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Horizontal light-pipe study

Doctoral thesis

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Abstract

Daylighting design has always been an inseparable component of architectural design. With the sun as the primary source of light and heat, daylighting design has historically been a point around which the entire process of architectural design is based. Moreover, daylighting design has traditionally been viewed as requiring a combination of both artistic and technical skills.

Nowadays, daylighting in architecture is seen as a segmental design task, as building codes prefer its expression through numerical values. This new perspective makes daylighting design less inspiring from an aesthetical point of view and more trivial, as solutions tend to be oriented around simply fulfilling a minimum requirement.

The transition of the value of ‘good daylighting in the architecture’ within the design process is not known in advance, as it depends on mediation. Design professionals reflect on the daylighting issues within the entire design process and try to fit them in what looks like a never-ending circle of demands (Fig. 1).

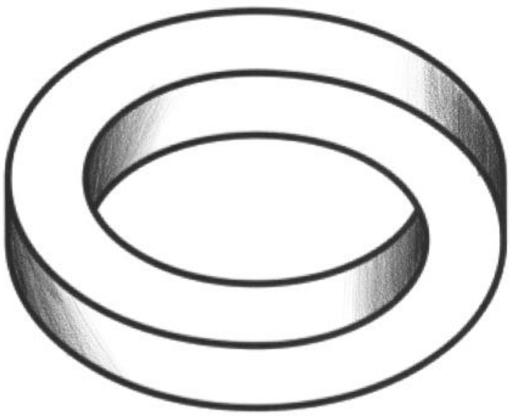

Figure 1 Illustration of the complexity of daylighting design in architectural design.

Nowadays, there are many innovations in the present sustainability marked. Many new daylighting systems have been developed based on the idea of increasing the energy efficiency and reducing the carbon footprint of buildings by enabling more daylighting indoors. These systems have been floating in the market of building components for the last 20 years but have yet to come to the shelves as a standard solution. The reason for this is a lack of reliable information on the effectiveness and profitability of the systems as well as whether they are appreciated by humans. Therefore, the research in this thesis aims to develop reliable evidence that daylight transport systems (DTSs) can improve the human visual experience, increase the daylight levels indoors, and, thus, save lighting energy. This study, which is focused on the above aims, is divided into three research parts. The findings

are reported through five scientific papers (comprising the PhD dissertation) in addition to an overarching essay.

In the first part of the study, a comprehensive literature review of the DTS is performed, specifying the systematization of the DTS technology, the system components, and the products available on the market or in the development stage. The conclusion is that a passive system, such as the horizontal light pipe (HLP), installed on a southern façade would have the greatest applicability in multistorey office buildings in the solar microclimate of Oslo—the location of this study. The literature also identifies improvement possibilities in the light transmission efficiency of the HLP for low solar altitude areas via the application of laser-cut panels (LCPs).

The second part is an experimental-scale model study at a daylighting laboratory at the Faculty of Architecture and Design, NTNU. The aim was to determine the light transmission efficiency for an HLP as well as the improvement potential of LCP configurations when used as collectors for daylight. To perform this study, which aimed to examine whole-year sunlight conditions, a customized method needed to be designed. The new method proposal presented measurements based on a matrix of the sun's positions as well as a temporal matrix, which was used in the analyses. The collected data was analysed further using a theoretical model of an office space based on the concept of daylight autonomy (DA). The results showed that an HLP with a length of 4.8 meters could ensure a daylighting supplement of 300 lux (DA_{300}) of four hours daily on average throughout the year, but using a certain LCP configuration could lead to results improved by 16%. The concept of DA here showed the potential of the HLP to supply deeper spaces of a room with daylight, which could directly relate to the energy saving of artificial light.

In the third part of the study, a full-scale office equipped with an HLP was monitored under whole-year daylight conditions to verify the overmentioned assumptions on the increase of the daylight levels indoors. This long term field study thus consisted of the recording of the indoor lighting level, outdoor daylighting level, and energy used for electrical lighting within a test and reference period. The conclusion was that there is an increased daylight level on the working area in the rear part of the office of approximately 200 to 300 lux during clear and sunny days at equinox. The increased daylight level on the working area near the window of approx. 50 lux was also recorded. Furthermore, a user-survey study under the same test conditions revealed positive user feedback regarding the visual impression of a daylighting concept in the office equipped with an HLP and custom-made reflector.

