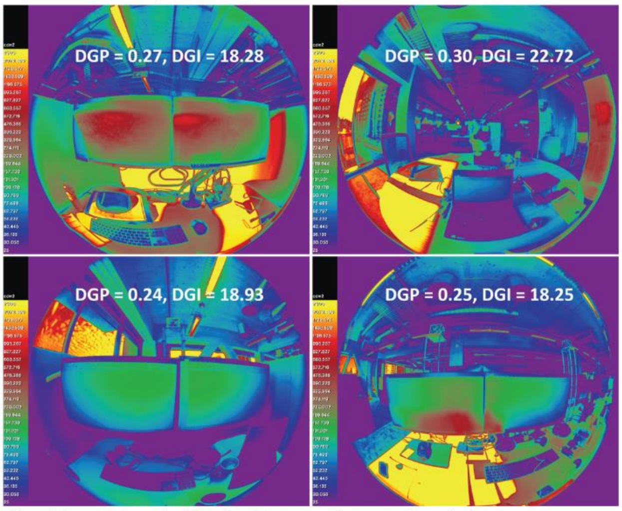


Fig. 5. Assessment of the luminous environment and glare sources using a mobile device and micro fish-eye lens, showing that the DGI detecting noticeable to just acceptable glare for occupants the four occupants reporting glare.

Sufficient colour rendering and illumination of occupant faces and objects are important in offices where communication and face-to-face collaboration are carried out throughout the day. The cylindrical illuminance was estimated in a selected area of the office, to evaluate colour rendering and illumination of objects (occupants' faces) (Fig.6). Low-cost sensors were mounted at occupant workstations (as close to eye height level - 1.7 m from the finish floor) to continuously record the horizontal and vertical illuminance (from four planer orientations) during typical work hours (07:00 AM – 05:00 PM). Spectral corrections were applied to minimise measurement error (error uncertainty of between 10-20%). A cylindrical illuminance above 150 lux was achieved at all workstations for more than 50% of working hours. Part of this result was from allowing manual control of blinds to enable occupants to adjust just enough for visual comfort but still allow for daylight permeation. As demonstrable in Fig. 7, occupants had individual preferences in terms of the fraction of shading that would meet their visual comfort needs.

Circadian potential

Aurecon's approach to deliver circadian lighting was to use daylighting and electrical lighting to achieve an Equiv-

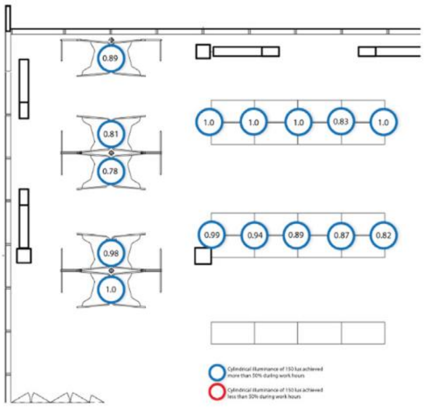


Figure 6. The measured cylindrical illuminance at multiple occupant workstations in a selected zone, showing that workstations receiving illumination above 150 lux for more than 50% of the time.

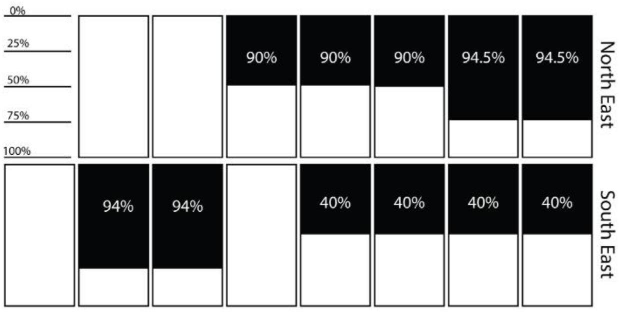


Figure 7. Blind profile showing the percentage of time blinds were closed when the cylindrical illuminance was above 150 lux for more than 50% of working hours.

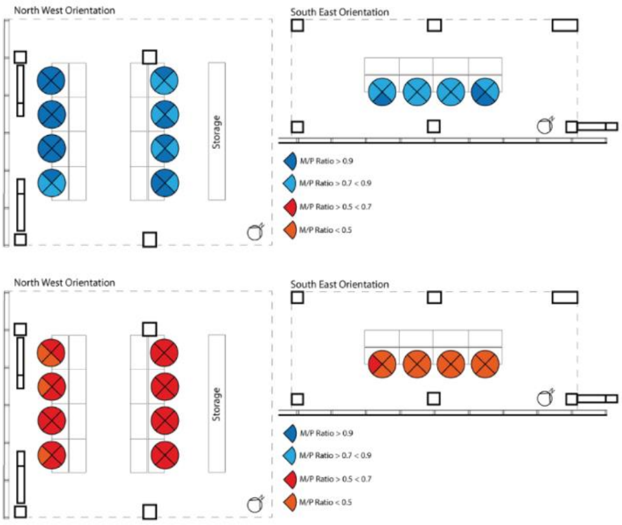


Figure 8. SPD measurements at 12 locations in two different orientations: north-west and south-east. (Top) The M/P ratio under daylight conditions only, showing most locations achieved an M/P > 0.9, however for locations facing south-east, the M/P was largely between >0.7 and <0.9. (Bottom) M/P ratio well below 0.7 indicating that the circadian potential would be from daylighting.

Evidence-based management to monitor and improve indoor lighting

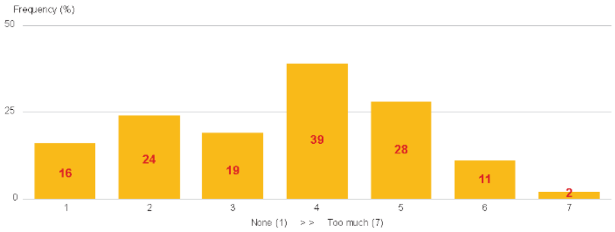


Figure 9. Perceived glare from windows.

Figure 10. A copy of the POE results conducted by Aurecon, showing close to half believed in the importance of personal control over lighting.

alent Melanopic Lux (EML) of 200 lux or more, for at least 75% of workstations (Feature 54 1a). This included on-site verification pre-occupancy. In this case study, the circadian potential was also measured under similar conditions: daylight only (cloudy sky between 11:30 AM to 12:30 PM) and electrical lighting only. Measurements were taken at eye height level (at seating position) at twelve workstations in two areas: one facing north-west and the other south-east. The results indicate that even without electrical lighting, circadian stimulation can be achieved with daylighting under clear to somewhat cloudy conditions for perimeter workstations predominately oriented North, East and/or West (Fig. 8). Workstations oriented south-east typically had a M/P ratio between 0.7 and 0.9 – congruent with solar conditions being less available and having some daylight obstruction from an adjacent building. However, due to sky conditions, the M/P ratio would most likely be higher under clear sky. The M/P ratio under electrical lighting conditions were well below 0.7, which was consistent with the results from their on-site verification. However, this criteria would not be critical since passive lighting is already abundant during typical office hours and is a more energy efficient strategy.

> ***"User feedback for fine tuning"***

User perspective

User feedback was collected by Aurecon as part of their POE program using the Building Use Studies (BUS) methodology involving standardised questions about the indoor environment quality (IEQ). This was also carried out in their former office building and was one of the reasons why manual blinds were installed in their new office building. Lighting questions were focused on user satisfaction and comfort towards the perceived brightness from electrical lighting, daylighting from windows and glare. Results

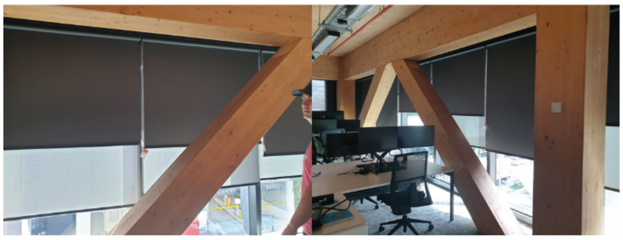


Figure 11. Real outcomes from conducting a POE survey, where glare was reported by a significant number of occupants. Additional blinds were installed with lower VLT (<10%), to deliver a double roller strategy for increase control of daylighting.

showed 70% of occupants were overall satisfied with the indoor lighting conditions, 64% with electrical lighting and, 59% with natural lighting. Significantly, 89% reported glare from windows, with 12% suggesting a high degree of discomfort (Fig. 9 and 46% believing in the importance of personal control over lighting (Fig. 10) These results provided evidence to install additional blinds with lower visible transmittance (VLT < 10%) to allow occupants to completely block off unwanted glare, but still use the existing blinds with higher VLT (>40%) when more daylighting is desired (Fig. 11).

> ***"Balance between individual control and energy efficiency"***

Lessons learned

Open plan offices are by far the more challenging environments to conceive energy efficient and visually comfortable indoor lighting. Whilst technologies (occupant sensors and photosensors) can provide better management of both daylighting and electrical lighting systems, and are important components in integrated lighting for energy efficiency, it is difficult to achieve occupant comfort without occupant feedback. Daylight responsive controls provided sufficient daylight illumination and circadian stimulation for workstations located along the perimeter, however, there was a significant number of occupants reporting glare. In sunny climates, issues of glare are prevalent but can be controlled with blind shades. However, direct glare from windows was still visible even when blinds were closed because the VLT was high. The key takeaway is in Aurecon's approach to identify the issues using POE questionnaires and installing additional blinds with lower VLT as a solution for better glare control.

Further information

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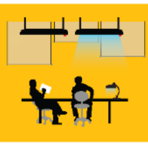


Lighting in shared spaces to support a sustainable and collaborative workforce

AECOM Brisbane promotes sustainable and collaborative work practices using practical lighting solutions

A POE assessment was carried out in a Green Star commercial office building in Brisbane Australia. Lighting strategies were evaluated which included observations of user behaviour and surveys. The combination of occupancy sensors, side-lighting and manual blind shades delivered a pragmatic solution for indoor lighting in shared environment, with room to improve energy efficiency and comfort.

Figure 1. AECOM Brisbane's open plan office located in Brisbane, Australia.

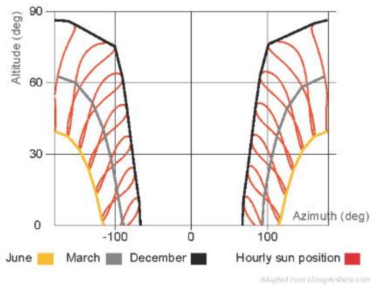
The project

AECOM Brisbane is an awarded Green Star building designed to support sustainable work environments for office workers (Fig. 1 and Fig. 2). Designed by BVN Architects, the 11-storey commercial office building optimizes ambient lighting in a both formal and informal workspaces to promote well-being, productivity, and cross collaboration. Consistent with their core values to find sustainable opportunities, large voids are used to deliver as much daylighting through multiple levels of the open plan office, which can house up to 150 occupants per floor. Timber features recycled from the native Australian Blackbutt tree are highlighted by natural side-lighting, providing a touch of warmth and ambience in the office. Conscious of energy efficiency, occupancy sensors are placed across the office perimeter to maximise electrical lighting savings via vertical glazing. Office workers are able to enjoy the urban city views anywhere within the building with individual control to adjust their local daylighting levels using manual solar blinds shades.

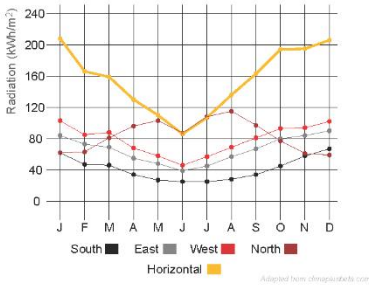
Monitoring

An initial site investigation was conducted on the 22nd of January 2019 and proceeded data collection between the 29th of January 2019 until the 15th of March 2019 (between

Location: Brisbane, Queensland, Australia
27° 27' 7.884" S, 153° 2' 1.95" E



Sun path for
Brisbane, Queensland, Australia



Global horizontal and vertical radiation for
Brisbane, Queensland, Australia

IEA SHC Task 61 Subtask D

Monitored by **Kieu Pham and Veronica Garcia-Hansen**
More info **Prof Veronica Garcia-Hansen,** Queensland University of Technology,
v.garciahansen@qut.edu.au

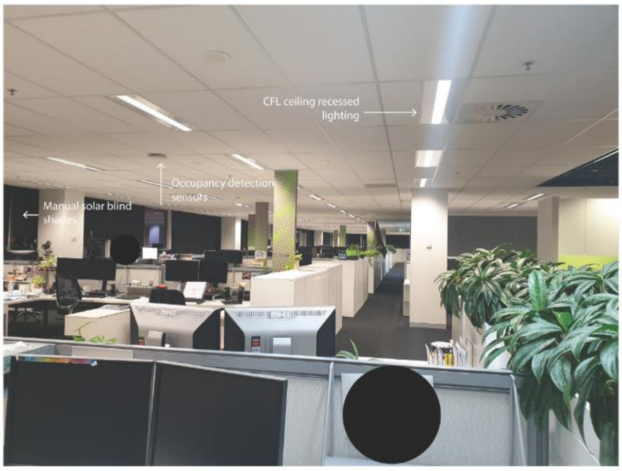


Figure 2. Photo inside AECOM Brisbane showing a portion of the open plan office where occupancy sensors, CFL lighting and manual blind shades are used as part of their lighting system.

Fig. 4. Assessment of the luminous environment and glare sources using a mobile device and micro fish-eye lens.

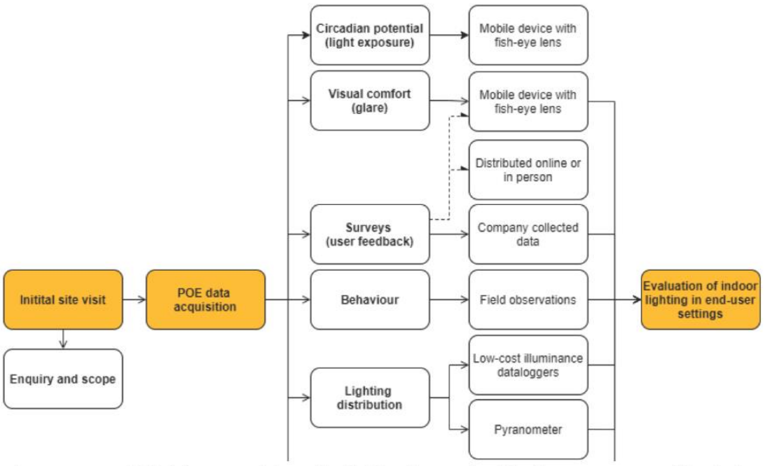


Figure 3. Post-occupancy (POE) framework to collect objective and subjective measures of the indoor lighting environment specific to occupied end-user settings in large open plan office environments.

summer solstice and autumn equinox). Data collection was carried out on a typical floor using a POE framework that was developed to collect objective and subjective measures about the indoor lighting environment (Fig. 3). Part of the framework was to develop methods and instruments specific to occupied end-user settings in large open plan office environments. In particular, HDR images were collected using an android mobile device and a micro fisheye lens and the indoor illuminance was measured using low-cost lux sensors.

Energy

The electrical lighting system consisted of 28W T5 linear fluorescent luminaires fitted to recessed troffers (LOR > 80% and efficacy of ~60 to 80 lm/W) and occupancy sensors. This was a conscious decision to provide an economic and energy efficient solution based on the available luminaire options at the time. Direct metering was not a target focus during data collection. However, we were informed that future solutions will be to integrate daylight sensing and dimming technologies to reduce the electrical lighting energy consumption.

Photometry

Open plan offices with vertical glazing façades are prone to glare issues, especially in sunny climates. HDR photographs were taken along the perimeter areas of the office where potential glare sources would occur. An android mobile device with a micro fisheye lens mounted on a custom MDF stand was given to occupants to capture their typical viewing position from their workstations.

Open plan offices with vertical glazing façades are prone to glare issues, especially in sunny climates. Glare assessments were carried out at perimeter workstations to identify potential glare sources using an android mobile device with a micro fisheye lens mounted on a custom MDF stand (Fig. 4.). Participants were asked to capture HDR images in their field-of-view facing their typical viewing position at the workstations. Unexpectantly, the DGP and DGI results did not detect glare sources, even though participants reported glare at the time the assessment was made (Fig. 5.). A subsequent survey also showed that 54% of occupants frequently or very frequently experienced glare that can last as briefly as 2 minutes or more than 2 hours (Fig. 6). Evidently, the HDR images were not taken at the right time when glare sources would be present. Considering the limitations to conduct follow-up assessments at the time for this study, asking occupants if they experience

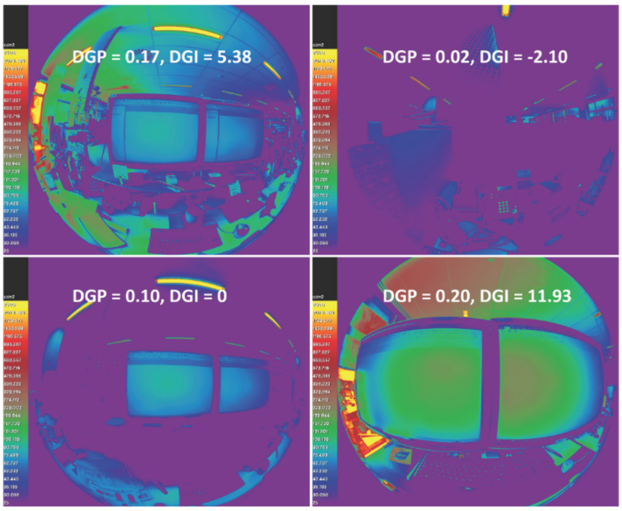


Fig. 5. HDR results of the participants who reported glare using an android mobile device with a fish-eye lens. Unexpectantly, DGP and DGI values were very low, indicating that photographs were taken at the time when glare sources were not present.

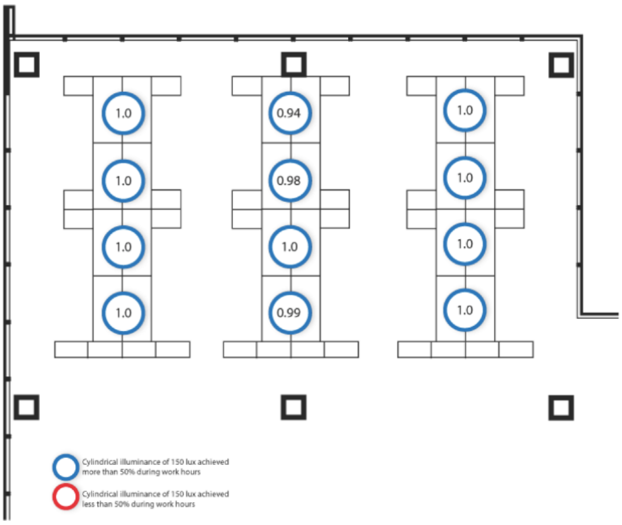


Figure 7. Cylindrical illuminance measured at occupant workstations across a one-day period, showing that sufficient lighting above 150 lux was provided well over 50% of the working period.

glare can still verify visual discomfort issues and warrant follow-up visits to capture additional images at times when occupants would expect glare sources to be present.

However, it is also important to provide sufficient illumination for colour rendering and illumination of faces and objects for communication and face-to-face collaboration. The cylindrical illuminance measures the quantity of illumination of objects. This was measured with low-cost sensors that were mounted at occupant workstations (as close to eye height level – 1.7 m from the finish floor). Continuous measurements of the horizontal and vertical illuminance (from four planar orientations) were recorded across a one-day period between typical work hours (07:00 AM – 05:00 PM). Spectral corrections were applied to minimise

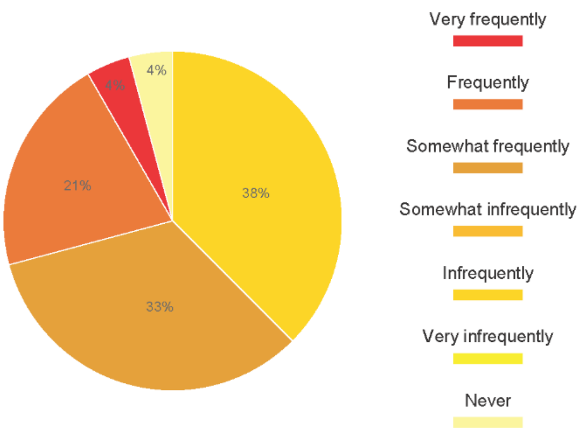


Figure 6. The percentage of occupants reporting glare, showing almost all have had experienced sensations of glare with 54% frequently or very frequently.

measurement error (error uncertainty between 10-25%). A cylindrical illuminance above 150 lux was achieved at all workstations for more than 50% of working hours (Fig. 7).

Circadian potential

Light exposure for circadian stimulation was not a deliberate control strategy. Nevertheless, for sunny climates where daylighting is abundant, this would not be difficult to achieve. Measurements were carried out at workstations facing north-east in the office using a handheld spectrometer. Measurements were recorded in five locations in four vertical directions at 1.2 m from the floor. Two scenarios were considered: melanopic light intensity under daylighting conditions only and the melanopic light intensity under electrical lighting only. Measurements were recorded around 12 noon for daylighting conditions under a semi-cloudy day and at night for electrical lighting. A melanopic/photopic ratio above > 0.9 is considered sufficient and ideal for circadian stimulation which was achieved largely from the vertical side-lighting, where a significant amount of daylighting was provided (Fig. 8).

User perspective

A total of 23 occupants completed a survey about the indoor lighting environment. These questions were focused on their satisfaction with the overall visual environment, colour appearance, views, window size, lighting controls, uniformity, lighting levels and the provision of electrical and natural lighting. A little over half of the occupants were satisfied or very satisfied with the overall visual environment (60.08%), colour appearance (52.17%), outside view (65.22%), light uniformity (60.87%), light levels (60.86%), light uniformity (60.86%) electrical lighting (56.52%) and natural lighting (52.17%). Just less than half were satisfied with the lighting controls (47.83%), whilst well over half were satisfied with the window size (78.26%) (Fig. 9).

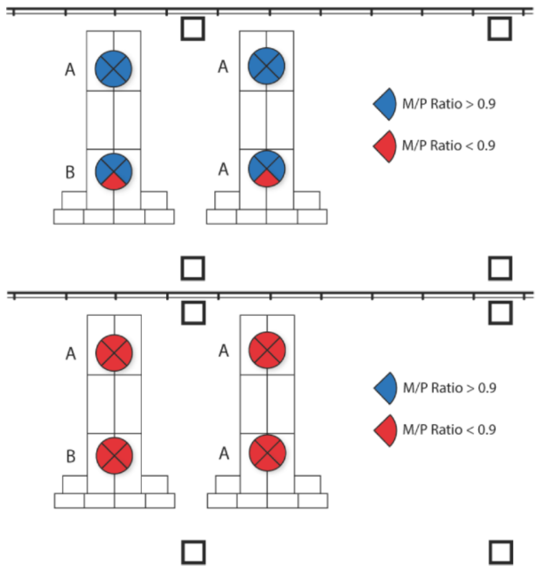


Figure 8. Melanopic/Photopic (M/P) ratios under daylighting conditions (top) and electrical lighting conditions (bottom) for workstations facing north east, showing daylighting via side-lighting provided sufficient circadian stimulation.

Providing user control in open plan office settings can be especially difficult to achieve when occupants are working in shared environments. It is important to provide this since their preferences and comfort levels vary. One way to do this, is to provide manual blind shades to allow occupants to shade blinds closest to their workstations when it best suits them. In Fig. 10, patterns of blind usage in different areas of the office are shown. Whilst there were strong patterns of blind use in the morning and afternoon, the time in which they use it still varied and consistent with the varying patterns of glare occurrences in Fig. 11.

Lessons learned

Open plan offices are shared environments that require thoughtful integrated approaches to achieve multiple objectives: energy efficiency, visual comfort and, occupant satisfaction. There is room to improve the energy efficiency by replacing fluorescent lighting in favour of energy efficient LEDs. Whilst the provision of manual blinds (VLT < 10%) provided individual control of daylighting levels, there are indications to improve lighting controllability and glare.

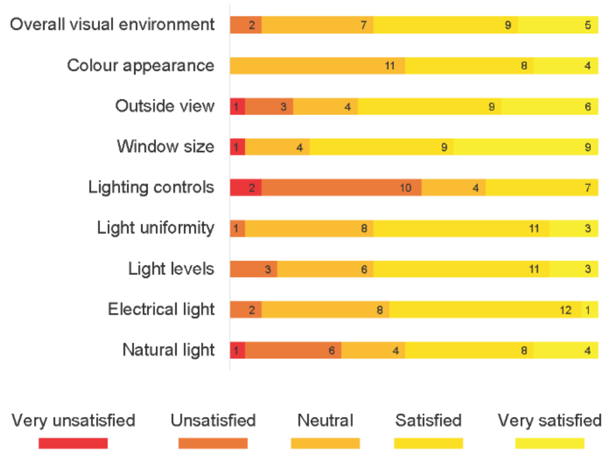


Figure 9. Survey response from 23 occupants about their satisfaction with the indoor lighting environment.

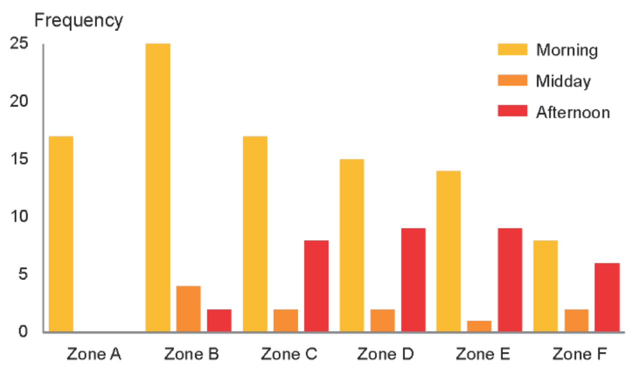


Figure 10. Frequency chart showing occupants having individual preferences to adjust blinds at different times of the day across various zones.

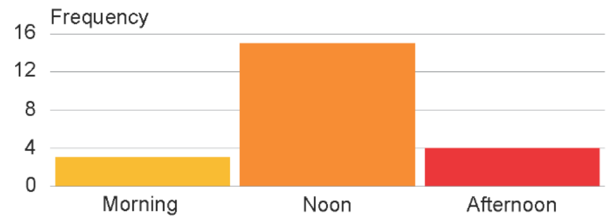


Figure 11. Reports on the occurrence of glare at different times of the day, showing a significant amount occurring in the afternoon.

Further information

Wagdy, A., Garcia-Hansen, V., Isoardi, G., & Pham, K. (2019). A parametric method for remapping and calibrating fisheye images for glare analysis. Buildings, 9(10), 219.

Pham, K., Garcia-Hansen, V., Isoardi, G., & Allan, A. (submitted 2021). Open-source hardware and software for in-situ measurements in real contexts: a use case scenario of its usability for lighting research. Energy and Buildings.

Acknowledgements

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Support on site: **Aecom Brisbane office team**
Special thanks to **Duncan Richards** (Technical Director – Buildings and Places)

Visual comfort and non-visual requirements for an ageing population

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Implementing daylight and electric light strategies in a care home in Brussels (Belgium) through a simulation-based approach.

A series of daylight and electric light strategies were proposed in a care home in Brussels (Belgium) to improve the visual comfort and circadian wellbeing of residents. The strategies were based on 3D simulations evaluating the quality and quantity of luminous exposures over time in several residents' living spaces.

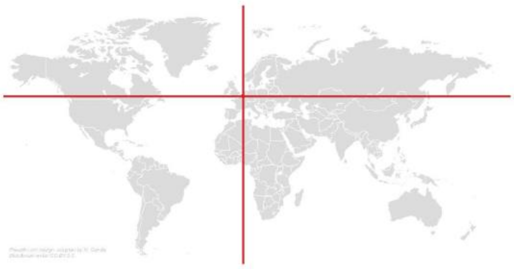
Figure 1. Stephenson Garden, Brussel.

The project

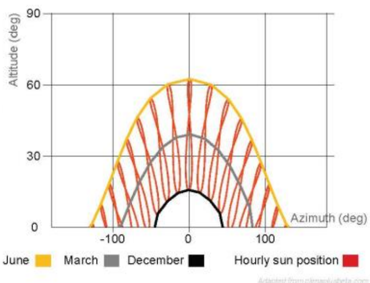
The Stephenson Garden (Fig. 1) is a 6-storey warehouse in Brussels that, in 2015, was refurbished into a care home. The renovation project – lead by the care home director, a former interior designer having worked for almost 20 years as nursing home manager – focused on conceiving spaces that could provide to the residents luminous continuity throughout their daily activities (Fig. 2). To this aim, several common spaces, open to daylight and external views, were arranged alongside patients' bedrooms at each floor (Fig. 3). The ground floor presents a different spatial organisation with fewer sleeping rooms, but two dining rooms (one in Fig. 4), a visit room and a living space. All spaces have access to daylight complemented by LED luminaires.

Monitoring

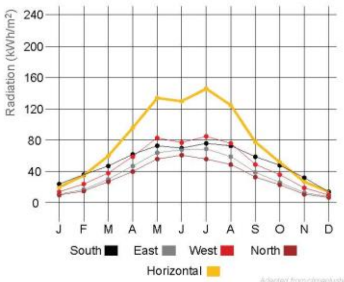
A detailed monitoring plan had been set up to take place in March 2020. Unfortunately, due to the SARS-CoV-2 pandemic, which inhibited access to all care homes in Belgium, the research strategy had to be adjusted, relying on computer simulations for the evaluation of visual and non-visual luminous exposures, and for the estimation of the energy performance of specific spaces within the building. The recently-released Climate Studio tool, alongside the DIVA-for-Rhino plugin, were used to perform climate-



Location: Brussels, Belgium
50.87°, 4.37°



Sun path for Brussels, Belgium



Global horizontal and vertical radiation for Brussels, Belgium

IEA SHC Task 61 Subtask D
Monitored by **Donatienne Carmon**, UC Louvain
More info **Prof Sergio Altomonte**, UC Louvain, sergio.altomonte@uclouvain.be

Figure 2. Rooms. Top: South-West oriented Bedroom, 2nd floor. Bottom: North-West oriented Dining Room (patio), Ground floor.

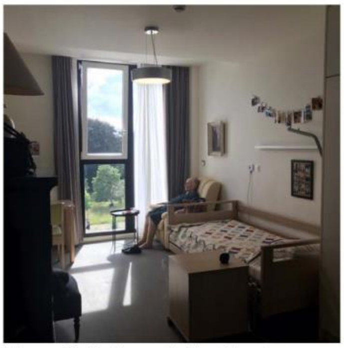


Figure 3. Bedroom in the Stephenson Garden.

based daylight simulations and to calculate the energy use. A circadian optimization of lighting calculation was done via the software tool ALFA.

Starting from the existing conditions (baseline), several scenarios aiming at providing access to the proper amount and quality of light were tested, of which some are shown here. The scenarios include the installation of complementary luminaires, adjustment of daily schedule or modification of furniture arrangement.

Energy

The energy performance compares the existing baseline situation (artificial lighting switched on based on occupants' presence, with no dimming) to a proposed improved scenario based on daylight availability, as well as visual and non-visual requirements.

The baseline scenario considered that, regardless of season or sky condition, between 07:00 and 23:00 electric lights are switched on whenever the rooms are occupied.

The proposed improved scenario dimmed electric lighting considering both visual (workplane photopic illuminance) and non-visual requirements (melanopic vertical illuminance). These required the installation of additional luminaires in the bedrooms and dining rooms. The evaluation was done for the 21st of June and 21st December, under overcast and clear skies.

Simulations were first run with daylight as the only light source. When electric lighting was needed, simulations were first run only with ceiling lamps. Finally, if daylight and the ceiling lamps did not provide sufficient photopic and melanopic illuminance, the additional luminaires were

Figure 4. Dining Room in the Stephenson Garden.

switched on. Table 1 shows that the proposed scenario allows a reduction of energy use in the South-West bedroom. For the dining room, energy consumptions associated with improved visual and non-visual luminous exposures are, however, mostly similar between the two situations. This was expected considering that the proposed scenario added 10 wall-mounted luminaires in order to respond to visual and non-visual requirements. Nevertheless, it must be considered that the simulations were run for the most disadvantageous location in the dining room in terms of orientation and visual and non-visual exposure. If other strategies were implemented, such as a change in the arrangement of the furniture, the adaptation of the schedules, and/or an individual control for each luminaire, the different thresholds could be more easily reached, reducing the need for electric lighting and its associated energy use.

Photometry

Figure 5 presents Spatial Daylight Autonomy (sDA) for the 300 lux threshold, Daylight Factor (DF), and Workplane Illuminance (provided by electric lighting only) for the bedroom and the dining room in the baseline scenario. The mean sDA for the bedroom is 18% and no place in the room achieves a value higher than 50%. A similar result was obtained for the North-West dining room, for which the mean sDA was around 5%. Regarding DF, the mean values for the bedroom and dining room are 2.1 % and 0.9%, respectively. The work plane illuminance levels reach the desired thresholds only at some specific points for the bedroom.

	June clear	June overcast	December clear	December overcast
Bedroom	kWh/m²/day	kWh/m²/day	kWh/m²/day	kWh/m²/day
Before	0.016	0.016	0.016	0.016
After	0.006	0.006	0.015	0.015
Dining Room	kWh/m²/day	kWh/m²/day	kWh/m²/day	kWh/m²/day
Before	0.021	0.021	0.021	0.021
After	0.018	0.024	0.022	0.022

Table 1. Daily energy use under baseline (before) and proposed (after) scenarios

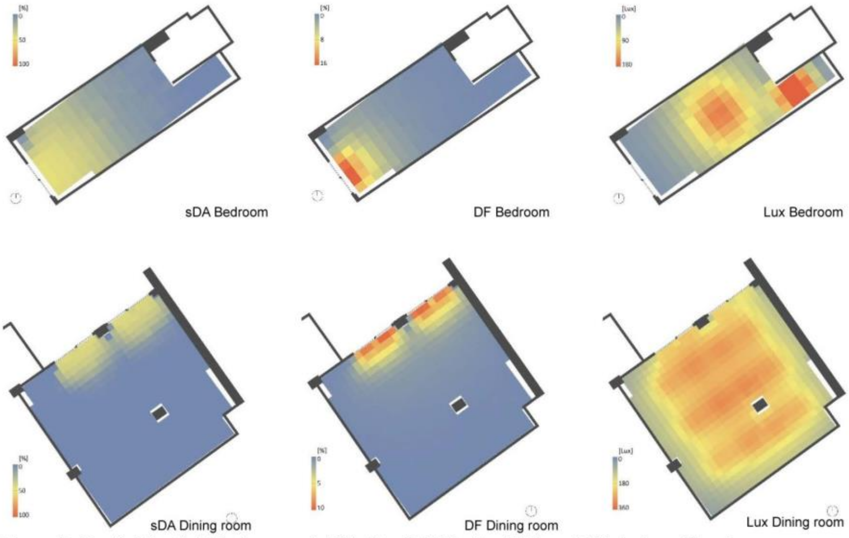


Figure 5. Spatial Daylight Autonomy (sDA), Daylight Factor (DF) and Workplane Illuminance provided by electric lighting for the monitored rooms. Top: bedroom. Bottom: dining room.

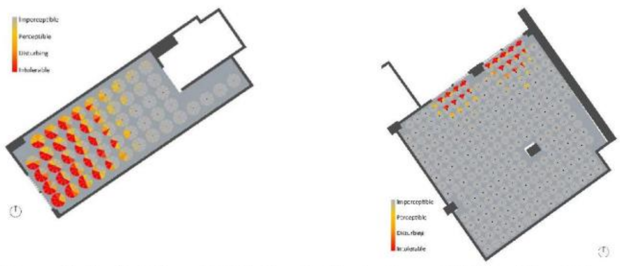


Figure 6. Spatial Glare Distribution for the bedroom (left) and the dining room (right)

In terms of annual spatial distribution of discomfort glare probability, near the window and facing outside the probability of disturbing glare is extremely high (Fig. 6). This would require the implementation of curtains, which could lead to an increase of electric lighting use. In the dining room, the risk of glare is lower and could simply be addressed by having tables located at a distance higher than 1.5 m from the windows.

Circadian potential

ALFA allowed to evaluate the circadian potential of various spaces through the estimation of the melanopic illuminance (equivalent melanopic lux, EML), and the M/P ratio. For all situations analysed, the Circadian Stimulus (CS) index was also calculated. The results obtained for these three metrics were compared to the thresholds defined by the current literature. However, since light transmission in the retina decreases with age, and phenomena such as the yellowing of the lens can further impair the circadian stimulation for the elderly, existing thresholds had to be adjusted.

The melanopic threshold at 250 EML for a person of 85 years of age was set via the SpeKtro tool by EPFL. Concerning the M/P ratio, it was considered that, when its value is above 0.9, the light source can have an alerting effect (during the day) or foster melatonin suppression (at night). Conversely, a M/P ratio lower than 0.35 does not inhibit melatonin secretion. On these bases, the chosen thresholds aimed at maintaining a M/P ratio above 0.9 until 11:00 and under 0.35 from 17:00. For the CS, between 07:00 and 11:00, a value higher than at least 0.3 was sought, while after 19:00, the CS must not exceed 0.1.

The analysis was based on the use of three "personas", that is, personal representations of occupants' activities that can exemplify different lighting requirements and conditions experienced through a series of typical days. The simulations recorded the luminous exposures of these personas based on a schedule of daily activities provided by the care home, and were ran every 3 hours, in both winter and summer, under clear and overcast sky conditions.

The two examples shown in this section are for the 21st of December with an overcast sky condition, to stress out the need for integration of daylight and electric lighting. The bedroom is originally electrically lit by a LED ceiling lamp and a LED spotlight in the entrance. The simulations present the luminous exposures for a persona, at the times of breakfast and dinner. The dining room is electrically lit by 12 LED ceiling lamps. Since some residents also attend afternoon activities in the same room, simulations were run at 16:00 and 19:00 in that space. In this case, the simulation was done for two personas, one located near the windows and facing outside, the other looking in the opposite direction and placed at the back of the room (see the results presented in Table 2).

An initial analysis of the simulation results led to detect a lack of potential circadian stimulation in the morning (07:00) due to low melanopic illuminance in the resident's rooms, see Table 2. Thus, it was proposed to use a desk lamp with two switches triggering, respectively, a blue-shifted or a red-shifted LED light. By doing so, in the morning, the residents would have blue-shifted light to entrain their circadian rhythm, while a red-shifted light in the evening could ensure visual comfort without inhibiting melatonin secretion. Based on this simple strategy, the required thresholds could be achieved in the morning: 772 EML, a CS of 0.51, and a M/P ratio of 1. In the evening, this strategy led to detect the following values: 8 EML, a CS of 0.02, and a M/P ratio of 0.02. Although the use of the red-shifted desk lamp, combined with the presence of two ceiling lamps, did not alter substantially the quantity and quality of light towards the circadian well-being of residents, it resulted in an increase of the workplane illuminance values from 11 lux (i.e., with two ceiling lamps) to 307 lux.

Visual comfort and non-visual requirements for an ageing population

SOLAR HEATING & COOLING PROGRAMME
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	Before				After			
Bedroom	**M/P**	**EML**	**CS**	**Plane lx**	**M/P**	**EML**	**CS**	**Plane lx**
07:00	0.75	12	0.02	12	1.00	772	0.51	357
19:00	0.71	5	0.01	11	0.02	8	0.02	307
Dining Room	**M/P**	**EML**	**CS**	**Plane lx**	**M/P**	**EML**	**CS**	**Plane lx**
16:00	0.95			306	0.68			975
	0.82			232	0.23			768
19:00	0.85	120	0.23	247	0.01	2	0.01	456
	0.79	39	0.08	224	0.01	4	0.01	459

Blue-enriched
Neutral
Blue-depleted
Do not meet threshold
Meet the threshold

Table 2. Results of the ALFA Simulations of the 21st of December, with an overcast sky

In the dining room, the simulation detected the risk of excessive melanopic stimulation in summer during the evening hours. At the most exposed seating positions, both the EML and CS values were substantially above the required thresholds: 120 EML and a CS of 0.23. Moreover, the workplane illuminance was not sufficient across the entire space. The challenge, therefore, consisted in lowering the values of melanopic illuminance while preserving sufficient horizontal light distribution. Therefore, a dynamic electric lighting system was proposed to provide abundant light during the afternoon and a dimmed ambiance for the evening. This was done through the implementation of 12 ceiling lamps with a M/P ratio of 1, and 10 wall-mounted lights with a 0.01 M/P ratio. Both systems were set to be switched on in the afternoon, while only the wall-mounted lights were active in the evening, providing sufficient workplane illuminance and a sufficiently low melanopic exposure (2 and 4 EML) and circadian stimulation (0.01 for both personas included in the simulations).

Further strategies to respond to occupants' visual and non-visual needs consisted in the review of the residents' schedule of activities (so as to choose the rooms occupied throughout the day based on the effective daylight availability) and adjustments to the arrangement of the furniture (to guarantee proper exposure, or protection, from light sources). In some cases, compromises would need to be made between responding to requirements for visual comfort and circadian entrainment or rather supporting the psychological desires of residents to have direct access to an external view.

User perspective

The strategies proposed were discussed with the health care personnel (n = 7), to also gain insights on the habits of the residents, and with the director of the Stephenson Garden. The responses were generally supportive of the strategies proposed. It was, in fact, emphasised that most residents spend a relevant amount of time in their bedroom, making it essential to provide them with suitable lighting conditions by ensuring an efficient work plane illuminance along with appropriate EML and CS values throughout the day. The proposition of dynamic lighting settings via the use of blue-shifted lighting in the morning, and red-shifted lighting in the evening, could provide substantial benefits, especially since residents tend to often keep their curtains closed. However, the director stressed that it would be challenging for the health care personnel to implement the required lighting strategy at the appropriate timing, therefore suggesting the use of an automated system that could provide the residents with the adequate light exposure based on season and time of day.

Lessons learned

The analysis showed that with relatively simple measures – a careful integration of daylight and electric lighting strategies, the proper selection of lighting systems, schedule of daily activities, and spatial organisation – a care home can offer to its elderly residents proper lighting conditions to enhance their visual comfort, support their circadian well-being, and guarantee an effective energy performance for its lighting needs.

Logically, some limitations have to be acknowledged before the results of this analysis can be transferred to other contexts. In fact, the results were uniquely obtained through computer simulations without data having been validated by real measurements (e.g., to verify the effective daily 'lighting diet' of residents or the extent of any circadian disruption symptoms as revealed by biological markers). Also, it must be considered that – to guarantee a manageable volume of data to be analysed – the age of the residents was considered as fixed to 85 years. People of different age could have different lighting requirements. A further step of analysis would therefore consist in defining appropriate methods to adapt the necessary thresholds to the needs and subjective conditions of building users.

Further information

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Acknowledgements

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A modern heritage office building looking at energy and users satisfaction

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Lighting control and automation system, combined with daylight in the Ministry of Mines and Energy (MME) in Brasilia.

The modern building designed in 1958 by Oscar Niemeyer is an architectural heritage, limiting interventions on facades. The electric lighting control and automation system optimizes light integration and reduces energy use, while improving user satisfaction. The building makes good use of daylight, thanks to the laminar shape; most offices are located in east façade to prevent glare and overheating.

The project

The Ministry of Mines and Energy (MME) is a modern building, designed in 1958 by the architect Oscar Niemeyer and part of the Ministries Esplanade (figure 1), a complex of 17 identical buildings. The complex is a cultural heritage listed by the Brazilian National Historical and Artistic Heritage Institute (IPHAN).

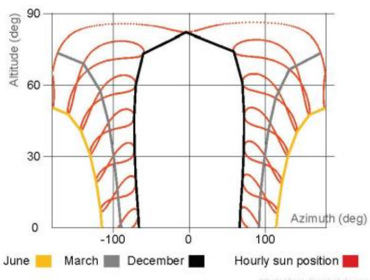
On a construction site of around 5,000 square meters on aThe building has an area of 19 734 m2 distributed in 11 floors (including two underground floors). Its laminar shape (102.5 x 17.4 m) allows daylight penetration. East and west façades are totally glazed, with solar protection (brise soleil) on the west façade and solar control films on east façade. Most offices are facing east, to reduce over-

Figure 1. Ministries Esplanade in Brasilia.

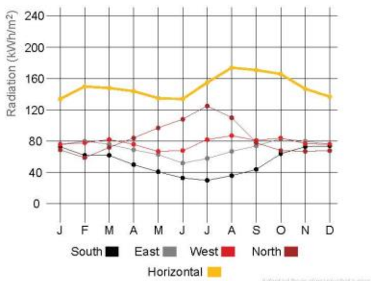
heating and glare. Because of the heritage restrictions, the façades cannot be changed, so actions to improve lighting and reduce energy consumption were done by means of a sophisticated artificial lighting control and automation system that optimizes light integration and reduce energy consumption, improving wellbeing and user satisfaction with the light environment.

The lighting control system implemented is the EcoSystem© from LUTRON and it was installed during the building retrofit, consisting in five control possibilities: on off, dimming, individual controls on daylit workplaces, central

Location: Brasilia , Brazil
-15.80°, -47.87°



Sun path for
Brasilia, Brazil



Global horizontal and vertical radiation for
Brasilia, Brazil

IEA SHC Task 61 Subtask D

Monitored by **Ayana Dantas**, **Flavia Bukzem**, **Gabrielle Toledo**, **Igor Silva**, **Adriana Sekeff,** Laboratory of Environmental Control and Energy Efficiency - LACAM, University of Brasilia
Info **Prof Cláudia Naves David Amorim**, University of Brasilia, clamorim@unb.br

Figure 2. West and East façades of the building.

Figure 3. Photosensors close to windows and lighting switch interfaces in corridor.

control for workplaces far from windows. The main innovation is the dimming; in order to integrate day and electric lighting there are photosensors near to the windows (figure 3), and the luminaires in the nearby lamps are dimmed according to the amount of daylight. Users can request changes in light intensity by contacting the responsible for the central system. The system configurations also include the regulation of lamps intensity in 50% of luminous flux e and automatic turn off at 7:30 pm every day. Besides, there are switches in the corridors that control rooms lighting (figure 3), remote controls for dimming in some special rooms and occupancy detection sensors in common areas (corridors and WCs). A monitor placed in the main entrance displays in real time the global energy consumption of the building.

Monitoring

The first field monitoring was performed on 7th October 2019 at night and on 8th October 2019 around 12 pm. The condition was clear sky, with global illuminance values between 39 000 lux and 120 000 lux. The second field monitoring took place on November 10th, 2020 between 12pm and 13pm. The sky condition was overcast and global illuminance values ranged between 23 300 lux and 38 200 lux. All measurements were performed in a representative office room on 6th floor in east façade (figure 4), with 50.32 m2 area and 7.40 m deep (figure 5), same of all other rooms in east façade. The limited depth ensures good daylight penetration. Internal reflectances are as follows: floor 38%, walls 62%, ceiling 80%, partitions 70%. Windows in east façade are composed by a 6 mm glass with solar control film (silver coloured from Intercontrol©), with visible light transmission of 15%. All rooms have internal vertical blinds, but all measurements were done with opened blinds.

Energy

The electric lighting system consists of efficient fluores¬cent T5 recessed luminaires 2x28W (103 lm/W) providing lighting at 4000K -, and a closed-loop daylight harvesting system. Sensors are located in the ceiling next to the window, controlling the row of light fixtures near to the window in the room, which are automatically dimmed according to this sensor. The other light fixtures are centrally controlled,

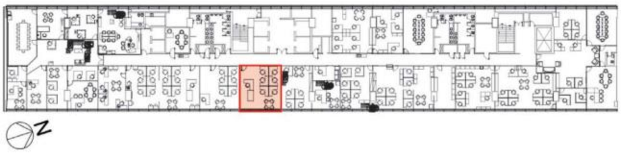


Figure 4. Plan of 6th Floor, with the monitored room.

Figure 5. Layout and pictures from monitored room.

and workers can ask the central to diminish or enhance luminosity according to their preferences. There is no separate energy meter for lighting, so the calculation of energy consumption for lighting was made based on EN15193-1:2017, and the calculated LENI was 17.23 kWh/m²year.

Measurements of actual savings were also made with the following method: lighting control system was turned off for two days and the global energy use registered and compared with normal consumption (lighting control system on). According to measurements performed, the lighting dimming system can reduce by 9% the global energy savings of the building.

Photometry

The field monitoring was conducted with three different conditions: daylighting, electric lighting and day+electric lighting (Table 1).

Factors such as the distance between buildings allow daylight penetration. Both with clear and overcast sky, average illuminances (E_{avg}) (day+electric light) are above recommended values of 500 lux according to NBR ISO/CIE 8995-1. Regarding lighting uniformity, all values obtained are below the recommended minimum (0.5). Daylight Factor (DF) values measured with overcast conditions for three points in the room also lack in uniformity: 8.0% next to the window, 2.5% in the middle of room and 0.4% in the back of the room. The high DF near the window suggests potential thermal discomfort and glare.

The directionality of daylight was measured via produc-

Table 1. Measured illuminances, uniformity ratio, and directionality.

	E_{avg} (lux)	E_{max} (lux)	E_{min} (lux)	U_0 (E_{min}/E_{avg})	Directionality (E_v/E_s)
Electric light	292	586	95	0.30	-
Clear sky (8/10/2019)					
Daylight	898	3360	127	0.14	-
Day+ Electric	1213	4130	243	0.20	1.39
Overcast sky (10/11/2020)					
Daylight	730	2776	113	0.15	-
Day+ Electric	1002	2540	179	0.27	1.53

Figure 6. HDR photographs for directionality calculation.

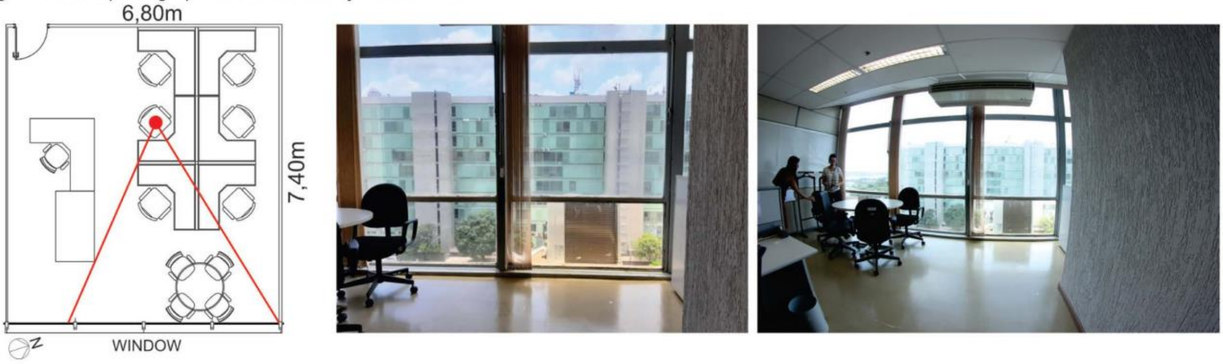


Figure 7. Monitored position in the room and pictures of the view out.

Table 2. Quality of view out for the East room, thresholds as defined by the EN 17037:2018.

	Measured vs threshold	Rate
Horizontal sight angle	100% > 54° /83°	High
Distance of view	> 50m / > 50m	High
Number of layers seen from 75 % of area	3 / 3	High
	General view rate	***High***

tion and manipulation of HDR photographs of a diffusive sphere (Figure 6).The directionality values in both clear and overcast sky (Table 1) are adequate and comfortable for the human eye, according to Cuttle (2003), that recommends values between 1.2 and 1.8. Ambient light produces diffuse shadows, which do not cause visual discomfort. The combination of artificial lighting and natural lighting from the window produces a weak and comfortable shadow for the user's eye.

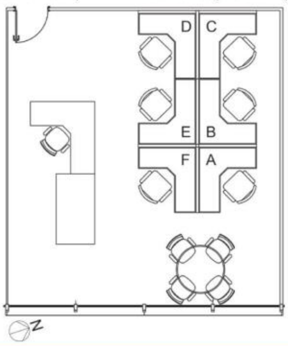
Regarding view out assessment, photographs of the view were taken at a height of 1.2 m from the floor, simulating a seated person (Figure 6). The evaluation (Table 2) shows that view out is rated as High, in all parameters proposed by EN 17037 – Daylight in buildings.

Regarding contrasts, the luminances of the main vertical surfaces were measured, in three different workstations, during the field monitoring in November 2020.

Circadian potential

Equivalent Melanopic Lux (EML) values were calculated via Lucas toolbox and verified against the WELL v2 criteria. The credit requires verification of the EML value re-

Table 3. Equivalent Melanopic Lux (EML) measured via Lucas toolbox with photopic illuminance data



Equivalent Melanopic Lux (EML)			
Workstation	**Electric lighting**	**Daylight + Electric lighting**	
		Clear sky (8/10/2019)	**Overcast sky (10/11/2020)**
A	167.2	283.1	308.5
B	219.4	534.1	705.2
C	41.6	107.9	111.2
D	71.5	148.8	165.3
E	290.9	743.6	716.0
F	219.4	451.3	380.0

ceived at the eye of the occupant during specific times of occupation, awarding a number of credits. Results are showed in Table 3.

According to the WELL v2 criteria,not all the workstations reach the requirements. Only 66% of the workstations reach 200 EML, when combining day- and electric lighting. Again 66% of the workstations reach the target level of 150 EML from electric lighting alone. However, according to the results from the questionnaire, this does not seem to affect psychological health.

User perspective

The building hosts 850 employees and 87 valid responses from questionnaires were obtained. The survey was limited to rooms in east facade, where the field monitoring was performed. Considering that the luminaire close to windows are dimmed by a photosensor, the respondents were divided into two groups: Group 1 consisting of workstations up to 3.7m from the window, and Group 2 with workstations more than 3.7m from the window (figure 8). Most respondents (70) are from Group 1. Overall, 54.5% of respondents were men and 45.5% women, between 17 and 81 years old, working 5 days a week, from 8 am to 6 pm, using monitors.

Most work environments are shared. This is reflected in the users' perception of lighting control, especially the rate of control over electric lighting. In rooms with up to two employees, the rate of respondents who consider that they have a lot of control over electric lighting on their workstation is 65%. In rooms with five or more users, this rate drops to 39%. It can be inferred that the more users share an environment, the more difficult it is to reconcile personal preferences, which can lead to friction. Overall, only 46% of users consider that they have a lot of control over electric lighting in their workspace, even though there is a central lighting control. 43% consider having little or no control over electric lighting. In conversation with the employees, it became clear that most of them were unaware of the existence of the control system, which can explain these results.

> ***"Controls for electric lighting are not available to us – it´s necessary to make a formal request"***

Regarding daylight control, in Group 1 (near the window), 78% of users consider that they have a lot of control over daylight in their workspace, while in Group 2 only 59% consider that they have a lot of control. Possibly the proximity of the window gives the users more freedom to interact with the shading devices (internal blinds).

The combination of electric and daylighting is the preferred condition for both groups, with the preference of 74.3% of respondents in Group 1 and 82.4% in Group 2. 67.2% of users rarely, if ever, work using only daylight. This can be explained because daylighting illuminance is low for carrying out visual activities, requiring the combination to achieve satisfactory illuminance rates. But daylight is very much appreciated (79% satisfied or very satisfied), as it is the windows size (79,5%) and the view out (80.0%). Discomfort due to reflections with daylight is mentioned by 61% of users, mostly in Group 1, although Group 1 users are generally very satisfied with daylight (80%). Despite the generous glazing, there are few complains at all about discomfort with daylight, with mentions that it occurs only in first hours of the morning.

> ***"With closed blinds, daylight becomes poor and it is difficult to do my task"***

Lessons learned

Daylight dimming helps to save around 9% of global energy of this building, despite the high luminous efficacy of the installed fluorescent lamps, which is comparable to that of many today's commercial LEDs.

The building has a good daylighting design, especially due to the laminar shape and limited room depths. Despite the east/west orientation being not the ideal for solar protection, most offices in east façade did not show particular glare issues. The high quality of view out and the presence of daylight helps to improve visual environment. The addition of more efficient internal solar control elements could help to avoid some reflections mentioned by users in the morning. The combination of electric and daylighting produces a weak and comfortable shadow for the user's eye.

Users opinion shows that they are quite satisfied with daylighting in rooms, and they most prefer to work with the combination of day- and electric lighting. The perceived control over electric lighting is poor, even if the users consider the control system easy to use. Informing and educating users about the functioning of the control system would greatly help.

Further information

D.Silva, I. and Amorim, C.N.D. (2020). *Qualidade da iluminação e impactos no usuário: monitoramento do ritmo circadiano e satisfação do usuário em edifícios de escritório*. Proceedings of the XXVI Congress of Scientific Initiation 2020, University of Brasília, Brazil.

Toledo, G. and Amorim, C.N.D. (2020). *Qualidade da iluminação, vista exterior e direcionalidade: monitoramento em ambientes de edifícios de escritórios*. Proceedings of the XXVI Congress of Scientific Initiation 2020, University of Brasília, Brazil.

Acknowledgements

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Special thanks to Engineer Alvanir Carvalho and Architect Terêncio Júnior from MME.

Light and shadows in an Amazon building

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Challenges to integrate daylight and solar protection elements in an iconic building of the Brazilian modernism

In a representative Amazon building daylight use and solar control elements are examined. Occupants are satisfied with the indoor space, despite some changes done to the original design. Computational simulations suggested good daylighting design overall, with little risk for glare occurrence, as in the intention of the original design.

The project

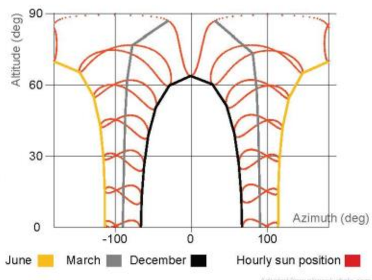
Forum Sobral Pinto (Figure 1) is an important building in Boa Vista City, capital of Roraima state, extreme North of Brazil. Located close to Equator line, immersed in Amazon Forest, the place serves to the local judiciary authority. The Forum Sobral Pinto was built in 1979, designed by Severiano Mário Porto - an icon of Brazilian modernism architecture -, internationally recognized as the "architect of the Forest "or the "architect of the Amazon". Elected man of the year by the French magazine *L'Architecture d'Aujourd'hui* in 1987, he developed in the Amazon a design with its own identity, using resources such as integration and use of local bioclimatic potential, with focus on cost optimization, renewable materials, and regional techniques. In the Forum Sobral Pinto building, Severiano

Figure 1. Forum Sobral Pinto building.

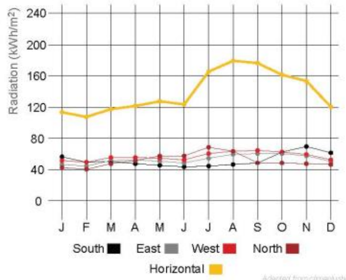
Mário Porto applied bioclimatic strategies – like fixed solar shading elements - with impressive quality, while the limited depth of the building still allowed for abundant daylight penetration.

The building has an area of 5686 m^2 distributed in four floors (including an underground one). All the windows are oriented Northeast and Southwest, with fixed concrete elements used as solar shading (Figure 2). Originally, these windows had a single glass, but solar and light control films were added later for privacy and security. The windows films are of smoked type, with 50% of light transmittance. Such modification represents a major change in the original daylighting design by Severiano Mário Porto.

Location: Boa Vista, Roraima, Brazil
-11.99°, -84.14°



Sun path for
Boa Vista, Roraima, Brazil



Global horizontal and vertical radiation for
Boa Vista, Roraima, Brazil

IEA SHC Task 61 Subtask D
Monitored by Ayana Dantas de Medeiros, **Derick Lucas, Leslie Oliveira, Nathalya Melo, Poliana Pires,** Lab of Environmental Control and Energy Efficiency - LACAM, UnB
More info **Cláudia Naves David Amorim**, University of Brasilia, clamorim@unb.br

Figure 2. Forum Sobral Pinto, Northeast Façade.

Figure 6. Workstations in Office 2.

Sun radiation in the Amazon context is often intense; the design from Severiano Mário Porto in this building includes fixed horizontal and vertical frames, providing sun protection at critical times, with good shading angles (Figure 3). In this building, solar elements block solar radiation after 9:00 am in the Northeast façade and until 3:00 pm on the southwest façade. The climatic context challenges the architectural project to optimize daylight in indoor spaces, without compromising thermal comfort of the building. Therefore, shadows and sun protection are an important strategy to keep environmental quality in the Amazon building, and to minimize energy use.

Monitoring

The first field monitoring was performed on 28th and 29th August 2019, around 11:30 am. The sky condition was partly cloudy, with global illuminance values between 13800 lux and 28700 lux. A second field monitoring was done on 2nd and 3rd January 2020, at the same time as the first monitoring. The global illuminance ranged between 7100 lux and 16400 lux, with overcast sky conditions. The measurements were performed in representative offices on ground floor and 2nd floor, in Northeast and Southwest façades (Figures 4, 5 and 6).

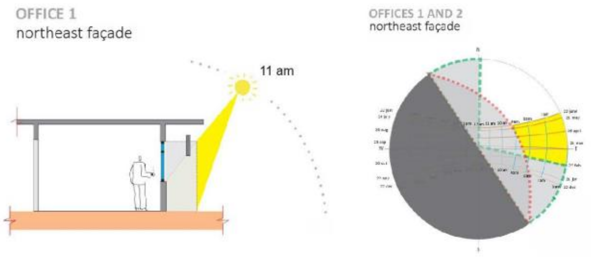


Figure 3. Section and solar chart showing solar protection elements in Northeast façade.

Figure 4. Plan of the building floors, with monitored offices.

Figure 5. Plan of monitored offices.

The investigated aspects were illuminance (grid based and on task), uniformity, directionality, reflectance, view out, circadian potential, energy use, and users' perspective.

Energy

The electric lighting system consists of LED T8 luminaires 2x18W, providing lighting at 6500K and an on-off system. In the building, there is no separate energy meter for lighting, so the calculation of energy use was made based on the European Standard EN15193-1:2017. The Lighting Energy Numeric Indicator (LENI) average in three measured offices was 16.84 kWh/m²yr, varying between 20.10 kWh/m²yr in Office 1, 16.70 kWh/m²yr in Office 2 and 13.70 kWh/m²yr in Office 3.

Photometry

The field monitoring was done for two different conditions: daylighting and day+electric lighting (usual condition). Table 1 present some of the results.

Regarding illuminance, in both monitoring with partially cloudy sky and overcast sky, the workstations did not reach the minimum illuminance levels with daylight only,

Table 1. Measured illuminance and uniformity.

Monitored room	Source	E_{avg} (lux)	E_{max} (lux)	E_{min} (lux)	Uniformity (U_0) E_{min} / E_{avg}	E_{avg} (lux)	E_{max} (lux)	E_{min} (lux)	Uniformity (U_0) E_{min} / E_{avg}
		28-29 August 2019 (partly cloudy)				**2-3 January 2020 (overcast)**			
Office 1 (Northeast)	Daylight	58	118	21	0.36	35	75	5	0.14
	Day + Electric	657	1018	155	0.23	639	1050	245	0.38
Office 2 (Northeast)	Daylight	57	210	8	0.13	62	180	16	0.38
	Day + Electric	517	875	113	0.21	470	880	150	0.31
Office 3 (Southeast)	Daylight	57	455	10	0.17	115	500	33	0.28
	Day + Electric	354	620	130	0.36	461	1090	160	0.34

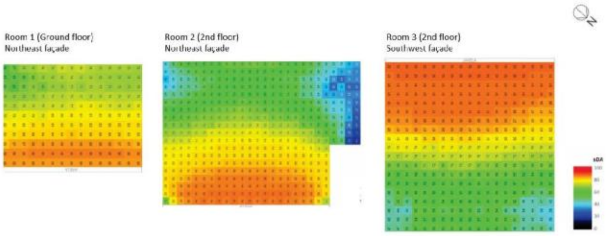


Figure 7. Spatial Daylight Autonomy (sDA).

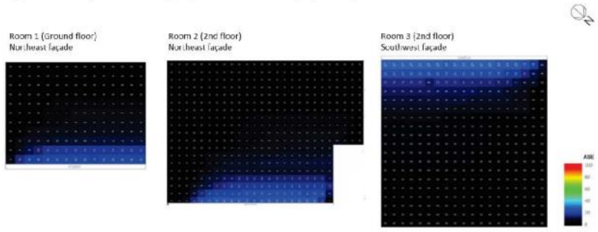


Figure 8. Annual Sun Exposure (ASE).

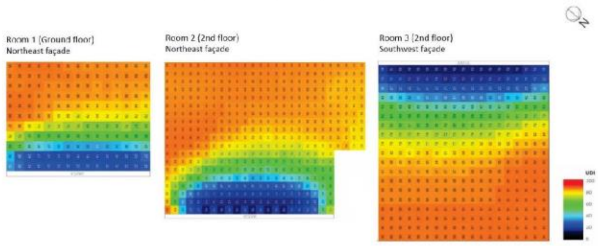


Figure 9. Useful Daylight Illuminance (UDI).

Table 2. View out quality according to EN17037:2018.

Office	Criteria	Results	Rate
1	Horizontal sight angle	104°	High
	Distance of view	> 50 m	High
	No. layers	2	Medium
	General view rate		***Medium***
2	Horizontal sight angle	97°	High
	Distance of view	> 50 m	High
	No. layers	3	High
	General view rate		***High***
3	Horizontal sight angle	90°	High
	Distance of view	> 50 m	High
	No. layers	2	Medium
	General view rate		***Medium***

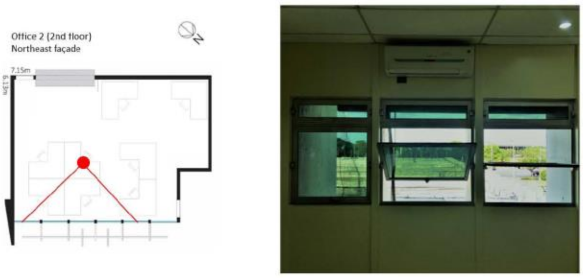


Figure 10. View out in Office 2.

which should be 500 lx according to the Brazilian standards. Most probably, this was due to the very low visible transmittance of the control films applied to the existing glazing. Therefore, the field monitoring was complemented with computer simulations, where the daylighting performance of original design (without solar control films) was tested. The simulations were performed with the software DesignBuilder 6.0 and Radiance. The original condition of the project was considered, with simple 6 mm glazing, with 89% light transmission (instead of 50%, with solar control films). The following daylight performance metrics were simulated: Spatial Daylight Autonomy (sDA), Annual Sun Exposure (ASE) and Useful Daylight Illuminance (UDI). Figures 7, 8 and 9 present the results.

Spatial Daylight Autonomy (sDA) shows that in all offices illuminance values are higher than 500 lux for most of the year. Regarding glare risk, the levels of Annual Sun Exposure (ASE) higher than 2000 lux are reached only for 25% of the working hours, with open blinds. The occurrence of values above 2000 lux is only in the areas close to the windows, representing a small area. Useful Daylight Illuminance (UDI), between 100 and 2000 lux, shows a great vocation to daylight use in all simulated rooms, in the original design condition. Close to the windows, the daylight illuminance is sometimes above the UDI threshold (2000 lux), which explains the low UDI percent in such areas.

Regarding view out assessment, the evaluation follows parameters proposed by EN 17037 Daylight in buildings (CEN, 2018). All offices have a high view range, a good external distance but the number of layers varies from medium to high, determining the general quality of the view in the studied offices: Medium in two and High in one. Figure 10 illustrates the view out from one of the office. In Figure 10, the effect of the solar control film can also be appreci-

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ated.

The results for the view out are presented in Table 2.

Circadian potential

Equivalent Melanopic Lux (EML) values were calculated using the Lucas spreadsheet using the approximate method via measured illuminance levels. The results were benchmarked against the Circadian System criterion of the WELL v2 building standard. Results are showed in Table 3. Considering that 75% or more of the workplaces must have at least 200 equivalent melanopic lux according to WELL v2, only Office 3 does not meet minimum requirements. Since the control film filtrates the incoming daylight, it would be interesting to test further the resulting melanopic lux when measuring the actual Spectral Power Distribution of light.

Table 3. Measured Equivalent Melanopic Lux (EML).

	Workstation	08/10/2019 (partly cloudy)	10/11/2020 (overcast sky)
Office 1 (Northeast)	1	395	237
	2	233	253
Office 2 (Northeast)	1	379	**197**
	2	316	403
	3	292	261
	4	252	**150**
	5	**110**	**103**
	6	284	245
	7	221	**69**
	8	**103**	**66**
Office 3 (Southeast)	1	**123**	**111**
	2	**126**	**170**
	3	**123**	**150**
	4	**79**	**123**
	5	**87**	**111**
	6	**103**	237
	7	**158**	**134**
	8	**32**	**96**
	9	284	229

User perspective

A questionnaire was used to investigate users' opinion regarding daylight and well-being conditions in the building. The building hosts 260 employees, and 37 valid responses were obtained. Roughly, half of the respondents were women; 27.3% of the respondents were under 30 years old, 19.6% between 30 and 40 years old, 44.7% between 40 and 50 years old, and 8.4% over 50 years old. Regarding the general impression, almost 60% of users were satisfied or very satisfied with the space. However, only 44% were satisfied with daylight, probably because the addition of solar films reduced illuminance levels. In fact, 86% of users answered that they could never work using only daylight. Regarding view out, the answers were more scattered: 31% were very satisfied, 34% tending for neutral and 31% very dissatisfied. Here is important to note that solar control films tend to distort colours and this can also influence the user's perception.

" Too much electric light in my workstation with just a little of daylight coming from the windows. I also notice a 'conflict' between electric light and computer monitor light. "

"Artificial lighting is widely used. It's possible save energy. "

Lessons learned

In terms of daylighting, when applied the monitoring protocol on the usual condition of the case study, the illuminance values are not satisfactory according to Brazilian standards (average, on task and uniformity). Regarding the exterior view out, results showed medium and high quality, with the number of layers being decisive. Analysing the circadian potential, either with only daylighting or with the day+electric lighting combination, the results are satisfactory in most of monitored rooms. When considering the users' perspective as an element of investigation of these environments, the answers corroborated with some of these results: most mention that there is little daylight availability in their work plan and the totality of the respondents stated that they do not use only daylighting for work. However, satisfaction with space are polarized and point to a positive majority. Satisfaction with the view out and other qualities of the space can justify this fact.

The addition of solar films, due to security and privacy needs, reduced the luminous transmission of glazing from 89% to 50%. Lighting simulations with original condition without solar films shows the potential for daylight of original design. The results show good illuminance levels, without glare. As a lesson learned, retrofit measures should be selected carefully and coherently with the intention of the original design. In this case, for example, Severiano Mário Porto's original design for Boa Vista, - with fixed solar control elements and a thoughtful building shape, achieved a satisfactory daylighting performance despite all concerns with sun protection and shading for buildings in the Amazon. However, the later application of solar films for privacy reasons partially spoiled an impressive daylighting design.

Further information

Medeiros, A. D. (2020). *A arquitetura de Severiano Mário Porto na cidade de Boa Vista: um olhar com enfoque bioclimático (Severiano Mário Porto's architecture in Boa Vista city: a bioclimatic perspective).* Master thesis in Architecture and Urbanism Programme, Faculty of Architecture and Urbanism, University of Brasilia, Brasilia, Brazil

Acknowledgements

This work was supported by the **National Council of Scientific and Technological Development (CNPq)** of Brazil. Support on site: Forum Sobral Pinto Management
Special thanks to **Jorge Jaworsk** (building manager)

Good daylighting design can exploit use of lighting controls

North and south oriented facades, internal courtyard, limited depth, and large windows shielded this building from direct solar radiation.

At this office building in the University of Brasilia daylighting is the main lighting source thanks to the building shape, the internal courtyard, and well-designed solar protections. Daylighting and view out with high quality improve user´s satisfaction in the workplaces. Energy use for lighting is high and it could be exploited using electric lighting controls.

Figure 1. Office building at the University of Brasilia campus.

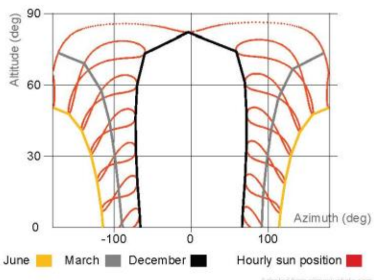
The project

The office building at the University of Brasilia (UnB) is located in the Darcy Ribeiro Campus, near to the Scientific and Technological Park and houses the Deans' offices for 'Research and Innovation' and 'Graduate Studies'. The building was chosen because of its good daylighting design, as well as its potential for lighting control use. The main facades are North and South oriented, and the offices are distributed alongside them, with large windows shielded from direct solar radiation via external horizontal brise soleil in North facades, solar control films and curtains in South facades. The building has an internal courtyard and the office rooms have limited depth, which improves the daylighting performance. Since daylight is abundant in the whole building, there is a huge energy saving potential from the installation of lighting control systems. The building floor area is approximately 4000 m² and around 150 users work from 7:30 am to 7:30 pm.

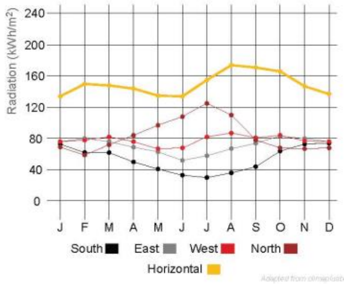
Monitoring

Photometric measurements were taken in selected occupied rooms, located along the North and South facades (figure 3). The assessment included measurement of horizontal/vertical/cylindrical illuminance and external view quality. The measurement points were located on a grid, as suggested by the CEN standard. External view quality was evaluated based on CEN criteria. The first monitoring was performed on 7th May 2019 at day and night times, with overcast sky and global illuminance values between 28 300 and 77 000 lux. The second monitoring was performed on 10th November 2020 at daytime, with clear sky

Location: Brasilia , Brazil
-15.80°, -47.87°



Sun path for
Brasilia, Brazil



Global horizontal and vertical radiation for
Brasilia, Brazil

IEA SHC Task 61 Subtask D

Monitored by **Ayana Dantas, Flavia Bukzem, Gabrielle Toledo, Igor Silva, João Francisco Walter Costa** and **Adriana Sekeff**, LACAM, University of Brasilia

More info **Prof Cláudia Naves David Amorim**, University of Brasilia, clamorim@unb.br

Figure 2. Internal courtyard of the building.

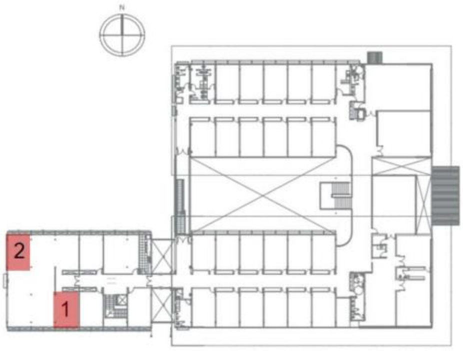


Figure 3. Plan with the monitored rooms 1 (North) and 2 (South).

Figure 4. Picture from monitored Room 1 (South).

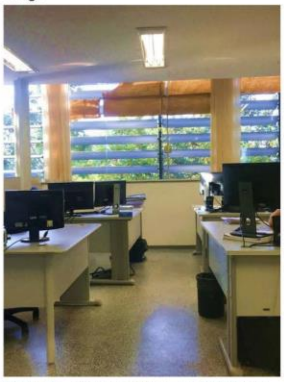


Figure 5. Picture from monitored Room 2 (North).

and global illuminance values between 81 000 and 120 000 lux. All measurements were performed in two representative office rooms on 2th floor (figure 1), Room 1 in South façade, with 22.65 m2 area and 6.00 m deep (figure 4), and in Room 2 in North façade (figure 5), with 24.36 m2 area and 5.47 m deep. The limited depth of rooms ensures a good of daylight. Internal reflectances are as follows: floor 59%, walls 85%, ceiling 80%, partitions 70%. Windows have 6 mm simple clear glass with visible light transmission of 89%.

Energy

The electric lighting system consists of efficient fluorescent T5 recessed luminaires 2x32W providing lighting at 4000 K. The lighting power density is around 10.56 W/m². The buildings at University of Brasilia are not provided with individual energy meters, so a simulation with Design Builder Software of the building was carried out to verify energy consumption, based on a survey of the location. The results are presented in Table 1.

The total energy use is around 182.69 KW/h/m²/year, where lighting accounts for approximately 62% and air conditioning 20%. With these data, the building's potential for modernization and automation of electric lighting is evident.

Table 1. Yearly energy use for different building services (kWh).

Lighting	Air conditioning	Other
428 914	118 069	116 138

Photometry

The field monitoring was conducted with three different conditions: daylighting, electric lighting and day+electric lighting (Table 2). The results show adequate conditions of horizontal illuminance according to NBR ISO/CIE 8995-1. Regarding uniformity, values are just a pinch below the recommended minimum (0.5).

Directionality of light was measured via HDR photographs of a diffusive sphere (figure 7). The directionality values are above recommended limits (strong and moderately strong). Accentuated shadows are present on objects, especially in the South room. According to the method developed by Cuttle in 1971, the vector-scalar illuminance values found are between 1.91 and 2.70, which represents a strong discomfort. Room 2 (North), with solar control elements, does not have as much discomfort as room 1, but it is still classified as "moderately strong".

Regarding view out assessment, photographs of the view were taken at a height of 1.20 m from the floor, simulating a seating person. The following results for both room 1 (South) and 2 (North) were obtained (Table 3). The evaluation (Table 2) shows that view out is rated as 'high' for room 1 according to the EN 17037- Daylight in Buildings, while is rated 'medium' for room 2.

Due to the pandemic Coronavirus conditions, the monitoring was interrupted in 2020. To complement monitoring, some computer simulations were performed, namely Daylight Factor (figure 8) and Annual Daylight Glare Probability (figure 10), using the software Grasshopper and DIVA for Rhino. The simulated values of verage Daylight Factor range from 3.93 to 12.21%, showing potential glare, especially in Room 1 (south). Simulations shows that there are potential critical glare occurrences especially in Room 1 (south) (figures 9 and 10). These potential glare situations can be avoided if, for example, solar films (with reduced visible light transmission of 70%) were added to windows, as simulated in figure 10.

Table 2. Measured illuminance, uniformity, and directionality of light.

	E_{avg} (lux)	E_{max} (lux)	E_{min} (lux)	U_0 E_{min} / E_{avg}	Directionality E_v / E_s
Room 1 South - 7 May 2019 (clear sky)					
Daylight	687	1580	200	0.29	-
Electric light	411	542	230	0.56	-
Day+ Electric	1119	1740	630	0.56	2.7
Room 1 South - 10 November 2019 (clear sky)					
Daylight	1901	5250	490	0.25	-
Day+ Electric	2328	5210	1006	0.43	1.9
Room 2 North - 7 May 2019 (clear sky)					
Daylight	349	880	97	0.27	-
Electric light	251	400	99	0.39	-
Day+ Electric	899	1900	330	0.37	2.0
Room 2 North - 10 November 2019 (clear sky)					
Daylight	710	1120	280	0.39	-
Day+ Electric	886	1415	390	0.44	2.0

Circadian potential

Equivalent Melanopic Lux (EML) values were calculated using the Lucas toolbox (Lucas et al, 2014) and evaluated against the Lighting for the Circadian System criteria of the WELL v2 building standard. The credit requires verification of the EML value received at the eye of the occupant during specific times of occupation, awarding a number of credits. Results are showed in Table 4.

When combining day- and electric lighting, 100% of the

Table 3. View out quality according to EN17037:2018.

Room	Criteria	Results	Rate
1	Horizontal sight angle	> 54°	High
	Distance of view	> 50 m	High
	No. layers	3	High
	General view rate		***High***
2	Horizontal sight angle	> 54°	High
	Distance of view	> 50 m	High
	No. layers	2	Medium
	General view rate		***Medium***

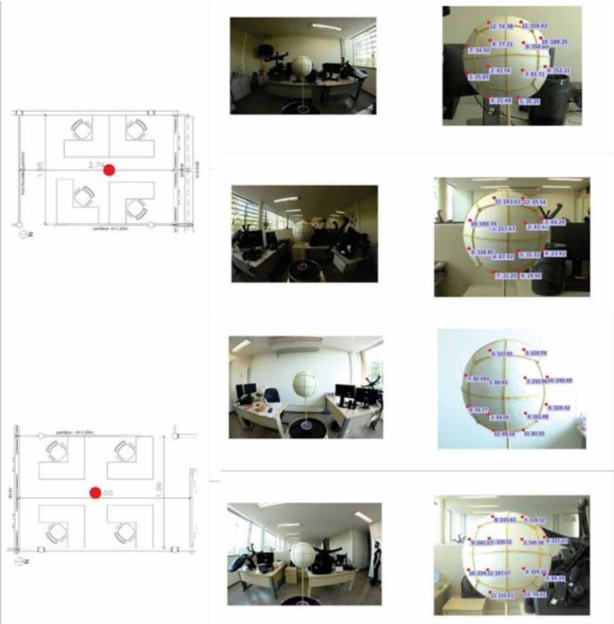


Figure 7. HDR photographs of the sphere to calculate daylight directionality in Room 1 – South (top) and Room 2 - North (bottom).

workstations reach 200 EML. The second requirement is that all workstations must have at least 150 EML with electric lighting alone. In room 01, only 50% meet the recommendation and in room 02, no workstation reaches the required minimum.

User perspective

The building hosts 150 employees, and 17 valid responses were collected for a survey handed out to the employees working in the monitored rooms. The survey included 45 questions structured in three sections: general data, social and physical climate, and user experience with lighting. It was distributed to 17 users who work in the monitored rooms.

Overall 42.3% of respondents are male, 53.8% are female, between 18 and 56 years old, working 5 days a week from 8 am to 5 pm. 85.2% of respondents are located less than

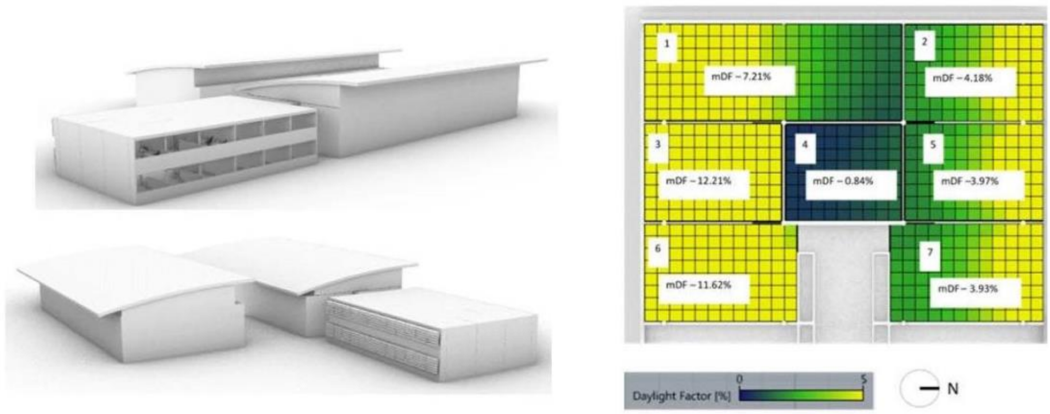


Figure 8. Building model and simulated Average Daylight Factor values in building plan, including Rooms 1 and 2.

Good daylighting design can exploit use of lighting controls

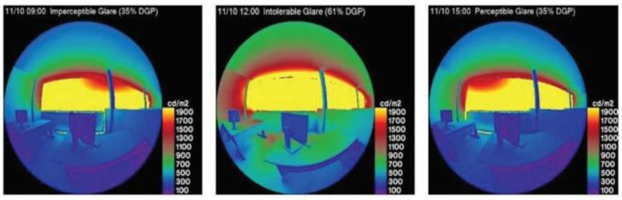


Figure 9. Point in time glare in South facing room, 10th November at 9 a.m. (left), 12 p.m (center) and 3 p.m. (right) with clear sky.

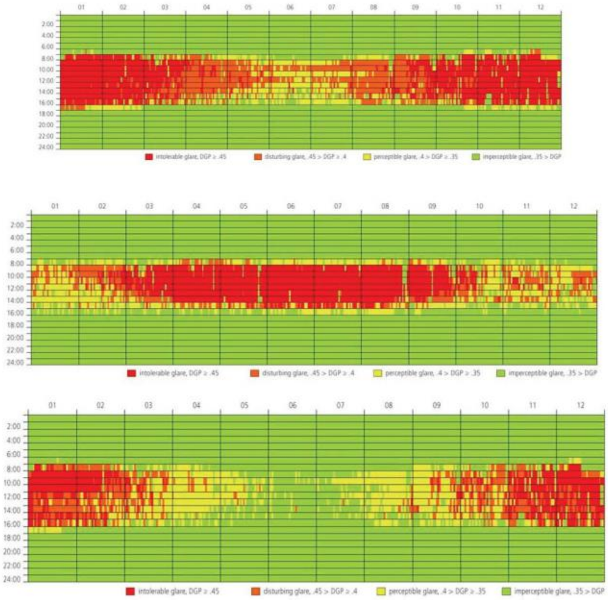
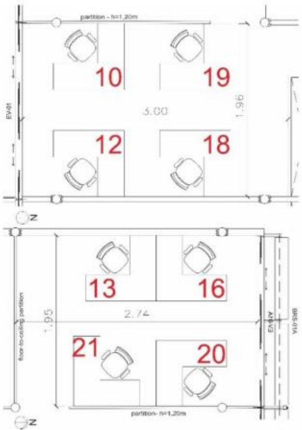


Figure 10. From top to bottom: Annual Glare Probability for South room, North room, and South room with solar film added (LT 70%).

5 meters from the window and 70.4% work with a monitor. Most work environments are shared. 74% of respondents consider that work requires a lot of concentration. 77.7% answered that they felt tired in the last four weeks, the main causes being the fatigue of the routine, the demand for work and the route between the residence and the work. Regarding daylighting in the work area, 75% of respondents are very satisfied with daylighting and 88.2% are satisfied or very satisfied with the overall impression of the environment. 88% responded that they have a lot of light in their work area, but 48% declare to have discomfort with daylight, what confirms the monitoring results. 60% of users prefer to work only with daylighting and 40% prefer the combination. 76% say they have medium or a lot of control over daylighting. Regarding electric lighting, 47% responded that they have a lot of electric lighting in the work area, 70.5% responded that they have medium or a lot of control over lighting and 58.8% usually feel little or no discomfort with electric lighting.

"There is a lot of daylight, but we don´t like to close the curtains"

View out is much appreciated



ROOM 01 (south) - Equivalent melanopic lux (EML) values			
Workstation	Electric lighting	Day+electric lighting	
		07/05/2019 (clear sky)	10/11/2020 (overcast sky)
10	192,68	838,08	1351,95
12	195,79	1207,85	1222,57
18	142,96	1138,69	772,28
19	139,23	670,73	696,78

ROOM 02 (north) - Equivalent melanopic lux (EML) values			
Workstation	Electric lighting	Day+electric lighting	
		07/05/2019 (clear sky)	10/11/2020 (overcast sky)
13	124,31	692,31	438,97
16	130,53	916	837,13
20	48,48	336,02	230,65
21	131,77	754,74	573,4

Table 4. EML values in room 1 (South) and 2 (North).

Lessons learned

The integrated daylighting design in the building was relatively successful, both due to the orientation of the main facades (north/south) and the building form. Office rooms are not very deep and can take advantage of daylight during daytime and also from high quality view out, especially in South façade, which can compensate glare occurrences. Despite this, problems with reflections and glare from daylight were detected in the simulations, in South façade, that has no solar protection, but also in North facade. These problems could be reduced with the addition of solar control films in glazing, reducing daylight but preserving view out, very much appreciated.

Users are satisfied with daylighting, which most of them prefer as sole source of illumination. They have also a good perception about their control over daylighting. While the office can rely on quite efficient light source, it is clear that the building could largely improve its lighting energy performance regarding electric lighting if adequate daylight-linked controls were installed.

Further information

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Santos, A.C. and Amorim, C.N.D. (2019). *Iluminação, aspectos fotométricos e ritmo circadiano: aplicação de protocolo de monitoramento em edifícios de escritório*. Proceedings of the XXV Congress of Scientific Initiation 2019, University of Brasília, Brazil.

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Acknowledgements

Financial support: National Council of Scientific and Technological Development (CNPq), Brazil.

Integration for daylight and electric lighting plays an important role for NZEB

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Integrated solutions for daylight and electric lighting in NZEB office building

In CABR NZEB office building, the integrated solutions for daylight and electric lighting have improved the luminous environment and achieved nearly 75% energy-saving rate.

The project

China Academy of Building Research Near Zero Energy Office Building is located in No.30, BeiSanHuanDong Road, Chaoyang district of Beijing. The building was officially put into use in 2014, and the certification target is 3-star level green building and LEED-NC platinum (Fig.1).

According to the principles "passive priority, active optimization, economical and practical", this office building integrates advanced building technology, evaluating with actual data, as a demonstration for the development of ultra-low-energy buildings in China. This project is located at east longitude 116°20', north latitude 39°56', nearby BeiSanHuan road in Beijing (Fig.2). The north and northeast side of the office building is the high-rise office building of CABR, and the south side is the office building of institute of building fire research (Fig.3).

The first and second floors of the office building are significantly sheltered, and the third and fourth floors have good views and daylighting.

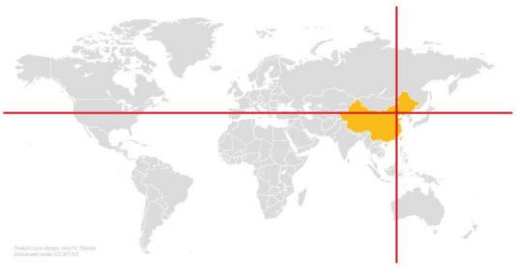
This 4-storey office building, with a total area of 3692 square meters, is mainly used for office and conference, hosting a staff of about 160 people.

Figure 1. China Academy of Building Research (CABR) in Beijing.

Daylighting and lighting solutions

Different daylight and electric lighting solutions are tested in the rooms of this building.

Horizontal blinds are used for sidelit windows. Compared with the traditional roller shade, the embedded horizontal blind has a better adjustment performance, which can make indoor illuminance more uniform and make full use



Location: Beijing, China
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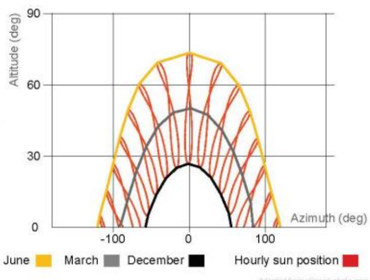

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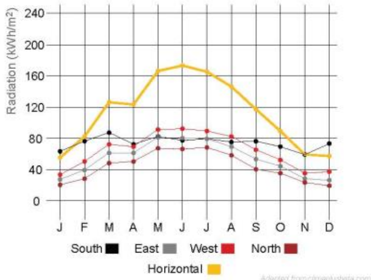

Global horizontal and vertical radiation for
Beijing, China

IEA SHC Task 61 Subtask D

Monitored by **Luo Tao**
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Integration for daylight and electric lighting plays an important role for NZEB

SOLAR HEATING & COOLING PROGRAMME
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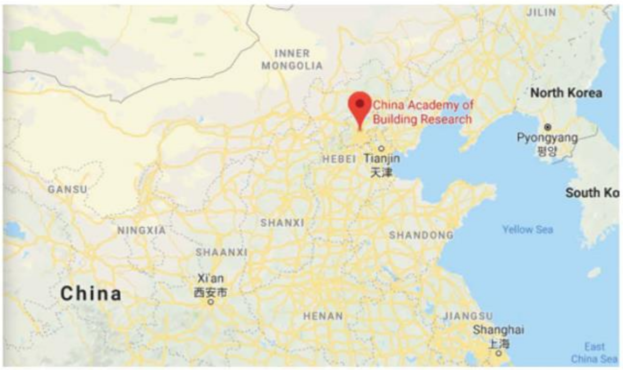


Figure 2. Location of CABR NZEB in the eastern part of China. Map data ©2019 Google

Figure 3. Sorroundings of the CABR nZEB building.

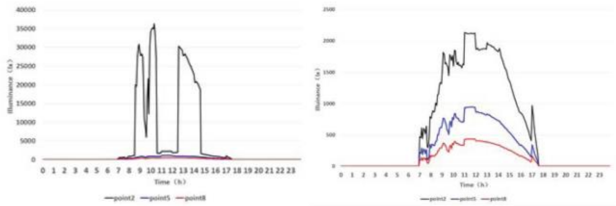


Figure 4. Measured illuminance (lux). Indoor illuminance distribution without blinds (left) and indoor illuminance distribution with embedded blinds (right)

Figure 5. The CABR conference rooms. On the ceiling, the tubolar daylighting system can be seen.

of daylight while avoiding glare, as shown in figure 4.

The conference room on the fourth floor of CABR demonstration building adopts an adjustable light pipe lighting system to ensure daylight and avoid excessive heat entering the room (Fig.5).

A total of 655 sets of high-efficiency energy-saving luminaires and 167 sensors of illuminance, infrared, mobile and so on are used in this project. The luminaires used in this demonstration building are all from Philips. Office general lighting adopts fluorescent grille with T5 fluorescent lamps and LEDs (for comparative analysis). In addition, corridors and public spaces adopt LED downlights. Detailed information are shown in Table 1.

Room 407 on the fourth floor adopts POE power supply technology with 8 sets of luminaires, which can realize centralized control and single luminaire control mode with mobile phone APP.

We carried out the optimization lighting design on the basis of choosing high-efficient luminaires, and under the premise of meeting the lighting requirements, the lighting installation power is reduced to achieve lighting energy saving. The illuminance distribution of typical rooms is provided in Figure 5.

Table 1. List of the luminaires installed in this case study.

	Luminaire type	Luminaire specification	Installation	Application area
1	Embedded fluorescent grating lamp	TBS737 2XEco TL5-25W HFE ETO	Embedded	Office
2	Embedded fluorescent grating lamp (light sensor)	TBS737 2XEco TL5-25W HFR 1-10V ETO	Embedded	Office by the window
3	Embedded LED luminaire	PowerBalance RC600B LED41S/840 W30L120 PSD	Embedded	Office, conference
4	Embedded LED luminaire(light sensor)	PowerBalance RC600B LED41S/840 W30L120 PSD + ACL	Embedded	Office by the window
5	Embedded LED luminaire	SmartPanel RC160V LED34S/ 840 PSD W30L120	Embedded	Reception room
6	Embedded LED luminaire	GreenPerform Troffer RC100C LED35S/840 PSD W30L120	Embedded	monitor room
7	Embedded LED downlight	LuxSpace BBS489 1000lm 4000K PSD-DALI	Embedded	conference
8	Embedded LED downlight	GreenSpace DN181B 1000lm 4000K	Embedded	Corridor, toilet
9	Embedded LED downlight	GreenSpace DN182B 1500lm 4000K	Embedded	Main entrance hall
10	LED ceiling light	Hengjie LED ceiling lamp	Surface mounted	staircase
11	LED batten luminaire	GreenPerform Batten BN208C LED40/ NW L1200 FR	Surface mounted	air-conditioning control room, storeroom

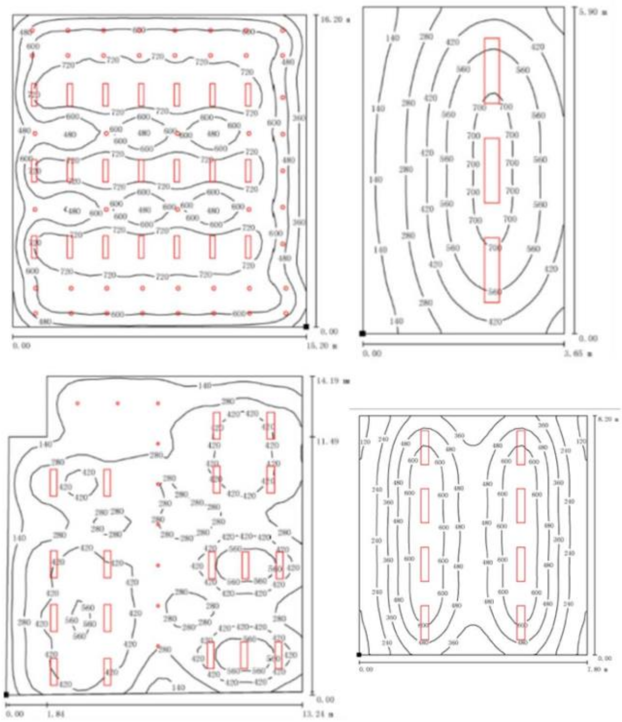


Figure 6. Distribution of artificial lighting illuminance (lux) for the following rooms: conference room at the fourth floor (top-left), reception at the second floor (top-right), open-plan office at the second floor (bottom-left), a private office (bottom-right).