The aforementioned activities within this PhD study resulted in a profound understanding of the daylight techniques and daylight transport systems that can be used in buildings in the Scandinavian microclimate. Then, further work developed understanding of the quantity and quality of light delivered through an advanced daylighting system (that which was found to be most suitable, an HLP) and how it is possible to combine some other daylighting systems (that which was found to be most suitable in this study, a LCP) to improve the effectiveness. Further, the full-scale study provided several insights in terms of the photometry of daylight supplemented via an HLP in reality, integration with an artificial lighting system, and lighting control. The energy-saving potential for artificial lighting, recorded via this full-scale study, is

an important factor for further Zero-Emission Building (ZEB) development. The last and probably most important finding was the positive human appraisal of the space daylit by a DTS in a full-operative building. This provides a very important knowledge foundation for architects, lighting designers, and policymakers for the implementation of HLPs in practice.

This project represents an industrial PhD and has been conducted in collaboration with Norconsult and the Norwegian University of Science and Technology (NTNU) with financial support from the Norwegian Research Council (NFR).

Key words: light, daylight, sunlight, skylight, daylighting systems, light pipe, daylight tube, laser-cut panels, sustainable building development

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The greatest support and guidance I received during the preparation year and performance years were from my supervisor professor, Barbara Matusiak. I also thank her for the inspiration to reflect on the topic of daylighting over the many years before the start of this study, especially after reading her related articles and hearing her lectures and speeches. Thank you, Barbara; your knowledge on and enthusiasm for daylighting are unparalleled.

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I appreciate the sponsorship of the full-scale test office from Glamox along with the luminaires and photosensors as well as Carlo Gavazzi for the outdoor illuminance meters and control units. I am also grateful to Norconsult for allowing access to the test office for an entire year and the caretakers of the building for their additional technical support.

Finally, I would like to thank my family for help and support shown.

Publications

Scientific articles providing the basis for this PhD

1. Daylight Transport Systems for Buildings at High Latitudes, Biljana Obradovic, Barbara Szybinska Matusiak Journal of Daylighting 6 (2019) 60-79, Published on 29 September 2019 http://dx.doi.org/10.15627/jd.2019.8

Status: peer reviewed, published

Roles of the co-authors: the second co-author gave feedback on the scope of the paper, review method and contributed by performing quality assurance and proofreading.

2. Daylight autonomy improvement in buildings at high latitudes using horizontal light pipes and light-deflecting panels Biljana Obradovic, Barbara Szybinska Matusiak, Solar Energy Volume 208, 15 September 2020, Pages 493-514, Published on 14 August 2020. https://doi.org/10.1016/j.solener.2020.07.074

Status: peer reviewed, published

Roles of the co-authors: the second co-author helped with the topic and methods used in the study, gave feedback on the content of the paper, analyses, and contributed by performing quality assurance and proofreading.

3. A customized method for estimating light transmission efficiency of the horizontal light pipe via a temporal parameter with an example application using laser-cut panels as a collector, Biljana Obradovic, Barbara Szybinska Matusiak, MethodsX 2021 Vol. 8, Published on 24 April 2021. https://doi.org/10.1016/j.mex.2021.101339

Status: peer reviewed, published

Roles of the co-authors: the second co-author helped with methodology, protocols, gave feedback on the content of the paper and assisted in performing quality assurance.

4. The effect of a horizontal light pipe and a custom-made reflector on the user's perceptual impression of the office room located at a high latitude, B. Obradovic, B. S. Matusiak, C. A. Klockner and S. Arbab, Energy and Buildings 2021 Vol. 253 Published on 30 September 2021. https://doi.org/10.1016/j.enbuild.2021.111526

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Roles of the co-authors: the second co-author helped develop topic, scope and method of the study, gave feedback on the content of the user-survey interview, paper and contributed by performing quality assurance; the third co-author contributed in decisions about the statistical analyses and performing quality assurance of the paper and statistical analyses; the fourth co-author gave feedback on the content of the user-survey interview, contributed during the user-survey, and by performing quality assurance and proofreading of the paper.

5. Illumination and lighting energy use in an office room equipped with a horizontal light pipe with a reflector, field study at a high latitude, B. Obradovic, B. S. Matusiak,

Status: submitted to the Journal of Daylighting

Roles of the co-authors: the second co-author helped with the definition of the study, topic, and methodology, contributed by performing quality assurance and proofreading of the paper.

Other publications

- Poster: Daylighting strategies in context of ZEN: How to design urban areas to ensure daylight availability for future development, Biljana Obradovic, M. Arch., Nordic ZEB+ conference, Trondheim November 2019

- Poster: Electrical lighting solutions for energy efficient developments: a practical approach, Biljana Obradovic, M. Arch., Nordic ZEB+ conference, Trondheim November 2019

- Dagslys transportsystemer med bevist effektivitet for høye breddegrader, written by Biljana Obradovic, Nærings PhD kandidat, Norconsult AS, Lyskultur nr 1/2020 https://issuu.com/merkurgrafisk/docs/magasinet_lyskultur_nr_1_-_2020/54

- Hun slipper lys inn i mørke kroker, interview in the Teknisk Ukeblad 01/21, p 58-62 https://www.tu.no/artikler/hun-slipper-lys-inn-i-morke-kroker/508208

- Rapport om brukerundersøkelse av visuelle forhold i et kontor med installert horisontalt dagslys tube, written by Biljana Obradovic, Nærings PhD kandidat, Norconsult AS, Lyskultur nr 2/2021 Magasinet Lyskultur nr 2-2021 by Merkur Digitale Magasiner - issuu

Presentation and lectures, portal, and website presentations

- Forskning på dagslys, Horizon Conference Norwegian Research Council, February 2019 Oslo

- Innovativ løsning for dagslys i bygninger, november 2018, Norges energy Bedrift https://norgesenergi.no/bedrift/spar-strom/innovativ-losning-for-dagslys-i-bygninger/

- Dagslys og dagslysteknikker i arkitektur, presentation for an architectural forum in Norconsult, September 2019

- Daylighting and Lighting in Architecture, presented to Nordic Office of Architecture, October 2020

- Daylight Transport Systems, lecture given to the students at Lighting Design studies, at University of Southern Norway (USN), February 2021

- Designing with daylight and sunlight, presentation given to the Energy and Environment department at Norconsult, March 2020

- Dagslys transport systemer (DTS) I Skandinaviske lysforhold: resultater fra et full-skala prosjekt, oral presentation on a Forum for Electro and automatization in Norconsult, march 2021

- Daylight Transport Systems, lecture given to the students at Lighting Design studies, at University of Soutern Norway (USN), February 2022

Contribution to IEA task 61

- Literature review- Energy saving potential of user centred integrated lighting solutions T61.D.1 – A Technical Report of Subtask D IEA SHC Task 61 / EBC Annex 77 Integrated Solutions for Daylighting and Electric Lighting https://task61.iea-shc.org/Data/Sites/1/publications/IEA-SHC-Task61--Technical-Report-D1-Literature-Review.pdf

- Energy saving potential for integrated daylighting and electric lighting design via user-driven solutions: A literature review. Gentile, Niko ; Osterhaus, Werner ; Altomonte, Sergio ; García Alvarez, Maria ; Garcia-Hansen, Veronica ; Naves David Amorim, Claudia and Obradovic, Biljana (2019) Proceedings of the 29th Session of the CIE Washington D.C. USA http://files.cie.co.at/x046_2019/x046-OP32.pdf

- Lighting designers improve lighting energy performance through user-centred lighting design, V Osterhaus, W ; Gentile, N ; Altomonte, Sergio ; Alvarez Garcia, M ; Naves David Amorim, C Obradovic, B.5, Garcia Hansen, V. ; et. al. PLDC - 8th Professional Lighting Design Convention (Rotterdam, NL, du 23/10/19 au 26/10/19) https://dial.uclouvain.be/pr/boreal/object/boreal%3A220279/datastream/PDF_01/view

- Workflows and software for the design of integrated lighting solutions T61.C.1 – A Technical Report of Subtask C IEA SHC Task 61 / EBC Annex 77 Integrated Solutions for Daylighting and Electric Lighting From component to user centered system efficiency. https://www.iea-shc.org/Data/Sites/1/publications/IEA-SHC-Task61-Workflows-and-software-for-the-design-of-integrated-lighting-solutions.pdf

- Integrated Daylighting and lighting in practice - Lessons learned from international case studies T61.D.3-D4 – A Technical Report of Subtask D IEA SHC Task 61 / EBC Annex 77 Integrated Solutions for Daylighting and Electric Lighting https://task61.iea-shc.org/Data/Sites/1/publications/IEA-SHC-Task61--Technical-Report-D3-D4-Integrated-Solutions-for-Daylighting-and-Electric-Lighting.pdf