Table 2. Measured average daylight factor (ADF), illuminance, and uniformity ratio (U_0) for the tubolar daylighting system without electric lighting. The outdoor illuminance was 500 lux during the test.

Mode	ADF (%)	Illuminance (lux)	U_0 (%)
Side window with Tubular Daylighting System	0.73	365	0.4
Tubular Daylighting System	0.61	305	0.3

The lighting control system adopts the intelligent lighting control system provided by Philips and Lutron, which includes absence sensing, dimming and other control methods. Luminaires near windows can adjust the light output according to the daylight and areas such as conference room, office and corridor are equipped with absence sensing so as to automatically turn off lights when people out. A variety of lighting modes are set up in conference room to reduce lighting energy consumption.

Monitoring

Energy

According to the actual test data, the annual lighting energy consumption is 6.15 kwh/m^{2}y.

Photometry

The daylight factor of conference on the fourth floor was test, as shown in Table 2. The actual test results of the light environment of typical rooms in this demonstration building are shown in Table 3. The actual lighting effect is shown in Figures 7, 8, and 9.

Table 3. Test results for the rooms in CABR.

Room	Room type	Light source	Parameters		Lighting standard value	Measured value
401	Conference room (major)	LED	E_h (lux)		300	603
			U_0 (%)		0.6	0.74
			CCT (K)		4000	4048
			CRI		$R_a \geq 80$	83.2
					$R_9 > 0$	22
			LPD (W/m^2)		9	5.7
213	Open plan office	T5 lamps	E_h (lux)		300	448
			U_0 (%)		0.6	0.74
			CCT (K)		3300-5300	4212
			CRI		$R_a \geq 80$	80.6
			LPD (W/m^2)		9	7.9
412	Private office	T5 lamps	E_h (lux)		500	631
			U_0 (%)		0.6	0.84
			CCT (K)		3300-5300	4212
			CRI		$R_a \geq 80$	80.6
			LPD (W/m^2)		15	10.6
311	Private office	LED	E_h (lux)		500	768
			U_0 (%)		0.6	0.67
			CCT (K)		4000	4048
			CRI		$R_a \geq 80$	83.2
					$R_9 > 0$	22
			LPD (W/m^2)		15	5.3
319	Open plan office	LED	E_h (lux)		300	832
			U_0 (%)		0.6	0.8
			CCT (K)		4000	4048
			CRI		$R_a \geq 80$	83.2
					$R_9 > 0$	22
			LPD (W/m^2)		9	5.5
	Video conference room	LED	E_h (lux)		750	1108
			U_0 (%)		0.6	0.6
			CCT (K)		4000	4048
			CRI		$R_a \geq 80$	83.2
					$R_9 > 0$	22
			LPD (W/m^2)		-	5.2
	Entrance hall	LED	E_h (lux)		200	404
			U_0 (%)		0.60	0.67
			CCT (K)		-	3990
			CRI		$R_a \geq 80$	84.6
					$R_9 > 0$	23
			LPD (W/m^2)		-	3.9
	Corridor	LED	E_h (lux)		100	162
			U_0 (%)		0.60	0.94
			CCT (K)		-	3990
			CRI		$R_a \geq 80$	84.6
					$R_9 > 0$	23
			LPD (W/m^2)		-	3.9

Figure 7. Lighting environment for a private office equipped with LED panels. Electric lighting set to 100% output (left) and 50% dimming (right).

Figure 8. Lighting environment of the open-plan office (LED)

Circadian potential

All the offices are daylit spaces, providing plenty natural light to the staffs. To our experience, daylight can provide a sufficient circadian stimulus.

User perspective

Survey questionnaires on the luminous environment for the staffs were proposed. According to the survey results, more than 85% people expressed satisfaction or great satisfaction in general. More than 90% are satisfied with the automatedcurtains. The staff showed appreciation for the daylight, which makes them more active and happier.

Lessons learned

Daylight plays an important role in offices, and it's also the key factor for energy-saving. Based on good daylighting design and control, the energy-saving rate could reach 75%, compared to the Chinese lighting design standards.

In this project, fluorescent lights are also used in some areas, in order to do a comparative study. LED lighting is more efficient than other sources, combined with intelligent control, and integrated with daylight, the lighting energy consumption of the project could be less than 5 kWh/m^{2}y if all LED lights are used, based on the simulation results.

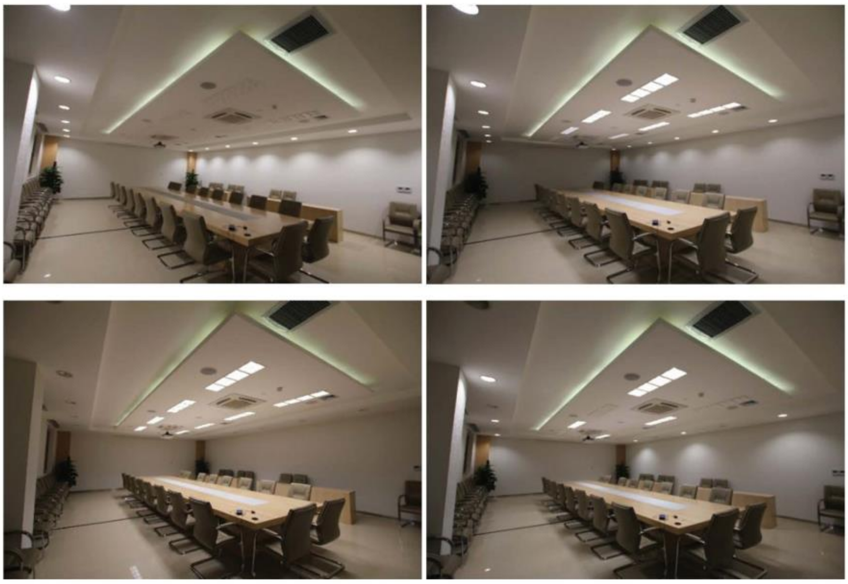


Figure 9. Lighting environment for different scene settings (or “modes”) in the video conference room equipped with LED.

Further information

http://www.chinaibee.com/

Acknowledgements

Financial support: China-US Clean Energy Cooperative Research Project
Support on site: www.chinaibee.com

Integrated design for daylight and electric lighting in Olympic competition venue

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

ETFE inflatable pillow, daylight harvesting and High-power LED Lighting in National Aquatics Center

In National Aquatics Center, daylight was brought into the competition area. Combined with high-power LED and intelligent control lighting system, this venue improves the race experience for athletes and meets the requirements for various competition modes in winter and summer.

The project

The National Aquatics Center (NAC), better known as “Water Cube” will serve as a curling site of the 2022 winter Olympics in Beijing & Zhang jia kou, and the original site lighting system is used for aquatics, such as swimming, diving and synchronized swimming. The retrofitted site lighting system needs to be considered simultaneously for using as ice sports and aquatics in winter and summer, also needs to adapt to the requirements of site conversion to achieve energy saving and efficient operation. NAC is located in Beijing, which has abundant natural light resources (Fig. 2 and Fig. 3). In this project, daylight is used as an important design strategy.

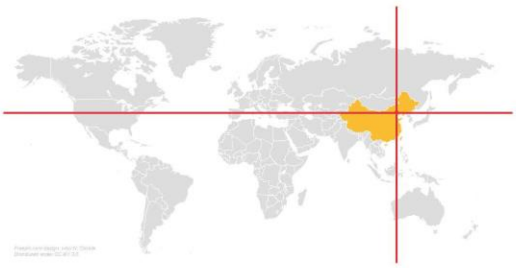
Daylighting and lighting design

The building envelope of the “Water Cube” adopts a new type of ETFE inflatable pillow, and the indoor spaces are sufficiently lighted. The average daylighting factor of the competition hall is 2.2%, whilte it is 2.1%, 3.8%, 2.4%, and 3.1% for the leisure pool, the bubble bar, the South Commercial Street, and the multifunctional large space respectively (Fig.4).

Figure 1. The National Aquatics Center.

In order to meet the needs of the game, the air pillow on the east facade of the game hall is shielded during the game to reduce glare (Fig. 6). The high illumination required for broadcasting is guaranteed by artificial lighting (Fig. 5 and Fig. 6).

Before the renovation, the original site lighting was 1 KW (without ballast) metal halide lamp, and switching the lighting mode through the switch could only meet the needs of



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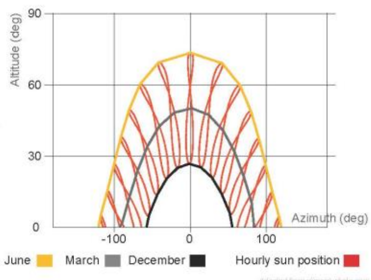

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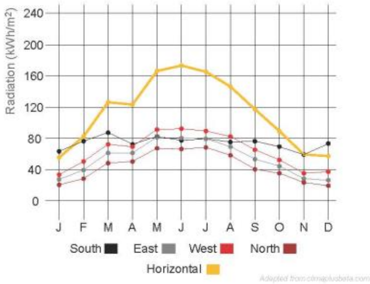


Global horizontal and vertical radiation for
Beijing, China

IEA SHC Task 61 Subtask D

Monitored by **Luo Tao**

More info **Luo Tao,** China Academy of Building Research, daylighting@126.com

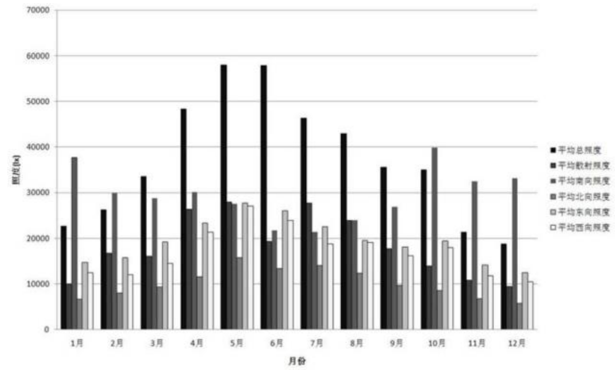


Figure 2. Annual illuminance distribution in Beijing.

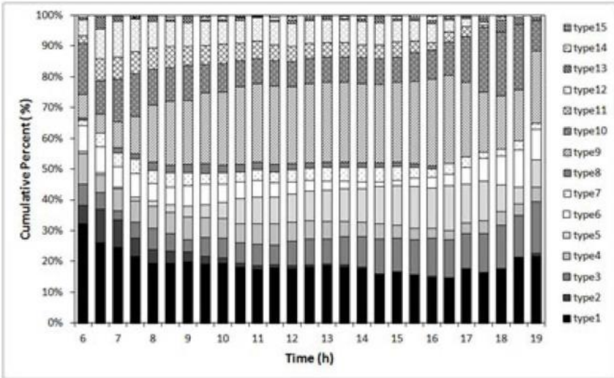


Figure 3. Sky type distributions observed at different times in a year in Beijing.

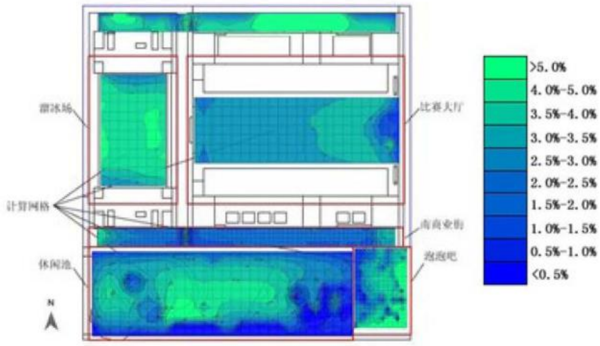


Figure 4. Distribution of Daylight Factor at the NAC.

swimming and diving. After a long time of use, the light decay was large, the color of the light source also appeared different, and the ballast and other accessories also had some problems. It was difficult to meet the lighting requirements for high-level sporting events.

After the renovation (Fig. 7), the venue lighting fixtures have been all high-power LED lamps, which can not only meet the requirements of curling events of the Winter Olympic Games, but also meet the requirements of curling, ice hockey, swimming and diving competitions, realizing two application modes of winter and summer, indicated as Mode A and Mode B respectively in Table 1.

Through the intelligent lighting control technology, the scene (or mode) can be quickly switched. With the help of the new control system and new control strategy, the overall energy consumption of the project has been greatly reduced, which can meet the goal of achieving the lighting system energy saving rate of no less than 60%.

All LED lighting is used in this renovation, among which 186 sets of lamps are used in curling mode, and the power of single lamp is 1200 W (Fig. 8).

A venue for winter Olympic games requires an innovative approach when it comes to lighting. High quality LED lighting providing perfect illumination and high colour rendering is must. In this project an in-depth study of power

Table 1. Test results for the lighting in the curling mode.

Test items	Mode A	Mode B	OBS requirements
Average Horizontal of illuminance	3731 lx	5425 lx	/
Minimum illuminance of main camera	1871 lx (3 m) 1961 lx (6 m)	2300 lx (3 m) 2540 lx (6 m)	1600 lx
Vertical minimum illuminance (A)	1718 lx	2144 lx	1200 lx
Vertical minimum illuminance (B)	1843 lx	2617 lx	1200 lx
Vertical minimum illuminance (C)	1436 lx	2245 lx	1200 lx
Vertical minimum illuminance (D)	1903 lx	2864 lx	1200 lx
Average Horizontal of illuminance of the audience	1154 lx	1855 lx	/
Average vertical illuminance of the auditorium	496 lx	764 lx	/
Glare index	13.1	12.2	≤30
Glare index to the camera	13.2	10.1	≤40
Correlated color temperature T_{cp}	5490 K		/
Color rendering index R_a	92		/
Special color rendering index R_9	66		/
TLCI	94		>85

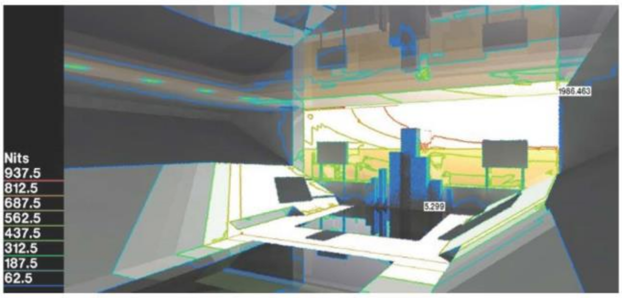


Figure 5. Glare simulation for the NAC.


Figure 7. Demonstration after renovation.

supply and control technology was also required. It helped pushing forward the choice of LED products, by selecting those providing excellent technical performance. Since high-power LED luminaires are required for such venue, the choice of top products was key to achieve both high quality illumination - as needed for high-level sport events which are also broadcasted - and reduce the energy use for lighting.

The lighting scheme here presented is used for the curling hall of the Winter Olympics. The hall has a height of 30 m, and the renovated lighting area is about 8000 square meters. After the renovation, the lighting can not only meet the requirements of curling competitions of the Winter Olympics, but also meet the requirements of high-definition TV broadcast of swimming and diving competitions after the Games.

We use DMX512 system, constant current technology, for lighting control. During each type of competition, each venue lighting fixture can use an independent DMX512 channel, which can achieve 5%-100% dimming. Considering the characteristics of harmonic control and LED dimming performance curve, the minimum dimming ratio is controlled at about 15%. Switching between different types of matches can still be done using the switch mode.

Monitoring

Energy

Lighting energy saving is not only reflected in the system energy efficiency of LED luminaires, but also very important in actual operation. The actual operation and usage mode of the control scheme have a very important influence on lighting energy consumption.

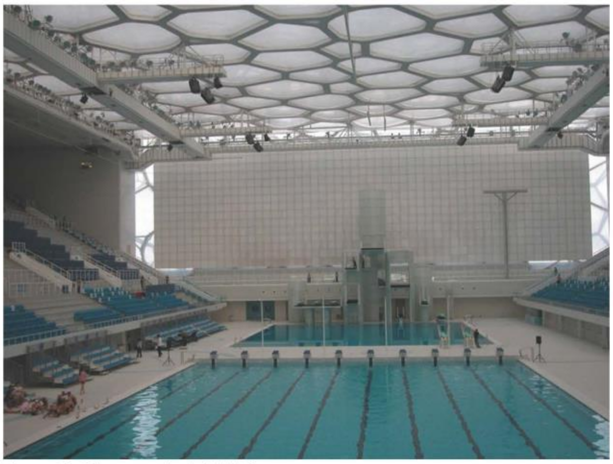


Figure 6. Glare control at NAC.

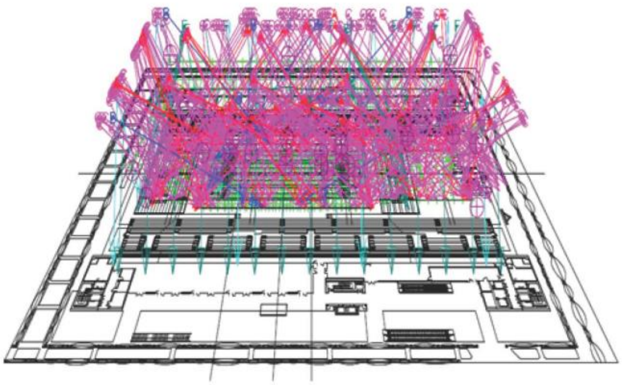


Figure 8. Lighting layout.

Compared with Chinese standard JGJ 153, lighting power density in swimming mode is 290 W/m^2 (Height is 25 m to 30 m), and the lighting total power in actual modified swimming mode is 217.6 kW, with the lighting power density to be 174 W/m^2, which corresponds to energy saving of about 40%. Considering the accurate control of LED luminaires, there will be an extra 20% power reduction, which means the overall energy saving is more than 60% compared to the standard.

Referring to current operating mode, we can set the run time as 200 hours per year in curling mode and swimming mode, 300 hours per years in diving mode. If supposing the average load is 50%, annual energy consumption of the modified site lighting system is about 60 000 kWh.

Photometry

From December 1 to December 11, 2019, before and after the junior open curling competition, the research team conducted a comprehensive test on the lighting environment of the curling arena.

The research group selected two modes of curling for testing, and the test results are shown in the Table 1.

It can be seen that all the indicators meet the requirements of Chinese standards and OBS. Figure 9 shows the space

Integrated design for daylight and electric lighting in Olympic competition venue

Figure 9. Site inspection.

during the measurement campaign.

Circadian potential

In this project, circadian potential has not been considered.

User perspective

Athletes and visitors are satisfied with the luminous environment, especially interested in the introduction of natural light into the venue. They feel happier and more active.

Lessons learned

Daylighting serves not only an energy-saving strategy, but also an important factor for luminous environment promotion. For high-level competition venue, which requires to avoid the effects of light fluctuations, there is usually the need to completely block out the natural light. But to our experience, the introduction of natural light could make people happier and more active. The daylighting strategy for high-level competition venue should be reconsidered.

For ice sports, LED luminaires have more advantages than other sources, due to less thermal radiation, more efficiency and easier commissioning.

Acknowledgements

Financial support: The 13rd five-year plan research project: Study on Standards and Integrated Demonstration for Luminous Environment Promotion of Public Building, Beijing Municipal Commission of science and technology. Special thanks to Beijing National Aquatics Center Co. Ltd

Human Centric Lighting in an office building

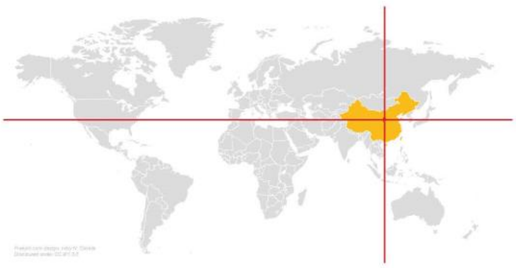
Improving the light environment of an office building with different technological solution

In this office building, a lighting retrofit with Human Centric Lighting (HCL) system is provided. The HCL can fully change brightness and colour temperature. Based on ZPLC (Zero Power Line Communications) technology, it takes less than three months to complete the replacement and commissioning, without changing the original power line. After renovation, the luminous environment was greatly improved, while achieving more than 60% energy saving compared to the previous lighting system..

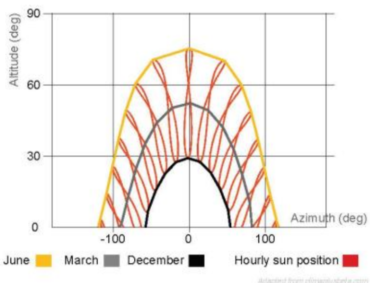
Figure 1. The Xining Central Sub-branch of the People's Bank of China.

The project

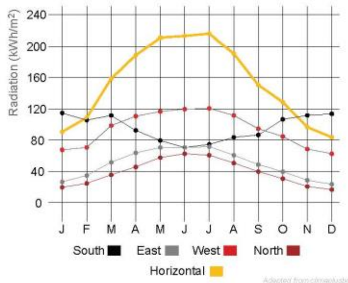
The project is in Xining, the largest city on the Qinghai-Tibet Plateau in China, with an altitude of 2261 meters. It belongs to the typical plateau alpine cold temperature climate, light climate zone II. The Xining Central Sub-branch of the People's Bank of China is an agency of the People's Bank of China. Its main responsibility is to implement the monetary policy formulated by the head office, maintain financial stability, and provide financial services in the Qinghai area. The office building of the People's Bank of China Xining Center Branch is a typical comprehensive office building for financial business. Built in the 1990s, it was once a landmark building in Xining City, Qinghai Province. It has 20 floors and a building area of about 18,000 square meters. The walls are all decorated with natural warm-colour marble, and the decoration style is solemn. After years of operation and use, the lighting facilities are gradually aging, the lighting is seriously not up to standard, and the energy consumption is high. In 2019, the building underwent a lighting upgrade and renovation. The lighting renovation project is also included in the Chinese "13th Five-Year" national key research and development



Location: Xining, Qinghai, China
36.62,101.72



Sun path for
Xining, Qinghai, China



Global horizontal and vertical radiation for
Xining, Qinghai, China

IEA SHC Task 61 Subtask D

Monitored by **Luo Tao**

More info **Luo Tao,** China Academy of Building Research, daylighting@126.com

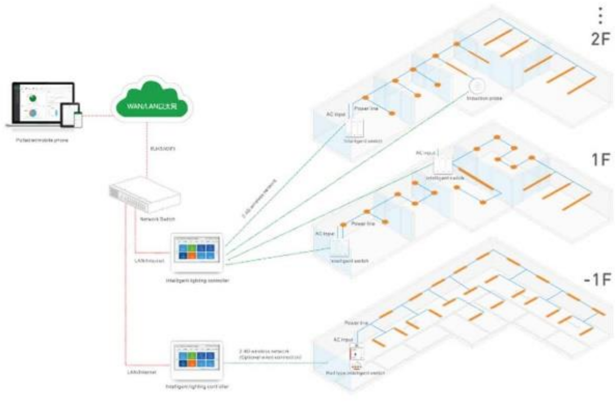


Figure 2. Conceptual scheme of the networked lighting control system with data collection in the IoT based cloud platform.

plan for green buildings and key special technology demonstration projects for building industrialization.

The new building lighting system consists of a completely peer-to-peer distributed network. The system network uses the gateway group as the subnet node. Each subnet can connect to 256 (32× 8) device, the system network can accommodate up to 64 subnets, and the maximum capacity of the system is 16384 (256×64) devices. The system uses distributed software processing technology to realize the functions of centralized control and management of the lighting system, data storage, and data input and output.

Different lighting strategies were adopted in the project. First, based on the design concept of healthy lighting, all light sources in this project adopt a dimmable and colour tunable LED lighting system, which can dynamically adjust the luminous flux from 0% to 100%, and the colour temperature range is from 2700 K to 6000K . According to current knowledge on healthy lighting technology, all of the office spaces are provided with a dynamic adjustment of intensity and colour of lighting during the day. This is expected to follow the natural daily path of sunlight, thus respecting the human biological rhythm. The dynamic lighting is designed by taking the vertical illuminance needs at the human eye position.

Then, according to the characteristics of public areas and office areas, different energy-saving operation strategies have been set up. In areas such as halls, corridors, and el-

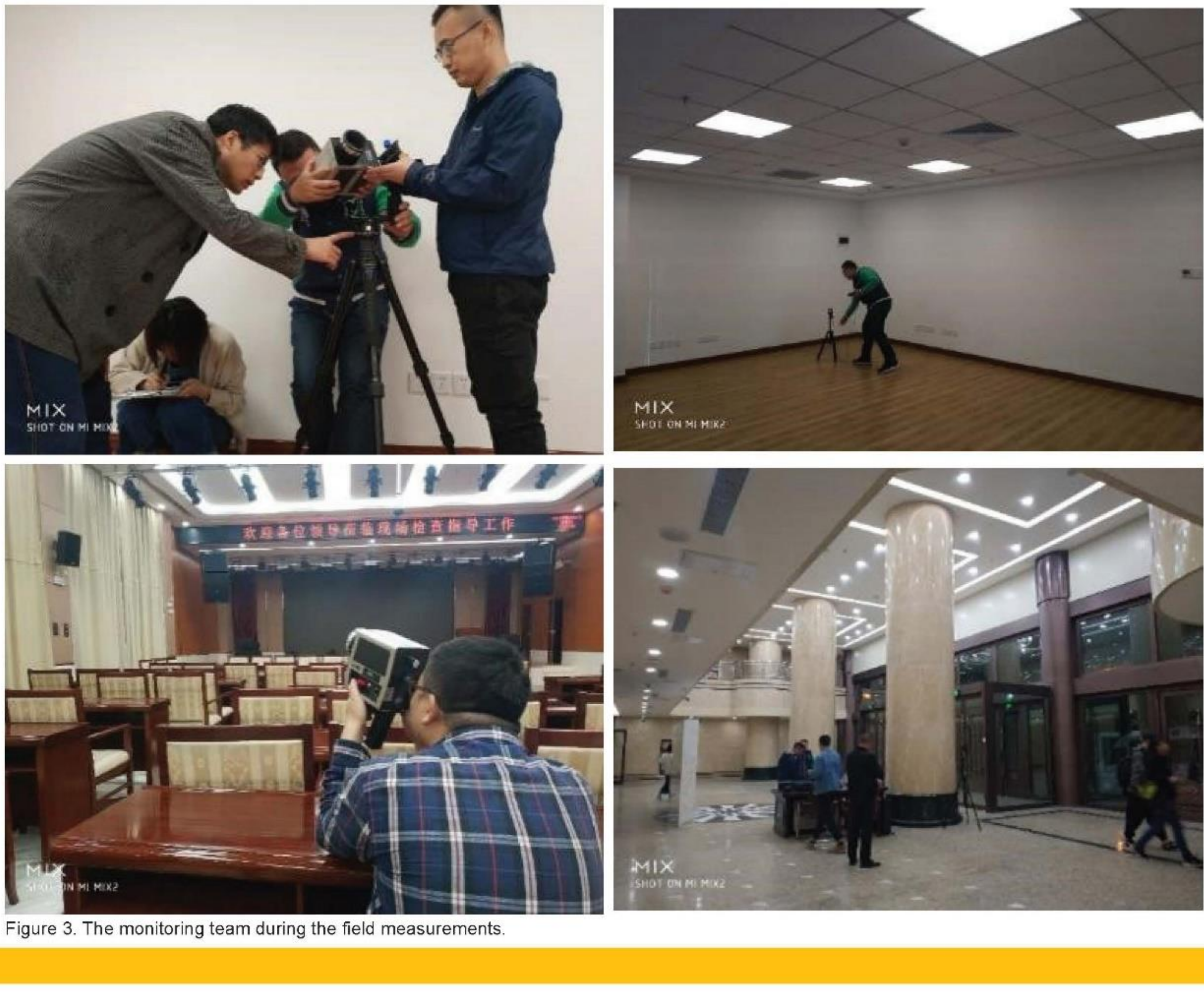


Figure 3. The monitoring team during the field measurements.

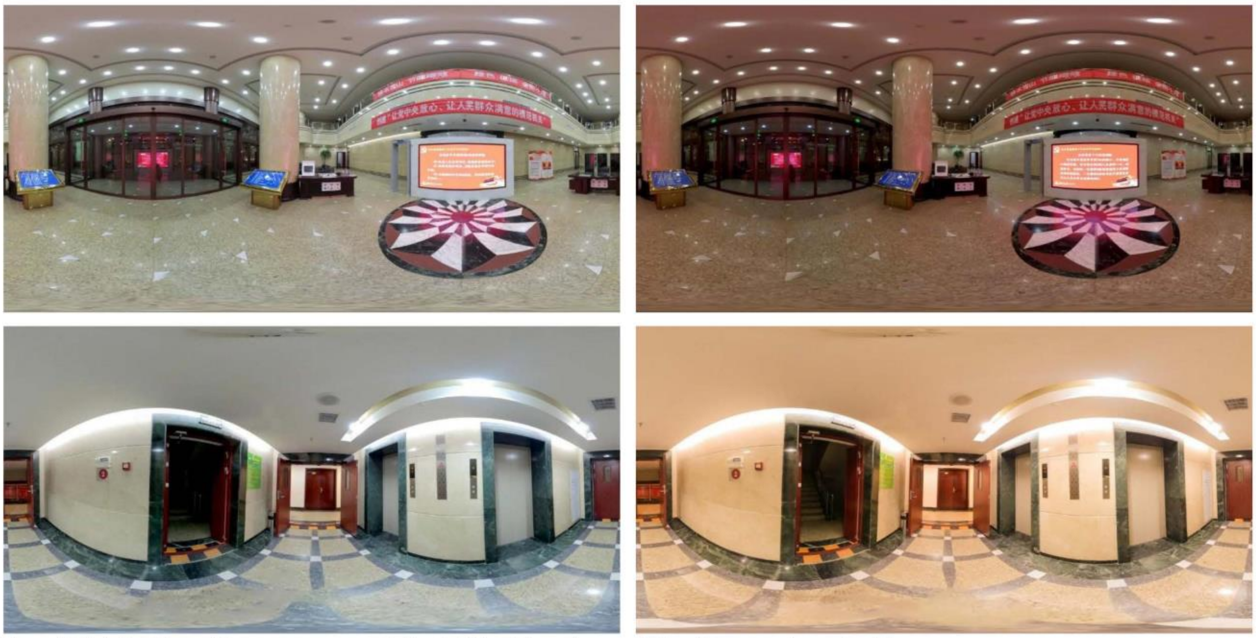


Figure 4. Details of two of the common areas in the building. The extreme CCT settings are shown in picture.

evators, in accordance with the characteristics of the flow of people and usage requirements of government offices, time sequence control is adopted during working days to achieve dynamic adjustment of luminous flux, but also correlated colour temperature. At the same time, the areas are also equipped with occupancy sensing control for turning off the lights when the space is unoccupied. The meeting rooms in the office area adopt scene control. Lamps are grouped, and the control scene can be adjusted at any time to meet the needs of various lighting modes. The office has set two control modes. The first is health-based: the lighting system follows a HCL schedule, which combines the working habits of personnel and the needs of healthy lighting to realize the dynamic adjustment of light colour. The second is energy saving based: lighting is adjusted according to occupancy and natural lighting, in a combination of daylight harvesting and absence sensing.

Finally, Intelligent lighting cloud platform control based on the Internet of Things. The lighting operation data of this project is connected to the cloud platform through the Internet of Things. The cloud platform can use big data analysis methods and adapt and improve the control strategy algorithms based on such data. If remote control is required, selected users with administration permissions can log in to the web page to control the brightness, colour temperature, and scenes of lighting of all areas.

Monitoring

Offices, conference rooms, halls, and corridors were selected on site for testing the light environment. The test items included the illumination of working plane, uniformity ratio of illuminance, colour rendering index, correlated colour temperature, stroboscopic effect and unified glare rating. The light environment parameters under different lighting modes in offices, meeting rooms, halls, corridors, and other areas were tested.

Energy

The project replaced and installed 4878 light sources and 409 control devices, and the total installed power of the system was 83534 W. The project system has energy consumption measurement and monitoring capabilities, which can monitor lighting energy consumption data in

Table 1. Energy use for lighting for the whole building after retrofit compared with the benchamark value.

Electricity use	Total energy use (kWh/y	LENI (kWh/m2y)
Calculated value (kWh)	81 000	8.1
Reference value (kWh)	212 000	21.2
Energy saving	61%	

Table 2. Evaluation of the luminous environment (electric lighting). R = Reference value or benchmark, M = Measured value.

Evaluation index		Office	Meeting room	Hall	Corridor
Illuminance on working plane (lux)	R	300/500	300/750	200	50/100
	M	475	322/762	228	54
Uniformity ratio U_0 (%)	R	0.6	0.6	0.6	0.4/0.6
	M	0.8	0.9/0.7	0.8	0.8
Colour Rendering Index R9	R	80	80	80	80
	M	84	85	84	83
Correlated Colour Temperature Tcp (K)	R	> 0	> 0	-	-
	M	9	2.3	-	-
Stroboscopic ratio (%)	R	≤ 3	≤ 3	-	-
	M	2	1	-	-
Unified glare rating URG	R	19	19	-	25
	M	8	19	-	18

Table 3. Measured lighting characteristics for the lighting system in an exemplary office. Results are shown for the seven available settings.

Parameter		Mode 1	Mode 4	Mode 7	Mode 5	Mode 2	Mode 6	Mode 3
Light output ratio		100%	100%	100%	80%	60%	30%	20%
Output Power (kW)		0.225	0.225	0.225	0.180	0.135	0.0675	0.045
Use time /h		2	2	2	1	0.5	1.5	0
Illumination of working plane	Average value (lux)	615	610	604	475	356	193	127
	Uniformity ratio U_0	0.7	0.8	0.8	0.8	0.8	0.87	0.8
Vertical illuminance (lux)		287	—	—	—	—	—	—
Luminance (cd/m^2)	Panel Light	3340	—	—	—	1842	—	623
	Wall	120	—	—	—	73	—	26
	Ceiling	64	—	—	—	39	—	15
Luminance ratio (excluding lamps)		1.9	—	—	—	1.9	—	1.7
Correlated Colour Temperature (K)		5394	5132	4637	4642	4289	3451	2939
Colour Rendering Index Ra		82	83	84	84	84.3	86	83.3

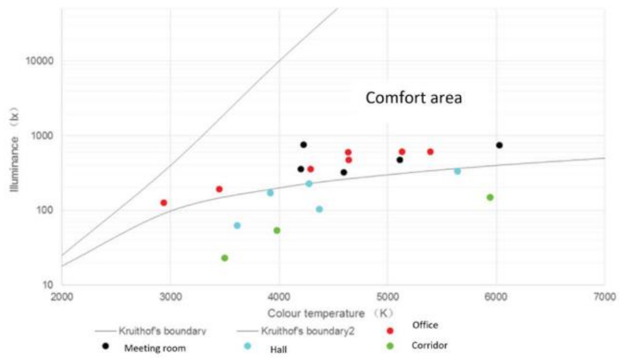


Figure 5. Kruithof diagram with illuminace and CCT coordinates for different lighting settings in the monitored rooms.

real time. After comparison, the total energy saving rate of the project lighting has reached 61%.

Photometry

The test results of on-site light environment are as follows.

All values resulted significantly better than the standard requirements. The light environment parameters under different lighting modes in offices, meeting rooms, halls, corridors, and other areas were tested. In Table 3, those for an exemplary office as shown.

Illuminance and colour temperature for the different modes were plotted on the Kruithof curve. The Kruithof curve propose a so-called comfort area for specific combination of illuminance and colour temperature. Although the Kruithof curve is currently criticized in the scientific lighting community, it remains a widespread tool in lighting design practice.

Circadian potential

At time of writing, no specific monitoring was conducted for the circadian potential of the project. However, since the lighting design is expressly based on HCL principles, it is very much likely that the electric lighting provide the right lighting stimuli at the right time as suggested by current knowledge in the field.

User perspective

Informal chats with building managers and employees suggest that lighting has been significantly improved after renovation. At the same time, the project has achieved an energy saving rate of more than 60%.

Lessons learned

This retrofit project combined principles of HCL with energy saving strategies. Depending on space and needs, HCL or energy saving were favored. The dual goals allowed to design an "healthy" lighting and still save an impressive amount of energy. The implementation of a cloud platform collecting lighting and occupancy data provides an additional instrument to further reduce energy demand, while keeping high the occupants' satisfaction.

Further information

www.heuvan.com

Acknowledgements

Financial support: 13rd five-year plan research project: Study on Standards and Integrated Demonstration for Luminous Environment Promotion of Public Buildings
Special thanks to the Xining Central Sub-branch of the People's Bank of China and HEUVAN (CHONGQING) SCI-TECH CO., LTD.

LED lighting for improving well-being in a psychiatric hospital – A first look

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

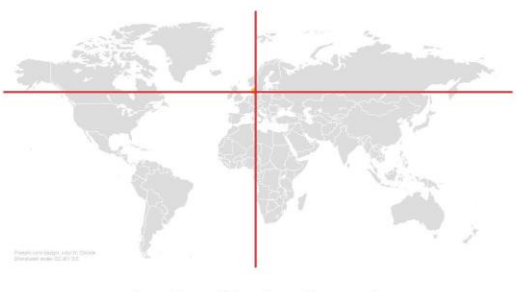
A simple solution with separate day and night lighting systems, attempts to provide better experiences for staff and patients

At Slagelse Psychiatric Hospital, they apply a simple strategy in an attempt to improve the well-being of staff and patients. In patient rooms, daylight and three downlights with a warm colour appearance provide sufficient light during the day. At night, two downlights reduce light levels and colour temperature to help create a calmer atmosphere.

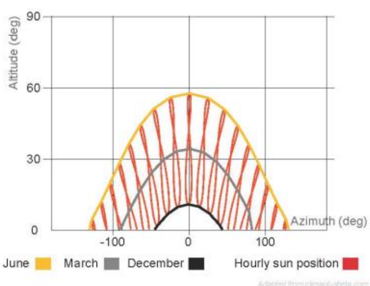
Figure 1. Psychiatric Hospital in Slagelse, Denmark: Exterior (top left), inner courtyard (bottom left) and corridor in patient ward (right) under partly overcast sky on 26 February 2020.

The project

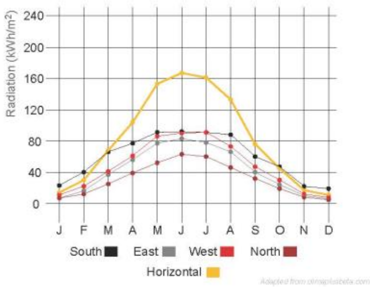
Completed in 2015, Slagelse Psychiatric Hospital (Fig. 1) is one of the largest psychiatric facilities in Denmark. The building's 44,000 m^2 floor area includes general and high-security wards, as well as training and research facilities. It was designed as a network of clusters with good connections between the different functions of the hospital. It achieved a silver rating in the Danish DGNB green building certification system that was first established in Germany in 2008. The lighting designers planned an extremely simple lighting design strategy in an attempt to provide better health and well-being for both patients and staff. An LED lighting system consisting of two separate circuits of luminaires was installed in the patient bedrooms and other areas of the hospital. The focus of this case study is on the patient bedrooms (Figs. 2 and 3). During the day, daylight is supplemented by three LED downlights with a correlated colour temperature (CCT) of around 2700 K providing an additional average illuminance of 250 lux on top of the daylight levels. At night, only two LED downlights in positions different from those operating during the day provide an average illuminance of just above 100 lux at a CCT of around 2000 K (measurements varied between 1750 K and 2200 K). Average daylight factor levels (DF) in the patient bedrooms are between 2 and 3 percent. A wall-mounted orientation light is installed adjacent to the base



Location: Slagelse, Denmark
55.40° N, 11.37° E



Sun path for
Copenhagen, Denmark
(55.67° N, 12.52° E)



Global horizontal and vertical radiation for
Copenhagen, Denmark
(55.67° N, 12.52° E)

IEA SHC Task 61 Subtask D
Monitored by **W. Osterhaus, I. Erhardtsen, M. Gkaintatzi-Masouti, K. Nielsen and F. Dobos**
More info: **Prof. Werner Osterhaus,** Aarhus University, werner.osterhaus@cae.au.dk

LED lighting for improving well-being in a psychiatric hospital – A first look

Figure 2. Daylight (left), as well as day-time (center) and night-time (right) scenarios for electric lighting in a patient bedroom.

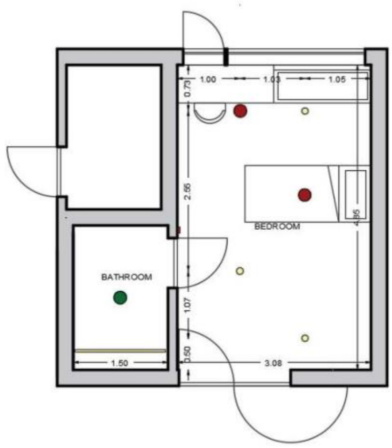


Figure 3. Typical floorplan of a patient room with bathroom.

of the bathroom door for wayfinding at night. The intention was to reduce patient anxiety, enhance their sleep quality and reduce the need for medication or fixation of patients. At the same time, it should help staff experiencing calmer conditions with fewer emergency responses (especially at night) and falling asleep more easily after returning home from a night shift. The lighting is controlled predominantly through programmed schedules via a central touch screen panel in each of the nurses' stations. The setting is changed from day to night and back to day the next morning. Patients and staff can turn on or off the lighting that is in effect at any time via switches in the patient rooms. In the rooms, however, they cannot change from night to day or day to night settings. Daylight-dependent dimming systems or occupancy sensors were not implemented. The Danish Building Code permits this, if the lighting predominantly serves a therapeutic purpose.

Monitoring

Researchers from Aarhus University's Lighting Design Research Laboratory visited the hospital on 26 February 2020. Photometric measurements were conducted on site throughout the day, including for several hours after sunset. Six members of the medical staff from different shifts working with psychiatric patients were interviewed in a process that allowed them to add their own impressions and comments. In addition, researchers collected technical information about the lighting installation and its operation from the technical service leader. Monitoring closely followed the protocols as established by the IEA-SHC Task 50 and extended by the current IEA-SHC Task 61.

Table 1. Energy Use and Lighting Energy Numeric Indicator (LENI) for the different lighting scenarios.

	Standard reference	Existing	Proposed change
Day (DF = 2%), (Average Illuminance -->)	300 lux	218 lux	218 lux
Hours	3000 Hours	3000 Hours	
Number of Luminaires	4 Ceiling	3 Ceiling	
Power per Luminaire	18.1 W	19.5 W	
Daylight-Dependent Control	yes	no	yes
Occupancy Sensor	no	no	yes
Total Annual Energy Use Day	98.5 kWh	175.5 kWh	64.9 kWh
Night (Average Illuminance -->)	100 lux	135 lux	135 lux
Hours	1000 Hours	1000 Hours	
Number of Luminaires	4 Ceiling	2 Ceiling	
Power per Luminaire	6 W	10.5 W	
Total Annual Energy Use Night	24.0 kWh	21.0 kWh	16.8 kWh
Total Annual Energy Use	122.5 kWh	196.5 kWh	81.7 kWh
LENI (for Room of 15 m²)	8.2 kWh/m²	13.1 kWh/m²	5.4 kWh/m²
Energy Savings compared to Standard Reference		-60.5%	33.3%
Energy Savings compared to Existing			58.4%

If avg. 300 lux during day and 100 lux at night	Standard reference	Existing	Proposed change
Total Annual Energy Use	122.5 kWh	257.1 kWh	104.4 kWh
LENI (for Room of 15 m²)	8.2 kWh/m²	17.1 kWh/m²	7.0 kWh/m²
Energy Savings compared to Standard Reference		-109.9%	14.7%
Energy Savings compared to Existing			59.4%

Energy

The building's lighting energy performance was evaluated via calculations according to the European

Standard EN 15193-1. The Lighting Energy Numeric Indicator (LENI) was determined for three different lighting scenarios (Table 1):

- A standard reference scenario with four ceiling-recessed LED panels and a daylight-dependent control system (representing a typical Danish code-compliant design)
- The actually existing lighting system with its different day and night scenarios
- A variant of the actually existing system with added daylight-dependent lighting control and passive infrared (PIR) motion sensors

The maximum power (W) of the LED luminaires and driver combinations were measured at Aarhus University and dimming values estimated on the basis of spectral and illuminance measurements taken on site. Subsequent DIALux simulations and EN 15193-1 calculations in an Excel-based spreadsheet provided the energy performance data. The actually existing lighting design with its different day and night scenarios would likely have resulted in a 60.5% higher lighting energy use than the standard reference case, because daylight-dependent dimming was not implemented. Added daylight-dependent dimming and occupancy sensors (absence factor 0.2) would have resulted in 33.3% energy savings compared to the standard reference. With illuminance settings of 300 lux from electric lighting during the day and 100 lux during the night, the existing design would have used 109.9% more lighting energy than the standard reference case without daylight-dependent dimming or occupancy sensors, and 14.7% less energy than the standard reference with the additional installation of daylight-linked dimming and occupancy sensors.

Photometry

Illuminance measurements were taken in one-metre steps along the centreline of the room for (a) daylight only, (b) electric lighting in the day setting and (c) electric lighting in the night setting. During the daylight assessment, the exterior horizontal illuminance was measured (approximately 20,000 lux around 13:00). The sky on 26 February 2020 was partly overcast. Some clear patches occurred. Direct sunlight did not strike the illuminance metre. The average daylight factor was above 2.1% in the patient bedroom and the illuminance above 300 lux for more than half of the room, thus meeting the recommendations for spatial daylight autonomy (sDA) of the European Standard EN 17037. Electric lighting alone provided more light in the day setting than required by the European Standard EN 12464-1, but would not meet the levels for "simple patient examinations" or "reading". A reading light could be added to the room, but was not present during monitoring. Night lighting provided sufficient light for "night observation". Luminance maps for the assessment of room brightness distributions and glare ratings (DGP and UGR) were created from two viewpoints (from the door entering the bedroom from the corridor and from the bed facing the bathroom wall with the TV) in the bedroom for all three lighting scenarios studied. Daylight could cause discomfort glare when entering the room facing the window (DGP clearly above 0.45). Electric lighting alone could potentially cause discomfort glare (UGR above 19) under the day setting, as one of the ceiling-recessed downlights is just above the patient when sitting on the bed. This is mitigated by the presence of daylight for most of the daytime hours, adapting the occupant to higher light levels. From the two viewpoints, the light source spectrum, correlated colour temperature (CCT) and colour rendering index (Ra) were determined. Differences between day and night settings were not as expected in the assessed bedroom. The spectral measurements were repeated in another bedroom on 23 November 2020, where they showed the expected differences (ca. 2000 K at night vs. 2700 K during the day).