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Abbreviations

DTS	Daylight Transport System
HLP	Horizontal Light Pipe
LCP	Laser-Cut Panel
DA	Daylight Autonomy
SE	Sunlight Exposure
DF	Daylight Factor
CCT	Correlated Color Temperature
CRI	Color Rendering Index
ZEB	Zero-Emission Building
netZEB	Zero-Energy Building
ZEN	Zero-Emission Neighbourhood
BREEAM	Building Research Establishment Environmental Assessment Method
PV	Photovoltaic Panel
IEA	International Energy Agency
CIE	International Commission on Illumination (Commission Internationale de l'éclairage)
CEN	European Committee for Standardization (Comité Européen de Normalisation)
CBDC	Climate-Based Daylight Calculations
USM	Urban Solar Microclimate
HCL	Human Centric Lighting
DLC	Daylight Linked Control
LENI	Lighting Energy Numerical Indicator

1. Introduction

1.1. Research motivation and the research topic

The author of this thesis is an educated architect with a postgraduate degree in energy-efficiency and green architecture as well as 15 years of practical experience as a professional architectural lighting designer. The author was interested in investigating the influence of innovative daylighting systems on artificial lighting in buildings in high-latitude areas. This PhD research is built on the author's passion and enthusiasm for daylighting in architecture and green and energy-efficient buildings and, further, the need in practice for greater support of the applicability of some design ideas.

Within the last years, which have been permeated with sustainable development initiatives, and as a result of new regulations to achieve a Passive House Standard and Zero Energy Buildings (net ZEB), building projects began to focus on achieving less energy-dependent buildings. The collaboration between designers has been seen as essential for achieving a successful design. But, in the field of building energy consumption, it frequently occurs that the objectives are not met. Challenges in achieving energy-efficient designs lay partly in buildings' form and position. Challenges appear to be more associated with the simulation tools used in these cases, as these apply too rigid threshold values in the calculations. In practice, it was also shown that another challenge resides in the complexity of the equipment and its integration.

During the years of the author's practice, it was personally experienced that own designs in artificial lighting and controlling scenarios did not produce the intended results. There are many factors affecting lighting design in the indoor space, the most radical of which has been shown to be the daylight availability in the space. The functionality of the artificial lighting system is often affected by an insufficient daylight amount and distribution, which was supposed to be ensured by the sun-shading strategy; however, in reality, it is rare that the sun-shading and daylighting strategy are coordinated with the lighting control strategy. Thus, the authors personal goal was to enhance understanding of reliable daylighting indoors and increase the visibility of this topic. The author of this thesis particularly wanted to work toward solutions that would provide occupants of the space with more reliable daylight supplement during the day.

The focus on better daylighting indoors has, in the last decade, been introduced by environmental certification of buildings, like BREEAM[1], which is voluntary but very often used in Norway as a design guideline. In the *BREEAM Technical Manual*[2], the criteria related to health and wellbeing (e.g., visual comfort [HEA1] requires a certain amount of daylight inside the space). Projects applying BREEAM in their design aim to have improved daylighting

[1] BREEAM official website http://www.breeam.com/

[2] Technical Manual BREEAM NOR ver. 1.1 (2012): http://ngbc.no/wp-content/uploads/2015/09/BREEAM-NOR-Engl-ver-1.1_0.pdf SD-5075NOR-BREEAM-NOR-2016-New-Construction-v.1.2.pdf (byggalliansen.no)

indoors. However, at the same time, there are other requirements regarding the personal control of solar shading (HEA3) that suggest the individual control of sun-shading devices. This might lead to reduced daylighting via sun-shading devices, as it might be dependent on individual feelings of glare discomfort.

Clear skies and sunlight are appreciated in Scandinavian countries. In contrast to the equatorial areas of the globe, the high-latitude areas are characterized by a variating solar azimuth angle—at least during the summer—and, more importantly, a low solar altitude angle of the sun above the horizon. In Fig. 2, a solar chart for Oslo (59.9°N) and Roma (41.9°N) are illustrated. It can be seen that, during the summer, the sun's low angle exists over many hours during the morning and afternoon unlike Roma where sun's angle is highly changeable. During the winter, a low sun angle exists during the entire daylight period (which is usually short). This sun's position brings direct, excessive sunlight against vertical windows. The most frequently used solutions for sun-shading, such as outdoor blinds, are incapable of effectively redirecting the sunlight and transforming it into functional daylight. Individuals react instantly and close the sun-shading device, when they experience excessive light and do not open them until long after such conditions disappear. This PhD study was mainly inspired and motivated by this issue. The users of a space lack interior daylight if they close the blinds to protect themselves in situations of excessive, low-angled sunlight. Fig. 3 illustrates such situations—i.e., where the energy consumption of artificial lighting is also affected and increased.

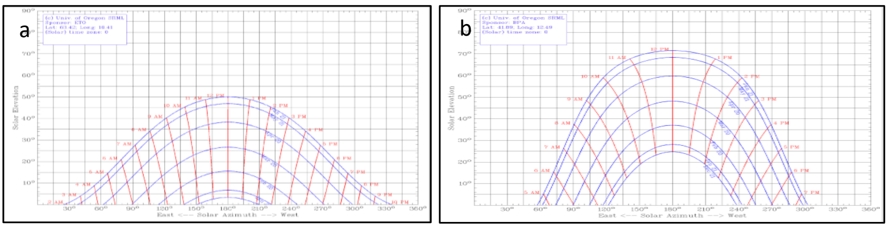

Figure 2 Solar charts for a) Oslo and b) Roma; retrieved from the internet webpage, SRLM[3].

Figure 3 Typical office with windows oriented against south or west, a) excessive low-angled sunlight brings discomfort to the users of an office space; b) the sun-shading device is closed and adjusted to protect visual comfort and enable daylight; c) the sun shading slats are completely closed to ensure the visual comfort of the office user.

[3] University of Oregon Solar Radiation Monitoring Laboratory http://solardat.uoregon.edu/SunChartProgram.php

The necessity of using daylighting systems is based on today's assumptions regarding clean energy production for artificial lighting (preferably generated on the site, and with low carbon footprint). All other technical systems in the building can use some other form of renewable energy (geothermal), but artificial lighting is the only system that can use only electrical energy. This is why an alternative method for providing functional illumination is needed; maximized daylighting can be seen as a solution in this regard. Photovoltaics panels (PVs) are seen as a renewable alternative, but the fact that they generate electricity from solar radiation with a very low effectivity factor put them under doubt. Moreover, the carbon emissions are considerably higher for a PV panel when compared with a window of same size, as estimated in the report by ZEB Research Centre (Dokka, Houlihan Wiberg et al. 2013). If the energy consumption of functional lighting needs to be reduced, daylighting must be enabled there—where the consumption of artificial lighting is unavoidable—such as in the deeper areas of buildings. Daylighting guided to these deeper areas with DTSs can potentially be a solution (Fig. 4).

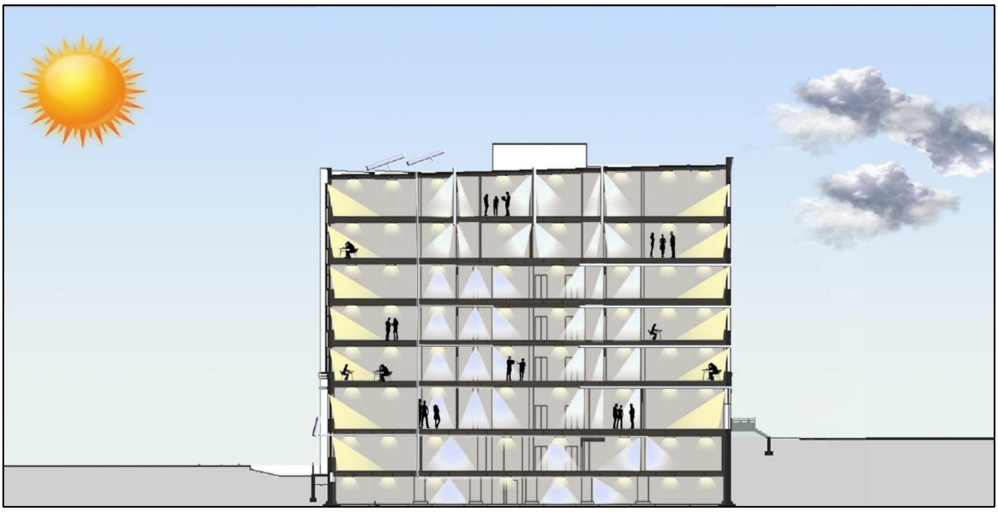

Figure 4 Integrated solution for daylighting (with daylight transport systems [DTS]) and artificial lighting, adopted from (Gentile, Osterhaus et al. 2021)[4]. https://www.iea-shc.org/ All rights reserved.