Circadian potential

Spectral information, appropriately weighted, allows for assessment of the circadian potential of different lighting scenarios. The circadian potential expresses how a specific lighting scenario could potentially support a building occupant's daily sleep/wake rhythm and well-being. This was evaluated using two metrics: the Melanopic Equivalent Daylight (D65) Illuminance (M-EDI) and the Circadian Stimulus (CS). Experience with these state-of-the-art metrics is still limited, but initial recommendations for appropriate values exist. Different spectrally weighted M-EDI levels contribute to inhibiting or enhancing the production of the

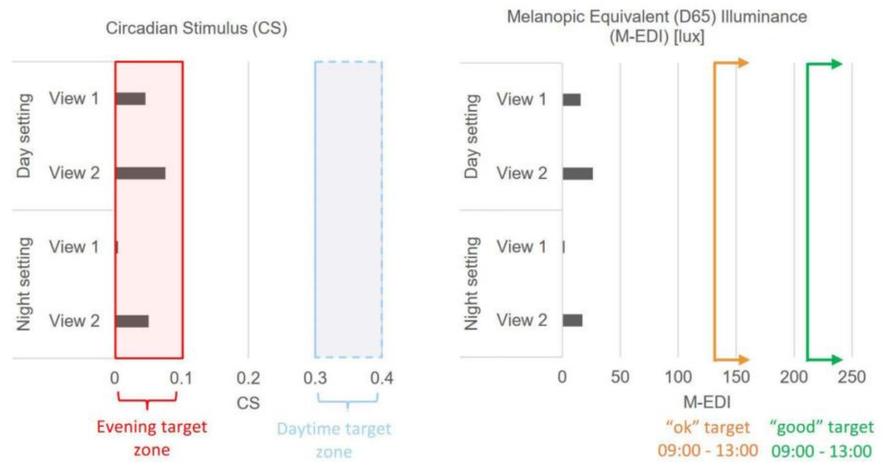


Figure 4. Left: Circadian Stimulus (CS) measured on 26 February 2020 at the eye of a hypothetical observer, 1.2 m above the floor from the two viewpoints. The target zones for evening and daytime refer to the recommendations of the Lighting Research Institute. Right: Melanopic Equivalent Daylight (D65) Illuminance (M-EDI) for the same situations. The target limits for "ok" and "good" refer to the recommendations of the WELL Building Standard V2.

LED lighting for improving well-being in a psychiatric hospital – A first look

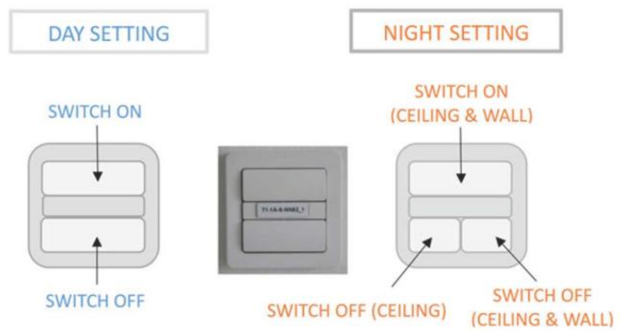


Figure 5. Wall switch that controls the electric lighting in a patient bedroom with changing functionality from day to night setting.

sleep hormone melatonin. To obtain good circadian conditions for increasing alertness and supressing melatonin production in the hours before midday, the WELL Building Standard V2 recommends an M-EDI of at least 218 lux at eye level. CS is the effectiveness in suppressing the production of melatonin from threshold (CS = 0.1) to saturation (CS = 0.7). The Lighting Research Center in Troy, New York suggests, that CS should be kept below 0.1 in the evenings and at night to enhance melatonin production for a good night's sleep. For increasing alertness, a value between 0.3 and 0.4 is recommended. For both metrics, the electric lighting scenarios during both night and day would provide good conditions for putting patients and staff to sleep. It is, however, highly unlikely that the electric lighting as installed can contribute to a well-balanced circadian rhythm of patients or staff, as the M-EDI and CS values for increasing alertness cannot be reached (Fig. 4).

User perspective

Six employees from the medical staff were interviewed about their experiences with the lighting system. The interview guide included questions on the visual experience, potential circadian effects on staff and patients, emotional impacts and practical aspects with implementation and use. Between 50% and 83% of the staff members thought the installed lighting was appropriate for the different rooms, with the highest percentage given for the patient bedrooms and 67% for the staff room and 62% for the corridors. The corridor was too dark for some. Only half of the staff members felt the common room lighting was appropriate. The others thought it was either too yellow or too sharp. The transition from night to day settings was seen as too sudden. Three persons experienced glare in the staff room. Compared to experiences in their old workplace, staff did not appear to notice any improvements in their personal energy level during work. Only one of the employees felt that sleep had improved to some degree since using the lighting system, and that physical well-being had greatly improved. Two employees felt that security in the ward had increased to a small degree. Two staff members indicated slightly less patient activity at night. One believed that there was a little less physical restraint use. Otherwise, they could not identify any effect of the lighting on the patients. While most of the staff believed the lighting made sense in their everyday activities and they would probably recommend it to others, they made clear suggestions for improvements. Instructions on the use of the lighting system were seen as insufficient by four of the six staff members. Half of the staff experienced weekly or monthly challenges in the everyday operation, such as not being able to switch off lights at the central touch panel and problems with the PIR-sensors in the bathrooms. Two experienced problems with the lighting during emergencies, including the lights turning off. The switches used, especially in the patient bedrooms, were confusing with functions changing between day and night settings and no labelling at all (Fig. 5).

Lessons learned

The lighting designers planned an extremely simple lighting design strategy in an attempt to provide better health and well-being for both patients and staff. Researchers also believe that simple systems can often outperform highly complex lighting systems. Unfortunately, the lighting in Slagelse was not as successful as perhaps possible as some of the original ideas were not implemented. Gradual transitions between the day and night setting and between night and day would have clearly improved the system, as would the introduction of daylight-dependent dimming of the electric lighting and occupancy sensors for saving electric lighting energy. Electric lighting during the day, especially on winter mornings when daylight is scarce, could not provide sufficiently high levels to provide energizing boosts.

Great, extremely simple initial idea with unfortunate implementation. With a little more effort, this could have been a great lighting success story.

Clear instructions for staff and patients about the purpose and use of the lighting system and its operation appeared to be missing, and control interfaces like switches were unnecessarily complex and confusing. Frequent operational problems also contributed to staff frustrations. The researchers recommended to review technical and operational challenges and to address them as soon as possible.

Further information

W. Osterhaus, I. Erhardtsen, M.Gkaintatzi-Masouti, K. Nielsen and F. Dobos. ELFORSK Project Report (PSO-351-041): Case Studies – Circadian Lighting, December 2020. https://elforsk.dk/sites/elforsk.dk/files/media/dokumenter/2021-03/351-041_AU_Circadian_Lighting_Case_Studies_Report_22Jan2021_Corrections.pdf

Acknowledgements

Financial support: The **Danish Energy Agency** and the **Danish Electricity Research Agency**
Support on site: Medical and technical staff at **Slagelse Psychiatric Hospital**

NAVITAS – A Testbed for Integrated Daylighting and Electric Lighting Aspects

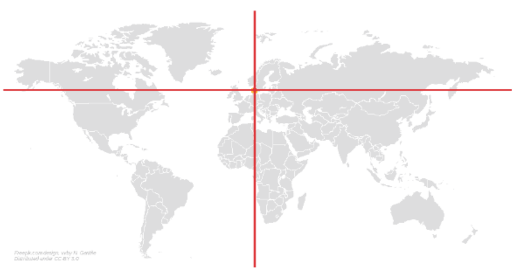
Largest low-energy building in Denmark provides good daylighting and allows for a detailed study of integrated electric lighting and solar shading

A study of integrated lighting at a research and education centre reveals that a highly energy-efficient building could be further improved through relatively simple measures. Such measures include shades that automatically return to a fully open state at the end of a day, a manual on-switch for electric lighting and better light sensor positions.

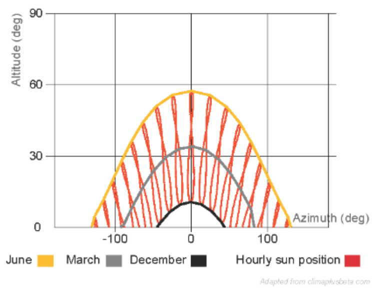
Figure 1. Navitas Building at Aarhus harbour front viewed from South.

The project

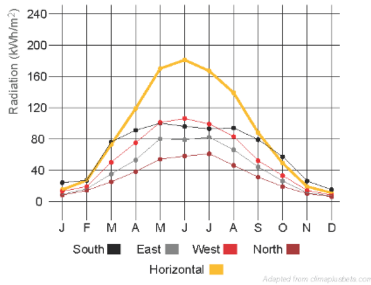
Navitas (Fig. 1) is a centre for education, research and innovation addressing climate, environment and energy at the harbour front of the City of Aarhus housing up to 3,000 students, educators, researchers and innovators on a floor area of 38,000 m^2. Navitas was built between 2011 and 2014 as a joint venture between Aarhus University, INCUBA Science Park, and Aarhus School of Marine and Technical Engineering at a cost of ca. € 95 Million. The final design was chosen through a competition requiring a turnkey contract with integrated designer and contractor teams. The chosen design also had the most appealing daylighting. All spaces used for extended periods have daylight access through the façade or interior courtyards/ atria (see also Fig. 4). The building is Denmark's largest low-energy commercial building and meets the stringent "Energy Class 1" requirements of the 2015 Building Regulations. Simulations could demonstrate that the building's energy use would be less than 50% of that needed by a standard commercial building. This was achieved through integrated energy design during the planning phase, a highly insulated building façade with triple-pane windows (t_{vis} = 53%), daylight-responsive electric lighting control with occupancy detection, 5,500 m^2 of photovoltaic panels on its roof, and cooling of ventilation air with water from the harbour. An intelligent building management system (BMS) permanently monitors indoor climate and lighting and adjusts values as needed. The lighting system (Figs. 2 and 3) uses T5 fluorescent luminaires (4,000 K) aimed at an illuminance of 300 lux on the work plane in offices, meeting rooms and classrooms and additional manually-operated desk luminaires to



Location: Aarhus, Denmark
56.16°N, 10.22°E



Sun path for
Aarhus, Denmark
(56.16°N, 10.22°E)



Global horizontal and vertical radiation for
Aarhus, Denmark
(56.16°N, 10.22°E)

IEA SHC Task 61 Subtask D

Monitored by **W. Osterhaus, M. Gkaintatzi-Masouti, K. Nielsen, T. Baumann and F. Dobos**
More info: **Prof. Werner Osterhaus,** Aarhus University, werner.osterhaus@cae.au.dk

Figure 2. Lighting and solar control in typical office space (04.103) at Navitas.

Figure 3. Typical classroom (04.121) at Navitas.

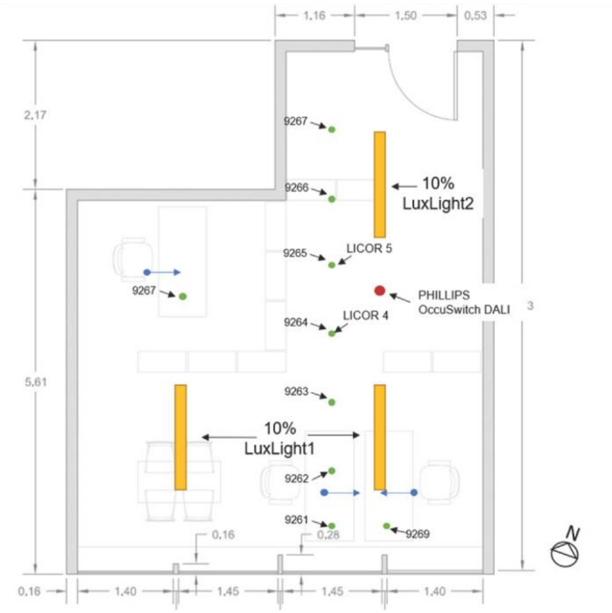


Figure 5. Floorplan of representative office (04.103) with installed luminaires and placement of illuminance sensors and luminance measurement locations (blue arrows).

Figure 4. Fourth floor at Navitas with monitored spaces (blue).

reach 500 lux where required. Two luminaire circuits parallel to the window façade dim automatically according to available daylight levels via ceiling-mounted illuminance sensors and turn off completely when occupancy sensors no longer detect activity. Users can manually adjust the light output between 0% and 100% via a control panel at the entrance of each room. Shading consists of black, manually-operated, perforated interior roller blinds with 50% openings. These also serve for reducing light levels for media presentations during teaching.

Monitoring

Researchers from Aarhus University's Lighting Design Research Group established Navitas as a testbed for trialling established and novel ways of assessing integrated daylighting and electric lighting in the fall of 2019. A typical office space for academic staff (04.103) was fitted with various illuminance sensors, as well as two Raspberry-Pi computers with fisheye-lens cameras, whereas eight other offices and classroom spaces (fig. 4) were each fitted with a Raspberry-Pi at the ceiling centre looking at the floor. Long-term illuminance measurements every 15 minutes over a period of nearly 2.5 years until June 2021 were made in 04.103 (fig. 5). The Raspberry-Pi computers recorded luminance maps of the room surfaces in all rooms every 15 minutes (fig. 6). Luminance maps were used to assess illuminance levels (via surface reflectance values) and positions of manually operated window blinds. Measured readings were compared to data from the BMS gathered by in-ceiling light and occupancy sensors installed in the respective rooms and resulting light output values (0% = lights off; 100% = lights fully on). Supplementary spot luminance, vertical illuminance and spectral values were recorded at selected times at the workstations from the perspective of the user. The COVID-19 situation severely restricted which data could be used for analysis, as the lock-down limited access to the building and lighting systems were off for most of the time. The case study thus focussed on exploring connections between various lighting, energy and user aspects.

Energy

As part of the energy assessment for the offices and classrooms, data from the BMS for the nine spaces were

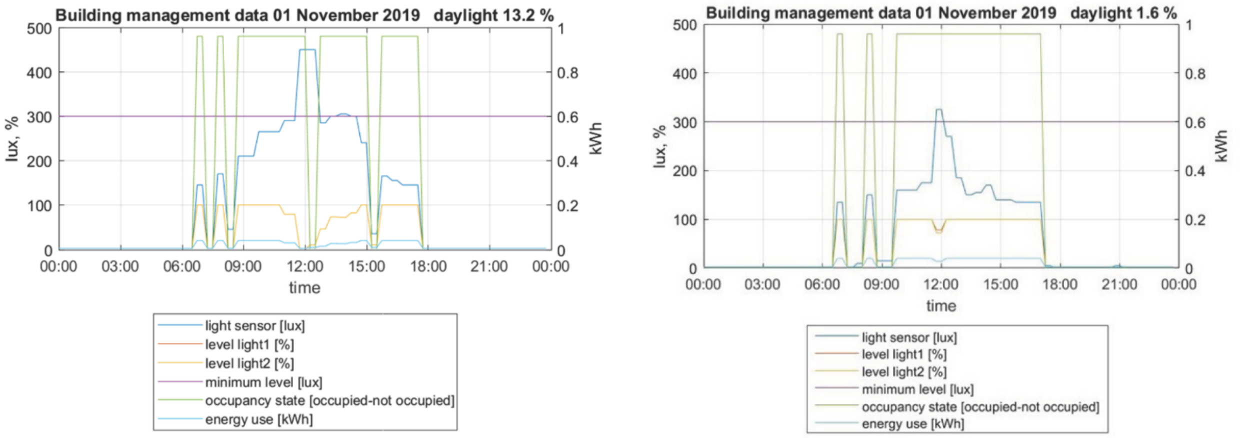


Figure 6: Building management system data for rooms 04.103 (left) and 04.106 (right) for 01 November 2019 showing detected illuminance level and light output percentage for the respective circuits, desired minimum illuminance at 300 lux, occupancy state (30 minute delay) and energy use.

reviewed. However, the long lockdown periods and only periodic use of Navitas for essential project work do not reflect normal use and energy consumption patterns. Emphasis was thus placed on assessing those aspects likely to affect energy use negatively. At present, the electric lighting turns on automatically when the detected illuminance levels are below the set-point when a person enters a room and stays on for a minimum of 30 minutes, even when users only briefly enter a room and leave again. A manual on-switch at the door would enforce deliberate action by an occupant, who may decide not to turn on the light in such a case. In September 2020, an unexplained error in the BMS raised the desired illuminance setting from 300 to 900 lux. Electric lighting would have failed to dim as the daylight levels alone never reached 900 lux below the in-ceiling sensors. Had it not been for this project, the error might not have been detected. User behaviour with respect to operating the manual roller blinds in offices and classrooms (see also under Photometry) was found to be a major factor in energy use. Active users frequently change the blind settings in response to daylighting conditions and direct sunlight penetration. Passive users often leave the blinds in a specific "workable" position for longer periods of time. Motorised blinds that move up at the end of each day and require new action by the user(s) the next day could increase daylight availability in and reduce energy for electric lighting.

Photometry

Measurements in 04.103 indicate that a daylight factor of at least 2.1% or 300 lux for half of the daylight hours across the year (EN 17037) can be reached 2.5m into the room from the façade. Most of the workstations at Navitas are located along the building's exterior façade. The desk in the north-west corner of 04.103 does not receive sufficient daylight. In classrooms with a depth of 8 to 10m from the façade, however, two thirds of the area fall below the 300 lux threshold from daylight alone, requiring electric lighting for most of the occupied hours. Electric lighting reaches on average 250 lux on the working plane. Below the luminaires, levels reach between 300 and 350 lux, but the workstation in the north-west corner of the room only receives 50 to 100 lux. Figure 6 shows an example of electric lighting performance based on data from the BMS for the nearly identical rooms 04.103 and 04.106 for a day with similar occupancy schedules. After the cleaning staff activities (two short peaks), academic staff arrive around 08:30 in 04.103 (left) and around 09:30 in 04.106 (right). Electric lights turn off 30 minutes after the last detected occupant movement. During midday, electric lighting turn off in 04.103 due to sufficient available daylight detected by the in-ceiling light sensor and occupants leaving. The lights in 04.106 stay on due to continuing occupancy, but are slightly dimmed as the lux level moves above 300 lux. The detected light levels are lower for 04.106 throughout the day, resulting in higher energy use. Daylight alone covers 13.2% of the occupied time in 04.103, but only 1.6% in 04.106. Luminance map images clearly show that blinds in 04.106 were pulled down about half-way, while blinds in 04.103 were fully open. Users had not moved the blinds in 04.106 between 22 October and 4 November 2019, whereas users in 04.103 actively adjusted blinds based on conditions in the room.

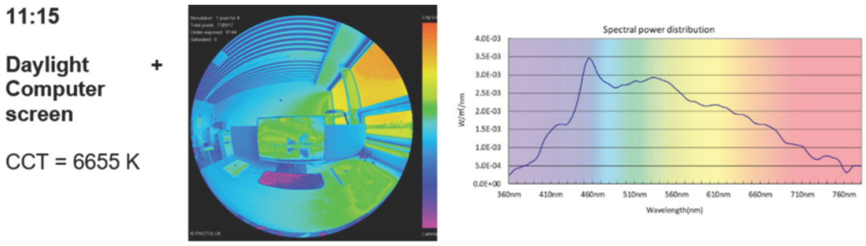
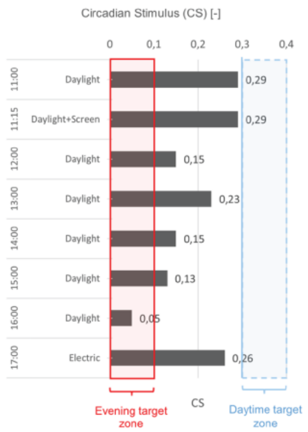


Figure 7. Recorded luminance map (left) and spectral power distribution for daylight and the computer screen (right) for a workstation adjacent to the window in room 04.103 at 11:15 on 21 January 2020. The vertical illuminance measured at the eye was 183.4 lux.

Circadian potential

Spectral information, appropriately weighted, allows for assessment of the circadian potential of different

NAVITAS – A Testbed for Integrated Daylighting and Electric Lighting Aspects



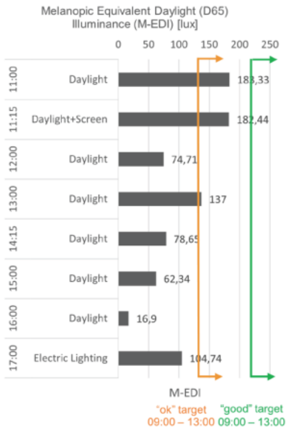


Figure 8. Circadian Stimulus (CS) calculated for a vertical illuminance at a height of 1.2 m above the floor in front of the computer screen. The target zones refer to the recommendations of the Lighting Research Center, Troy, NY.

Figure 9. Melanopic Equivalent Daylight (D65) Illuminance (M-EDI) calculated by CIE Toolbox for a vertical illuminance at a height of 1.2 m above the floor in front of the computer screen. The target limits refer to WELL building standard v2.

lighting scenarios (fig. 7). The circadian potential expresses how a specific lighting scenario could support a building occupant's daily sleep/wake rhythm and well-being. This was evaluated using two metrics: the Melanopic Equivalent Daylight (D65) Illuminance (M-EDI) and the Circadian Stimulus (CS). Spectral power distributions (SPDs) were measured at workstations at a height of 1.2 meters at different times during the day. The results for on 21 January 2020 indicate CS values of between 0.05 and 0.26 for "daylight" and 0.26 for "electric lighting", and M-EDI values between 16.9 lux and 183.33 lux for "times with daylight" and 104.74 lux for "electric lighting" (figs. 8 and 9). For electric lighting alone, both CS (0.26) and M-EDI (104.74 lux) have been calculated as being too low for "ok" and "good" target zones. This suggests that occupants starting work during winter mornings will not receive sufficient circadian stimulus from the ceiling luminaires. Daylight at 11:00 does not fulfil the recommendations for the "good" target of 218 lux M-EDI, but reaches the "ok" target of 136 lux M-EDI. During the summer, the circadian stimulus at workstations near the window would be sufficient.

User perspective

The study was severely affected by COVID-19 impacts. Only essential operations or research activities needing access to specialised laboratories were permitted during lockdowns. Offices and classrooms stood vacant. The planned structured user surveys could not be conducted. User experience reports were thus relying on informal comments made prior to the lockdown in March 2020. Most users seemed generally satisfied with the spaces they occupy, especially with the view to harbour or city. Spaces facing into inner courtyards or the atrium were found to be less desirable. A repeating concern was inadequate window glare protection. Direct sunlight striking the roller blinds was penetrating the perforated fabric, creating high luminance contrasts. Direct sunshine penetrating the blinds also interferes with media presentations when teaching and can reflect into students' eyes. Some users had asked for opaque roller blinds in addition to the black perforated blinds. These reduced glare, but also the view out. Others suggested that exterior shading devices would be more effective in preventing overheating, especially since operable windows are few and small. The desire for manual electric light switches near doors and the reduction in energy use has already been mentioned above. A few users expressed desire for relocating the in-ceiling light sensor. Its current location near the door results in its inability to "see" some of the occupants located in the corners of a room. Lights turn off when only occupants in such locations are present. Users must then get up and move closer to the sensor to turn lights back on. Others mentioned that luminaires were mounted with their long axis perpendicular to the viewing direction for most desk locations in offices and classrooms. The brightness of fluorescent tubes is thus directly viewed by occupants looking straight ahead. This can result in an experience of glare, especially at night.

Carefully considering all aspects of integrated daylighting, electric lighting and shading design can make all the difference for a highly desirable user experience and low energy use.

One should never underestimate the power of simple, often low-cost measures that are thought through in all details.

Lessons learned

This case study emphasises the importance of carefully considering all aspects of integrated lighting. The Navitas building already meets the stringent "Energy Class 1" requirements of the 2015 Danish Building Regulations. Seemingly small issues like in-ceiling sensor locations, manual on-switches for lighting, as well as window blinds that are effective against glare and move automatically into the fully open position at the end of the day could further reduce lighting energy use and improve user satisfaction.

Further information

T. Baumann, M. Gkaintatzi-Masouti and W. Osterhaus. Luminance maps for investigation of lighting in indoor environments from HDR images with the use of a Raspberry Pi computer. Proceedings of LICHT 2021 – Nach Leuchten. Bamberg, Germany, 21-24 March 2021, pp. 506-520, https://licht2021.de/sites/default/files/LICHT2021_Online_Tagungsband.pdf

Acknowledgements

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SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Integrative lighting for health and well-being in a rehabilitation facility

Lighting with added vertical focus creates better daily rhythm for patients and staff, but light levels at night and controls need attention

A first study of the dynamic LED lighting installed in a section of the rehabilitation centre allows for comparison with the old fluorescent lighting and suggests that patients and staff experience better sleep under the new system that meets the target values for morning and evening circadian lighting suggested by state-of-the art research.

Figure 1. Typical patient bedroom at Vikaergaarden. Bedroom façade faces approximately East. Vegetation outside the window protects patients from people looking into their room, but also contributes to some loss of daylight.

The project

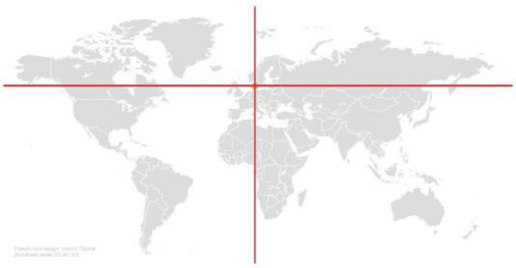
Vikaergaarden is a short-term rehabilitation and care facility where patients receive treatment and support for returning to normal life, for example after major surgery in a hospital. Located in the Vejlby district of the City of Aarhus, it was built in 1975 as a retirement home. Between 2014 and 2016, it was substantially renovated and converted into the rehabilitation facility it is today.

The City of Aarhus, who runs the facility, aims at providing conditions for their citizens that will help them recovering and returning to independence as early as possible. Stays vary in length, depending on the medical condition of a patient. A circadian lighting system was seen as one measure that could support this effort.

The dynamic LED lighting installed on one floor in one section of the rehabilitation facility (Figs. 1 and 2) provides a full-scale testbed for evaluating integrative lighting compared to the existing compact fluorescent lighting (CFL). Beyond programmed integrative lighting sequences implemented based on current knowledge and supporting circadian needs of patients and staff, the new lighting is used to energise or calm patients therapeutically by boosting or lowering light levels when needed (Fig. 3).

Monitoring

Researchers from Aarhus University's Lighting Design Research Laboratory conducted photometric measurements at Vikaergaarden in March 2019. These resulted in the addition of a wall-washing luminaire opposite the patient bed and the relocation of the other two LED luminaires a bit closer to the room centre (Fig. 4). Further photometric measurements and recordings of activity lev-



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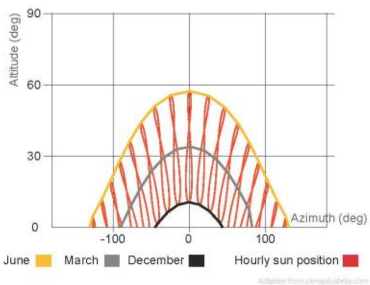
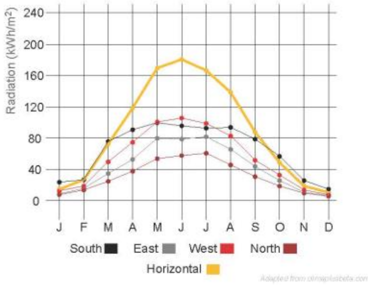


Sun path for
Aarhus, Denmark
(56.19°N, 10.21°E)



Global horizontal and vertical radiation for
Aarhus, Denmark
(56.19°N, 10.21°E)

IEA SHC Task 61 Subtask D

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Integrative lighting for health and well-being in a rehabilitation facility

Figure 2. Exterior night view of Vikaergaarden rehabilitation facility with existing fluorescent lighting (two top floors) and new dynamic LED lighting (bottom floor).

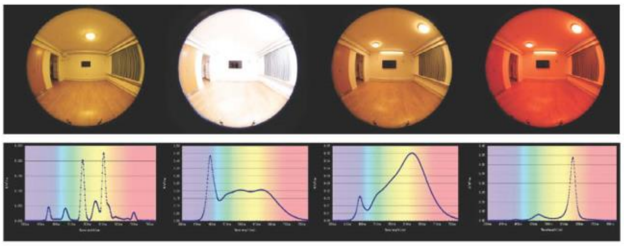

Figure 3. From left to right showing patient room lighting scene and its spectrum - original compact fluorescent lighting from 2014, "light therapy" setting, "night care" setting and "calming" setting.

els and sleep patterns via ceiling-mounted and wearable devices (Fig. 5) occurred in October/November 2019. Six members of the medical staff in a section with the original compact fluorescent lighting and seven in the section with the new integrative LED lighting were interviewed during June/July 2020. Monitoring closely followed the protocols established by the IEA-SHC Task 50 and extended by the current IEA-SHC Task 61.

Energy

The building's lighting energy performance was evaluated via calculations according to the European Standard EN 15193-1. DIALux simulations and EN 15193-1 calculations in an Excel-based spreadsheet based on measured luminaire and driver power values provided the energy performance data. The Lighting Energy Numeric Indicator (LENI) was determined for three different lighting scenarios (Tab. 1):

- A standard reference scenario with four ceiling-recessed LED panels and a daylight-dependent control system (representing a typical Danish code-compliant design)
- The actually existing new integrative LED lighting systems with its programmed and switchable lighting scenes and
- A variant of the actually existing system with added daylight-dependent lighting control and passive infrared (PIR) motion sensors.

The actually existing lighting design with its different scenarios and longer lighting operating hours would likely have resulted in an 83% higher lighting energy use than the standard reference case, because daylight-dependent dimming was not implemented. Added daylight-dependent

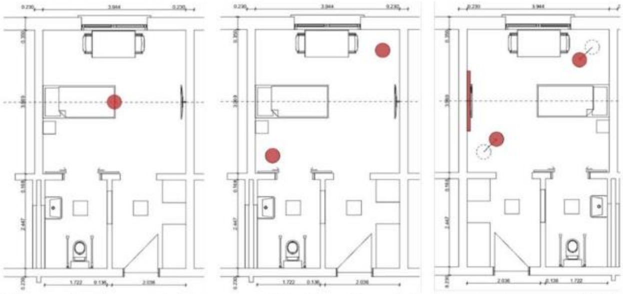

Figure 4. Compact fluorescent lighting in original patient rooms (left). Initially installed integrative LED-lighting system (middle) and integrative LED system after addition of wall washing luminaire and relocation of the other two luminaires (right).

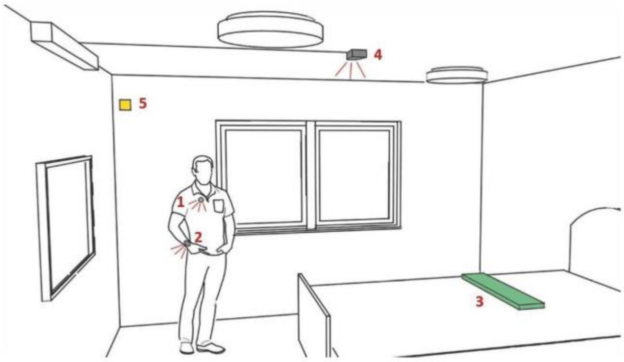

Figure 5. Devices used for monitoring over a period of two weeks in November 2019. 1) and 2) wearables, 3) mobility monitor, 4) camera sensor, 5) temperature sensor.

dimming and occupancy sensors (absence factor 0.2) would have resulted in 16.4% energy savings compared to the standard reference and 54.3% compared to the LED system as currently implemented. With standard operating hours, the existing design would have used 33% more lighting energy than the standard reference case without daylight-dependent dimming or occupancy sensors, and 39.4% less energy than the standard reference with the additional installation of daylight-linked dimming and occupancy sensors. Compared to the currently installed new LED lighting, the operating-hour-adjusted solution with daylight-linked dimming and occupancy sensors would have saved 54.4% energy.

Photometry

Illuminance measurements were taken across a 0.5m grid at 0.85 m above the floor and the on the wall opposite the bed in two rooms for (a) daylight only, and (b) electric lighting under one (CFL) or three different light settings (LED), respectively. During daylight assessment, the exterior horizontal illuminance was ca. 5000 lux around 17:00. The sky on 04 March 2019 was mostly overcast. Direct sunlight did not strike the illuminance metre. The average daylight factor was 1.4% in the patient room, reflecting exterior obstructions from vegetation, thus not meeting the aims of the European Standard EN 17037. Electric lighting from the original CFL lighting provided an average illumi-

Table 1. Energy Use and Lighting Energy Numeric Indicator (LENI) for the different lighting scenarios.

	Standard reference	Existing	Proposed change	Existing Adjusted	Proposed Change Adjusted
Day (DF = 1.4%), (Average Illuminance -->)	300 lux	47 - 431 lux	47 - 431 lux	47 - 431 lux	47 - 431 lux
Hours	3000 Hours	4927.5 Hours		3000 Hours	
Number of Luminaires	4 Total (4 Ceiling)	3 Total (2 Ceiling + 1 Wall)		3 Total (2 Ceiling + 1 Wall)	
Power per Luminaire	27 W	24 - 131 W*		24 - 131 W*	
Daylight-Dependent Control	yes	no	yes	no	yes
Occupancy Sensor	no	no	yes	no	yes
Total Annual Energy Use Day	181.4 kWh	381.4 kWh	170.8 kWh	232.2 kWh	104.0 kWh
Night (Average Illuminance -->)	100 lux	26 lux	26 lux	26 lux	26 lux
Hours	1000 Hours	1825 Hours		1000 Hours	
Number of Luminaires	4 Ceiling	1 Wall Washer		1 Wall Washer	
Power per Luminaire	8.1 W	5.4 W		5.4 W	
Total Annual Energy Use Night	32.4 kWh	9.9 kWh	7.9 kWh	5.4 kWh	4.3 kWh
Total Annual Energy Use	213.8 kWh	391.2 kWh	178.7 kWh	237.6 kWh	108.3 kWh
LENI (for Room of 15 m^2)	13.7 kWh/m^2	25.0 kWh/m^2	11.4 kWh/m^2	15.2 kWh/m^2	6.9 kWh/m^2
Energy Savings compared to Standard Reference		-83.0%	16.4%	-33.0%	39.4%
Energy Savings compared to Existing			54.3%		54.4%

* : power range for luminaire groups, as several lighting scenarios with different spectrum and illuminance levels are used throughout the day.
Calculation done on 16 Dec 2020 - WO_IVE

nance of just 80 lux at a height of 0.85 m. According to the European Standard EN 12464-1, 100 lux are needed in wards in health care facilities for general illumination (at floor level), and 300 lux for reading at the appropriate level and area. Regarding medical needs, 300 lux should be provided for simple examinations, 1000 lux for treatment. For the integrative LED lighting, illuminance and correlated colour temperature vary throughout the day according to the programmed schedule. Three specific settings that can be selected through a switch panel on the wall were assessed instead: “light therapy”, “night care” and “calming”. The average horizontal illuminance was 430 lux with the “light therapy” setting, well above the recommendation of 300 lux and aimed at activating patients' alertness. With the “night care” and “calming” settings, the horizontal illuminance was less than 100 lux (on average 70 and 47 lux, respectively), which was the intention. Luminance maps for the assessment of room brightness distributions and glare ratings were created from various viewpoints in the bedroom for the lighting scenarios studied. Glare might be experienced for the brighter light settings in rooms with the dynamic LED lighting. The light source spectral power distribution (SPD, Fig. 3), correlated colour temperature (CCT) and colour rendering index (Ra) were also determined. Figure 3 illustrates that settings which aim to increase alertness (like “light therapy”) have a larger component towards the blue part, and in contrast, the settings which aim to create a calming environment occupy more of the red part of the spectrum (like “calming” and “night care”). The slowly changing SPDs of the daily schedule used with the dynamic LED contain more blue light in the morning and more red light in the evening. Similarly, the CCT follows a daily schedule that features cooler light in the morning and after lunch (to provide an afternoon boost) and moves towards warmer light in the evening (Fig. 6).

Circadian potential

Spectral information, appropriately weighted, allows for assessment of the circadian potential of different lighting scenarios. The circadian potential expresses how a specific lighting scenario could potentially support a building occupant's daily sleep/wake rhythm and well-being. This was evaluated using two metrics: the Melanopic Equivalent Daylight (D65) Illuminance (M-EDI) and the Circadian Stimulus (CS). Experience with these state-of-the-art metrics is still limited, but initial recommendations for appropriate values exist. Different spectrally weighted M-EDI levels contribute to inhibiting or enhancing the production of the sleep hormone melatonin. To obtain good circadian conditions for increasing alertness and supressing melatonin production in the hours before midday, the WELL Building Standard V2 recommends an M-EDI of at least 218 lux at eye level. CS is the effectiveness in suppressing the production of melatonin from threshold (CS = 0.1) to saturation (CS = 0.7). The Lighting Research Center in Troy, New York suggests, that CS should be kept below 0.1 in the evenings and at night to enhance melatonin production for a good night's sleep. For increasing alertness, a value between 0.3 and 0.4 is recommended. For both metrics, the electric lighting scenarios during both night and day would provide good conditions for putting patients and staff to sleep. The integrative LED lighting as installed now can likely contribute to a balanced circadian rhythm of patients or staff, as the M-EDI and CS values for increasing alertness reach the desired “daytime” target zone (Fig. 7).

User perspective

The user perspective was evaluated in terms of light exposure and activity levels of staff and patients, and answers of medical staff to the semi-structured interviews regarding

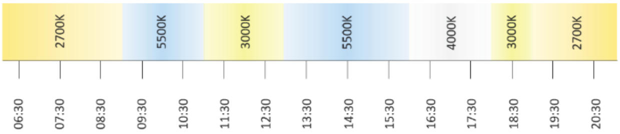

Figure 6. Daily schedule for CCT implemented at Vikaergaarden.

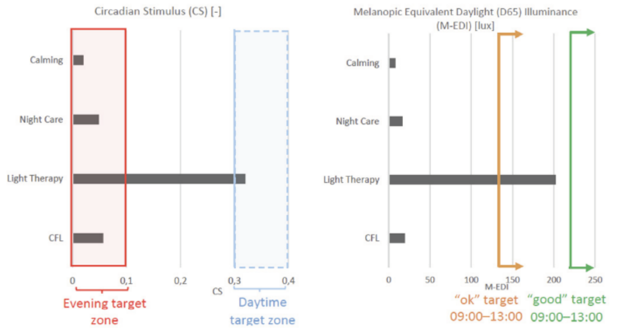

Figure 7. CS (left) and M-EDI (right) both calculated for an estimated vertical illuminance simulated by DIALux at a height of 1.2 m above the floor for the four lighting scenarios. The target zones for CS refer to the recommendations of LRI and target zones for "ok" and "good" refer to the recommendations of the WELL Building Standard V2.

their experiences with the two lighting systems in June/July 2020. Unfortunately, the small scale of this study did not allow for drawing any statistically robust conclusions. Some trends could still be observed. In the ward with dynamic LED lighting, medical staff rated their own sleep quality, as well as the perceived calmness, lower voice volume, physical well-being and security higher than in the wards with the older CFLs. The patients' activity levels at night were also lower, suggesting better sleep. For the wards with CFLs, the light did not seem to affect their own or their patients' mood, attention or energy, whereas in the ward with LEDs, some of the nurses claimed to notice an effect on their. Nurses generally liked the circadian LED lighting, except when moving between different wards with and without the integrative lighting (high contrasts and some glare), or in the morning, when the dynamic LED lighting was changing from the night light to the morning light a bit too abruptly. Here, staff thought there was a need for transition settings before the light turned to the morning light. During the daytime, all interviewed employees rated the dynamic lighting as suited for their work. This was different at night, when half of the employees found the light rather too dark or to red for working. They sometimes manually changed the light to perform visual tasks requiring higher light levels. Some indicated that patients had difficulties with the switches in their rooms (poor and too small labelling). Some staff said that they had not received sufficient instructions for using the integrative LED lighting. In all rooms, curtains were usually opened after waking up and closed around sunset. This suggests that staff and patients wanted to allow for as much daylight access as possible.

Lessons learned

Providing light on the wall faced by a patient sitting in the bed – in addition to the ceiling lights – contributed to a more balanced lighting environment. Ceiling light fixtures could use better shielding to prevent glare, especially for the high light levels of the "therapy lighting". Some adjustments of the transitions between lighting scenarios and additional task lighting for medical staff at night are needed, as is the introduction of daylight-dependent dimming of the electric lighting and occupancy sensors for saving electric lighting energy. In addition, better instruction on the purpose and use of the circadian lighting system and its control for both staff and patients and clearly labelled control switches in patient rooms would be beneficial. Trustworthy wearable devices are essential for getting reliable data. Not all of the available devices were found to be suitable. Careful comparison of devices and their data is important prior to use in case studies as measurements can vary widely, even between devices of the same type. Manufacturers of the devices often do not know or do not want to reveal details of technical specifications or accuracy levels.

Providing light on the wall faced by a patient sitting in bed – in addition to the ceiling lights – contributes to a more balanced lighting environment. Some adjustments of the transitions between lighting scenarios and additional task lighting for medical staff at night are needed.

Further information

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Office space with light-emitting structures in upper part of the façade

Large-scale micro-optical panels were integrated into the upper part of a façade. The lower part is operated with venetian blinds for sun and glare protection.

At the Fraunhofer IBP in Stuttgart, large scale light-emitting panels were integrated into glazing units and integrated into the upper part of the façade of a lab room. The evaluation of the performance of the lighting conditions and the energy related parameters were compared to a second identical room, with conventional lighting.

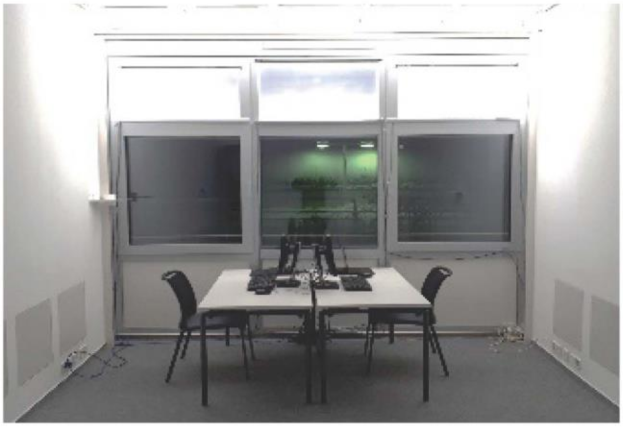
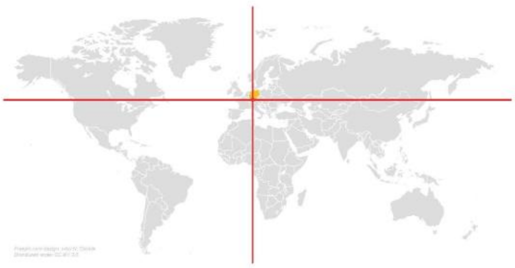


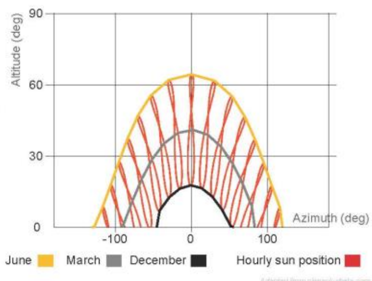
Figure 1. The lab room seen from the inside. The light-emitting structures are placed on the top part of the windows and provide illumination to the room interior.

The project

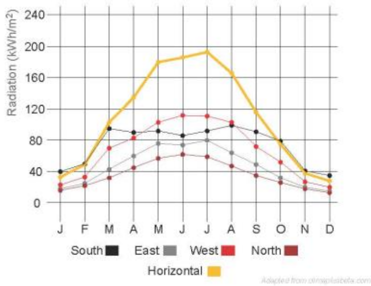
This case study is part of a bigger project project called TaLed, which was funded by the Federal Ministry for Economic Affairs and Energy (BMWI) (Project Management Jülich). The main purpose of TaLed was to improve the energy efficiency, life cycle balances and indoor comfort by employing micro-structured optical components for daylighting and electrical lighting. For this case study, a micro-optical structure, namely - Light-emitting structures, have been optimized for redirecting glare-free artificial light deeply into the building interior. The structure is placed on the surface of transparent substrates, which emit laterally injected LED light on one side only,. In this use case, large scale micro-optical panels were integrated into glazing units and placed into the upper part of the façade of a lab room at FHG-IBP (Figure 1). On the lower part of the window a standard venetian blind is being operated for sun and glare protection. To evaluate system performance the lighting conditions and the energy related parameters are compared to a second identical room, which has



Location: Stuttgart, Germany
48.74° N, 9.10° E



Sun path for
Stuttgart, Germany



Global horizontal and vertical radiation for
Stuttgart, Germany

IEA SHC Task 61 Subtask D

Monitored by **Carolin Hubschneider, Yuen Fang and Daniel Neves Pimenta**
More info **Jan de Boer,** IBP Fraunhofer, jan.deboer@ibp.fraunhofer.de

Figure 2. The facade seen from the inside, with the light-emitting structure on the upper part of the window.

Figure 4. An exterior view of the lab. The facades of both the reference and test room can be seen in the picture.

also blinds in the upper part of the façade. All blinds are automatically closed when direct sunlight reaches the façade.

Extensive documentation on the project and the monitoring is provided in the references at the end of this factsheet.

Monitoring

In order to test the developed light-redirecting in practical application, the Fraunhofer IBP installed the new systems in two test rooms with identical construction. The two test rooms resemble an ordinary two-occupants office room, they are south-facing and have dimensions of 6.0 mx 3.5 mx 3.0 m (Figures 1, 2, and 4). In each case three window elements are separated by a bolt into an upper and a lower window element. In each case the test panels were installed into the upper part of the facade. The installation of two separate blind boxes per room allows a separate shading of the two window elements.

The reference room was equipped with six direct-indirect pendant luminaires for general lighting (Figure 3), the test room was equipped with the light emitting structures only, which were built into the façade system (Figure 1, 2).

Figure 3. Luminaire with direct and indirect light output.

The lab room was equipped with sensors and actuators. As actuators, the luminaires and two separate blinds determine the lighting situation in the room. Five illuminance sensors were installed as sensors in a line in the middle of the room at the working level (distance between façade and sensors 1.0 m). Energy use is recorded separately for the luminaires with electricity meters. In total, the following data was recorded in both spaces:

- illuminance levels of the illuminance sensors positioned on the working plane,
- power and energy for the luminaires and light-emitting panels,
- temperature in the room,
- dimming levels of the luminaire group.

Energy

The energy use is proportional to the installed power of the lighting system. In relation to the entire room, the installed power (normalised to 100 lx) was 3.92 W/m²100lx for the light-emitting system and 1.83 W/m²100lx for the reference lighting system. As already shown in the calculated potential assessment, the installed power and thus the energy use of the façade-integrated light-emitting system in the test rooms is also significantly higher than the reference lighting system.

Photometry

To validate the light-emitting system, triple-pane laminated glass with light-emitting PMMA elements was installed in the upper window elements of the test room. The lower window elements and the window elements in the reference room were fitted with conventional triple-pane glazing. LED boards were installed on the lower edges of the PMMA panes, which are thermally connected to the frame by means of a copper braid. The two test rooms were each equipped with two computer workstations.

Figure 5 shows the course of illuminance measured over the depth of the room. Up to a depth of about 1 m, the lighting levels required for office workplaces are measured.

The required 500 lx is achieved at a depth of 1 m, and

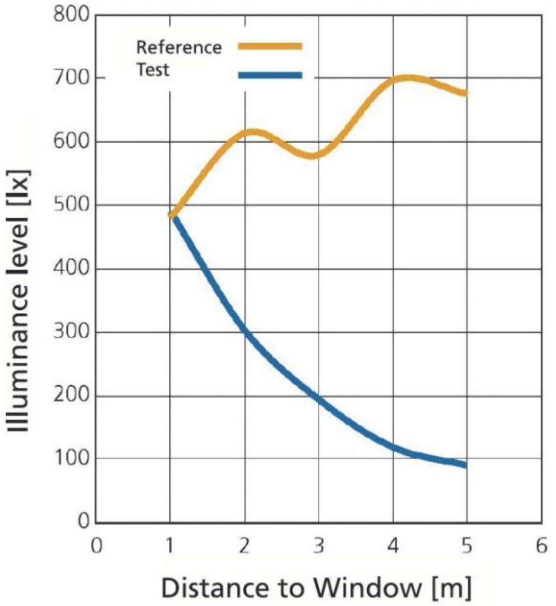


Figure 5. Horizontal illuminance on the working plane provided by electric lighting only. The illumination of the test room with light-emitting structures is provided by the structure only, which is located on the upper part of the window.

300 lx at a depth of 3 m. In areas far from the façade, the illuminance then drops to about 100 lx, which could be simulated via Dialux (Figure 6) in advance.

Circadian potential

The Circadian potential was not evaluated, but due to the lower lux levels (Figure 5) and the perceived lower light levels in it can be assumed that it was low.