The necessary application of daylighting systems is also grounded in the urbanization and densification of city centres, which, as argued by Brown (2008), bring about daylight shortages in buildings. Governments did not have good strategy in mind when allowing for such densification. Even with stricter requirements regarding energy efficiency, densification increases energy use demand, as it reduces the possibilities to apply principles for passive energy design. Commercial buildings are often located in city centres, where economic considerations prevail against urban regulations. These building are often designed as tall glass cubes, resulting in the primary challenges of overshadowing and daylight stealing, preventing good daylighting.

[4] Used by permission. Permission granted by Pamela Murphy, SHC secretariat, on the 21th of February 2022; Permission granted by IEA Terms and conditions: https://iea.blob.core.windows.net/assets/3bf6ce57-3df6-4639-bf60-d73ee8f017c0/IEA-Terms-April-2020.pdf

The interaction of different disciplines in building engineering is an essential component of achieving good building practice. This research focuses on how to better utilize daylight in buildings, presenting a combination of the fields of architecture, daylighting and lighting design, and engineering. Since the solar angle throughout the year in Norway is different than in other parts of Europe, many of the daylighting systems developed and used in Europe today would not demonstrate the same potential in this context; therefore, this research focuses on selecting and examining daylight systems suitable to the specific condition of a low solar altitude.

1.2. Industrial PhD framework: The 'mode' of knowledge production and the multidisciplinarity of this research

This research lies on the basis of an industrial PhD, a framework also called 'mode 2' knowledge production. When a research activity results in new knowledge, it is thus called a knowledge production activity (Hessels and Van Lente 2008). Originally, there was only one way to produce knowledge: by conducting research within academia. In the middle of the 20 century, other knowledge production models received more attention. Once the interconnectivity between science, industry, and innovation was more firmly planted in society, a new model of knowledge production (called 'mode 2') emerged. As defined by Nowotny, Scott et al. (2003), the main difference between mode 1 and mode 2 knowledge production lies in the applicability of the new developed knowledge. In mode 1, theories are tested, and a knowledge base is built within the limits of one discipline and without any context of applicability. The results are universal law and primary cognition. Mode 2, on the other hand, is characterized by knowledge produced for application and is always contextually embedded. Moreover, mode 1 is characterized by measurements and the logical validation of knowledge, where the researcher is meant to be a neutral observer, while, in mode 2, knowledge is validated by experiential, collaborative, and transdisciplinary processes, with researcher socially accountable, immersive, and reflexive. Table 1 presents the systematization of these modes' main characteristics.

Thus, the traditional scientific research model (mode 1) differs from mode 2 in terms of the definition of a problem, usefulness, and the application of the result. Mode 2 is also, in most cases, multidisciplinary or transdisciplinary research. Mode 1 is homogenous, but mode 2 is heterogeneous, as it consists of not single disciplines, but the arts, skills, and practical experience. The current research is characterized as mode 2, because the topic has evolved from major issues in building design practice. The objectives of the research are based in the everyday challenges encountered by architects, lighting designers, and building engineers as well as, to some extent, contractors and commissioners. The research questions were developed so that their answers could be directly used in practice and help determine whether some assumptions are realistic (and, if so, to what extent). Further, the results should help engineers in design process from the start as well as reduce the number of design iterations, reduce the number of common mistakes, and provide a more accurate foundation for calculations and simulations.

Table 1 Systematization of the research modes' main characteristics.

Mode 1	Mode 2	Mode 3*
Academical context	Context of applicability	Context of innovation
Solely inside universities	Inside and outside universities	Universities-industry-government-public-environment
Internally oriented	Externally oriented	Globally oriented, democratic
Mono-disciplinary	Multi-disciplinary	Trans-disciplinary
Homogenous	Heterogenous	Diverse
Independent, detached, and neutral researcher	Socially accountable, immersive, and reflexive researcher	Socially accountable, immersive, and reflexive researcher
Traditional method of open criticism, inside own discipline	Open criticism within many disciplines, open view	Open criticism
*Author's own interpretation		

In the last decade, several scientific circles began discussing 'mode 3' knowledge production (Etzkowitz and Leydesdorff 2000, Carayannis and Campbell 2011, Carayannis and Campbell 2012). Mode 3 knowledge production is mostly described as an innovation process with coexistence and co-development happening on different levels (Fig. 5). These levels are multidimensional, including the individual (micro or local), structural and organizational (meso or institutional), and systemic (macro or global). The 'mode 3' always involves mutual interdisciplinary and transdisciplinary knowledge, and it is based on the concepts of the creative milieus (entrepreneurs and employees), and via different platforms (e.g. knowledge clusters, innovation networks, entrepreneurial universities, and academic firms). This knowledge production mode is situated within the concept of a 'democracy of knowledge' (i.e., knowledge within a democratic system).