User perspective

The studies for the user acceptance were conducted as a within-design, so the test persons experienced both rooms (reference room and test room). They completed various performance tests and questionnaires. The performance tests were not evaluated, but only served to simulate a working atmosphere. The questionnaires examined the following topics:

- task completion (perceived performance in completing the tasks),
- fatigue and visual stress,
- Perception,
- room atmosphere,
- subjective management atmosphere,
- light distribution,
- artificial lighting for the light-directing system.

The data collected was analysed using the SPSS statistical software. For the individual questions of the questionnaires, a t-test was carried out in each case to compare the test room and the reference room.

In the user study the acceptance of the light-emitting element was tested on six days from 11th December 2018 to 19th December 2018. Twenty test persons with a student background (7 female, 13 male) aged between 23 and 29 were invited.

The results show, that 2 out of a total of 52 measures show a statistically detectable difference between the two rooms ($p \leq 0.05$). Compared to the reference room, the light-emitting elements in the test room were rated with a slightly higher glare of the façade and at the same time with a lower brightness inside the room. Other glare phenomena on the table, wall and screen did not show any significant result. The perceived difference in brightness inside the room is reflected in the lower illuminance levels measured inside the room.

"What if we could have light, instead of luminaires?"

Office space with light-emitting structures in upper part of the façade

Figure 6. DiaLux rendering of the light-emitting structure used in this case study.

Lessons learned

The development and future use of micro structured optical components for artificial light utilisation is intended to improve energy efficiency, life cycle balance and the quality of interior usage in buildings. The starting point for the work of this joint research project was formed by new types of optical structures that are applied to transparent carrier layers. One was a structure that emits light. This emits LED light (brought in via the edges of the pane) in a targeted manner from the substrate surface. The elements remain transparent. The structure is to be used directly in façade glazing and in new types of luminaires. The basic structure was available as laboratory sample at the beginning of the project.

In the project, the structure was optimised, scaled to practical building sizes with newly developed manufacturing processes and the system integration was implemented in glazing units. Lighting and energy parameters were determined and prepared for use in planning tools. Life cycle balance and influence on the energetic building behaviour were estimated. Furthermore, the structures were tested in real installation situations in test rooms in terms of energy and user acceptance. Future architectural application concepts were developed. The main project results are summarised below.

Manufacturing processes for scaling for construction applications

The production process used, "UV nanoimprints" with structures of less than 100 µm has been further developed, that components can be produced in sizes for building applications (windows) on the one hand and in high quality at low cost on the other. The processes allow the structuring of rigid PMMA sheets. In the project, dimensions of 1,200 mm x 600 mm were realised for testing in the test rooms. Larger dimensions can be produced. The costs for the light-coupling structure are around 30 - 35 €/m².

Subsequently, a modular system was developed for integrating the elements into different façade and luminaire solutions. Based on this, the structural integration into a façade system consisting of glass composite, frame constructions took place.

The light-emitting structure was implemented as a transparent, luminous window, with thermal management of the LEDs via the frame construction. The LED light guides with coupling construction were designed to meet the special requirements such as the provision of high luminous flux, high positioning accuracy to the edge of the substrate, reversibility and heat dissipation.

The light-coupling structure itself showed a light-coupling efficiency like comparable LED systems today, with a luminaire operating efficiency of 64 %. However, the actual installation situation in the façade composite had an efficiency-reducing effect.

Recycling possibilities of the glass laminates were evaluated as uncritical. The measurement data was processed for use in planning and evaluation tools such as DIALux Evo, IEA SHC Task 50, CFS Express and Trnsys.

Validation in pilot projects

In areas close to the façade, sufficient lighting could be provided by the light-emitting elements integrated into the façade. The previously calculated energetically less favourable behaviour was confirmed. In contrast, the design advantages of the solution (free ceiling, transparent light sources) and roughly comparable as user acceptance compared to conventional lighting could be demonstrated.

Further information

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Jakubowsky, M. et al: "Design, Manufacturing and Experimental Validation of a Bonded Dual-Component Microstructured System for Vertical Light Emission", submitted to Applied Optics, 2019.

Jakubowsky, M.; Hubschneider, C.; Neyer, A.; Fang, Y.; de Boer, J.: "Microstructured Light Guiding Plate for Single-Sided Light Emission as Light Source for Room Illumination", Applied Optics, Vol. 58, Nr. 1, S. 76-86, 2019.

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Acknowledgements

Financial support: The **German Federal Ministry for Economic Affairs and Energy** (BMWi) Project Management **Jülich** (PTJ).
Special thanks to **Leonard Buchty** (Durlum) and **Mike Bülters** (Temicon).

Office space with light redirecting structures in upper part of the façade

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

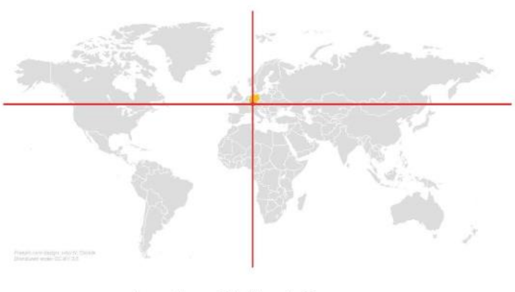
Large-scale micro-optical panels were integrated into the upper part of a façade. The lower part is operated with venetian blinds for sun and glare protection.

At the Fraunhofer IBP in Stuttgart, large scale micro-optical panels were integrated into glazing units and integrated into the upper part of the façade of a lab room. The evaluation of the performance of the lighting conditions and the energy related parameters were compared to a second identical room, with blinds in the upper part of the façade.

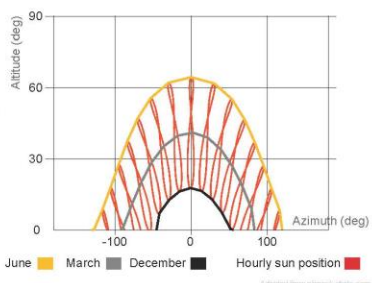
The project

The goal of this project, called TaLed, was to improve the energy efficiency, life cycle balances and indoor comfort by employing micro-structured optical components for daylighting and electrical lighting. A micro-optical structure, currently under development, is applied to both sides of transparent substrate layers. The structure have been optimized for redirecting glare-free daylight deeply into the building interior. In the case here reported, large scale micro-optical panels were integrated into glazing units and integrated into the upper part of the façade of a lab room at FHG-IBP (Figure 1). On the lower part of the window a standard venetian blind is being operated for sun and glare protection. The lighting conditions and the energy related parameters are compared to a second identical room, which has standard venetian blinds on the whole window. All blinds are adjusted automatically, and they close when direct sunlight is on the façade. Both test rooms were equipped with six direct-indirect pendant luminaires each (Figure 3), controlled in two groups (window group with four luminaires and door group with two luminaires). The luminaires were coupled to a daylight harvesting system.

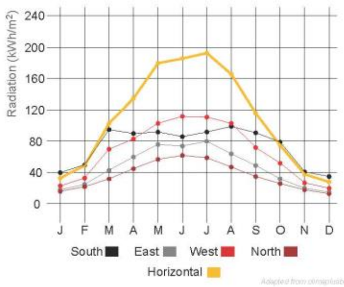
Figure 1. The lab room seen from the inside. The micro-optical panels are placed on the top part of the windows and provide a soft daylight illumination deep in the room.



Location: Stuttgart, Germany
48.74° N, 9.10° E



Sun path for Stuttgart, Germany



Global horizontal and vertical radiation for Stuttgart, Germany

IEA SHC Task 61 Subtask D

Monitored by **Carolin Hubschneider, Yuen Fang and Daniel Neves Pimenta**
More info **Jan de Boer,** IBP Fraunhofer, jan.deboer@ibp.fraunhofer.de

Figure 2. An exterior view of the lab. The facades of both the reference and test room can be seen in the picture.

Figure 3. Luminaire with direct and indirect light output.

Extensive documentation on the project and the monitoring is provided in the references at the end of this factsheet.

Monitoring

In Figure 1 the installed sensors and actuators can be appreciated. As actuators, the luminaires and two separate blinds determine the lighting situation in the room. The outdoor illuminance is installed on the roof of the building. Energy consumption is recorded separately for the two groups of luminaires. The following data was recorded in both spaces: outdoor illuminance, illuminance near windows and near doors (via KNX bus), illuminance levels of the illuminance sensors positioned on the working plane, blind position and slat angle for the upper and lower blinds, power and energy consumption for the two luminaire groups, temperature in the room, dimming levels of the luminaire group. The rooms were occupied by test subjects who performed cognitive tests. The measurement data was processed for use in planning and evaluation tools such as DIALux Evo, IEA SHC Task 50: CFS Express and Trnsys.

Energy

The energy use in both test rooms was recorded separately for the two groups of direct-indirect pendant luminaires (window group with four luminaires and door group with two luminaires) with electricity meters. Figure 5 shows the examples of a clear sky day, July 8th 2018, and an overcast day, September 14th.

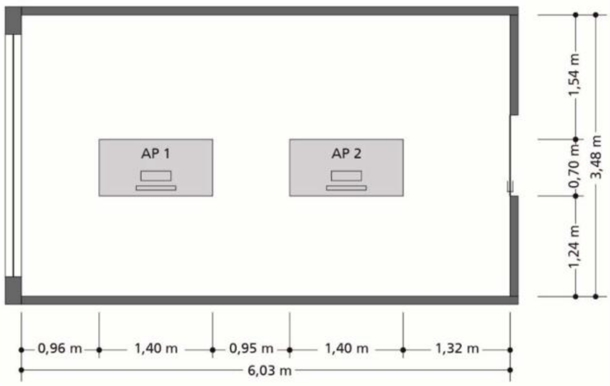


Figure 4. Plan of the lab with the two working spapce (AP 1 and AP 2), where the test subjects performed their tests.

Photometry

The laboratories were equipped with two tables for the subjects to sit and work on their cognitive tests (Figure 4). The Illuminance levels were tracked with five illuminance sensors positioned on the working plane on both tables (distance between façade and sensors 1.0 m, Figure 2), also there were two KNX sensors on the ceiling (calibrated on the basis of the sensors on the working level), which were used to control the artificial lighting.

On the roof of the building the outdoor illuminance is recorded with a weather station, where up to 60 000 Lux were measured (Figure 5).

Circadian potential

The circadian potential was not evaluated. However, considering the high illuminance levels, the significantly higher use of daylight (Figure 5), and the positive feedback from the test subjects, it can be assumed that the circadian potential was significantly increased.

User perspective

The studies for the user perspective were conducted as a within-subjects design, so the test persons experienced both rooms (reference room and test room). They completed various performance tests and questionnaires. The performance tests were not evaluated, but only served to simulate a working atmosphere. The questionnaires examined 50 measures on the following topics: task completion (perceived performance in completing the tasks), fatigue and visual stress, perception, room atmosphere, subjective management atmosphere, light distribution, sunshade or lighting system for the light-directing system.

The data collected was analysed using the SPSS statistical software. For the individual questions of the questionnaires, a t-test was carried out in each case to compare the test room and the reference room.

In the user study, the acceptance of the light-directing element was tested on three days in the period from 20 June

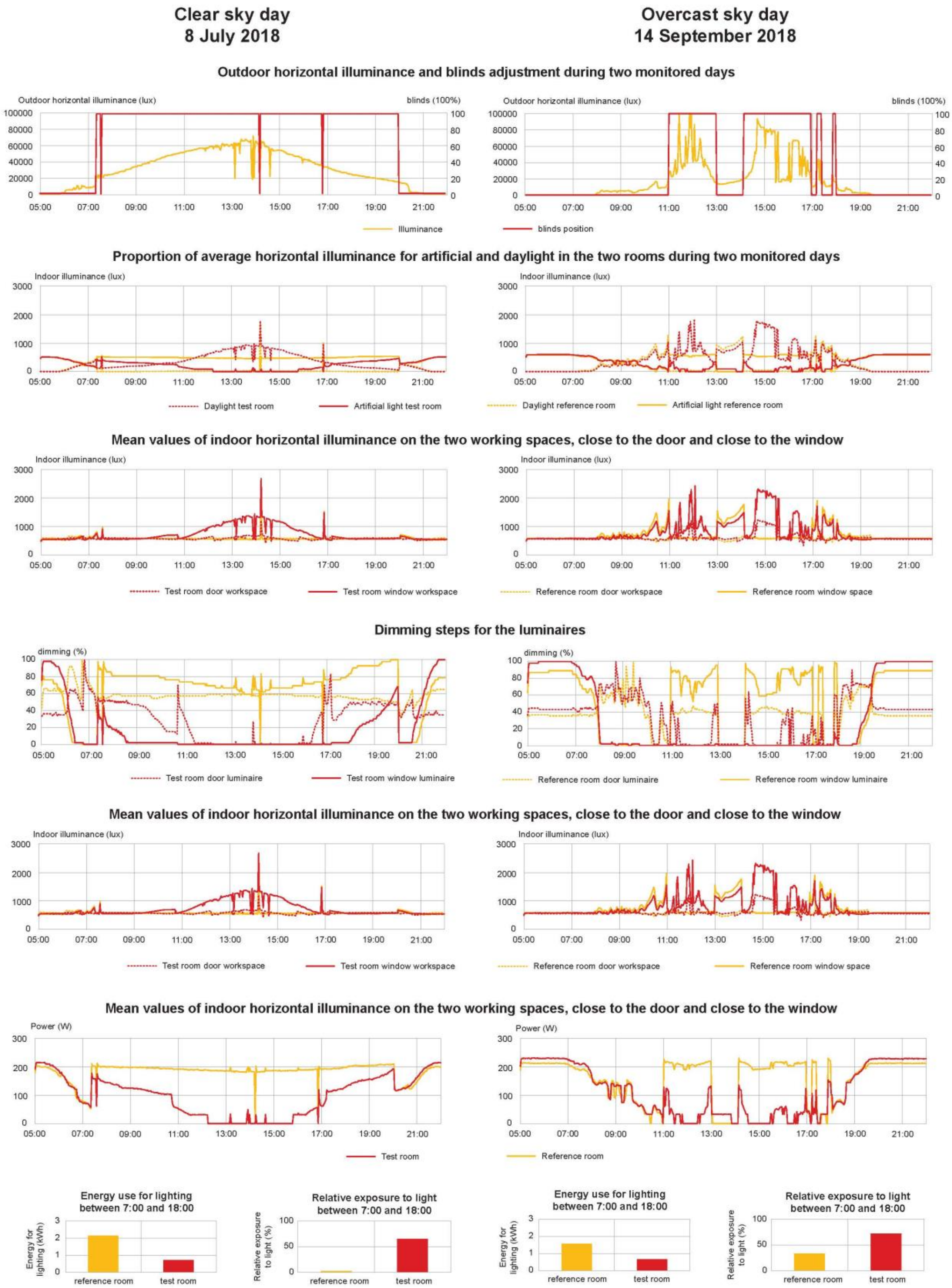


Figure 5. Logged information on outdoor and indoor illuminances, as well as power and energy figures for the installed luminaires. The data refers to both the test and the reference rooms. See DIN V 18599 for the definition of relative exposure to light.

Office space with light redirecting structures in upper part of the façade

2018 to 3 August 2018. 22 subjects (students, 10 female, 12 male) aged between 22 and 31 years were invited.

16 out of a total of 50 measures show there was a statistically significant difference between the two rooms ($p \leq 0.05$). General and visual fatigue was perceived as lower in the test room. The lighting environment was also assessed differently by the test persons. In the test room, daylight was described as more pleasant, sufficient and natural. The redirection of daylight into the depth of the room was perceived as more pronounced in the test room. However, the façade system in the test room was perceived as more dazzling.

Lessons learned

The development and future use of micro-structured optical components for daylight utilisation is intended to improve energy efficiency, life cycle balance and the quality of interior usage in buildings. In the project, the structure was optimised, scaled to practical building sizes with newly developed manufacturing processes and the system integration was implemented in glazing units. Lighting and energy parameters were determined and prepared for use in planning tools. Life cycle balance and influence on the energetic building behaviour were estimated. Furthermore, the structures were tested in real installation situations in test rooms in terms of energy and user acceptance. Future architectural application concepts were developed. The main lessons learned are summarised below.

Compared to the reference room, the light-directing façade reduced the lighting energy demand in an office situation by about 55 % with increased evaluations by the users.

The real-life use of the developed solutions was tested in comparison to reference solutions in test rooms. The light-directing components in the façade reduced the lighting energy demand in an office situation by 58 % during the measurement period (May to September 2018). The user evaluations were significantly improved for the test room.

The light-directing structure was integrated into the space between the panes of a standard thermal insulation glazing. In order to avoid cast shadows on the room side, the glazing units were supplemented with linear structured cast glass as a linear diffuser. In order to ensure a generally sufficient supply of daylight to normally deep office rooms, approx. 0.4 - 0.6 m high light-diverting elements are required in the upper window area.

The required material use of plexiglass (PMMA) could be reduced by over 75 % compared to comparable structures.

In a life cycle perspective, the solutions achieved great performance, both in terms of reduced use of raw materials and recycling possibilities. The production process used, "hot embossing" with structures in the order of 500 µm has been further developed so that components can be produced in sizes for building applications (windows) on the one hand and in high quality at low cost on the other. The processes allow the structuring of rigid PMMA sheets. In the project, dimensions of 1,200 mm x 600 mm were realised for testing in the test rooms. Larger dimensions can be produced. The costs of the ready-to-install PMMA micro-optics for light deflection are 30 - 35 €/m² compared to approx. 250 €/m² for the light-deflecting, encapsulated PMMA rods of a functionally comparable product. Recycling possibilities of the glass laminates were evaluated as uncritical.

"Why wasting energy, if we can use daylight?"

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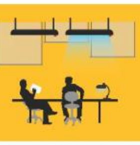
Acknowledgements

Financial support: The **German Federal Ministry for Economic Affairs and Energy** (BMWi)
Project Management **Jülich** (PTJ).
Special thanks to **Marcus Neander** (Saint Gobain) and **Michael Hof** (Jungbecker).



Building System Design for an intelligent building

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Building System Design offers intelligent solutions using the example of the DIAL headquarters in Lüdenscheid

At the DIAL headquarters, an intelligent building was created with the help of modern technology. The aim was to find solutions that satisfy the needs of people, employees and visitors, without staging technical solutions as an end in themselves. Technology and architecture go hand in hand in a holistic concept. The result is an energy-efficient building with the highest standards of comfort and aesthetics.

The project

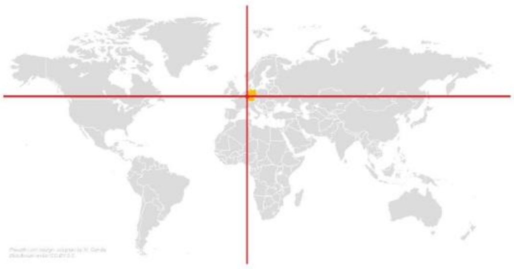
DIAL GmbH sees the future in intelligent, fully automated buildings that are geared towards the needs of their users. That is why the architecture and the overall technical concept for the company's own headquarters in Lüdenscheid were also designed in-house and managed until the move in 2013. Since then, the software-controlled building has been continuously developed.

On a construction site of around 5,000 square meters on a former train station site, DIAL realized a striking new building complex that set new standards, particularly with regard to the integral planning of the technical building equipment - the building system design. One of the results is the high energy efficiency of the new building, which is

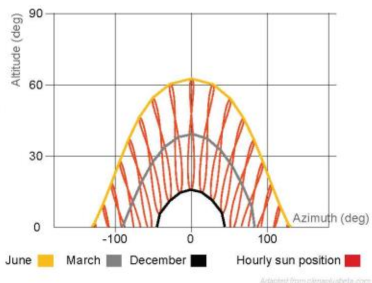
Figure 1. DIAL Headquarter Lüdenscheid. The windows are floor-to-ceiling and lintel-free.

almost built using a passive house design and does not require a conventional heating system. Around 2,000 square meters of usable space will be available on three floors. The complex space program includes a central foyer with bistro and catering, offices, conference rooms and several laboratories for measurement, lighting experiments and training.

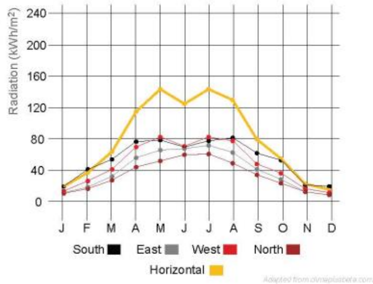
DIAL is a rapidly expanding company with currently 90 employs, but the new building is designed for up to 100 workplaces. If even more space is required in a few years, there is an adjacent option area available, which provides



Location: Lüdenscheid, Germany
51.22°, 7.63°



Sun path for
Lüdenscheid, Germany



Global horizontal and vertical radiation for
Lüdenscheid, Germany

IEA SHC Task 61 Subtask D
Monitored by **DIAL GmbH**

Figure 2. The DIAL Headquarter and sorrounding

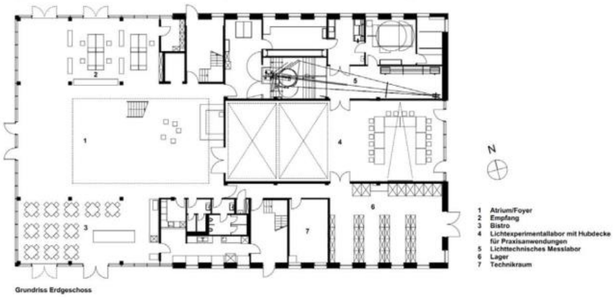


Figure 3. Plan of DIAL Headquarter

Figure 4. The atrium at daytime

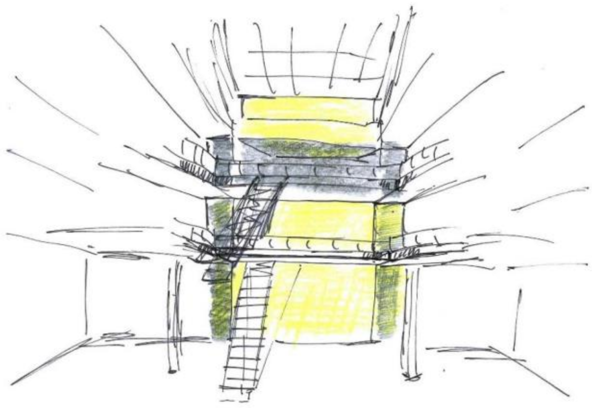


Figure 5. Concept study for the atrium

a further 3,000 square meters for a second construction phase.

Monitoring

From the beginning, thermal, lighting and energetic simulations were the focus of the design.

The technical systems were planned as a co-working function and run in a complex interplay. All trades are networked with one another, which means that no system works independently. An operating software controls and regulates the functions of the building on the basis of the information available. In order to operate the building in an energy-efficient and comfortable way at all times, it is necessary to implement dynamic operating strategies with the help of building automation.

The installation of the technical equipment is therefore largely carried out in a raised floor, to be able to update the installation at any time

From here, the supply air is introduced into the room and the exhaust air is discharged from the room. Since this arrangement does not conform to the textbook, it was simulated in terms of flow technology beforehand.

Energy

In order to balance daylight and artificial light as efficiently and ergonomically as possible, a dynamic light manage-

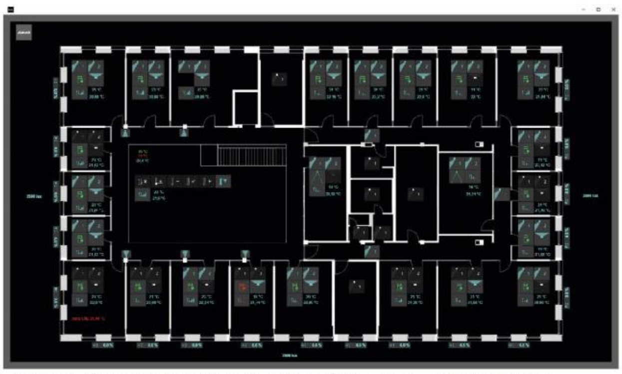


Figure 6. Overview interface for the building management system

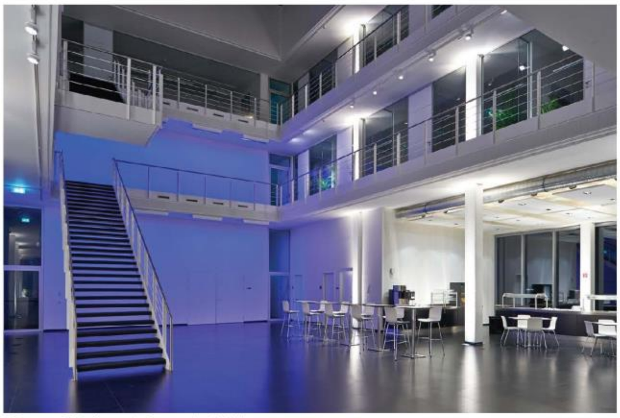


Figure 7. The atrium at night

ment of the external sun protection and the artificial lighting is required. In principle, all application functions are controlled by the building operating system as required (Figure 6). Nevertheless, great importance was attached to providing the user with individual influence. Conventional switches cannot be found in most rooms. Individual settings are made via PC app or smart phone (Figure 8).

Solid concrete ceilings and outer walls are integrated as thermal storage masses into the energy and climate concept, which is based on an extensive thermal simulation. Above all, automatic functions of ventilation and air conditioning systems such as night-time operation or free cooling should be mentioned here. In order to be able to use the storage mass of the building as effectively as possible, it must be freely accessible.

> ***"The intelligent building serves the user"***

The use of software-based technical building management is crucial for the successful operation of the intelligent building. On the one hand, the central display of the operating status and the operation of the technical systems of the building take place, on the other hand, the recording and continuous evaluation of the operating data with the aim of maintaining and optimizing the building's performance. The entire building is hybrid automated and based on KNX IP. At field level, in addition to KNX, DALI (lighting) is also used.

Figure 8. Interface of the PC-App used for the individual user settings

Lighting design

The lighting design is based on the natural effect of daylight and its dynamic course. The principle is: learning from daylight. It includes on 3 components:

1. Basic lighting

The basic lighting is used to create sufficient horizontal illuminance and illuminance on the eye. The direct view into the light sources is taboo, which is why indirect lighting is necessary. The light colour is uniform in all offices 6500 K and creates the impression of a clear sky without intrusive blue tones (Figure 9). The lighting is not switched on suddenly, but always gently dimmed up and down. It can also be used to achieve high lighting levels of up to 2000 lx. The floor-to-ceiling and lintel-free windows and lightsabres between the individual offices ensure that there is sufficient supply of daylight.

The basic lighting follows the brightness of natural daylight, whereby the user can choose between three different dynamic brightness gradients depending on his personal inclination (Figure 10). This corresponds to the philosophy of lighting planning at DIAL, as it is also taught in the training courses. It feels like artificial daylight.

Figure 9. Renderings of the individual light scenes

Building System Design for an intelligent building

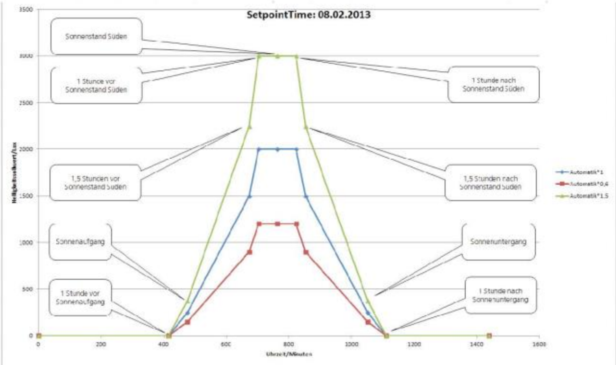


Figure 10. Set-points for basic artificial lighting. Three different luminous levels can be set by the user

2. Accent lighting

The accents give the feeling of direct sunlight and consciously rely on the positive effects of light and shadow, light and dark. They set logical perceptual focuses on objects in space. The light sources are arranged completely without interference and can be adapted to new conditions. Warm white was chosen as colour temperature corresponding to the sunlight.

"Basic lighting follows the brightness level of natural daylight"

3. Vertical lighting of the external walls

Positioning of the lights close to the wall (grazing light), continuous illumination of the entire outer wall. Its colour was a matter of controversy. Now it is either individually adjustable or fixed with a given light colour.

Following this basic concept, individual concepts were developed for the various usage profiles in the building for bistro, atrium, offices, meeting rooms, laboratories, training rooms, sanitary facilities and corridors, which each fit harmoniously into the overall concept. The additional costs associated with this rather complex lighting concept were consciously accepted in favour of the well-being of employees and guests.

User perspective

Right from the start, the focus was on people, their needs and their comfort in the building in accordance with the philosophy: The user doesn't have to operate anything, the intelligent building serves the user. This contains:

- No paternalism for employees
- The ventilation and lighting can be customized
- Brightness that can be freely set in wide areas

The integral design of architecture and technology followed a holistic concept. Even the building's reduced colour concept continues through to the digital user interfaces.

The building is operated mainly via PC apps on the smart phone, with which the employees can influence the air, temperature and light quality and adapt their workplace to their needs with just a few clicks.

Lessons learned

The decisive factor for the successful implementation of intelligent systems in this project turned out to be an integral design process. On the basis of a detailed project analysis, all essential features of the building's operational and operating philosophy were designed at the early stage of the architectural design.

On the installation side, the current solution combines ventilation and heat. Practice shows that this is not an ideal solution. However, the double floor offers the opportunity to remedy this shortcoming in the future.

"The additional costs associated with this rather complex lighting concept were consciously accepted in favour of the well-being"

Programming in *Codesys* also turned out to be difficult to maintain in retrospect. A modular and parameterizable software solution would be the method of choice for a future project.

Further information

M. Bali, D. Half, D. Polle and J. Spitz (2018). *DIAL GmbH case study: Licht und Mensch* in *Smart Building Design - Conception, Planning, Realization, and Operation*. De Gruyter. ISBN 978-3-0356-1629-3

Acknowledgements

Financial support: Trägergesellschaft DIAL e.V., Special thanks to all employees of DIAL Planning: DIAL GmbH; Planning and execution: Artec. Building automation and lighting design: Andreas Bossow, Dietmar Half, Dieter Polle, Jürgen Spitz (DIAL GmbH)

Daylighting integration is an asset for the retail sector

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Generous windows, daylight harvesting and Human-Centric LED Lighting in the pilot project IKEA Kaarst store

At IKEA Kaarst daylight was brought into the exhibition area. This, combined with clever integration of electric lighting, has improved the shopping experience for customers and left the mark on a bunch of enthusiastic employees.

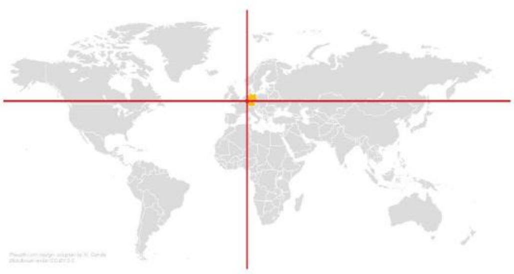
Figure 1. The IKEA shop in Kaarst as seen from the outside. The windows in the living room exhibition area can be seen at the top of the first flight of stairs.

The project

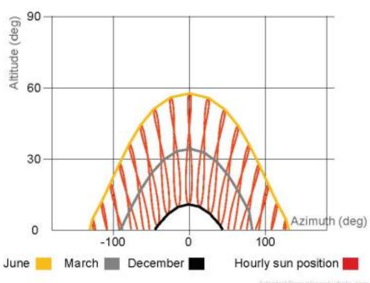
When you arrive at IKEA Kaarst, the feeling is that you are in front of yet another "blue-box" store of the famous furniture chain. But it is when you walk-in that the magic happens. In the "living room" exhibition area, large west-facing windows allows the afternoon sun illuminating sofas and tables (Fig. 2); the electric lighting is provided by LED luminaires dimmed with a daylight harvesting sensor (DHS), and a number of ceiling spot lamps. After walking through various departments, you will end up in the "home decoration" area, where fully-glazed windows provide most of the illumination and a most-welcomed connection to the outdoors; there, the electric lighting relies on traditional halogen spotlamps plus a proof-of-concept Human-Centric Lighting (HCL) consisting of LED panels with colour tuning. The light CCT changes overtime according to a predefined schedule which is intended to mimic daylight (Fig. 2).

Monitoring

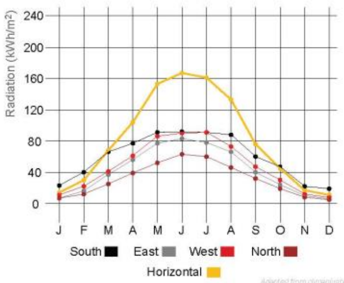
The site was first visited in February 2019, and then monitored for two weeks, slightly before the spring equinox. The field monitoring provided valuable insights as well as material to produce additional computer simulations. The simulations were used to evaluate daylight indicators such as the Daylight Autonomy (DA) or the Daylight Glare



Location: Kaarst, Germany
51.21°, 6.64°



Sun path for
Kaarst, Germany



Global horizontal and vertical radiation for
Kaarst, Germany

IEA SHC Task 61 Subtask D

Monitored by **Rafael Campama Pizarro**, Lund University
More info **Niko Gentile**, Lund University, niko.gentile@ebd.lth.se
http://www.ebd.lth.se

Figure 2. 'Living room' from the inside during the day (top-left), and from the inside druing evening (bottom-left). 'Home decoration' under daylight from the inside (top-right), and with the HCL LED lighting system in function, cool and warm CCT.

Probability (DGP). The monitoring shaped the recommendations of the IEA Task 61 Monitoring Protocol in a feed-forward/feed-back process (Fig. 3).

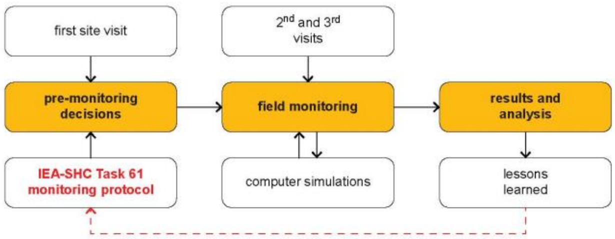


Figure 3. Workflow for the monitoring at IKEA Kaarst

Energy

The LENI was calculated based on the real operational conditions of lamps (schedules and dimming levels). Indeed, the lighting management system logged status (on/off) and dimming levels lamps. The performance was good for the 'living room', but not for the 'home decoration' (Table 1). Additional savings provided by the DHS were marginal, due to the fact that DHS dimmed only the general lighting, consisting of already highly efficient LED. Halogen spotlights, indeed, were never dimmed, due to exhibition purposes. In addition, a DHS sensor was taped by the staff, due to the fact that, by changing products collection, the reflectances were changing and the system overdimmed the luminaires. This is a pretty known issue with DHSs and periodic calibration should be planned.

	LENI DHS kWh/m^2	LENI No DHS kWh/m^2	Savings kWh/m^2
Living room Dpt.	40.3	41.4	**1.1**
Home decoration Dpt.	84.0	84.7	**0.7**

Table 1. LENI for the monitored departments. Benchmark 78.1 kWh/m^2.

Photometry

The exhibitions are provided with a suggested walking path for visitors, which invites customers through all the stock. Therefore, photometric measurements for the two departments were done following two criteria: grid-based, as recommended by lighting standards, and path-based, that is following the suggested visitors path. The latter is meant to be more meaningful to evaluate the shopping experience of customers.

The 'home decoration' (HD) department was highly illuminated by both daylight and electric lighting. With daylight, the cylindrical illuminance was over 1000 lx in some points (Fig. 4). In the 'living room' (LR) department, values were lower, but more spread, with peaks over 500 lx close to the side windows. Similary, the mean and median DF for HD were 1.2 and 0.6 respectively, and 0.5 and 0.2 for the LR. The Daylight Autonomy (DA) at 300 lx with real monitored schedule was 62% and 72% respectively for the LR and HD departments. The average horizontal illuminance at head heigth was 627 lx during daytime and 600 lux at night-time for the LR, while, for the HD, it was 1456 lx and 1011 lx. Overillumination for the HD case, and high con-

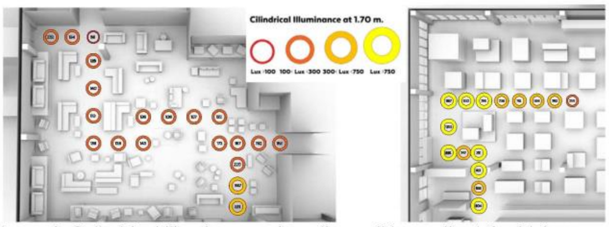


Figure 4. Cylindrical illuminance along the walking path at the Living Room (left) and Home Decoration (right) departments.

trast for the LR, suggest a potential risk for glare. Despite the extensive HDR imaging campaign during monitoring, there was no occasion with clear sky and sun in the field of view; the HDR were then used to calibrate a computer simulations. Once the model was calibrated, DGP analysis were run for time at glare risk. Not surprisingly, intolerable glare was occurring in many occasions; Figure 5 shows the example of February, 15th for the two departments at different time of the day.

But it is here that things get interesting. In the comments provided by customers and employees, glare from daylight was never mentioned as a problem. Instead, three customers complained about glare from spotlights. Arguably, penetration of sunlight, even at glaring levels, does not represent an issue in a retail store. Shopping for forniture is not a task which requires high visual focus, and actually direct sunlight resembles a common home situation. DGP has been created and validate for office tasks, afterall, and its use should be limited to these contexts. At a broader level, the discrepancy between measured DGP and actual users responses show the importance of combining technical and observed-based assessements when evaluating lighting projects.

Similar considerations apply to the view out. The floor area that had access to a quality view out, namely the area which had a vertical or an horizontal viewing angle to

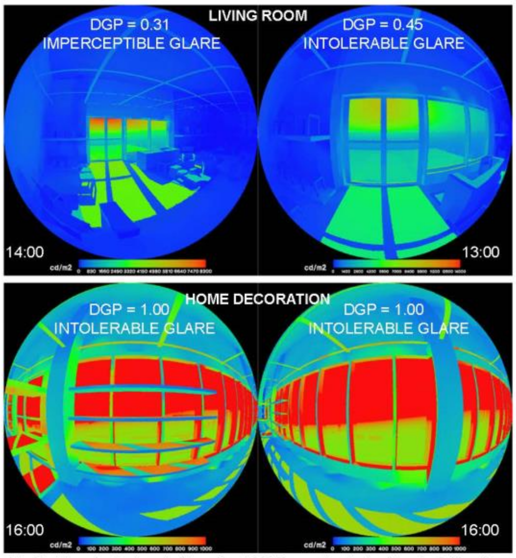


Figure 5. Calibrated simulation for DGP analysis in the LR (top) and HD (bottom) for February, 15th.

the outdoor equal or greater of 20 degrees, was 39% and 95% for the LR and HD department respectively. Namely, a pretty good access to the view out in both departments. But interviews showed that customers were a bit unhappy with the layers seen on the outside; one claimed that "*the view of the parking is not so great*", while another suggested that "*the most beautiful view is obstructed*". This is a good reminder that planning for a view is not only matter of guaranteeing visual connection to the outside, but also that aesthetic values of the view should always be considered.

Circadian potential

Daylight reaches the walking path, providing illumination and shaping the interior exhibition. But can it also provide a circadian stimuli? Certainly, short-term occupants like customers, can hardly benefit from high circadian potential, but it should not be forgotten that there is a permanent staff working in this shop. While office spaces are interested by a growing attention on circadian questions, there is a whole bunch of other workers which are daily exposed mainly to artificially lit environments. Therefore, the circadian potential of the space at IKEA Kaarst was evaluated by taking spot measurements of spectral power distribution (SPD) along the walking path in the LR and HM departments. The spot measurements were taken at eye level (1.7 m) and in four view directions per point. All the measurements were taken on the afternoon of March, 2nd 2019, with partly cloudy sky. The SPDs were imported to the so-called Lucas' toolbox using a 5 nm resolutions, and the Equivalent Melanopic Lux were calculated. A more intuitive representation of results is provided in Figure 6, where the ratio between melanopic and photopic illuminance (M/P) is reported. Ratios higher than 0.9 indicate a higher component of short wavelengths, namely blue-enriched, which may prompt alertness. For example, the WELL standard adopts a fixed M/P = 1.1 for daylight as illuminant. Figure 6 shows that even minor contributions of daylight are able to raise alertness all over the walking path. For the staff, it means they benefit from the sun as time-giver in large sections of LR and most of HM. Definitely not a secondary finding.

In HD, provided with HCL, the M/P ratio is generally very high, even at a distance from the windows. It is difficult to quantify if the effect is due to daylight only, or if the HCL system plays a major role too.

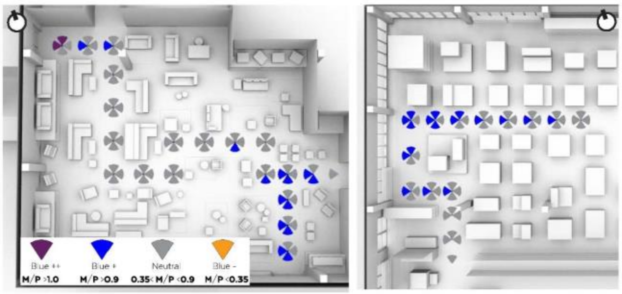


Figure 6. M/P ratio along the path for the Living Room (left) and Home Decoration (right) departments.

Daylighting integration is an asset for the retail sector

SOLAR HEATING & COOLING PROGRAMME
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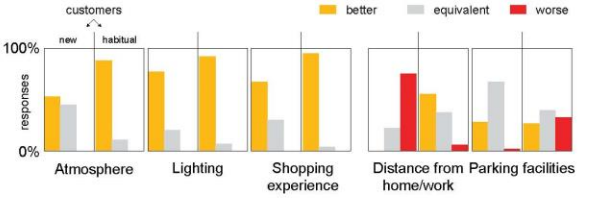

Figure 7. Evaluation from IKEA customers, either new or habitual to the shop in Kaarst.

User perspective

Customers could participate to an online survey by using a QR code hanged at some walls of walls of the LR and HD department. Workers who voluteered were interviewed. Ninety customers and twelve workers participated to the survey. None of the customers was new to IKEA, however some were habitual customers of this particular shop in Kaarst, while for other wast the first visit. Figure 7 is self-explanatory. The shop is not the most conveniently located for customers, and it does not provide more facilities or better parking. However, the great majority of customers thinks that the overall atmosphere and shopping experience is better than in other traditional IKEA shops. Most important, there is almost unanimity in judging the lighting better in this shop. Many customers took also the time to add some personal reflections on daylighting in the survey, like "*it is nice that the sun is coming in*". While nobody complained about glare from windows, one customer protested that "*The interesting products are not in the daylight*". Glare or direct sun can be sometimes a problem from the staff; for example, an employee at HD reported that "*is difficult to protect the plants and other items during sunny days*". However, this are minor issues in a bunch of positive comments, spacing from "*a lot of natural sunlight, one can see weather changes, natural light improves my mood*" to "*Light makes customers happy. They don't feel so locked up*". The staff showed appreciation for the HCL lighting too, claiming that was nice to see how electric lighting could follow the daily changes in natural light. Some of the staff complaints were actually about not having enough access to daylight: "[I don't like that there is] *no natural light in the neighbor department which also belongs to my workspace*". The interviewed staff have been working in another IKEA shops before and they described their current working environments in these terms: "*Today, my workplace it's much more pleasant*", "*I'm happier now*" and "*One is more positive and feels less like at work*".

"It is nice that the sun is coming in"

Lessons learned

Well-designed lighting means good presentation of products and, eventually, more sales. Lighting design in the retail sector focused on electric lighting, most probably for more than a good reason. But there are niches were daylight integration can actually improve the presentation of products; forniture shops are one of those. This case study demonstrates that integrated lighting schemes provide a number of assets beyond energy saving.

"The interesting products are not in the daylight"

Customers felt like at home in the new IKEA Kaarst shop and the employees where more satisfied of their working place. In a sense, integrated lighting may even built loyality to the brand.

In the context of this retails shop, we found that common daylight performance metrics are not always appropriate to describe the space. For example, DGP, which has been developed for office tasks, obviously could not describe the manifold feelings linked to glare in a shop context. This calls for a deeper understanding of integrated design, with more specific recommendations based on space usage and typology of users and activities.

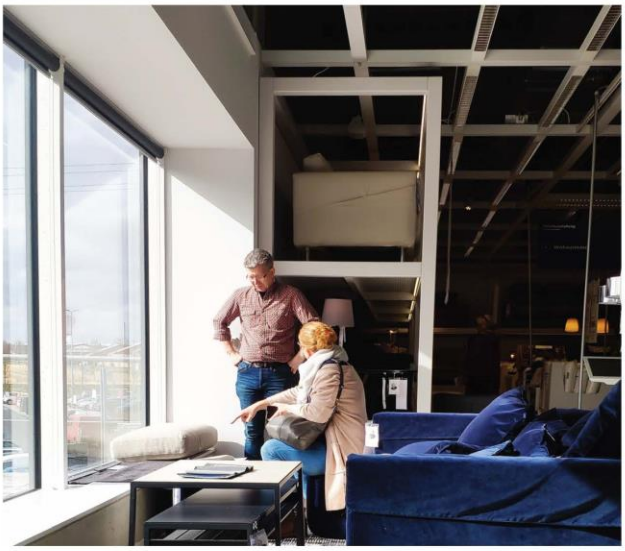

Figure 8. Customers bringing products to daylight, a scene which was repeteadly witnessed during the monitoring.

Further information

Campama Pizarro, R. and Gentile, N. (2020). *A case study addressing the benefits of integrated solutions for daylighting and electric lighting in the retail sector.* Proceedings of the ISES Solar World Congress 2019, pp. 1825-1836, Santiago, Chile https://doi.org/10.18086/swc.2019.38.02

Campama Pizarro, R. (2019). *Daylighting and electric lighting integration in the retail sector: case study of IKEA Kaarst store.* Master thesis in Energy-efficient and Environmental Buildings, Faculty of Engineering, Lund University, Sweden.

Acknoweledments

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Special thanks to Jonas Manual Gremmelspacher (Rescale) and Justin Karst (Tridonic)

Low-cost manually activated shades and tunable lighting in historical building

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Motorized roller blinds and dimmable-tunable LED to improve comfort and save energy at Abazia San Lorenzo ad Septimum.

A low-cost manually controlled system, consisting of two motorised roller blinds and six dimmable and tunable led-based luminaires, was installed in a "Living lab" at the Abazia San Lorenzo ad Septimum to investigate the integration of artificial lighting system with shading systems and to guarantee user satisfaction, while energy savings were achieved by simply training the users.

The project

In this study, users' behaviour and the energy use for artificial lighting were evaluated in a real-world office (living lab) while performing ordinary working activities. The office is a private one, which is located on the first floor of the Abbey San Lorenzo ad Septimum (Fig. 1). The only window of the office is placed on the outer side external wall with an orientation of 15° South-South West. The window has a total surface of about 3.70 m^2, a ratio glass area/total window area equal to 0.38. For this research, commercially available low-cost manually controlled shading and lighting systems were installed in the living lab. Since the building is listed, the shading and lighting systems were installed in a non-invasive way, without intervention on the masonry. The scope was to simulate a potential real life retrofit of existing listed buildings. The shading system consists of two motorised roller blinds manufactured by IKEA, with different visual transmission values: one is semi-transparent, while the other is a "blackout" one. The lighting system consists of six wireless LED-based luminaires manufactured by IKEA (29 W, about 76 lm/W). The luminaires are provided with seven-step dimming and three-step tunable Correlated Colour Temperature (CCT) (2200 K – 2700 K – 4000 K). Both roller blinds and smart luminaires are controlled with remote control. Fig. 2 displays the internal view of the living lab, the shading systems, the lighting system and the position occupied by the user.

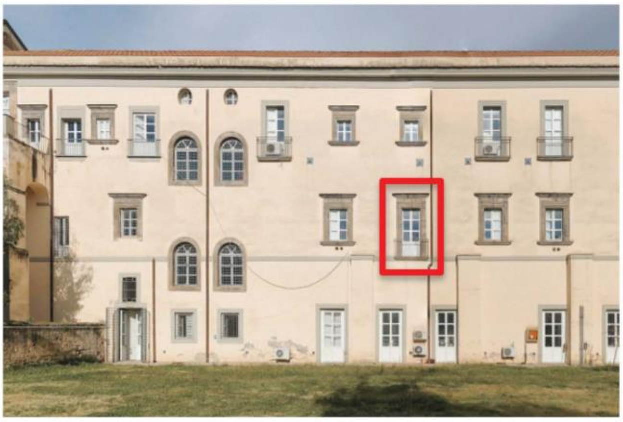
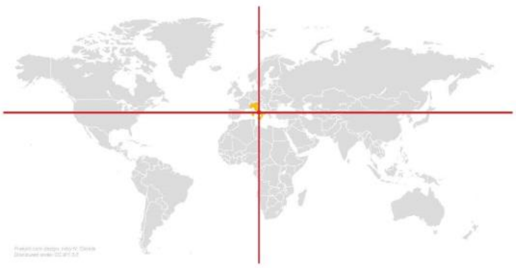
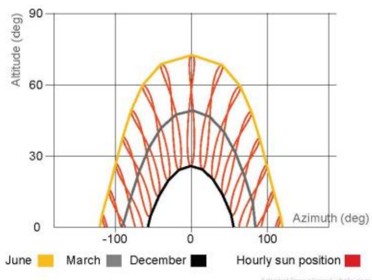


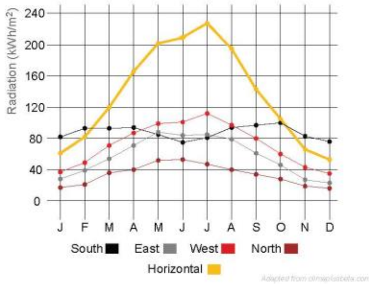
Figure 1. External view of the Abazia San Lorenzo ad Septimum façade.



Location: Aversa, Italy
40°59' N, 14°11' E



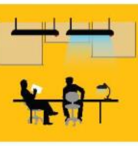
Sun path for Naples, Italy



Global horizontal and vertical radiation for Naples, Italy

IEA SHC Task 61 Subtask D

Monitored by **Michelangelo Scorpio, Giovanni Ciampi, Niko Gentile, Yorgos Spanodimitriou, Roberta Laffi, Sergio Sibilio**
More info **Michelangelo Scorpio,** University of Campania, michelangelo.scorpio@unicampania.it



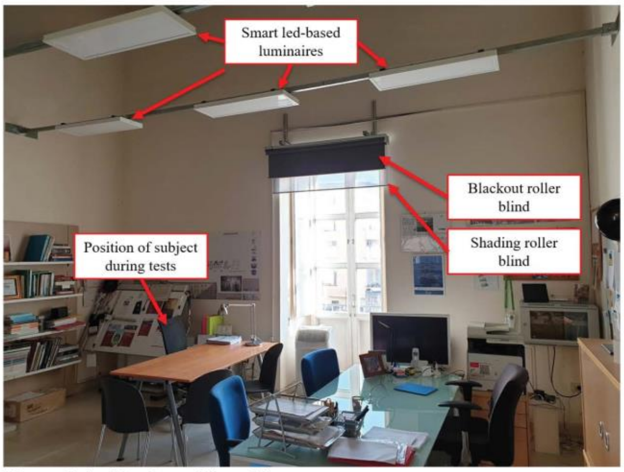


Figure 2. Inside view of the office.

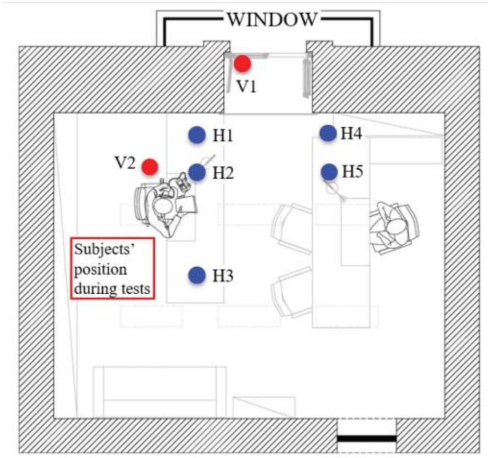


Figure 3. Office layout with the position of indoor sensors.

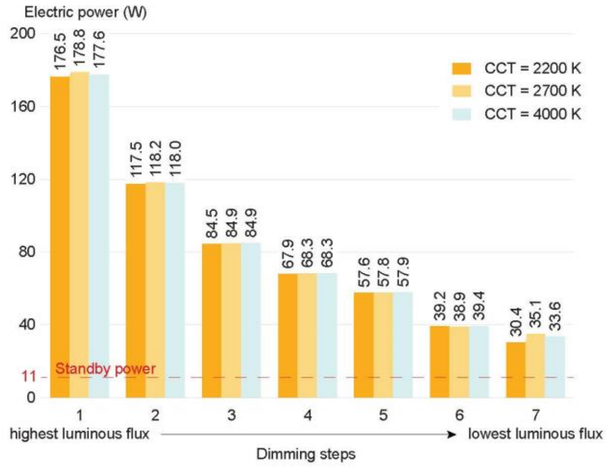


Figure 4. Electric power required by the lighting system for the different dimming and tuning steps, including standby.

Monitoring

Although two working stations were set up, the office was used only by one person during the tests. During the monitoring period, each subject performed ordinary office tasks, mainly focused on PC typing and reading, for two weeks. The subject was able to adjust the position of the two motorised roller blinds and the six smart luminaires through wireless devices, according to their needs, while sitting at the desk. Before the monitoring period, the subjects were trained on the use of the system and informed about the importance of good day-/lighting. During the two weeks experiments, the subjects received also email reminders about the importance of using natural light and combine it with the "right" type and amount of artificial lighting, if needed. Simultaneously, physical quantities were measured to evaluate the boundary conditions and user interaction with the systems. The monitoring follows the recommendations of the IEA Task 61 Monitoring Protocol.

Energy

The dimming level of the luminaires was evaluated by measuring the power required by the whole lighting system, while the CCT was assessed using an RGB sensor placed close to one of the luminaires. The electric power needed for the standby mode was also monitored. Fig. 4 displays the electric power required by the lighting system in the standby mode as well as upon varying dimming step and CCT values. Since each roller blind was equipped with a battery (no connections to the electric grid are required), their electrical use was neglected.

Photometry

The external daylight availability was evaluated by measuring: external horizontal global illuminance and external vertical global illuminance on the window's external side. Photometric measurements were performed to evaluate the reflectance and colour values of the internal surfaces, the indoor light distribution and outdoor daylight availability. The indoor light distribution was acquired by using five lux-meters placed in a horizontal position at the work plane level, 0.73 m from the floor, one lux-meter was placed in a vertical position just behind the glazing and one lux-meter was placed in a vertical position at 1.22 m from the floor to simulate the eye of a user seated at the desk (Fig. 3). Both roller blinds' positions were evaluated by measuring the distance between the bottom of each roller blind and the floor; the distances were measured using ultrasonic sensors installed on each roller blind. Finally, the subjects' visual connection with the outside was evaluated through the view out from the desk (Fig. 5). With a horizontal sight angle of about 15°, the view can be rated as "minimum", even if two layers are visible from the given position.

Fig. 6 reports the comparison between the outdoor vertical illuminance on the external surface of the window, the indoor vertical illuminance just behind the glazing, the illuminance on the task area, the vertical illuminance at eye level, the electric energy used by luminaires as well as the closing degree of both shading and blackout roller blind, for two subjects, while the regions in light green indicate the occupancy of the office. Measurements were performed in November 2020 and February 2021 and suggest a good daylight availability in the office, even in the winter, and

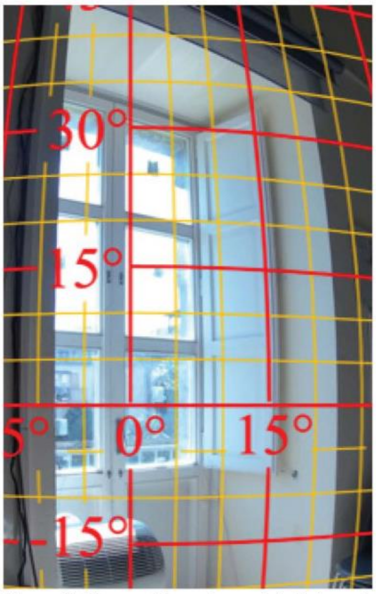


Figure 5. View out from the point of view of the subject seated at the desk.

that the user generally preferred to allow as much daylight as possible, even when the work plane is hit by direct sun radiation (graph on the right in Fig. 6). The figures underline that the blackout roller blind closing degree strongly influences artificial lighting system use, even with clear sky conditions. When the blackout blind is completely closed, the user considers the daylight amount in the room as not enough and then turns on the artificial lighting. Nevertheless, with better adjustment of the blackout blind position, the user may avoid glare - if occurring - and rely on daylighting only. Interestingly enough, when the shading is rolled up again, the artifical lighting is switched off. This contrasts with most of literature in the topic and it is arguably linked either to the training of the user or to the availability of both remote controls for shading and lighting at the desk. Finally, changes in dimming and CCT were very limited.

Circadian potential

During the day, daylight in the test room is mixed with artificial lighting following the individual choices of the occupant. To evaluate the light circadian potential at the work space, spectral power distribution measurements were taken at eye level (1.2 m) for artificial lighting only (varying CCT and dimming step) and for daylight only, with overcast sky. The SPDs were imported to the Lucas' toolbox and CIE S 026 alpha-opic toolbox, using a 1 nm resolution. Then, the photopic illuminance, the melanopic illuminance, the Equivalent Daylight Illuminance (EDI), and melanopic over photopic illuminance ratio (M/P) were calculated (Table 1). Regarding the EDI values greater than 250 lux would be desirable during the day (Brown et al, 2020). M/P ratios values higher than 0.9 indicate a blue-enriched lighting, supposedly prompting alertness. For example, the WELL standard adopts a fixed M/P = 1.1 for daylight as illuminant. Interestingly enough, none of the current artificial lighting scenario is able to achieve EDI > 250 lux, despite being dimensioned for the delivering the standard 500 lux (photopic) on the desk. For this location, instead, daylight can reach the threshold even during an overcast sky day (Table 1). Therefore, if the design aims at eliciting circadian response, either artificial lighting should be overdimensioned in respect to today standard - with obvious rebounds on the energy use - or more daylight should be allowed in the space. The latter appears to be a smarter solution for both the environment and the user.

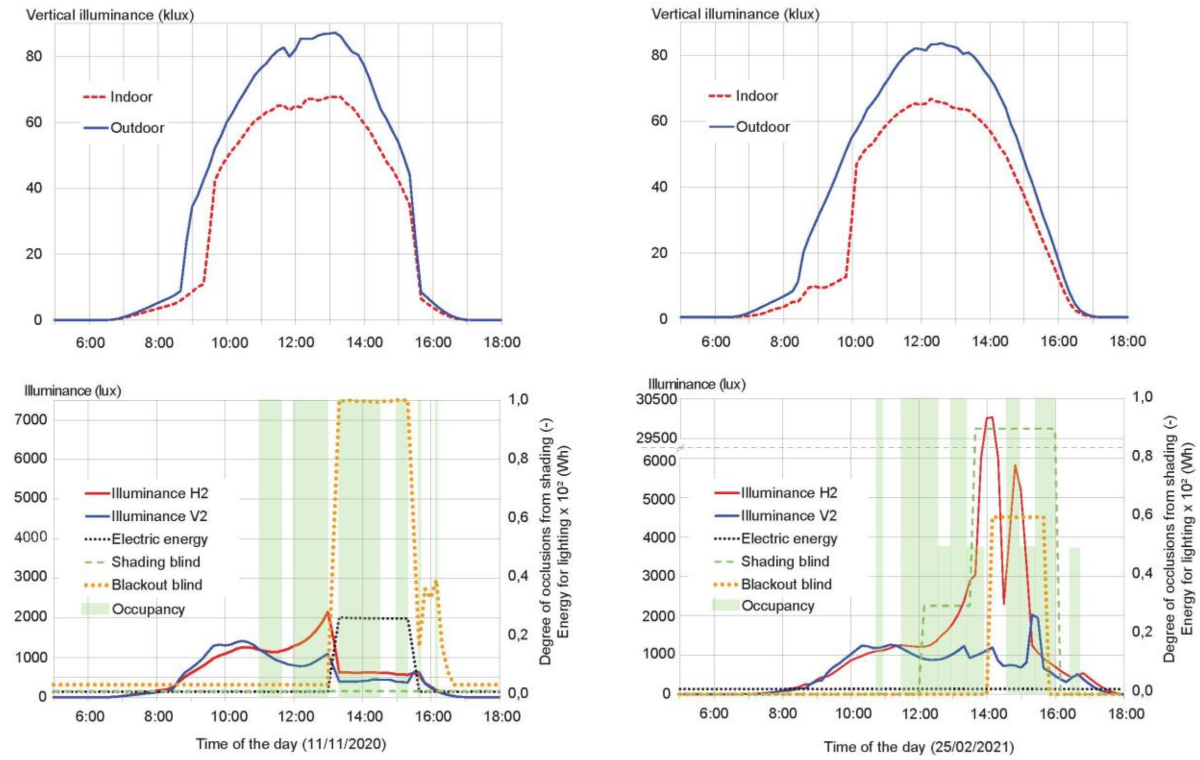


Figure 6. Indoor and outdoor physical quantities acquired during a day with clear sky conditions for two subjects.

Low-cost manually activated shades and tunable lighting in historical building

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Table 1. Photopic and melanopic illuminance, EDI and M/P ratio under different daylighting and artificial lighting conditions.

Artificial lighting CCT = 2200 K							
Dimming step	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Photopic (lx)	300	180	109	66	40	24	15
Melanopic (lx)	89	53	32	20	12	7	5
EDI (lx)	80	48	29	18	11	7	4
M/P ratio	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Artificial lighting CCT = 2700 K							
Dimming step	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Photopic (lx)	323	195	117	71	43	26	16
Melanopic (lx)	132	79	47	29	18	11	7
EDI (lx)	119	72	43	26	16	10	6
M/P ratio	0.4	0.4	0.4	0.4	0.4	0.4	0.4

Artificial lighting CCT = 4000 K							
Dimming step	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Photopic (lx)	351	212	128	78	47	29	18
Melanopic (lx)	210	126	76	46	28	17	11
EDI (lx)	190	114	69	42	25	15	10
M/P ratio	0.6	0.6	0.6	0.6	0.6	0.6	0.6

Daylight overcast sky									
Time (09:00-17:00)	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*
Photopic (lx)	180	165	240	141	105	121	171	413	325
Melanopic (lx)	168	154	225	133	98	112	160	382	304
EDI (lx)	152	139	204	121	89	102	145	346	276
M/P ratio	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9

User perspective

During the two weeks, the participants used rarely the artificial lighting. In contrast, they used quite extensively the shading devices. Because of the room orientation, direct sunlight resulted in glare or reflections during the early afternoon. All the participants decided to lower the shading at this time, although some opted for the blackout shading, others for the semi-transparent. In most cases, the artificial lighting was turned on right after, at different levels of dimming and typically with neutral CCT. The CCT itself was rarely adjusted and, if it was, that was not done in relation to the time of the day, namely cold light in the morning, warm in the afternoon, but according to individual preferences only. There was also little corelation between the chosen CCT and dimming level. The participants were exceptionally satisfied with the level of control they had on both day- and artificial lighting, and with the option of having remote controls available right next to the workspace. A participant was sad when the two weeks were over and wanted to stay longer in the test room. They considered that the system could accommodate all their needs. Extreme behaviours were observed, with some partipants preferring to use artificial lighting, and others making use of daylighting as much as possible. In any of the case, the participants had highly conservative energy behaviors. For example, the "artificial lighting" participants made a greater use of the dimming functionalities, while the "daylighting" participants simply did not use artificial lighting. In follow-up interviews, the participants claimed that the room was very well daylit and that they did not feel the urge of using additional artificial lighting. But they also claimed that the training helped them in thinking before acting on lighting. Opinions on the usefulness of email reminders were more spread, with some users being annoyed by them. All in all, it seems that a very simple integrated manual system, provided with extensive options (shading, dimming, CCT) and with available controls, can satisfy the most and allow interesting energy savings. In respect to the latter, a proper training and information of the user seems to be extremely useful.

"I told them I was not going to leave that office after the test!"

Lessons learned

The results are in line with the literature on the topic. Subjects show a general preference towards daylighting, limited use of artificial lighting, a limited interaction with the systems during working hours, and some minor occurrences of energy wasteful behavior. Results also generally suggest that artificial lighting is limitedly used when a good daylighting design is set up, which makes the energy use for standby not of secondary importance in private offices. Generally, accessible manual controls can help the users maintain visual comfort in the office. Users' training could guarantee quasi-optimal use patterns of shading devices and artificial lighting, possibly comparable to those of automatic systems. Results also underline that when the blackout roller blind is completely closed, the users preferred to switch on the artificial light system even for computer-based tasks. This calls for a deeper investigation of integrated design, with more specific recommendations based on user preferences and tasks. Results underline that the tested system is eligible for both to be installed in historical buildings as well as improve energy saving and visual comfort.

Further information

G. Ciampi, A. Rosato, M. Scorpio, S. Sibilio, *Daylighting contribution for energy saving in a historical building*, Energy Procedia. 78 (2015) 1257–1262. DOI:10.1016/j.egypro.2015.11.270

M. Scorpio, G. Ciampi, A. Rosato, L. Maffei, M. Masullo, M. Almeida, S. Sibilio, Electric-driven windows for historical buildings retrofit: Energy and visual sensitivity analysis for different control logics, Journal of Building Engineering 31 (2020) 101398. DOI: 10.1016/j.jobe.2020.101398

About the EDI thresholds: Brown, T., Brainard, G., Cajochen, C., Czeisler, C., Hanifin, J., Lockley, S., ... & Wright Jr, K. (2020). *Recommendations for healthy daytime, evening, and night-time indoor light exposure.* Preprint, not peer-reviewed.

Acknowledgements

"**V:ALERE program**" of the University of Campania Luigi Vanvitelli (Italy) and the **Swedish Energy Agency**

Horizontal light pipe brings natural light into office at high latitudes area

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Horizontal light pipe brings distinctive features of daylight to the back part of the office, increases light level, and saves energy

In this long-term pilot study at Norconsult AS, a horizontal light pipe (HLP) was used to bring daylight to the back part of the office. HLP brought up to 400 lux of natural light to the desk closest to the back part of the office, increased user appreciation of the space, and saved energy.

The project

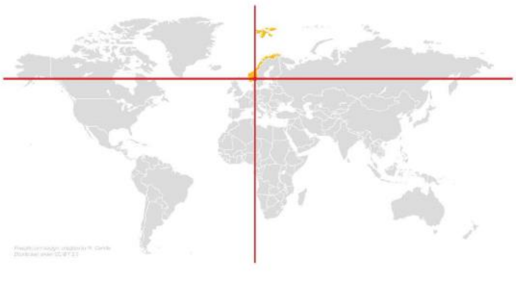
Clear skies and sunlight are appreciated in Scandinavian countries, but relatively simple solar protections are incapable of redirecting effectively sunlight and transforming it into functional daylight. People react instantly and close sun shadings when they experience excessive light, and do not open them until long after such conditions disappear. This study with horizontal light pipe (HLP) was mainly inspired by this issue. Norconsult AS dedicated an entire office of its headquarter near Oslo for this study (Fig. 1).

The test-office had standard finishes and colours and an area of 13 m^2. Windows are oriented southwest, and the HLP was installed at 45° from the southeast wall, Fig. 2. This design was chosen in order to place the pipe's exit above the desk closest to the door, without using any pipe-elbows (i.e., the pipe was straight), and to align the pipe inlet to the south. The installed HLP has a diameter of 22 cm, dictated by the building's constraints, and a length of 375

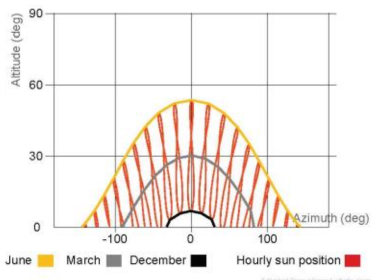
Figure 1. Norconsult AS Headquarter building.

cm (aspect ratio of 17). The light pipe has a clear diffuser and a custom-designed reflector to direct the light from the pipe down to the working area. The reflector helped to maintain the daylight's qualitative features like dynamics, variation, colour. Between 10:00 and 14:00, when the weather was sunny, the reflector provided delicate and balanced light patches, both on the desk and the wall (Fig. 3). Occupants' reaction to light patches are generally positive if the patches are of specific size and distance from the observer.

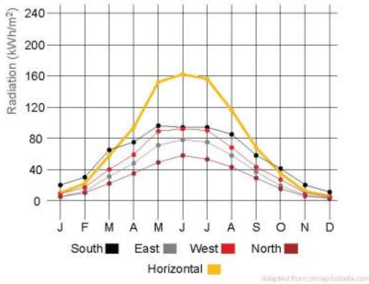
The office has also two windows oriented southwest. Man-



Location: Oslo, Norway
59.89°, 10.60°



Sun path for
Oslo, Norway



Global horizontal and vertical radiation for
Oslo, Norway

IEA SHC Task 61 Subtask D

Monitored by **Biljana Obradovic**, Norconsult AS
More info **Barbara Matusiak**, NTNU, barbara.matusiak@ntnu.no

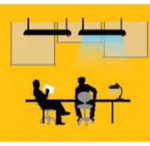


Figure 2. Building orientation (left) and office plan (right).


Figure 3. Working areas in the test office.


Figure 4. Office as seen from: the entrance to the office (left), the desk closest to door (middle), and the desk closest to the window (right).

ually operated sun shading were kept in a fixed position during the study, closed with slats angle of 40°, the latter found to be a suitable angle for this location. This shading strategy was developed to provide satisfying visual comfort at any time, a glare-free office. Fig. 4 shows the visual conditions from various view points. The hypothesis was that reducing glare occurences will reduce the occasions in which shadings are completely closed, which would in turn provide more lighting energy saving. Daylight calculations showed that the illuminance would be 120 lux and 50 lux at the desk closest to the window and door, respectively during an overcast sky (Fig. 5). During a summer clear sky day a 17:00 (sun altitude 30°), the illuminance will increase to 1000 lux and 500 lux at the desk closest to the window and door, respectively (Fig 5 right).

Two LED luminaires of 22W each were used to provide artificial lighting according to the NS-EN 12464-1: 500lux on both working desks, uniformity ≥ 0.6 and UGR < 19. The CCT was 4000 K, and the CRI was 80. Each luminaire had its own daylight-linked control system (DLCs). Luminaires should supplement additional light when daylight via the window and light pipe did not reach 500 lx (Fig. 6).

Monitoring

The pilot office was monitored continuously from March 2020 to March 2021. The monitoring was divided in two parts: a *test* period where the HLP was active and allowed daylight (21.06.2020 to 21.12.2020), and a *reference* period during which the HLP was disabled. These factsheets presents mainly results for the *test* period; preliminary results of users' perspective for both *reference* and *test* period are also presented.

Indoor illuminance values were recorded by logging values from five illuminance meters each minute: two meters were placed horizontally on the desks at 0.8 m height, two vertically illuminance on the wall at 1.2 m, while the last one was placed on a tripod to assess vertical illuminance at the eye position during the user's surveys. An outdoor illuminance meter was placed vertically, on the same vertical plane of the pipe's dome, and another one was placed horizontally at the roof level. The lighting energy use for each minute was provided by separate power meters 10-20A, one for each luminaire.

Energy

The lighting operating hours were 07:00-17:00 (10 hours) during both week days and weekends. The lighting was always on during working hours and dimmed according to the DLC, which accounts for a usage factor of 0,66%. The estimated LENI for this test office was 8,2 kWh/m^2, but the measured LENI was 6 kWh/m^2.

The energy consumption data need to be seen in parallel with the photometrical measurements. It was evident that the reflections from daylight on the sun shading slats affected the lighting sensors; the DLCs received wrong information on the level of artificial light they additionally supposed to provide. Typical sunny day showed that from 10:00 to 14:00, a high level of daylight was delivered through the pipe and enabled a luminaire to go on standby mode (Figure 8). After 14:00, the sun moved to the west and hit directly to the window/sunscreens, which affected the luminaire's sensors closest to the window more than the one closest to the door. During overcast days, there are higher daylight level closest to the window than close to the door. Energy use for artificial lighting is proportional to the daylight supplement (Figure 7).

It was expected that the energy use for the luminaire closest to the door would be higher than for the luminaire closest to the window. The first results suggest that the difference is approximately 35% for the total reference period and 29% for the entire test period. The window luminaire uses as much as two times the energy during the winter in respect to the summer. The luminaire closest to the door used 10% less power during summer than during winter in the reference period, but 20% less in the test period, indicating the beneficial effect of the HLP.

Photometry

Due to the reflected daylight/sunlight from the sun shading slats cut-off 40°, the DLC system did not perform as expected. Luminaires received incorrect information about the luminous output light they needed to provide, and the illuminance on the tables varied a lot. Following best prac-

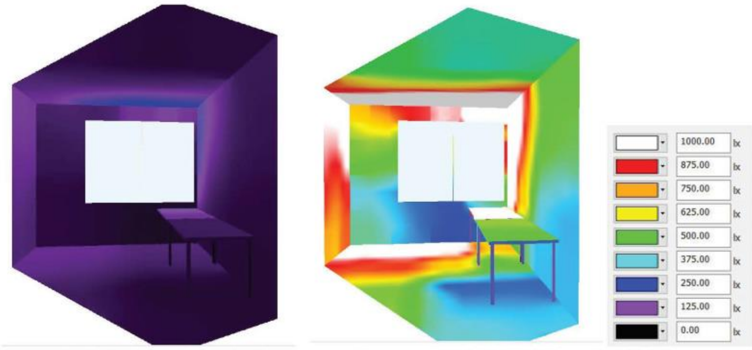


Figure 5. Calculated daylight illuminance for overcast (left) and clear sky (right).

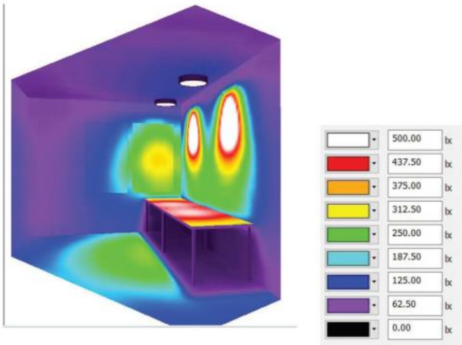


Figure 6. Calculated artificial light illuminance.

tice and considering rules-of-thumb for tolerance of light variation, a fade-out time of 10 minutes was applied to the DLCs. However, it was noticed that magnitude of changes in daylight intensity was substantial and the DLCs appeared unsuitable. The illuminance level on the desk closest to the door was as low as 230 lux in some situations, and the 500 lux could be guaranteed only with overcast sky, as the issue with reflections did not occur. When the photosensors was affected by reflections, the lighting was almost completely dimmed. In those cases, the illuminance registered on the desk (Figure 8) was given by daylight only and it did not reach the 500 lux set-point. During the overcast sky, both desks' levels are stable, starts with the 450-500 lux, and minor variations happen if the sky luminance changes (Figure 8). But, from noon, as the sun turns from south to west (windows are south-west oriented), the illuminance level on the desk closest to the window increases. The same happens with the illuminance on the desk closest to the door, but to a lower extent. For clear sky, the variation of illuminance values' starts already at 09:00M, as the sun approaches the south alignment. Both horizontal and vertical illuminance on the desk closest to the door follow the daylight supplemented via HLP, especially between 10:00 and 14:00.

Circadian potential

The melanopic lux level in the test office has not been measured. However, the adopted daylighting strategy guarantees permanent all-day and year-long presence of the natural light in the entire room, with clear impact on the circadian potential of the space.

User perspective

The user surveys were performed during September 2020 (equinox) to cover a yearly average daylighting condition. Fifty employees from Norconsult participated in the study, 26 male and 24 females, from 23 to 65 years old. Participants were without an architectural or lighting engi-

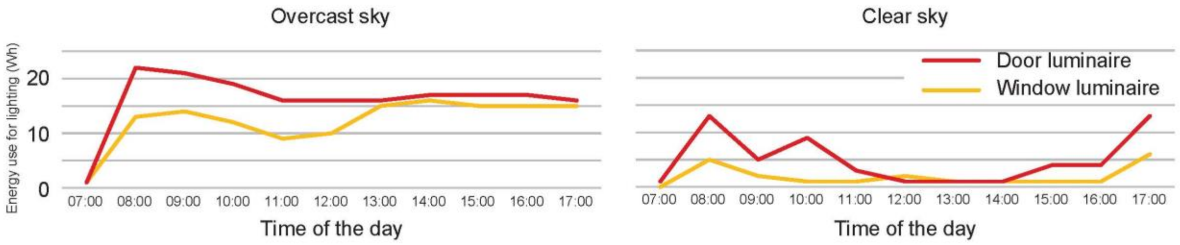


Figure 7. Energy use for lighting for the window and door luminaire during the test (HLP active), overcast and clear sky conditions.

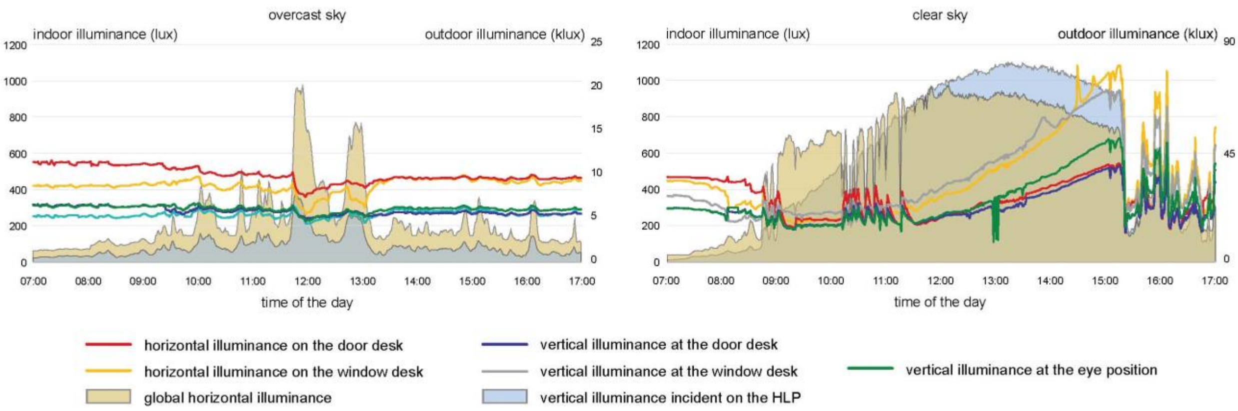


Figure 8. Indoor and outdoor illuminance values for occupancy hours during the test (HLP active), overcast and clear sky conditions.

Horizontal light pipe brings natural light into office at high latitudes area

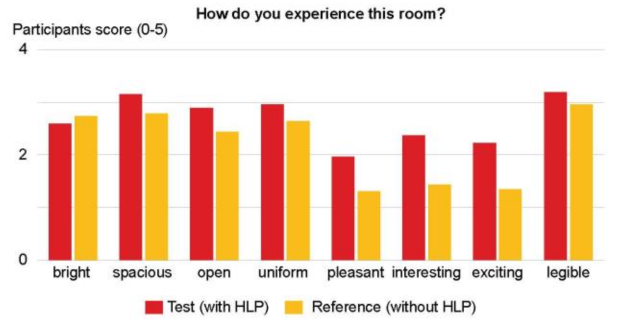


Figure 9. Visual experience and perceptual impression of the room.

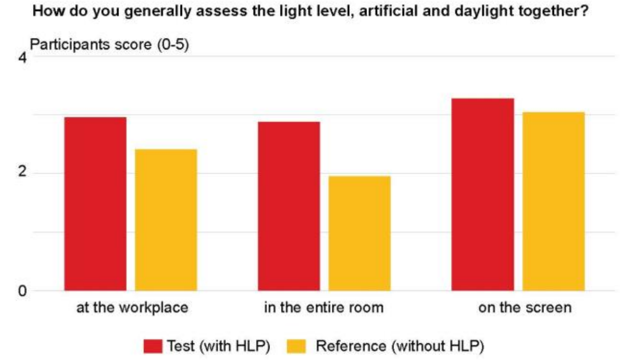


Figure 10. Evaluation of the level of light, artificial and daylight together.

neering background to avoid bias. The participants were only visiting the space and they did not use the office permanently. The weather conditions variated during the surveys, spacing from clear sky to completely overcast sky days. Consequently, the daylight provided through the HLP was different for the different participants. In order to test the hypothesis on occupant impression of the room the participants were divided into two groups, one with noticeably higher daylight and the other without noticeably higher daylighting provided by the HLP. There were 27 participants in the HLP group ("test") and 23 participants in the group withouth daylight from the HLP ("reference"). After the survey, the participants were assigned to different groups. This was done by analysing the logged information on indoor illuminance, outdoor illuminance, and energy for lighting. For the test group, there was on average 70% of the light on the test desk that was delivered by HLP, and just 9,5% that came from the artificial lighting, while for the reference group, those values were 14% of the light from the HLP and 70% from the artificial lighting..

Participants got the opportunity to stay and work (on their laptop) for half an hour before the survey. When they needed to fill out the questionnaire, they sat at the desk closest to the door to experience a working place under the light pipe's daylighting. Analyses of participants scores given for the test room's visual experience and perceptual impression revealed a more positive evaluation of the room as spacious, open, uniform, and legible in the test group. There was a significant better evaluation of the test room as pleasant, interesting, and exciting in the test group, Figure 9. The room's brightness was evaluated better in the reference group. That was expected since higher indoor illuminance levels were recorded just in case of an overcast sky (reference group). The test group evaluated the level of daylight and artificial light more positively than the reference group (Figure 10). The most significant difference in assessment is the light level in the entire room. When the light level on the desk was just about 350 lux, a noticeable share of daylight was provided by the HLP. In such occasions, the participants provided interesting comments like: "*it feels pleasant, and my eyes can relax*.", "*very unusual lighting, it feels simple/flat, but it's satisfying to work on screen.* ", "*The first impression was that the room was not bright, compared to the lighting in the corridor and neighbouring rooms, but the room is bright enough to be able to perform work.*". This contrasted quite clearly with comments provided in for surveys conducted under overcast sky conditions, with artificial lighting providing most of the 450-500 lux of illumination on the desk: "*The corner towards the door is dark*"; "*Rooms and work furniture/tables are white and uninspiring. Can probably seem a little cold in our climate*"; "*The room is somewhat monotonous and dull*"; "*No colour dynamics. It keeps me awake, but I can get tired faster with exertion.*"

"It feels pleasant, and my eyes can relax"

"Very unusual lighting, it feels simple/flat, but it's satisfying to work on screen"

Lessons learned

When daylight was provided by the HLP, the participants perceived the room appearance as uniform, open, exciting and pleasant. There was also a statistically significant positive evaluation from the test participants for the integration of daylight and artificial lighting in the entire room for the HLP case. Daylight reflected on the slats and pointed against ceiling affected DLC sensors, which resulted in wrongful information given further to the luminaires to adjust the artificial light level. In the case of an overcast sky, the fade time for DLC was less critical than in the case of clear sunny skies, where the magnitude of sun/sky illuminance variation was much higher.

Further information

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Obradovic, B. and B.S. Matusiak, *Daylight Transport Systems for Buildings at High Latitudes*. Journal of Daylighting, 2019. 6(2): p. 60-79.

Acknowledgements

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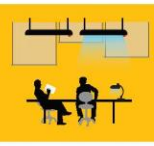


Saving energy with integrated lighting design: the headquarter of IDOM

Skylight, daylight harvesting and microperforated façade in a southern European landscape office in Madrid.

A range of daylight and lighting design strategies has been applied in the IDOM office building. The design is focused on the performance and well being of the workers as well as reduction of the electric lighting. Simultaneously the prevention of solar gains with blinds and a double skin façade has been successfully implemented.

The project

The new headquarter of IDOM is nature-inspired multistorey building. The entrance floor stands out for its biophilic design; surrounded by gardens and fountains, outdoors and indoors limits disappear. The façades have different designs: fully glazed on the north, and a distinctive double skin with microperforated sheet and landscape windows on the other sides. Offices, which are found in the upper floors, are at the focus of this monitoring. Common spaces are located facing south, the landscape offices are located north (Fig 2), while private offices are found in the core area. The latter is illuminated by skylights, bringing a sense of spaciousness to the interior. The materials in the indoor are basic: wood slats for the ceiling, visible bricks or white stucco for the walls, and dark vinyl flooring.

In the landscape office we found a daylight harvesting system, cleverly divided in several control groups, depending on the distance from the façade. Solar protection is guaranteed by internal roller shades.

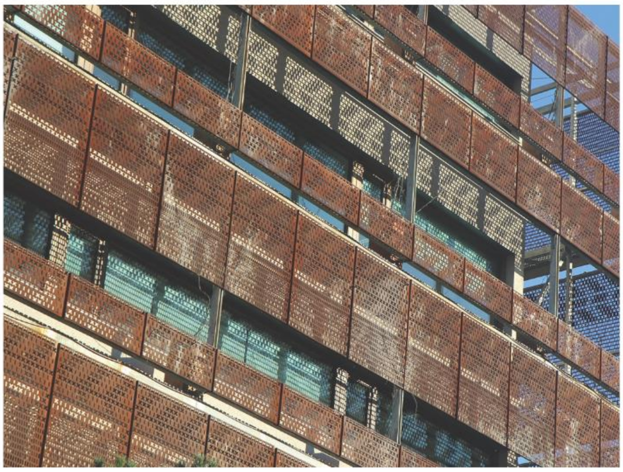
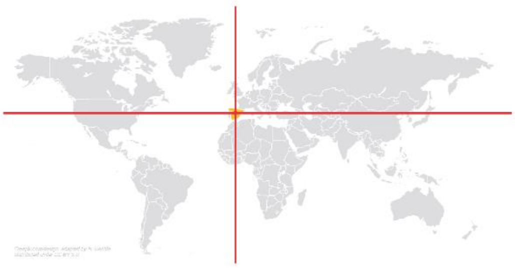


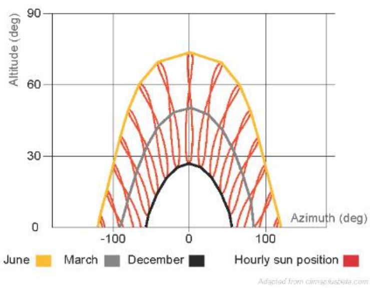
Figure 1. South view of the double skin micropeforated façade of IDOM Headquarter in Madrid. This façade is perhaps its most distinctive sign. The façade, which was designed to reduce overheating, provides also some glare protection if combined with roller shades.

Monitoring

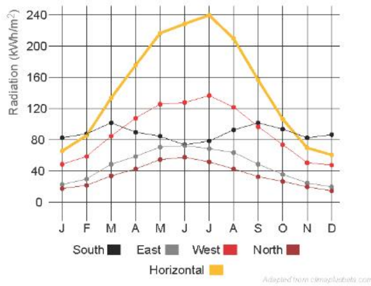
The building was visited for the first time in February 2020 and accessed for daily point-in-time measurements, surveys and pictures until March 15th, when the global Cov-



Location: Madrid, Spain
40.50°, -3.71°



Sun path for
Madrid, Spain



Global horizontal and vertical radiation for
Madrid, Spain

IEA SHC Task 61 Subtask D

Monitored by **Julio Fernandez Amodia**, Lund University & IDOM
More info **Niko Gentile**, Lund University, niko.gentile@ebd.lth.se
http://www.ebd.lth.se

Integrated lighting design in Madrid: the headquarter of IDOM

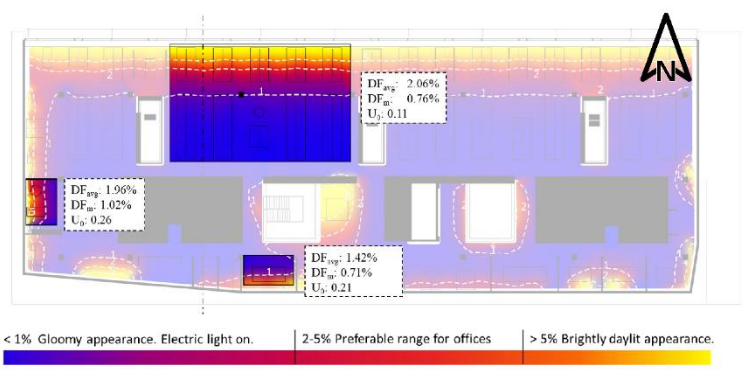


Figure 2. Average and median Daylight Factor(s), and daylight uniformity ratio under overcast conditions for the three monitored spaces: landscape office, west facing and south facing private offices.

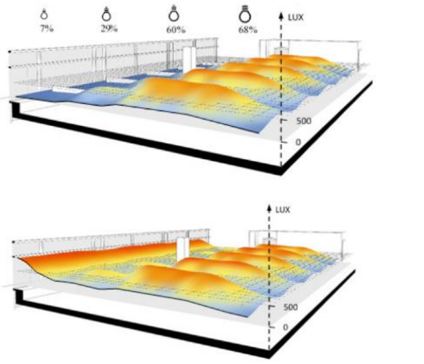


Figure 3. Illuminance profiles for the open plan office: daytime profile for electric lighting only (top), daytime profile for both daylight and electric lighting (bottom).

id-19 pandemic stopped the field monitoring. Nevertheless, the field measurements provided data to characterize the lighting system, to simulate daylight performance, to evaluate the circadian potential in particular conditions, and to draw some valuable conclusions. The model was created in Rhinoceros 3D and the simulations were run in Grasshopper by using Radiance and Daysim via Honeybee/Ladybug interface. The circadian potential was instead assessed with the Lark plugin for Grasshopper. The monitoring focuses on the landscape office, while glare assessments are provided for the private offices, in particular those facing the microperforated facade (Figure 2).

Energy

The electric lighting system consists of efficient fluorescent T5 pendants 2x28W (104 lm/W) combined with compact CFL 2x26W - both providing lighting at 4000 K -, and an open-loop daylight harvesting system. A single sensor located on the roof controls all the light fixtures in the open plan office, which are manually switched on-off. The light fixtures are grouped in four groups, which are calibrated in groups according to this sensor. There is no separate energy meter for lighting, so the system had to be simulated with Daysim. Daysim works with an ideal open-loop control, so this tool was quite appropriate to simulate this specific electric lighting system. For the simulation, the open office area was divided in four different control groups regarding the distance from the façade based on the Daylight Autonomy simulations (Figure 3). The simulation used standard occupancy schedule.

Despite the 15m depth of the office, even the areas close to the building core could slightly benefit from daylight, possibly thanks to the extra contribution of core skylight. This exploited the potential of the daylight harvesting

Table 1. LENI the open plan office simulated for an ideal open loop daylight harvesting system. Benchmark Tab M1 EN15193-1:2017.

	LENI DHS kWh/m^2	LENI Benchmark kWh/m^2	Savings %
Open plan office	4.90	23.23	**78.91**

system, resulting in very low energy use for lighting (Table 1). Although the results were obtained with computer simulations, site observations suggest that the open-loop daylight harvesting system was working as for design. It should be noted also that the luminous efficacy of the fluorescent lamps is comparable to that of many today's commercial LEDs.

Photometry

The headquarter is designed such that daylight is maximized and solar heat gains reduced; yet room for improvement exists. The daylight factor, which was both measured and simulated, showed that the workplaces close to the core lacked of daylight (DF < 1%) despite the contribution of the skylight, while some places closer to the façade were potentially at glare risk (DF > 5%). This also resulted in low illuminance uniformity (Figure 2). Not only the layout, but also the materials were responsible of the low daylight penetration; the ceiling, for example, is characterized by very low reflectance (35-50%). As a comparison, the EN12464-1:2011 recommends 70-90% reflectance for ceilings.

Another interesting is the dynamism of daylight for the west and south offices, where skylights and microperforated façade provide an ever-changing appearance to the space. This, however, makes also daylight much harder to control (Figure 4).

Indeed, daylight glare (DGP) simulations shows that the

Figure 4. Rendering for the west facing offices with clear sky conditions on June, 21st 18:00.

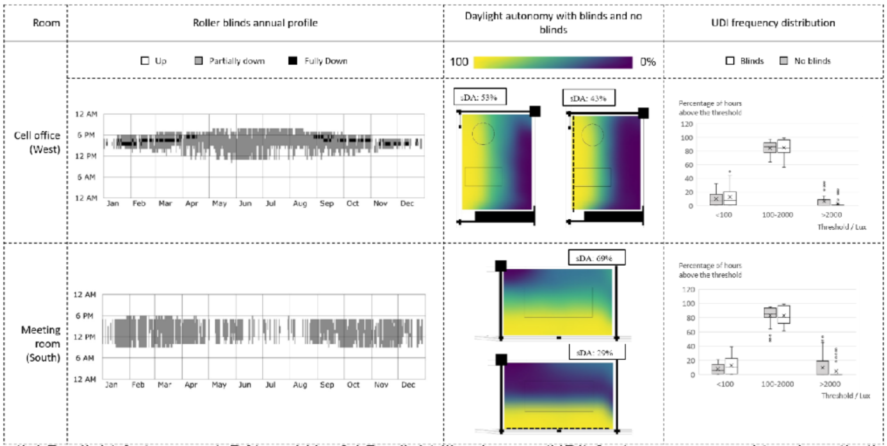


Figure 5. Simulated spatial Daylight Autonomy (sDA) and Useful Daylight Illuminance (UDI) for two spaces and two hypothetic scenarios: 1) no roller blinds in use, and 2) manually operated roller blinds with annual use profile as in figure.

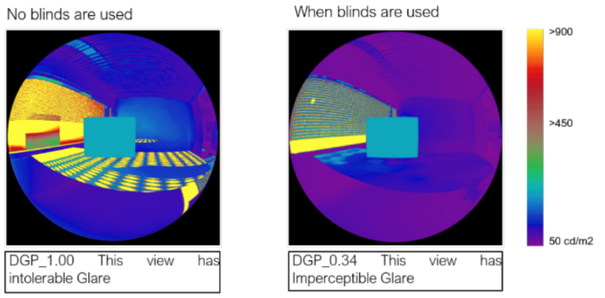


Figure 6. DGP analysis with and without roller blinds for the west facing office. Analysis performed for June 24th at 19:00.

perforated façade alone do not prevent glare, but it needs support by the roller blinds (Figure 6).

On the other hand, roller blinds may reduce the daylight penetration. For example, in the south meeting room, the spatial daylight autonomy (sDA) drops from 69% to 29% when occupant controlled blinds are included. The drop is less pronounced (53% to 43%) on the west façade for this south location, since that façade receives less hours of direct sunlight (Figure 5).

Circadian potential

Workers at the office spend on average about 8 to 9 hours per day seated in a fix position. This has a great impact in their well being and productivity, hence the importance of daylight also as a regulator for their circadian rhythms.

For the IDOM case study, some simple simulations for daylight conditions and for the workers sitting in the north-facing landscape office are shown (Figure 7).

The Melanopic over Photopic (M/P) ratio ranges between 0.7-0.9 even for workstations closer to the building core. These ratios suggest a blue-enriched light supporting alertness. The simulations were run only for March, 21st 12:00 and clear sky. More sun positions and weather conditions should be tested, but this is certainly a good news for a location like Madrid, which enjoys a prevalence of clear sky conditions throughout the year.

User perspective

Fifteen employees replied to a custom made questionnaire with few closed-ended questions dealing with the satisfaction about different aspects of the integrated lighting design. Their sitting positions were spread in the landscape office, with some employees sitting in the core of the building and others next to the windows. Therefore the survey provides an overarching picture of the space, albeit not detailed. The employees and the building managers shared additional thoughts during informal chats, including the interesting observations, which can be read in the quote boxes.