The mode 3 knowledge production is nowadays described as situated within the newly argued quadruple and quintuple innovation helix framework, which has evolved out of the triple helix mode originally described by Etzkowitz and Leydesdorff (2000) (Fig. 6). Carayannis, Barth et al. (2012) argued that the quadruple and quintuple innovation framework is situated within the university–industry–government–public–environment relationship and describes their interactions within knowledge production and its application.

Thus, the research activity performed within this PhD study can be argued to be mode 3 research as well, as it is situated in academia, industry, and governmental policies. It is also transdisciplinary, as it employs the formal discipline of physics, as well as the main theories inside it, while also employing arts skills and practice, traversing the relationships between them in order to establish coherency. It is impossible to investigate new knowledge, improvements, and innovation without considering their usability and applicability for society.

In regard to the quadruple helix context, on the micro scale, the research result is applicable for individual human health and wellbeing, and on the meso scale, would be applicable to, for instance, a group of office workers or workers of a certain age. But, the core issue of this research, besides the applicability of human health and wellbeing, is energy efficiency and sustainable building design, which suits into the quintuple helix model. The quintuple helix model discusses challenges of implementing step-by-step sustainability in the face of global warming.

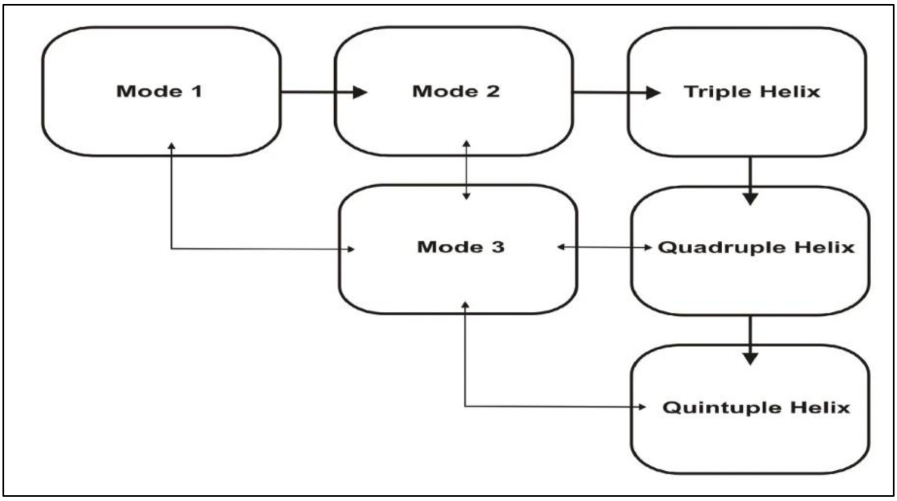

Figure 5 The evolution of the knowledge creation models adopted from (Carayannis, Barth et al. 2012)[5].