The results of the questionnaire, which are shown in Figure 8, inspires a first general deduction: daylight and view out are essential for the quality of a space. Indeed, the preference for light source is strongly oriented towards

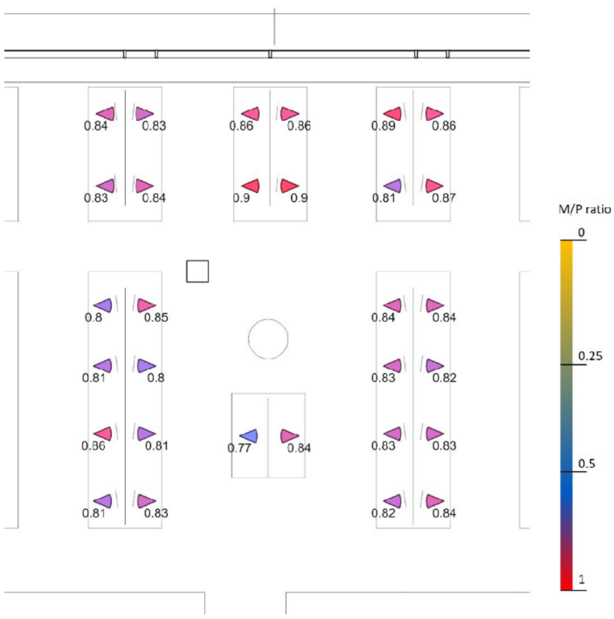


Figure 7. Lark M/P ratio simulation for one view direction of thirthy employees in the landscape office, March 21st 12:00, clear sky.

Integrated lighting design in Madrid: the headquarter of IDOM

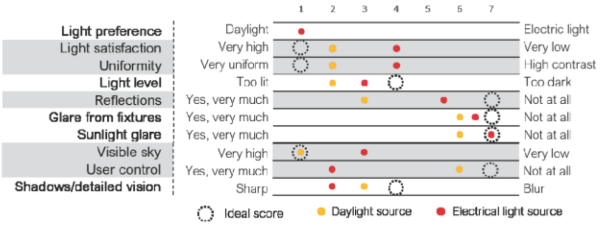


Figure 8. Results from the questionnaire submitted to fifteen employes. Results are filtered for sitting positions: "Daylighting" and "electric lighting" indicate sitting position with prevalence of daylighting or electric lighting respectively. Median values are shown.

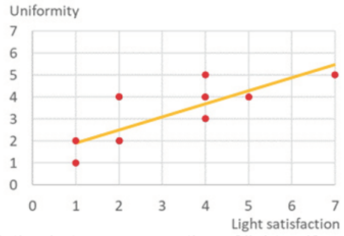


Figure 9. Correlation between perception of light uniformity and light satisfaction, Spearman's Rank Correlation $R_s = 0.79$, $p < 0.1$

daylight, while the possibility of viewing the sky – somewhat connected to the more general concept of view out, is also highly valued. Despite the generous glazing, there are no complains at all about daylight glare, possibly because the landscape office is oriented towards north.

The self-reported evaluation of light uniformity and light satisfaction has identical median values. A further analysis showed a strong correlation between uniformity and light satisfaction (Figure 9), despite the small number of subjects. In integrated design, one could speculate that choosing materials with higher reflectance materials in the darkest areas of the room can increase uniformity and possibly satisfaction.

For electric lighting, is interesting to see that employees wish more personal control over lighting, see quote box, which is in line with many other post-occupancy evaluations. The 4000 K for electric lighting seems also to be bit too high correlated colour temperature for this office space.

Lessons learned

The potential for energy savings from daylight harvesting systems have been claimed for years, but these systems have received much less market attention than what predicted. In part, lack of experts' knowledge for installation and calibration, little maintenance, and lighting designs caring little of users' desires, can be blamed for that. At IDOM Madrid we rather witness daylight harvesting as it supposed to be. A system that is designed to control fixtures per daylit area, which adopts efficient light sources, and which makes use of generous daylight provision on façade which is unlikely to receive direct sunlight. Most important, a system that seems to be correctly calibrated and installed. Although the numbers here reported are generated by computer simulations, there are no apparent reasons to believe that they deviate much from the actual ones, according to observation during the site visits. Even in a conservative perspective, and in respect to standard lighting installation, the IDOM solution is most likely to generate those 60% energy savings which are generally claimed for daylight harvesting systems.

> ***"We need more control over electrical light or task lights, sometimes it feels too bright and cold"***

While the open-loop daylight harvesting system on the north-facing façade was justified by abundant and more predictable daylight provision, daylight on the west and south façade is more difficult to control. The microperforated façade may prevent overheating, but it does not suffice for glare protection. The use of roller shades was fundamental in this perspective, but we have also seen that they may reduce dramatically daylight penetration throughout the year. The shading schedules provided here were determined by the software, but it is clear that the impact of user behaviour in the daylight performance is remarkable. This leads to two main observations with direct backlash on the final energy use for lighting. First, integrated design is a must; we cannot pretend anymore to design facades and electric lighting independently, and expect high performing lighting projects. Second, the integrated design should account for user behaviour to the highest level of detail, if the energy goals are to be achieved. Learning from post-occupancy evaluations may be very useful in this sense.

> ***"It is important for the people health and well being to see or feel daylight and the movement of the sun and not only the skylight coming from the north"***

The survey proposed at IDOM was limited to the general satisfaction of some aspects of the integrated design. Yet it showed a clear inclination towards daylighting. Daylighting benefitted energy, appreciation, and, not last, circadian potential. The electric lighting, which consisted of efficient light sources and established, simple automated controls, complemented a well-designed energy-efficient integrated lighting project.

Further information

Fernandez Amodia, J. (2020). *IDOM's high performance office building lighting audit: a case study.* Master thesis in Energy-efficient and Environmental Buildings, Faculty of Engineering, Lund University, Sweden.

Acknowledgements

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Thanks to IDOM consulting company, and Marie-Claude Dubois and Iason Bournas (Lund University). Special thanks to Sergio Arús Gutierrez and Antonio Villanueva Peñalver (IDOM).

Dynamic electric lighting and daylight can lift up office life

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

An integrative lighting system dynamically changing in colour and intensity during the day was well valued by office workers.

The Spark, a new office building Lund, Sweden, combines abundant daylight with new LED ceiling panels delivering cooler light in the morning, and warmer dimmed light during the afternoon. The system was appreciated by four office workers. It seemed also to increase their alertness, mostly when access to daylight was limited.

The project

The Spark is a seven-storey office building hosting nearly 2000 workers from different companies. Highly-glazed facades and sky openings provide the space with plenty of daylight. But when daylight cannot suffice, integrative LED panels should do the work. The lighting system works with a predefined “lighting recipe”, which provides cooler (Correlated Colour Temperature, CCT = 6200 K) and intense lighting during the morning, warm (2300 K) and dimmed lighting in the late afternoon. Each office has its own lighting control panel where workers can override the system and choose their own lighting scenes, and adjust the dimming (Figure 1). Except for the offices on the north façade, all perimeter offices are provided with automatic shading systems that are controlled by solar radiation. Shading can also be manually overridden via a switch provided in each office.

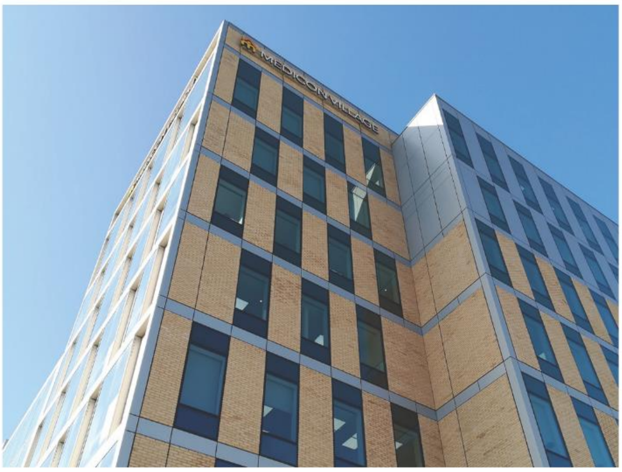
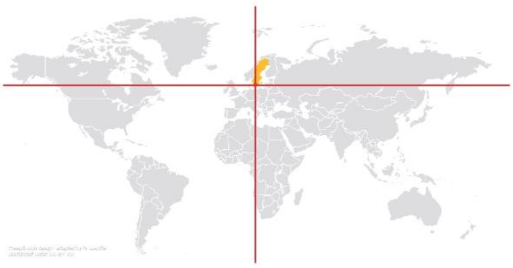


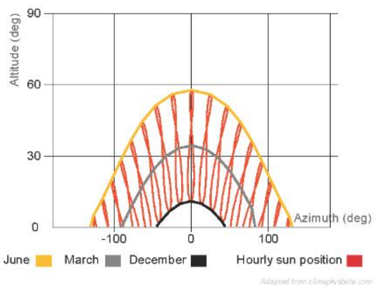
Figure 1. The Spark is designed with generous windows and skylights. The electric lighting uses a proprietary schedule called “biocentric lighting”, with a daily variation in intensity and correlated colour temperature.

Monitoring

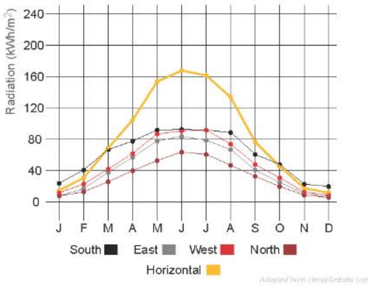
The site was visited several time starting from the end of February 2020. Four individual offices were monitored; they are located between the second and the sixth floor and with different orientations. For three consecutive weeks, the occupants were requested to use wrist-worn loggers for lighting (RGB, IR, lux) and movement. During this time and three times per day (morning, noon, and



Location: Lund, Sweden
55.71°, 13.22°



Sun path for
Lund, Sweden



Global horizontal and vertical radiation for
Lund, Sweden

IEA SHC Task 61 Subtask D

Monitored by **Rawan Abdulhaq** and **Ceren Yılmaz**, Lund University
More info **Niko Gentile**, Lund University, niko.gentile@ebd.lth.se
http://www.ebd.lth.se

Dynamic electric lighting and daylight can lift up office life

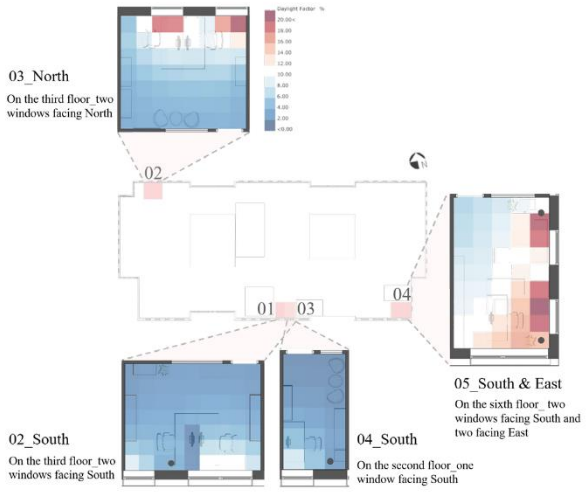


Figure 3. Overview of the building plan with the monitored offices and their measured daylight factors.

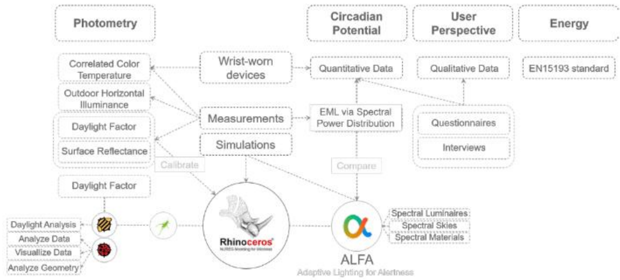


Figure 3. The workflow used to monitor The Spark case study. Due to Covid-19 restriction, field measurements served mainly as calibration to simulations.

Table 1. Average calculated LENI for the four offices. Benchmark "Standard direct lighting system", Tab M1 EN15193-1:2017.

	LENI DHS kWh/m^2	LENI Benchmark kWh/m^2
Average for the four offices	22.43	14.80

afternoon), an app on their smartphone asked to answer some questions dealing with self-reported alertness (KSS, Karolinska Sleepiness Scale). The field monitoring included a partial characterization of daylight and electric lighting in the rooms. The collection of these data was stopped by the Covid-19 pandemic, but they were sufficient to run a set of complementary simulations in Radiance and ALFA.

Energy

This project was designed with circadian health in mind, while energy use for lighting was not at the focus. Because there was no information available for electricity bills or meter-readings, lighting energy use was calculated for each office based on the European standard, EN15193. The *.ies file for the LED panel in a single state was available, and power requirements for the other states were derived proportionally after a site metering. The task lamps, which also exists, were not included in the calculation.

The delivered horizontal electric lighting illuminances at the desk height are well above the EN12464-1 recommendation, being as high as 1300 lux for some spots in the morning Scene 1, and 300-500 lux even for the dimmed Scene 4. The declared purpose of the designers was to increase the lumens reaching the eye in a circadian entrainment perspective; but this, together with relatively low efficient LED sources (≈ 88 lm/W) results in high lighting power density, about 18 w/m^2, and LENI above today's standard systems (Table 1).

Photometry

Site measurements of illuminance, spectral power distribution, reflectance, and surface colour provided a good starting point to characterize the offices. As general judgment, all monitored offices are well daylit, with daylight factor (DF) hardly dropping below 2% at any point of the rooms (Figure DF). The DF was both measured and simulated for a quick model verification.

The north-facing office shows higher daylight factors

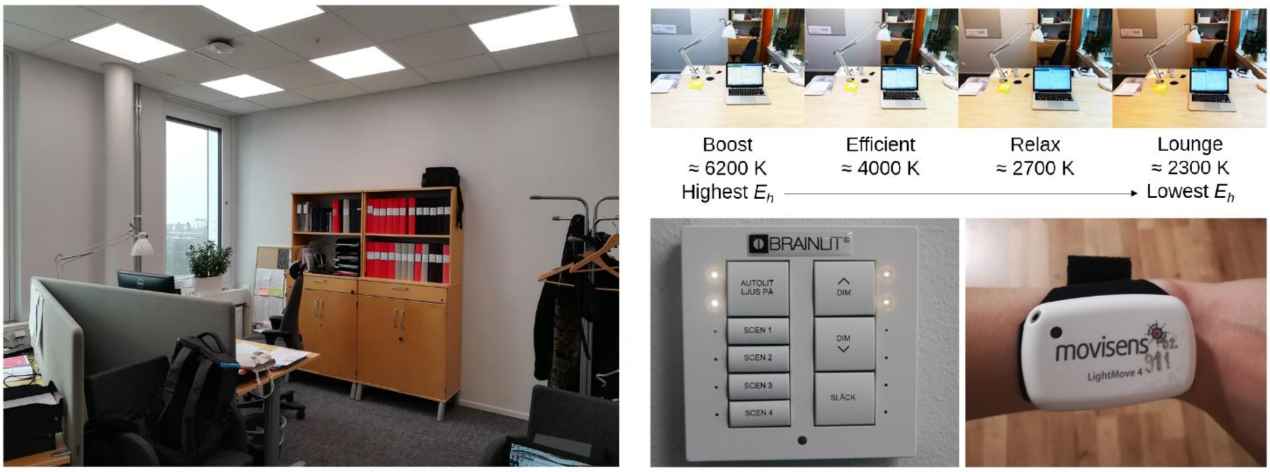


Figure 4. Left: one of the monitored offices. Top-right: overview of the scenes (E_h stands for horizontal illuminance Bottom-right: the manual switch to override the "lighting receipe" and the wrist-worn light logger used by the four employees.

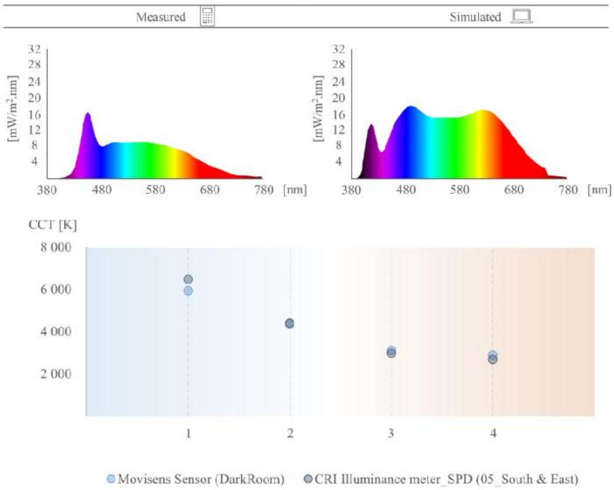


Figure 5. Comparison between SPDs for the measured Scene 1 and LED light source with equivalent M/P ratio (see "Circadian potential section for the definition") provided by ALFA (top), and comparison between CCTs measured with professional spectrometer and the wrist-worn light logger Movisens LightMove 4 (bottom). Scenes on x-axis (1="boost", 4= "lounge").

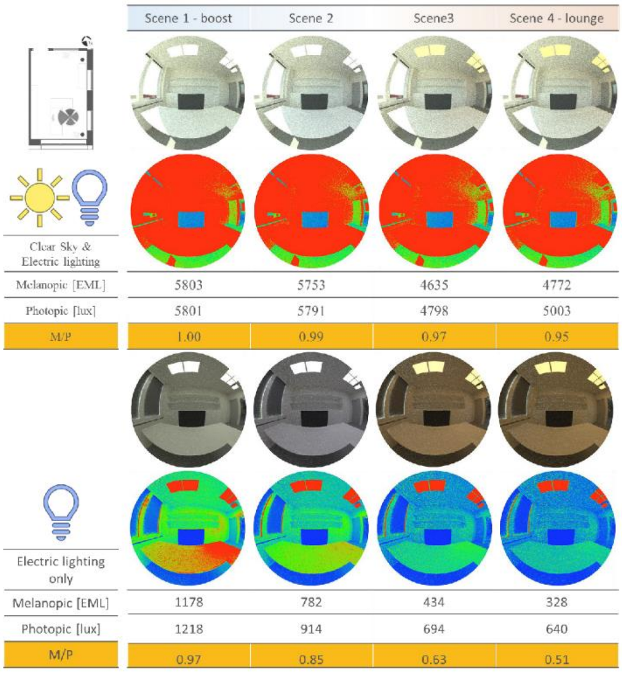


Figure 6. Results of ALFA simulations for the office with south and east facing windows. The results are shown for daylight and electric lighting (top) and electric lighting only (bottom), and for one view direction, sitting position.

than those facing south, the reason being a different and wider wall construction on the south designed to reduce overheating.

The horizontal illuminance (E_h) measured at the task height confirms what anticipated when discussing the high energy use by the system. For scene 1, the powerful morning boost, hardly drops below 950 lux at any point of the room, and it reaches as much as 1300 lux in some points. As far as the vertical illuminance at eye is concerned, this scene delivers about 500 lux at eye position, when the computer screen was left on. Even for the dimmed Scene 2 and 3, the vertical illuminance at eye position is still lying between 300 and 400 lux. For the most dimmed Scene 4, this value drops to around 200 lux, which is still considerable.

The spot measurements for electric lighting were also used to characterize the spectral power distribution (SPD) and CCT of the light source for the different scenes. These data were compared with SPD profiles provided by the software used to measure circadian potential, Alfa, and the CCT measured by the wrist-worn devices. There were substanstial differences with SPDs from Alfa, due to the fact that the software uses a preloaded library. This might be problematic for advanced simulations, but it did not affect much this monitoring. There was instead good agreement between CCTs measured with a professional spectrometer and with the wrist-worn devices, especially for lower CCTs.

Circadian potential

Apart from providing illumination, lighting affects a number of non-visual responses like alertness and a more general concept of well-being. A growing chunk of literature is providing evidence of the circadian effects of lighting, but there is still a limited knowledge of the practical impact of lighting in everyday life settings. The lighting industry is moving at fast pace, proposing a number of "circadian" or "human-centric" – more correctly defined as "integrative lighting" - solutions for offices, which should improve the overall well-being of employees, including their alertness during the day and their sleep quality during the night. But are these systems effective in practice?

The integrative lighting system monitored here is one of these solutions, and its "circadian" potential became the focal points in this case study.

The lighting was first characterized with field measurement of Spectral Power Distribution (SPD) for electric lighting, and for mixed daylight-electric lighting conditions. The SPDs were imported to the Lucas toolbox – a well-known instrument to account for circadian stimuli of lighting -, in order to obtain the Equivalent Melanopic Lux (EML, measured in lux), currently one of the most widespread circadian metrics among practitioners. The ratio between EML and the "ordinary" illuminance is called M/P ratio. Given the same illuminance, higher EML indicates a higher capacity of light to suppress melatonin production, a hormone responsible for tiredness. Therefore, high M/P ratios indicates a blue-enriched lighting which should prompt alertness. A proper integrative system should provide high M/P ratios in the morning (M/P > 0.90) and low in the afternoon (M/P ≈ 0.35 to 0.90, a neutral effect, namely neither alerting nor calming).

Indeed the system here tested does follow this pattern under electric lighting conditions. Scene 1, the morning boost setting, shows M/P ≈ 1.00, while Scene 4, the evening “lounge” setting, provides M/P as low as 0.50.

There are few simulation software today which are able to account for circadian light, one being ALFA. This software was used to simulate some additional lighting scenarios. A first electric lighting simulation was compared with the field measurements just mentioned. The results matched nicely, thus the model was used for a further simulation with a mix of daylight (clear sky) and electric lighting. In this case, the illumination provided by the daylight is at least five times stronger than that of electric lighting during the morning (Figure 6). Therefore daylighting becomes the main driver of circadian stimuli. During the late evening, when the sun is setting, but the working day is not over yet, a low M/P electric lighting can still provide illumination without preventing melatonin secretion (Figure 6).

User perspective

Five employees - one sitting in an office which was not modelled -, took part in this monitoring had a central role in understanding the benefits of the integrated project. They wore the wrist-worn device for three weeks providing an understanding of normal “lighting patterns”, replied to the KSS and were happy to share thoughts in some interviews. According to the results, all but one of the participants were more alert in the morning, when the offices were lit with the bright blue light. But later when the system started dimming down providing a warmer reddish light colour in the afternoon, they reported more sleepiness. The logged data showed also that the employees did not sit for the whole working day in the office, but they went to other rooms or enjoyed a break outside. Therefore figure 7, which correlates the alertness to CCT and illuminance, refers to the general lighting stimuli and not only to these from the integrative lighting system. However, one participant, who sits in an office next to the atrium space with no view-out, showed a very clear and consistent relation with alertness and lighting levels, although this single and limited observation cannot be seen as a scientific evidence.

“Other offices I had been in were darker. Here, it is like sitting outdoors and I do not need extra lighting like task light”

The integrative lighting system raised quite extreme feelings. One participant was particularly annoyed, finding the morning light too cold and too bright (’*It was terrible. I can’t stand this light* (...) *very upsetting* (...) *I got a migraine from the beginning*”). Note that the curve with different trand in Figure 7 represent this participant. The other three were enthusiastic about it, as reported in the box quotes. One

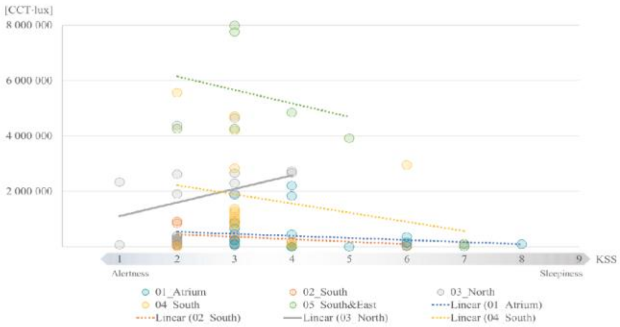


Figure 7. Alertness correlated to higher level of CCT and illuminance measured by the wrist-worn loggers.

interesting finding was that only the critical subject was used to override the system and fix Scene 4 during the whole day. The other participants sticked always to the proposed “lighting recipe”, which is rare according to literature on automatic lighting controls. On the contrary, all the participants believed that the shadings, which are also automatically activated, can be annoying and usually prefer to override the system.

“What I notice is that I am more alert, and I forget to go home at the end of the day”

Lessons learned

The Spark is a building designed for daylight, and the integrative electric lighting system provides a powerful addition during the darker months of the year. Looking at the hard numbers, the lighting system could really propel circadian stimuli throughout the day. If those numbers correspond to actual stimuli is more difficult to determine. The limited time and subject could provide nothing stronger than mere indications. Maybe as result of both the system design and a sort of wow effect, the employees perceived a lift in their working life. The monitoring helped also to verify that existing circadian lighting software are already mature enough to provide some support to designers.

Looking at the energy use, however, the needs of circadian lighting design were put above traditional lighting design rules, resulting in an overlit and energy consuming design. Future projects should look at a good balance between the different demands of modern lighting design for sustainable buildings.

Further information

Yilmaz, E.C., Abdulhaq, R., 2020. *Assessment of the circadian stimulus potential of an integrative lighting system in an office area.* MSc thesis, Faculty of Engineering, Lund University, Sweden.

Acknowledgements

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The participants to the study, the company Brainlit, the company Movisens GmbH, Madeleine Selvander (Brainlit) are acknowledged to make this monitoring possible.

Switchable windows demonstrated to provide increased view in offices

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

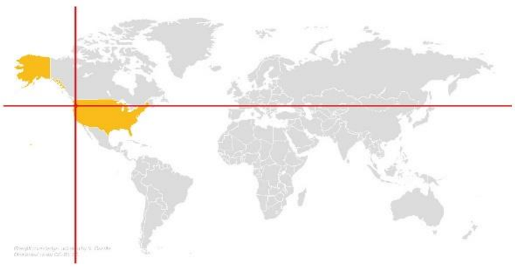
Transparent electrochromic windows increase user options for tuning their environment to satisfy personal preferences for daylight, view, and comfort

Low-emittance windows were replaced with variable-tint, electrochromic windows in forty private offices. 85% of the occupants preferred the electrochromic windows, citing increased view and visual comfort.

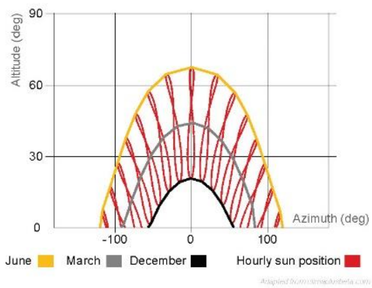
The project

The environment next to windows is the most variable of all areas in a building and yet is the most desirable due to proximity to outdoor views and natural light. Switchable electrochromic (EC) windows can temper broad fluctuations in solar radiation and daylight by modulating tint levels between clear and darkly coloured states based on a dimming signal from automatic or manually operated controls. With adequate control, the windows can reduce heating, cooling, and lighting energy use in buildings and provide daylight and transparent views to the outdoors. To better understand user satisfaction with this novel technology, a monitored demonstration of the technology was conducted on two floors of an eight-story, 29,000 m^2 office building (vintage 1953) in Portland, where EC windows were installed on the south facade (Fig. 1-3). The EC windows were controlled automatically to meet solar control, daylight, glare, and view requirements of office workers. The tint level could be manually overridden by the occupant at any time. Performance was compared to existing office conditions, i.e., dark tinted, dual-pane, low-emittance windows. Both the EC test and low-e reference

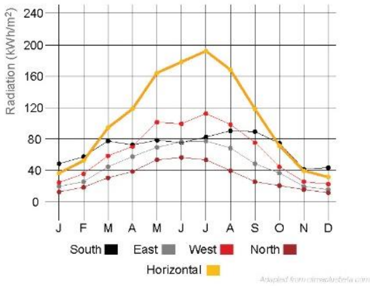
Figure 1. Exterior facade of the monitored commercial office building.



Location: Portland, Oregon, USA
45.50° N, 122.67° W



Sun path for
Portland, Oregon, USA



Global horizontal and vertical radiation for
Portland, Oregon, USA

IEA SHC Task 61 Subtask D

Monitored by **Luís L. Fernandes, Anothai Thanachareonkit,** LBNL
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https://facades.lbl.gov/demonstrations

Switchable windows demonstrated to provide increased view in offices

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

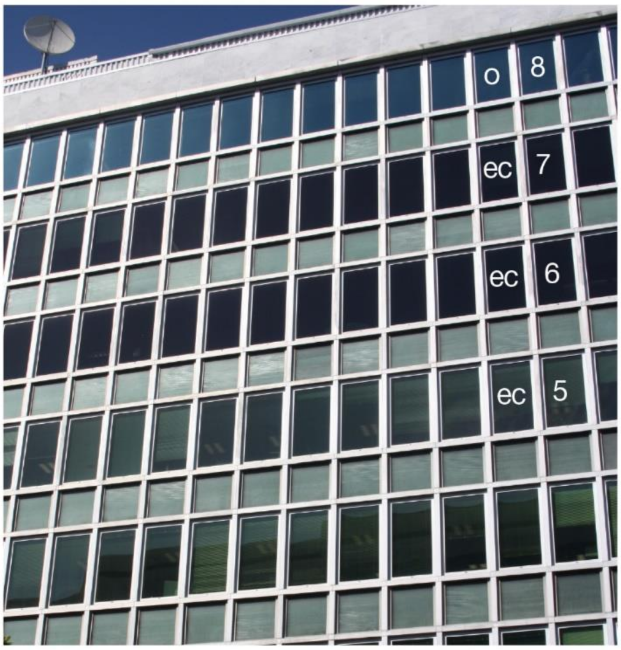

Figure 2. Outdoor view of the south façade with electrochromic (ec) and original (o) windows.

windows had indoor Venetian blinds. However, occupants in the test offices were deterred from using the blinds to assess the need for indoor shades (i.e., the blinds were tied in the fully raised position but could be untied at any time upon request). In both conditions, the existing fluorescent lighting was operated with a manual on-off switch and occupancy sensor. The installation occurred in Portland, Oregon – a northern city which is overcast during the winter and partly cloudy during the summer.

Monitoring

An assessment of energy use, comfort, and indoor environmental quality was based on continuous monitoring of outdoor and indoor environmental conditions in both the test and reference offices over a six-month, solstice-to-solstice period; time-lapsed luminance and infrared thermography imaging on select days; monthly surveys of venetian blind use; the facility's complaint log and surveys issued to occupants at the conclusion of the study. Performance was evaluated through simultaneous, parallel comparisons to the reference condition, which had similar space usage and layouts.

Energy

Annual lighting energy use in the 4.7 m deep private offices was estimated to be reduced from 9.37 to 5.96 kWh/m^2-yr (26%) due to greater availability of daylight from the EC windows compared to the dark tinted, low-e windows. In the EC normal automatic control mode, summer cooling loads on the EC test floors were increased by 2% compared to the reference floor because daylight admission was prioritized over cooling load control. Alternate tests were conducted to determine if the operational efficiency

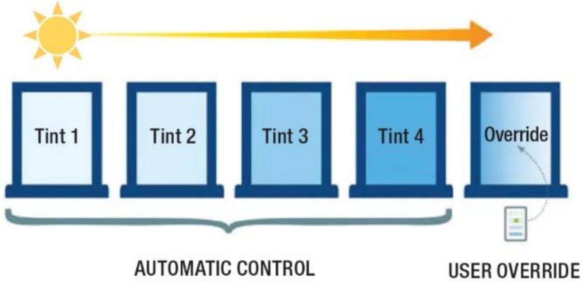

Figure 3. Illustration of EC window tint states.

Table 1. Visible transmittance (Tvis), solar heat gain coefficient (SHGC), and U-value (W/m^2-K) of EC window; Reference window: Tvis=0.15.

	Tint 1	Tint 2	Tint 3	Tint 4
Tvis	0.36	0.25	0.13	0.02
SHGC	0.43	0.28	0.16	0.09
U-value	1.65	1.65	1.65	1.65

of the air handler unit (and potentially thermal comfort) could be improved by minimizing differences in cooling load between the north and south zones of the building. Switching the EC windows to its darkest tint during sunny periods reduced solar transmission from 28 W/m^2 (reference office) to 3 W/m^2 (test office) per window area (89%), providing a more balanced load between zones. Trade-offs between daylight and solar control were evaluated by the facility managers and in the end, occupant preferences for more daylight won out, with thermal discomfort due to overcooling in the north perimeter zones addressed separately through recommissioning of the variable air volume boxes at the zonal level. Survey data indicated that occupants' thermal comfort on the south side increased during cold weather conditions.

Photometry

In terms of daylight quality, control of EC windows must also balance trade-offs between daylight admission (clear tint) and control of glare (dark tint). Glare perception is highly dependent on direction of view, type of task being conducted, position, size, and intensity of glare sources within the field of view, and sensitivity of the occupant to discomfort glare. Electrochromic windows can reduce luminous intensity but they can't block sunlight. Even at its darkest tint level, the luminance of the sun seen through the EC window can still exceed 1,000,000 cd/m^2, which can cause visual discomfort. In these instances, the occupant can use the Venetian blinds to control glare. In this study, the need for blinds was evaluated using periodic observations of Venetian blind position.

The EC windows in each private office were controlled as a single zone; i.e., all windows were switched to the same tint level. In response to occupant feedback, automatic tint levels were constrained to a narrower range (Tint 1-3, Table 1), with the darkest tint level available only through manual control. Occupants preferred daylight and

Switchable windows demonstrated to provide increased view in offices

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

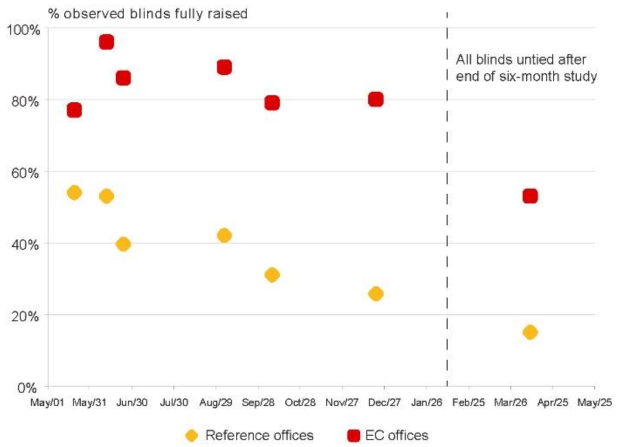

Figure 4. Percentage of Venetian blinds in fully raised position in reference and EC test offices before and after the six-month monitored period. After December, any remaining blinds were untied in the EC test offices.

views provided by light- to moderately-tinted EC windows. They controlled glare instead by using partially lowered blinds and individualized use of the darker EC tint level. Data revealed that manual override of automatic control occurred 11 times per weekday during the summer and three times per weekday during the winter across all 40 offices (six-month total monitored period; about half of the overrides were attributable to one office). When overridden, most commands were to darker tint levels when conditions were sunny and were about 10 minutes to one hour per day in duration. Venetian blinds were used in the offices but there were 40% less blinds lowered in the EC test offices compared to the reference offices (Fig. 4).

Discomfort glare levels were measured using high dynamic range (HDR) imaging on weekends with the blinds fully raised and with the full tint range permissible for automated control. During partly cloudy periods when the sun altitude was lower in the sky (from autumn to spring), discomfort glare levels ranged from “noticeable” to “intolerable” for occupant positions facing the window when both close to and further from the reference and test windows (Fig. 5). These data indicate that some occupants who chose not to lower their blinds accepted occasional glare discomfort, perhaps due to a stronger preference for daylight and views during the overcast and partly cloudy winter period. During sunny periods, discomfort glare levels were “intolerable” if the sun was in the field of view since the EC tint level was minimal (Fig. 7). Such times would warrant use of the blind or manual override.

Circadian potential

A detailed assessment of the non-visual effects of light on human health was not conducted in this study. However, time-lapsed HDR measurements performed for glare analysis on a single equinox day were used to assess whether melanopic light intensities due to daylight were sufficient to promote alertness in work areas. On a partly cloudy day (October 8th), the ratio of melanopic to photopic illuminance (M/P) was found to shift from M/P = 0.95 in the early morning and late afternoon when the EC window was clear to M/P = 1.3 from 10:30 AM to 4:00 PM when the EC window was fully tinted. A M/P ratio of greater than 0.9 indicates potential increased alertness due to transmission of shorter wavelengths, i.e., when the EC windows tint to a dark blue. Equivalent melanopic lux (EML) from daylight for views facing the unshaded EC window at a distance of 0.4 m and 1.8 m from the window was greater than 180 lx for 3.4 h and 1.2 h, respectively, for the period from 9:20 AM to 1:00 PM. The International Well Building Institute Standard (ver. Q4 2020) requires at least 200 EML of electric light between 9:00 AM and 1:00 PM (i.e., 4 h) year round. On this day, automated control prioritized solar and glare control, leading to low photopic and melanopic lux. The normal automated control mode, which prioritized daylight admission, increased daylight-driven EML.

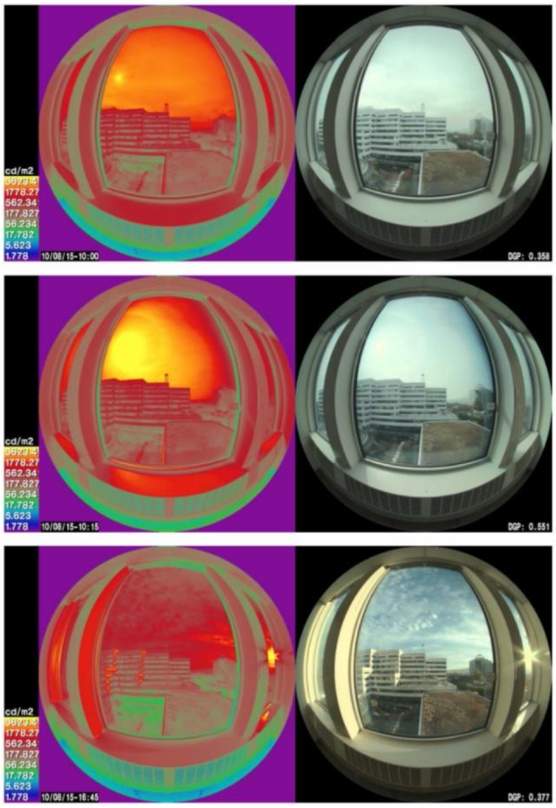

Figure 5. HDR image (left) and photographic view (right) from 0.4 m from the EC window, October 8th at 10:00 AM Tint 1 clear (top), 10:15 AM Tint 1 (middle), and 4:45 PM Tint 4 (bottom). discomfort glare was noticeable, intolerable, and noticeable, respectively.

User perspective

Pre- and post-installation surveys were issued to occupants in the test and reference offices. Of the 28 EC test and 38 reference office survey respondents, 48% and 43% faced the window, respectively, with the remaining facing the side or back wall. Regarding view, occupants agreed strongly that the outside view was sufficiently visible in the

Switchable windows demonstrated to provide increased view in offices

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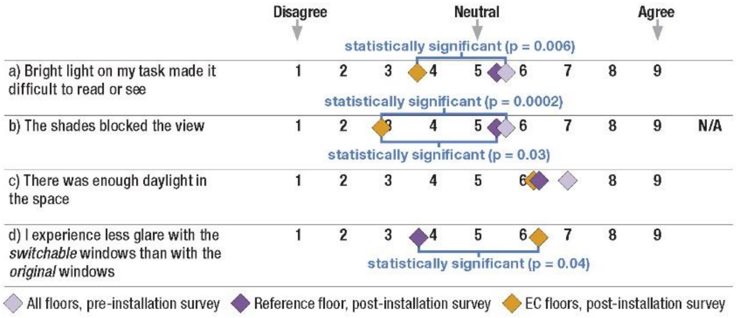

Figure 6. Occupant response on the reference floor (purple) versus EC test floor (orange).

Occupants were more satisfied with switchable windows than with the original windows.

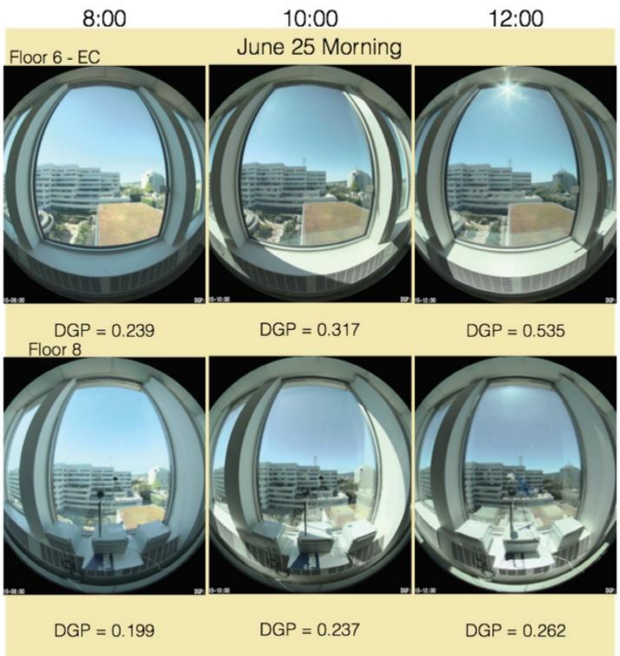

Figure 7. Discomfort glare levels in EC office (above) versus reference office (below) on a sunny day. Glare levels in the EC office were "intolerable" at noon due to the sun in the field of view. EC set to Tint 1.

EC test offices. At the conclusion of the six-month study, 30% of the blinds had been untied and there were 40% less blinds lowered in the EC test offices compared to the reference offices. Occupants in the EC offices also disagreed moderately that the blinds blocked the view while they agreed slightly in the reference offices (Fig. 6).

In terms of visual comfort, occupants reported that they experienced less glare in EC offices. This occurred despite the limit to moderate tint levels with automatic control. The darkest tint level could only occur with manual override and these overrides occurred infrequently. One possible reason for this result is that the Portland climate is predominantly cloudy so the bright sky, not the sun, is the primary source of glare. A moderate tint level is sufficient for controlling sky brightness.

Occupants reported that light levels were just below "just right" levels compared to reference office levels which were just above "just right". Perceived lack of sufficient light could be a result of a constraint that all windows in an office were zoned to be switched to the same tint level. EC windows can be controlled individually (e.g., some for glare or solar control, others for daylight), but this option was not implemented in this study. Another reason could be due to the narrow switching range of the EC window. Putting the EC coating on a dark tinted substrate is not recommended and was done in this study to match the existing glass.

Lessons learned

Daylight and views are essential in high performance buildings, as indicated by survey results which indicated that 85% of the occupants preferred electrochromic windows over the existing windows. This study underscored the importance of integrated design and control of dynamic building facades with respect to climate, occupant requirements, and facility management goals. Because windows have such a significant influence over occupant comfort and workplace satisfaction, it is critical that a dynamic facade be designed and controlled with enough flexibility to meet personal demands and preferences. Meeting workplace wellness and sustainability goals while minimizing operating costs will require finetuning of the EC automated controls in response to employee feedback. To maximize the full potential of EC windows, it will be important that facility managers educate occupants on the benefits and trade-offs of this novel technology.

Further information

Lee, Eleanor S., Luis L. Fernandes, Samir Touzani, Anothai Thanachareonkit, Xiufeng Pang, Darryl Dickerhoff, *Electrochromic Window Demonstration at the 911 Federal Building, 911 Northeast 11th Avenue, Portland, Oregon*, General Services Administration, Green Proving Ground Report, November 2016. https://eta-publications.lbl.gov/sites/default/files/gpg-portland-lee.pdf

Acknowledgements

This work was supported by the U.S. General Services Administration and Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Enhancing workplace quality in existing buildings with dual-zone shades

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Indoor shades with an upper daylight zone and lower view zone in a pilot office demonstration in California

A novel, operable shade left a positive impression on office workers by opening up views to the outdoors and increasing daylight and comfort compared to conventional shades. 80% of occupants were satisfied with the dual-zone shades. Cooling and lighting energy consumption were reduced by 20%.

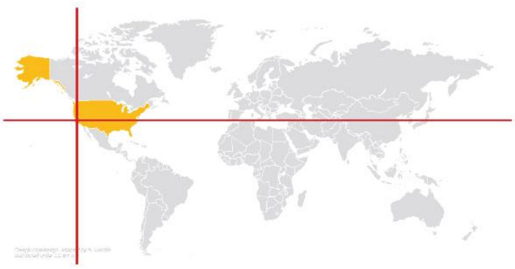
The project

Windows in existing commercial buildings pose a variety of challenges given today's demands for energy efficiency, comfort, and indoor quality in the workplace. Natural daylight fails to penetrate more than a meter or two from the window because blinds or shades are lowered to reduce discomfort, particularly for those sitting next to the window. When shades are lowered, views are obstructed. Novel shading and daylighting attachments can address these challenges by separating the shading attachment into functional zones. In this study, the concept behind a dual-zone, solar control (DZSC) indoor shade is to bring in more daylight through the upper zone and allow unobstructed views through the lower zone. The upper zone consists of inverted, curved, horizontal louvers that are manually or automatically controlled to reflect sunlight up to the ceiling and further from the window. The lower zone

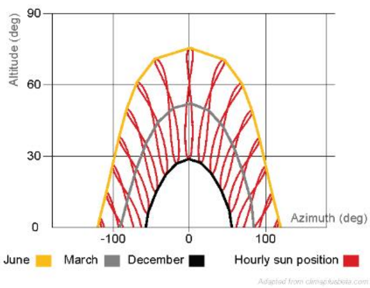
Figure 1. Exterior facade of the monitored commercial office building.

consists of a roller shade made of a transparent tinted or metallized reflective film (for additional solar control) that can be raised or lowered manually.

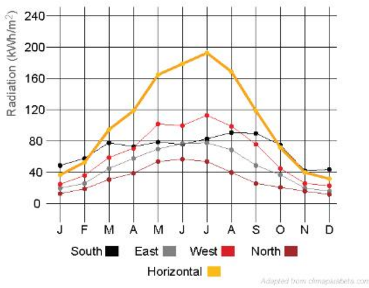
DZSC shades were installed on the seventh floor of a 99.87 km^2 commercial office building (vintage 1992) in Oakland, California (Fig. 1). The building has single-pane, tinted windows with non-thermally broken, aluminum frames, vertical fabric blinds, and pendant T8 fluorescent dimmable lighting. The workspace consists of 1.68 m high cubicles and a few private offices at the window. The climate is moderate and sunny and there are spectacular, sweeping views of the San Francisco Bay and low surrounding hills.



Location: Oakland, California, USA
37.80° N, 122.27° W



Sun path for
Oakland, California, USA



Global horizontal and vertical radiation for
Oakland, California, USA

IEA SHC Task 61 Subtask D

Monitored by **Christoph Gehbauer, Anothai Thanachareonkit**, LBNL
More info **Eleanor S. Lee**, Lawrence Berkeley National Laboratory, eslee@lbl.gov
https://facades.lbl.gov/demonstrations

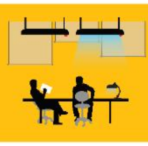


Figure 2. Indoor view of upper and lower zones of the DZSC shade.

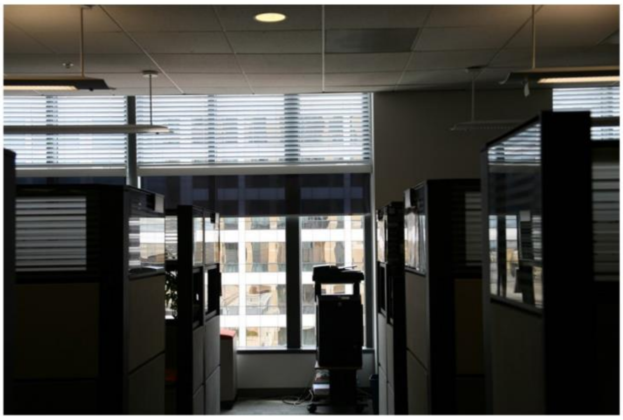


Figure 3. Indoor view of the DZSC shade in the open plan work area.

Monitoring

A six-month, on-site evaluation of the dual-zone shades included surveys of occupant comfort and satisfaction and recording the position of the existing and new shades every two weeks (Fig. 2-3). Several different configurations of the DZSC shade were evaluated: manual ("man") or automated ("auto") control of the white upper blind and manual control of the grey-grey (GG) tinted or grey-silver (GS) reflective lower shade.

A separate six-month, monitored evaluation (November 21 to June 19) was conducted in the Advanced Windows Testbed at the Lawrence Berkeley National Laboratory (LBNL), Berkeley, California. This facility consists of three side-by-side, 3.05 m wide by 4.57 m deep, private, unoccupied office test rooms with large-area, south-facing, dual-pane, low-emittance windows. Two types of reference shades were installed: a light grey fabric roller shade (3% openness factor; lowered to 0.64 m above the floor) or a fully-lowered, white Venetian blind with slat angles set to block direct sun. The DZSC shades had the same configurations as at the Oakland site. The fluorescent dimming level (20-100% power output, standby power of 30 W) was determined by the light level at 3.8 m from the window from 8 AM to 6 PM with a setpoint of 300 lx. Cooling loads were measured directly and converted to cooling energy use with a coefficient of performance of 3.0. Measurements of the three rooms were made simultaneously under the same weather conditions.

Energy

When compared to the reference roller shade in the LBNL testbed (Fig. 4), the auto-GG shade reduced daily cooling and lighting energy use in the south-facing perimeter office zone by 20% (number of test days, n=10). Manual control for the tinted man-GG (n=5) and reflective man-GS cases (n=4) provided savings of 8% and 14%, respectively. Savings are given for the summer period with the DZSC shades fully lowered. When compared to the Venetian blind, cooling and lighting energy use was significantly higher with the DZSC shade. The white blind was able to admit more daylight and was more effective at reflecting sunlight back to the outdoors.

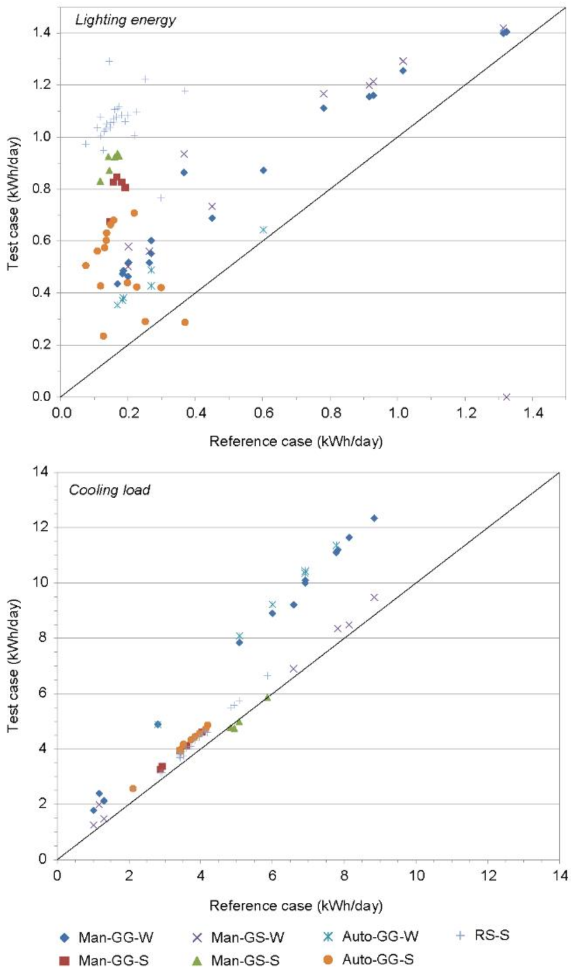


Figure 4. Daily lighting energy use (above) and cooling load (below) due to the window and shading system (kWh/day) for the reference Venetian blind (x-axis) and test shade (y-axis) conditions. W=winter, S=summer data, Man=manual, auto=automated, GG=tinted, GS=reflective, RS=roller shade.

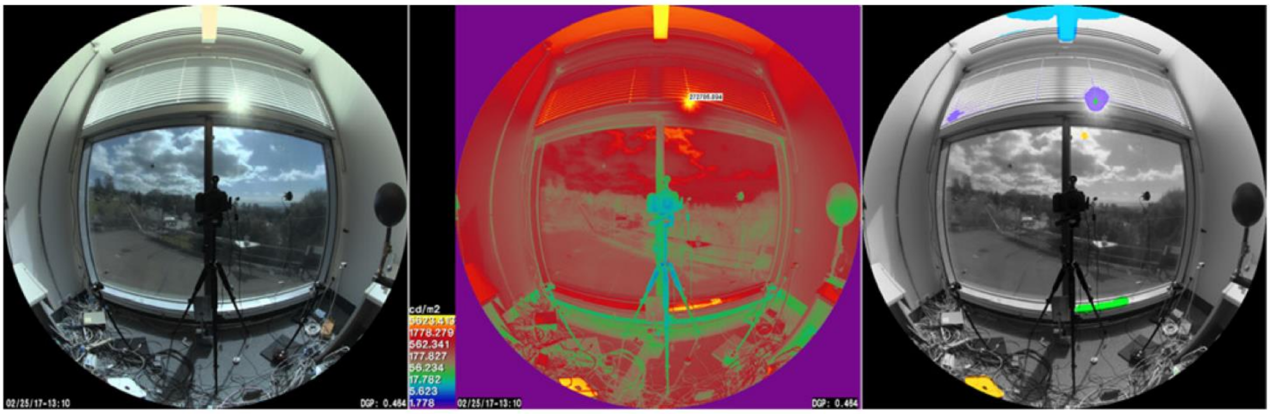


Figure 5. Left to right: Photograph, HDR image, glare sources for sunny winter day at the LBNL testbed. Glare was rated as “intolerable” due to sunlight through the man-GG upper blind when facing the window. Automated slat adjustments can prevent this from occurring.

Figure 6. Outdoor view of the roller shade, auto-GG shade, and Venetian blind (from left to right) in the LBNL Advanced Windows Testbed, Berkeley, California.

Photometry

High dynamic range imaging was used in the LBNL testbed (Fig. 5-6) to measure discomfort glare during winter and summer periods. For seated view positions parallel to the window, the DZSC and roller shades kept discomfort glare below “noticeable” levels (Class A) for 95% of the day while for the Venetian blind, discomfort glare exceeded “perceptible” to “disturbing” levels for most days (Class B-D). For view positions where the sun orb is in the field of view, glare levels are estimated to be “disturbing” to “intolerable” for both the grey-grey and grey-silver films (visible transmittance, Tvis, of 0.07 and 0.02, respectively).

During the winter on sunny days, the DZSC shade and Venetian blind provided adequate daylight for 85-98% of the day while on cloudy days, it was 55-100% of the day (for auto-GG, the upper blind was raised on cloudy days). During the summer, the DZSC shade and Venetian blind provided adequate daylight for 93-100% of the day while the roller shade provided daylight for 55-85% of the day under both cloudy and sunny conditions. Adequate daylight was assessed by computing the percentage of time from 8 AM to 6 PM when workplane illuminance levels were within a range of 100-2000 lx at a distance of 2.29 m from the window.

Circadian potential

Bright light levels with the proper spectral distribution can support alertness in the workplace. Based on photopic daylight illuminance levels measured in the LBNL testbed, equivalent melanopic lux (EML) levels were likely reached for the majority of the day in the case of the Venetian blind, perhaps for the DZSC shade, but is unlikely for the densely woven, lowered roller shade. EML levels were not evaluated in this study.

User perspective

Survey responses at the Oakland site indicated that the DZSC shades provided a more comfortable and higher quality visual environment (i.e., less glare, more view) compared to the existing vertical blinds.

Eighty percent of survey respondents indicated that they preferred the DZSC shade over the existing shade and thought that the new shade somewhat enhanced their ability to get their job done.

More occupants indicated that they liked their view somewhat or very much after installation of the DZSC shade (8 before the DZSC installation, 12 after, out of 21 total responses). Sixteen of the survey respondents sat next to the window with the remaining respondents seated further from the window with partial or fully blocked views to the windows (cubicles had both opaque and transparent walls). When standing in the open plan area, the upper DZSC blinds blocked views to the sky while the walls of the cubicles blocked lower outdoor views.

Glare discomfort was reduced from just below “uncomfortable” to “acceptable” levels. However, occupants commented on glare from daylight coming through the slats of the DZSC upper blind, from the window sill when sunlight was reflected onto the sill from the GS shade, and from reflected glare on computer screens. When partially lowered, reflected or transmitted sunlight and brightness contrasts between shaded and unshaded portions of the window caused glare for some occupants. Manual over-

Enhancing workplace quality in existing buildings with dual-zone shades

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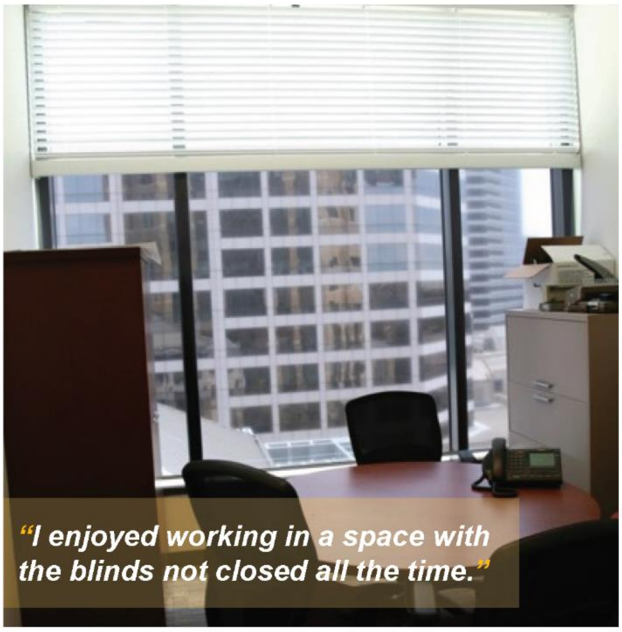


Figure 7. Indoor view of the DZSC GG tinted shade when fully lowered.

ride was provided with automation of the upper blind, but control of the blinds was grouped to lower the cost of installation, so comfort control per individual preferences was constrained even in the private offices.

Light levels were judged to be the same as before, so daylight quality (i.e., perceived room cavity brightness, absence of gloom) was not perceived to have been improved with the upper daylight system of the DZSC shade in the open plan or private office areas. This may in part have to do with the lack of sunlight redirection provided by the slats, since matte white slats (as opposed to the silvered reflective slats) provide soft diffusion of reflected sunlight towards the ceiling (Fig. 7). The dimmed output from the indirect-direct, pendant, fluorescent lighting system, which was not monitored in this study, also affects perceived room cavity brightness. Some open plan offices with the DZSC shades were also immediately adjacent to open plan areas with the existing shades, confounding assessments.

Rating of temperature conditions during warm or hot weather was improved. The surveys were issued May 30th (three months after installation) prior to the hot period, which occurs from summer through late autumn. In offices where the existing vertical blind had an opaque backing added to the fabric slats to reduce discomfort due to intense solar gains, occupants commented that the room was more comfortable with the existing blinds compared to the GS or GG films. Other occupants commented that thermal comfort was better but conditions were still too hot when the weather was warm. Heat could be felt

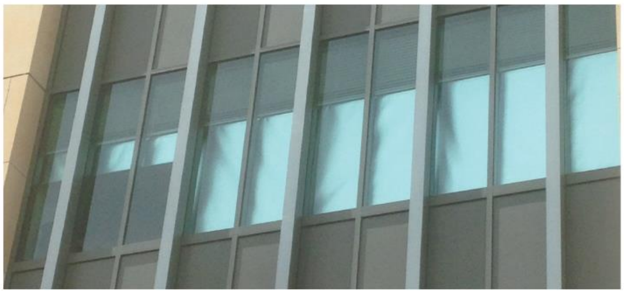


Figure 8. Outdoor view of the upper blinds (dark grey) and lower reflective shades (white) with the lefthand lower shade partially raised.

coming out of the bottom and sides of the DZSC shades. During cool or cold weather, temperature conditions were deemed "just right".

Some objected to the non-uniform, shiny, outdoor appearance of the reflective GS film (Fig. 8). Aesthetics will need to be judged on a case-by-case basis. Five out of the 21 survey respondents (and 51 total occupants) expressed dissatisfaction with automated control. This may be due in part because manual override of the shade was not on a personal level as mentioned above or because of occasional erroneous control.

Lessons learned

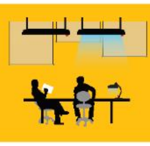
The DZSC shade was satisfactory to 80% of survey respondents despite a number of comments concerning visual and thermal discomfort. The lower view zone provided unobstructed views to the outdoors, which was positively received, but discomfort occurred during sunny periods for some seated next to the window. The upper daylighting zone did its job brightening the ceiling near the window but did not increase perceived light levels deeper in the open plan area. As a retrofit measure for existing buildings with inefficient windows (i.e., single pane, tinted windows with no low-emittance coatings), the DZSC shade offers a user-acceptable solution that balances difficult trade-offs between glare and solar control versus daylight and views. The shade would be most applicable to south-, east-, and west-facing windows, in rooms with light-colored walls and ceilings, and work areas where the workspace views are parallel to the window.

Further information

Lee, E.S. et al. *Dual-Zone Solar Control Indoor Shade: Demonstration at the Ronald V. Dellums Federal Building and U.S. Courthouse and the Lawrence Berkeley National Laboratory Advanced Windows Testbed*, Berkeley, California, Green Proving Ground Report, January 2018. https://eta-publications.lbl.gov/sites/default/files/lbnl_dual-zone_shades_lbnl2001196.pdf

Acknowledgements

This work was supported by the U.S. General Services Administration and Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.



Advanced lighting upgrades in daylit offices improve comfort and lighting quality

High-resolution lighting and shading controls enable comfortable, energy efficient, daylit work office environments

Four types of LED lighting with high-resolution, luminaire-level controls and automated roller shades were evaluated in a 3700 m² Living Laboratory in New York City. The innovative systems delivered significant lighting energy savings with enhanced indoor environmental quality and comfort.

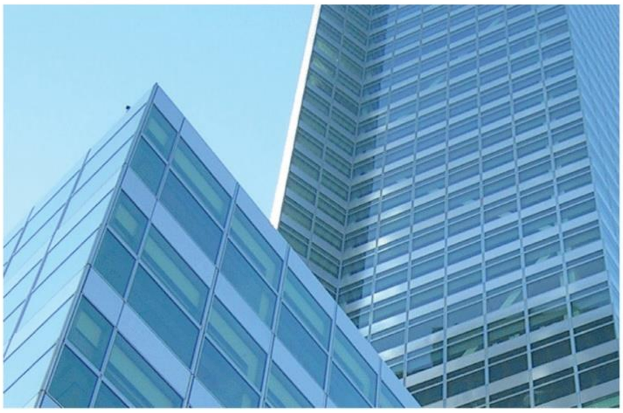
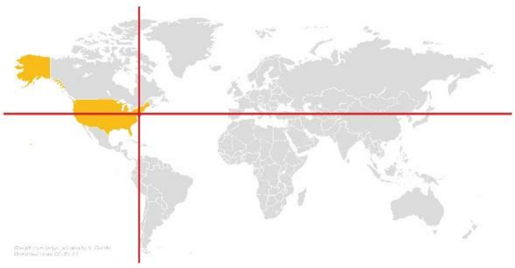


Figure 1. Exterior facade of the monitored commercial office building.

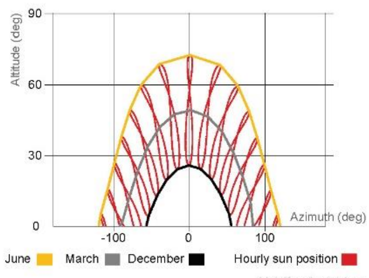
The project

A Living Laboratory was constructed on an upper floor of a high-rise office building in Manhattan (Fig. 1) to evaluate advanced lighting and daylighting retrofit options under normal occupied conditions. The owner intended to apply lessons learned across their global real estate portfolio. The Laboratory enabled the owner and employees to experience and compare the new visual environment to prior conditions, understand the unique features of the various solutions, obtain user feedback, and compare replacement options and costs associated with the upgrade. Monitored results, design guidelines, and procurement specifications were shared publicly to support a new New York City local law mandating energy efficient lighting upgrades and to reduce peak electric demand to improve grid resiliency. An educational series for design professionals, owners, installers, and facility managers was developed and delivered in over 100 interactive sessions. A second hands-on tech series trained over a thousand electricians on installation and commissioning best practices.

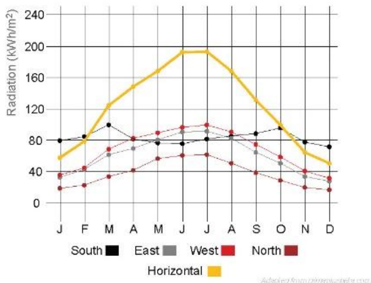
Retrofit options included high-resolution lighting systems with individually-addressable, direct-indirect LED luminaires, separate dimming control of up- versus down-light output, and setpoint tuning, occupancy, scheduling, and daylighting control. This network of luminaires enabled fine spatial, spectral (i.e., daylight + electric light mix), and temporal control across the open plan floor plate. A



Location: New York City, New York, USA
40.71° N, 74.0° W



Sun path for
New York City, New York, USA



Global horizontal and vertical radiation for
New York City, New York, USA

IEA SHC Task 61 Subtask D

Monitored by **Luís L. Fernandes, Taoning Wang,** Lawrence Berkeley National Laboratory
More info **Eleanor S. Lee**, Lawrence Berkeley National Laboratory, eslee@lbl.gov
https://facades.lbl.gov/nyclivinglab

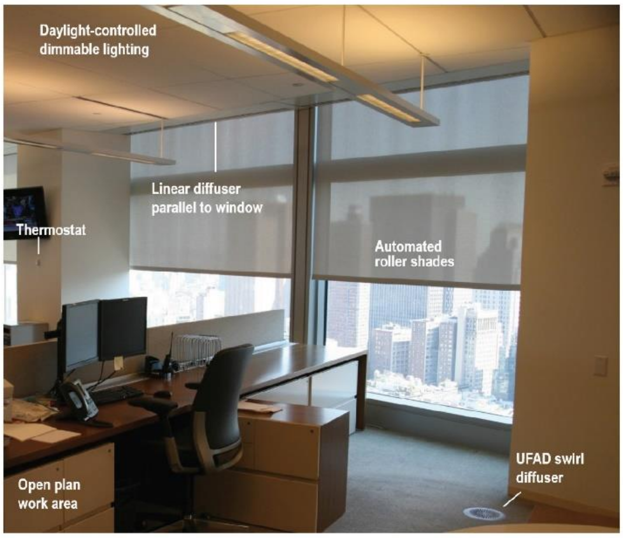


Figure 2. View of the open plan office with automated shades.

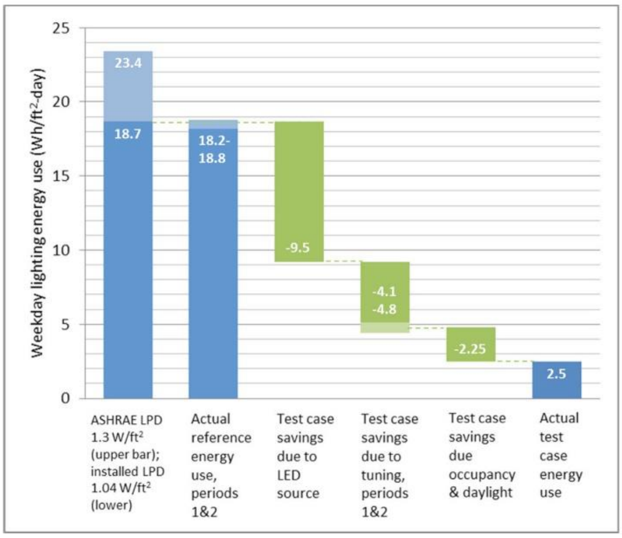


Figure 3. Annual lighting energy savings in southwest quadrant G1 (weekdays only).

mesh network of sensors throughout the open plan space detected local light levels and occupancy. A new shading system automated to control visual and thermal comfort, view, solar heat gains, and daylight was also evaluated (Fig. 2). The building's existing system consisted of direct-indirect T5 fluorescent luminaires with scheduled, area-wide controls, daylighting controls for the row of luminaires closest to the windows, and an alternate automated roller shade system.

Monitoring

The Living Lab floor was divided into four 12.2 m deep quadrants. Four lighting and two shading systems were installed. Monitored data were compared to data collected simultaneously on a reference floor with the existing conditions. Continuous monitoring of lighting energy use, illuminance, temperatures, humidity, air velocity, and control status of luminaires and shades was performed for a year leading up to the retrofit (March 2014 to June 2015) then for a six-month, solstice-to-solstice period following the retrofit (December to June 2016). Time lapsed, high dynamic range (HDR) and infrared thermal images were obtained on select days during solstice and equinox periods. A survey was issued to occupants on both reference and Living Lab floors at the conclusion of the monitored period to assess comfort and satisfaction with the installations.

Energy

Compared to the reference floor, annual lighting energy use was reduced by 36 kWh/m^{2}yr (79%) while peak electric demand was reduced by 6.78 W/m^2 (74%). Of the total savings during weekdays, 41-59% was due to the change from T5 to LED luminaires, 27-51% was due to setpoint tuning, and 8-14% was due to occupancy and daylighting (range in savings reflects the four zone orientations). On average, LED source savings made up 51% of the total savings while advanced controls made up 49% of the savings. Example quadrant-level savings are represented in the waterfall graph shown in Figure 3. Savings were due to dimming of all networked addressable luminaires across the entire perimeter zone, not just the luminaires nearest the window. Occupancy controls were implemented at a 40-60 m^2 resolution. The photosensor-to-luminaire ratio ranged from 1:1 to 1:6, where readings from one or more photosensors could be used to control a single luminaire.

Additional energy savings from daylighting could have been obtained but in some quadrants, the lighting dimming response was set more conservatively. In one quadrant, for example, daylight illuminance levels exceeded the 200-300 lx setpoint for 47%, 38%, and 25% of the monitored period at the three sensor depths of 0.76, 3.02, and 5.24 m from the window whereas dimming in the deeper zones was minimal to none (Fig. 4).

Photometry

Work close to the windows involved intense use of multiple, large-area computer displays so control of excessive daylight, direct sunlight, and glare was essential. At the same time, a spacious, well lit work environment with views to the outdoors is highly desirable. The combined lighting and automated shades helped to balance these two competing goals.

Total workplane illuminance levels at a depth of 0.76 m from the window were maintained within an acceptable

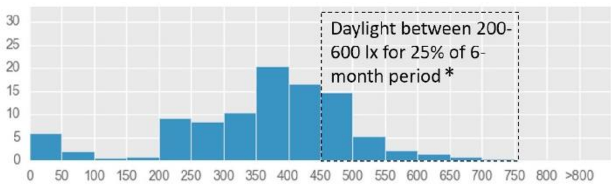


Figure 4. Percentage of time (y-axis) that total workplane illuminance at 5.24 m from the window was within the binned range. Daylight levels estimated assuming that 250 lx was provided by electric lighting at all times. Northwest quadrant G2.

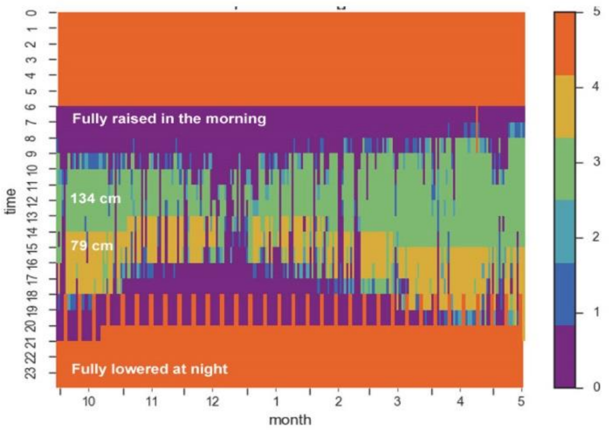


Figure 5. Height of automated shade per hour of day and day of year (including weekends) in the G1 southwest quadrant. Height of lower edge of shade above floor level (cm).

range due to the automated shades (light grey fabric with a 1% openness factor). For 81% of the monitored period, illuminance levels were within the range of 250-2000 lx and exceeded 2000 lx for no more than 1% or 21 hours of the monitored period in each of the four perimeter quadrants.

When possible, the shades were raised to a height that enabled views out, reduced glare from the bright sky, and provided diffuse daylight further from the window (Fig. 5 & 6). To counteract the brightness contrast between areas nearest and furthest from the window, all up-lights remained ON (at no lower than 70% output) irrespective of occupancy during core working hours so as to maintain a bright ceiling plane across the open plan work areas.

Measured data indicated minimal visual discomfort. HDR measurements were conducted with views parallel to the window at the first workstation closest to the window (Fig. 7) – the automated shading was programmed to control discomfort glare for this angle of view. During all periods, visual comfort was maintained within acceptable limits (Daylight Glare Probability (DGP) Class A) in all perimeter zones over the course of the day. The closely-woven fabric reduced discomfort glare for views facing the window.

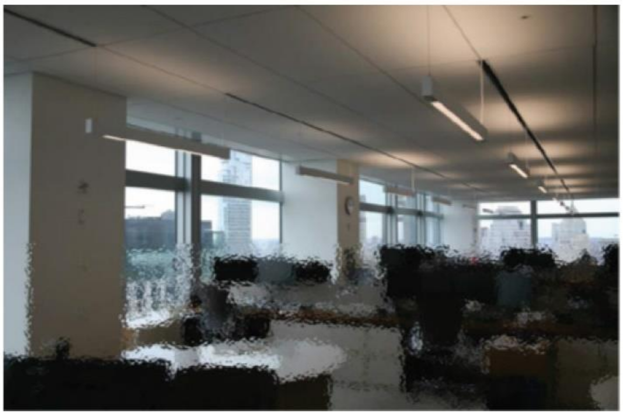


Figure 6. Northeast quadrant G4, full occupancy with daylight dimming of downlights and partial dimming of uplights.

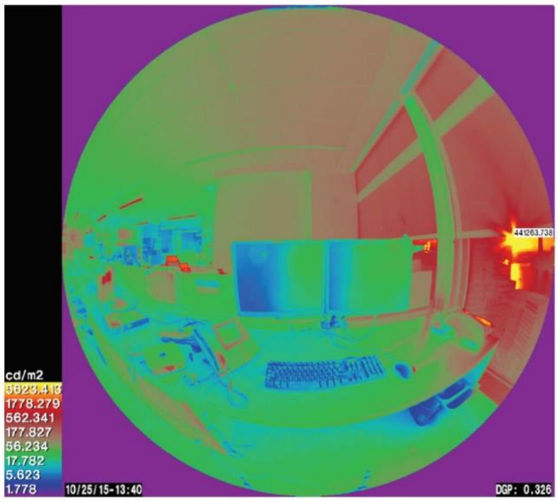


Figure 7. Falsecolor luminance map (cd/m^2) for a view parallel to the window with partial direct sun transmission through the fabric shade. DGP was 0.326 ("imperceptible" glare), October 25, 4:40 pm, southwest quadrant G1.

For the 1%-open fabric, Class A (best) was achieved for four out of the five (80%) monitored days, while with the existing 3%-open fabric, Class A was achieved for only two out of the six days (33%).

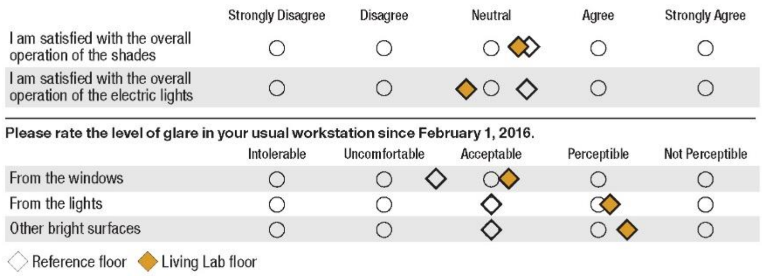
Thermal discomfort was also found to be minimal. Assuming business attire (clo=1.0), the amount of time that thermal discomfort levels were not acceptable (i.e., predicted percentage dissatisfied (PPD) greater than 20%) was less than 0.5-1.8% of the monitored period. The space was designed with an underfloor air distribution (UFAD) system with supplementary heating and cooling at the window wall. The automated shades controlled direct sunlight and reduced radiant asymmetry between the indoors and outdoors. The mean radiant temperature, for example, was maintained to within 6°C of the dry-bulb temperature when warm discomfort occurred while the predicted mean vote (PMV) was greater than 0.5 for no more than 7-16 hours over the six-month period, indicating that temperature asymmetry due to direct solar transmission through the shade fabric was not a significant factor in thermal discomfort.

Circadian potential

Deliberate, controlled use of daylight and electric light to stimulate circadian response was not implemented. However, this case study illustrates the potential of well-managed daylight to entrain Circadian rhythm without introducing additional discomfort glare.

User perspective

A total of 58 responses on the test floor and 20 responses on the reference floor were received from the survey. Survey responses indicated that the overall level of satisfaction with the lighting systems was neutral (neither agreed nor disagreed that occupants were satisfied with the lighting; Fig. 8). Occupants disagreed or were slightly below



"Automated shades allowed me to better focus on work"

"I prefer natural light and outside views over artificial lighting"

Figure 8. Occupant response on the reference floor (white) versus Living Lab floor (orange). Average response of the four quadrants.

neutral (toward "disagree") regarding whether the electric lighting was too dark in the test and reference areas. Overall light levels from both electric light and daylight were slightly above "just right".

High-resolution control based on occupancy sensing at the luminaire level resulted in a few comments of dissatisfaction, particularly during periods of low occupancy at night or on weekends. Erroneous control was likely a result of occupied areas that fell outside of the detectable area of the sensors (e.g., small table areas between the primary desks (Fig. 9)). Inadvertent shut offs during the day were not commented on, perhaps because they were less noticeable with the available daylight. Poor lighting quality resulted from contrasts in lighting level between occupied and unoccupied areas at night; dimming was graduated to lessen the contrasts.

With the automated shading, occupants were also generally neutral about whether they were satisfied with the reference (operated for the prior seven years) and test case automated shades. To override the position of the automated shades, occupants telephoned or submitted an electronic request to have the shades adjusted. Sixteen requests were made over the year to override the test shades and none were made to override the reference shades.

Glare from the windows was perceived as lower in the west test area with the more densely woven fabric compared to the west reference area, however there were far more comments about glare in the test areas with more densely woven fabric than the same reference areas. There were also comments about illogical shade movement. Both control systems provided options for the facility management team to finetune the controls to better suit occupant preferences.

Based on limited data for the test area shade and site observations by occupants and staff, the reference shading system tended to raise the shade more frequently to permit view. There were comments from the occupant surveys that indicated a desire to raise the shades more frequently

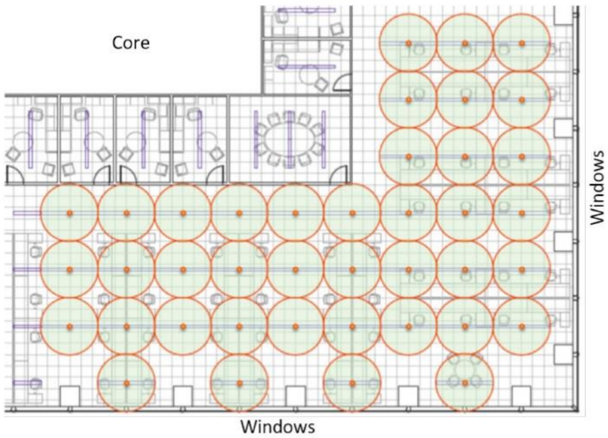


Figure 9. Floor plan showing detection range of occupancy sensors installed in each luminaire.

in the test area for unobstructed access to outdoor views.

Lessons learned

The project sought to balance the benefits of natural light with visual and thermal comfort and provide workers with views when possible. Because this was an installation in a high-end office building, there were many discussions amongst the design team and with the owner on how to deliver an aesthetically acceptable, high quality indoor environment. Use of dimmable direct/indirect lighting systems with high resolution controls and automated shading provided a multitude of options to fine tune the visual environment both spatially and temporally.

Further information

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Specifications for shade controls: https://facades.lbl.gov/newyorktimes/nyt_shades-controls.html

Acknowledgements

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Test and verify to take the guesswork out of achieving high performance goals

Following through on design intent across construction and commissioning phases helped owners achieve high performance goals

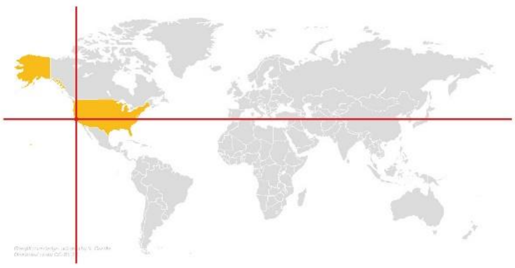
Monitored, full-scale, outdoor mockups were used to finetune design and control system details then, in the final building, performance was verified with monitored data prior to occupancy.

The project

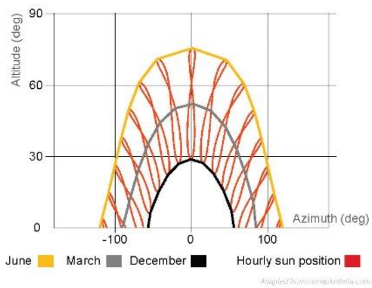
Many new projects start with aspirational performance goals for energy efficiency, comfort, indoor environmental quality, health and wellness, and operational efficiency. Following through on design intent over the design and construction phases of the project and then ultimately over the life cycle of the building, however, remains a key challenge for the buildings industry. In this project, the owner had institutional performance requirements that were verified and signed off at each phase of the design process. Prior to construction, the design and construction team transitioned from engineering calculations to monitored verification in full-scale outdoor mockups under real world conditions, enabling details, specifications, and control sequences of operation to be evaluated prior to procurement. A "burn-in" phase in the newly constructed building was used to commission and verify control system performance prior to occupancy, resulting in a workplace that met defined goals.

Figure 1. Rendering of the new commercial office building.

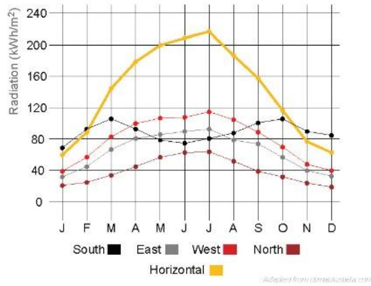
The design intent for the new building, a seven-story, 24,000 m^2 office building (Fig. 1) situated on the company's campus in South San Francisco, was to create a real estate asset with long term value based on rigorous energy efficiency requirements, functional flexibility, and an environment that enhanced employee well being. Daylighting and views to the Bay and surrounding hills were regarded as critical but the design team was also cognizant that solar control and minimizing discomfort ran counter to these goals. A myriad of details needed to be resolved to achieve a satisfactory balance between competing performance objectives. The design team relied on a rich, diverse set of sources to inform final decisions: empirical data from full-scale mockups, hands-on experiential



Location: South San Francisco, CA, USA
37.6547° N, 122.4077° W



Sun path for
San Francisco, CA, USA



Global horizontal and vertical radiation for
San Francisco, CA, USA

IEA SHC Task 61 Subtask D

Monitored by **Andrew McNeil, Christian Kohler**, LBNL
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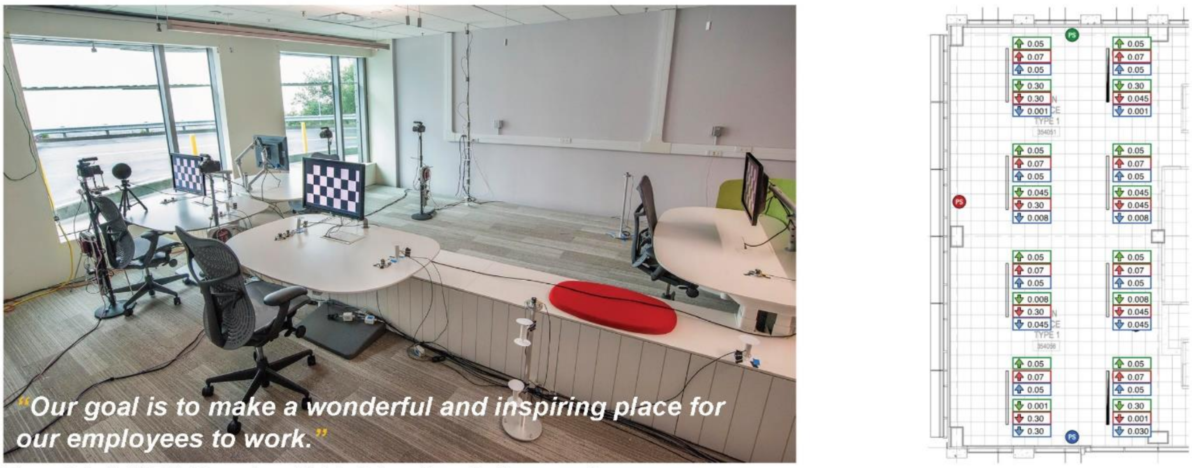

Figure 2. Left: FLEXLAB mockup. Right: Gain settings for the up- and downward dimming output for each of the eight fixtures in the north zone. The red, blue, and green values correspond to the photosensors at the window wall.

observations, and weekly collaborative team discussions between the owner, employee representatives, architects and engineers, interior designers, domain experts, and general contractor.

Monitoring

A monitored field test in the Lawrence Berkeley National Laboratory's rotating FLEXLAB testbed (Fig. 2) was commissioned prior to construction. At this stage of the project, details regarding siting, massing, and facade design had been finalized. The monitored evaluation was expected to resolve outstanding questions related to visual and thermal comfort and indoor environmental quality prior to specifying final interior finishes and procurement of dimmable LED lighting, automated shading, and open plan furniture systems. Mockups of the east, south, and west perimeter zones were evaluated for one week each three times over the summer season (July to October). Modifications were made prior to the next test to address flagged issues and improve performance.

Prior to occupancy, monitoring was conducted on site over a 30-day "burn-in" period in representative perimeter zones of the final building to commission the systems, verify performance, and train the building operations team on use of the shading, lighting, and HVAC control systems.

Energy

Daylight control to reduce lighting energy use has been characterized historically as unreliable: providing too little or too much light, causing occupant complaints, and failing to reduce energy use. Fortunately, digitalization has vastly improved performance despite the increased complexity of high-resolution lighting controls. FLEXLAB tests were conducted to evaluate the daylight dimming performance of the pendant LED lighting system with an open- versus closed-loop control system. The open-loop control system had unique self-commissioning features that enabled

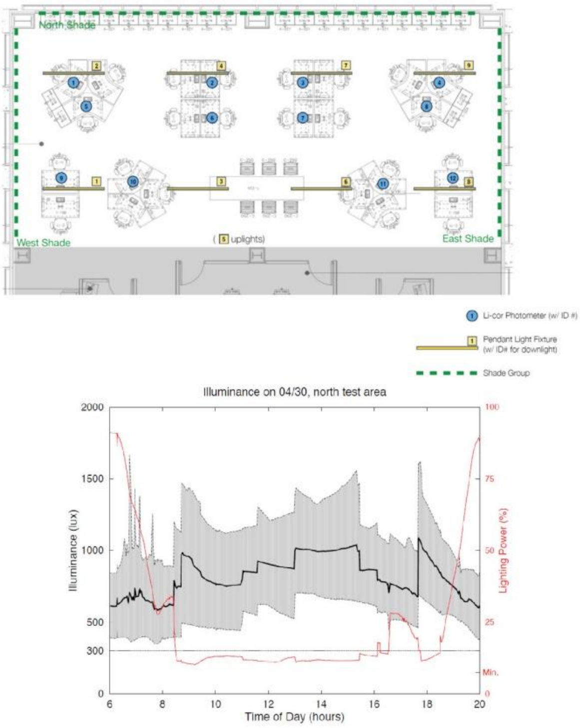

Figure 3. Top: Floor plan layout of furniture, work plane sensors, shades, and light fixtures in the north zone. Bottom: Minimum, average, and maximum work plane illuminance (lx) and average dimming level (%) in the north zone of the new building on a sunny day.

determination of source contributions to each photosensor: i.e., 1) contribution of up- and downward output per fixture to the photosensor signal, 2) photosensor signal versus source power level over the full dimming range, and 3) daylight work plane illuminance versus photosensor signal (Fig. 2). Monitored data were used to evaluate control performance, followed by adjustments to default settings for minimum dimming and light levels to improve energy efficiency, changes to grouping of sources to improve luminance uniformity, and then re-evaluations of dimming performance. Adjustments were made on a trial-and-error basis with observations of lighting quality playing a role in the final design. Based on monitored data, the open-loop system was selected for use in the final building: it dimmed lighting appropriately in response to available daylight for 70% of the monitored period, while the closed-loop system dimmed lighting appropriately 56% of the time. Peak hourly lighting energy savings due to daylighting in the 9.14 m deep open plan workspace with a 300 lx setpoint, 6.17 W/m² lighting power density (LPD), and relay shutoff to minimize standby power was: 71% (east at 12-1 pm), 59% (south at 11-12 am), and 58% (west at 1-2 pm) of nighttime power use (at 300 lx). These summer savings reflected daylight control with automated shades.

In the new building, FLEXLAB conditions were representative of most areas of the floor plan so lessons learned were transferrable, but for the end office areas, which had three facades that contributed daylight to the space, the controls had to be re-evaluated (Fig. 3). Here, daylight illuminance per work area needed to be correlated to the open-loop, ceiling-mounted photosensors at each facade with their respective automated shade controls (Fig. 2). Recommendations for sensor settings were made, then after commissioning, lighting was determined to dim appropriately with a resultant reduction in daytime LPD from 5.52 W/m² to as low as 1.4 W/m² (74%) for the 6.1 m to 9.1 m deep zones when LBNL-recommended settings were used. During afternoon peak periods, lighting demand was reduced to 0.005 W/m² with daylight controls.

Photometry

The critical task of balancing daylight and view objectives against opposing goals of minimizing glare and thermal loads is typically left to manual adjustments of indoor shades. This can lead to a poorly daylit building and defeats the good intentions of the design team. For this project, the team designed a facade with moderate-sized windows (window-to-exterior-wall area ratio of 0.31, solar heat gain coefficient of 0.23, visible transmittance of 0.42) and punched metal overhangs and/or fins, lessening dependence on indoor shades. To further improve performance, automated, motorized, roller shades were considered for purchase (Fig. 4) and so were evaluated in FLEXLAB. For fabric selection, improvements to simulation tools are underway to improve prediction of discomfort glare for light-scattering shades such as fabric roller shades. In the meantime, field assessments can be a good substitute for deciding which fabric to use for protection against discomfort glare.

Two fabrics were evaluated in FLEXLAB: a medium grey and a dark grey fabric, both with a 3% openness factor that provided views to the outdoors. High dynamic range (HDR) imaging was used to measure daylight discomfort glare. The medium grey fabric was found to be slightly less effective in controlling glare, particularly for east-facing windows. Two of six team members working in FLEXLAB observed that the 3% fabric would need to be denser for protection against glare from direct sunlight.

FLEXLAB tests also helped the team understand details

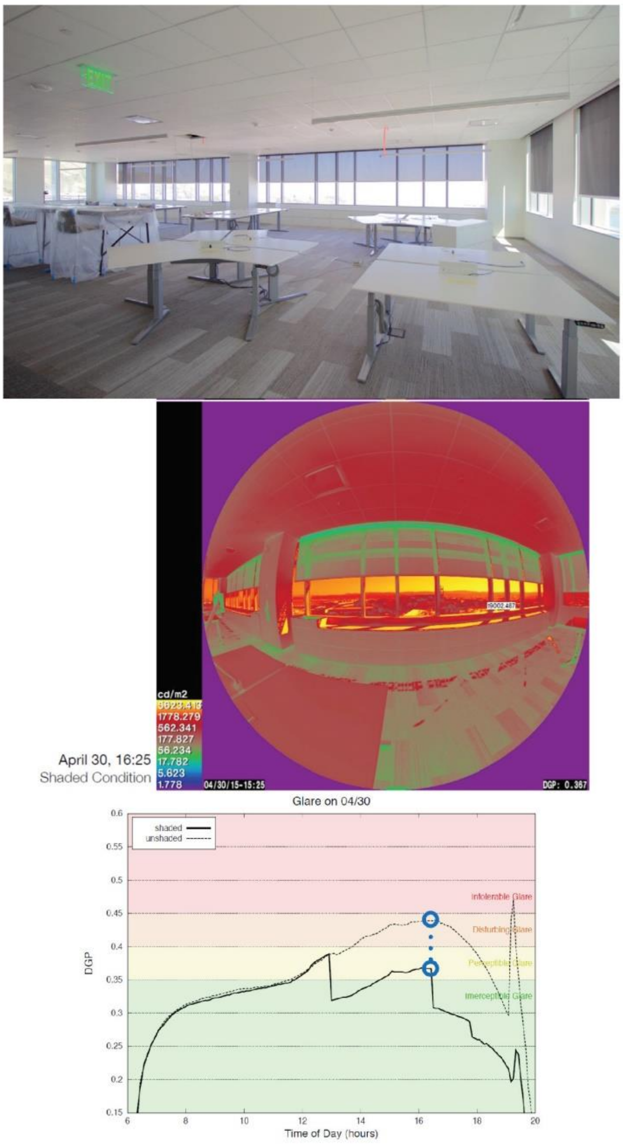

Figure 4. Upper: View of north area in the new building; Middle: HDR image with automated shades; Bottom: Daylight glare probability (DGP) in north area.

of the underlying shade control algorithm and identify options to finetune performance. Adjustments were made to the control system to increase daylighting: the lower stop limit was raised above sill height to admit more daylight and thresholds for determining sunshine were adjusted to be less conservative. Control of overcast sky glare was found to be inadequate, so thresholds were tightened in locations where occupants were seated close to and facing the window.

In the final building, glare and daylight levels were evaluated at key workstation locations across a typical floor. The automated shades kept glare below “imperceptible” levels for most desk locations in the north, east, south, and west areas. For atypical views looking toward the window, glare was maintained below “noticeable” levels (Fig. 4). Daylight

Figure 5. Exterior vertical fins on east and west facades.

Figure 6. Left: Monitoring set up in the new building during the burn-in phase. Right: Recommended furniture placement if visual comfort is achieved at 5.5 ft (1.68 m) from the window.

levels were bright but constrained within an acceptable range by the automated shades. For the north or south areas daylit by three facades, average desk illuminance varied from 600 lx to 1200 lx (Fig. 3), while for the east and west areas daylit by a single facade, average illuminance varied from 300 lx to 1200 lx over a clear sunny day (April 30). For the north and south areas, the automated shades raised the shades for unobstructed views throughout the day for at minimum one of the three orientations. For the east and west areas, the exterior fins provided partial glare protection from low direct sun (Fig. 5), enabling the shade to be raised more often.

Circadian potential

Controls for tunable white lighting were evaluated in FLEXLAB. Dynamic white lighting is thought to reinforce Circadian rhythms through shifts from warm to cool white throughout the day. Based on observations, the team opted for a static 4000K white light in part because 93% of regularly occupied spaces had access to daylight and by design there was a higher than average amount of daylight available in the building overall. Equivalent melanopic lux (EML) levels were not evaluated in this study.

User perspective

FLEXLAB tests were conducted to support space planning decisions related to occupant density and allocation of space. Locating desks close to windows allows increased occupant density but close proximity can reduce daylight and views for all others further from the window. A sensitivity analysis was conducted by measuring discomfort glare as a function of distance from the window, leading to recommendations for minimum seated distance from the window for views parallel and perpendicular to the window (Fig. 6). With exterior and automated interior shades, monitored data indicated that desks could be placed within 0.76 m from the south window for views parallel to the window while for views facing the window on the east, desks needed to be located greater than 1.8 m from the window.

The work place was designed with an open plan concept with unassigned seating so occupants could decide where to work based on personal preferences and tolerances for glare, daylight, and views. Switches to manually override the automated shade controls were not provided. The facility management team was open to feedback from occupants and made adjustments to thresholds to satisfy general requests such as "we'd like the shades raised more often" or "we'd like more daylight in our space". Surveys concerning satisfaction with the workplace were issued by the company but details were not shared publicly. Generally, the facility management team reported that occupants were satisfied with the daylighting and views and in the case of north-facing perimeter zones, occupants desired even more daylight.

Lessons learned

Achieving high-performance goals requires follow through during the later stages of procurement, construction, and commissioning in the final building. Monitored verification under real-world conditions can help identify critical issues well before procurement and occupancy. This is particularly relevant for integrated, innovative shading and lighting systems where balancing tradeoffs between competing performance criteria is required. This project was able to provide daylight and views throughout the workplace, reduce energy use significantly through daylighting and solar control, and meet comfort requirements. The facilities team was trained and occupants were educated on the advanced features of the building, enabling performance to be maintained over the long term.

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Acknowledgements

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