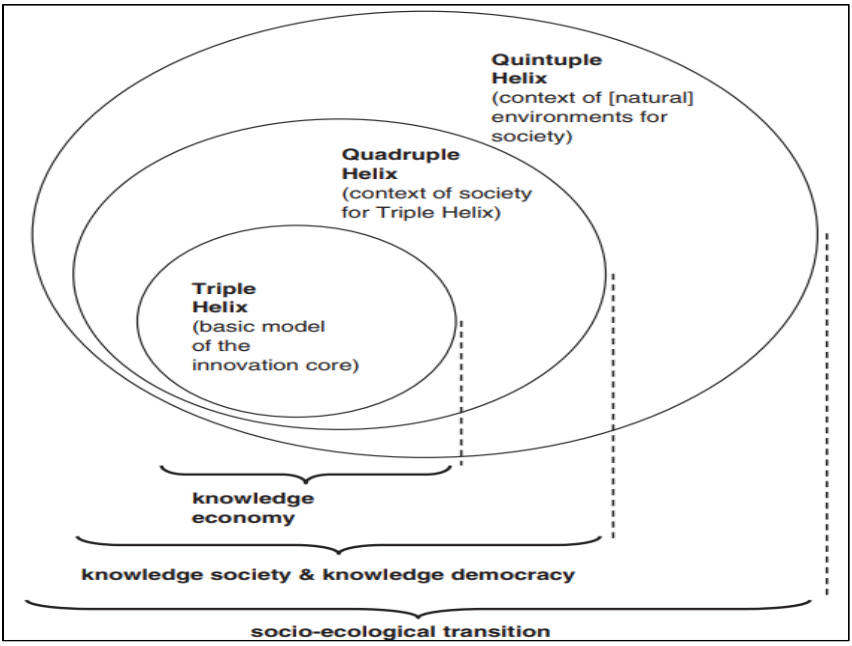

Figure 6 Knowledge production and innovation in the context of the knowledge economy, knowledge society (knowledge democracy), and the natural environments of society. Modified from Carayannis and Campbell ([2012], p. 18), Etzkowitz and Leydesdorff ([2000], p. 112) and Danilda et al. ([2009]) adopted from Carayannis, Barth et al. (2012) [6]

[5] Permission to use image granted by Elias G. Carayannis on the 15th of February 2022.

[6] Permission to use image granted by Elias G. Carayannis on the 15th of February 2022.

Finally, this research's applicability can be compared to suit inside:

- a triple helix model- where the economy of the gained knowledge lies in the applicability or a profitability of one innovation (the daylight transport system and a custom-made reflector are suited inside the industry),

And, as a hybridization of mode 2 it suits inside:

- a quadruple helix model within the context of usefulness for society via the improved health and wellbeing of users of a space; and
- the quintuple helix model in the context of a natural environment for society, addressing the energy saving issue.

Any scientific method for knowledge production should, according to Merton (1973), follow the CUDOS institutional norms. These norms are the ethos of science as a social structure. In Merton's perspective (developed in 1942), the norms include: *communalism, universalism, disinterestedness,* and *organized scepticism.*

- Communalism requires that scientific knowledge be public knowledge and its results should be published and available (i.e., exchangeable between scientists everywhere) and that scientists should be responsible for the trustworthiness of their work.
- Universalism requires that science is international and independent of race, colour, or creed.
- Disinterestedness means that the results must be honest and objective and should not be manipulated to serve a personal profit, ideology, or expediency.
- Organized scepticism means that every statement should be questioned and peer-reviewed and that the truth of any statement should ultimately rely on a comparison with an observed fact and never accepted based only on authority.

According to Ziman (2001), *originality* should be included among these aforementioned norms. Although originality is an essential characteristic of science, it was not included by Merton in his initial listing. Originality requires that scientific research is *nove*l to be considered as a contribution.

The author of this research acknowledges that the CUDOS norms—with the inclusion of originality, have been followed.

1.3. Main objective and limitations of the study

The main objective of this work is to evaluate the performance of advanced daylighting systems, such as daylight transport systems (DTSs) for providing functional lighting in buildings. The entire study is developed in the context of high-latitude areas. The aim was to test hypotheses about DTSs' potential to provide daylight useful for the performance of human activities indoors and, further, to examine hypotheses about the energy-saving potential of artificial lighting. This study is divided into three parts and has four objectives:

1. The investigation of which current DTSs are the most suitable for the solar micro-climatical conditions in Oslo (places around latitude around 60° N that have similar conditions like Oslo).

2. Examination of the system with the highest applicable potential via a small-scale experimental study.

3. Monitoring and analyses of the illuminance levels and energy consumption in a full-scale study where daylight is delivered via HLP and custom-made reflector.

4. Examination of users' perceptual impressions of daylighting conditions under full-scale conditions where daylight is delivered via an HLP and custom-made reflector.

The limitations of this PhD include the following: One of the limitations lays in the independent variables used in the studies, which are specific to the latitude and longitude of the setting chosen for the study and its distinctive sun altitude variation throughout the year. This impacts the generalizability of the findings but the calculation method can be used to develop more precise results for other locations.

Another limitation is that the study examines advanced daylighting systems, meaning that it researches daylighting systems in terms of a new approach that differs from traditional daylighting systems (e.g., windows, awning, prismatic systems). In this regard, the daylight systems that transport daylight to a remote place are, after the systematization done by IEA Task 21 (Ruck, Aschehoug et al. 2000), seen as advanced, as they use an innovative approach for daylight transport to deliver it reaching some remote place. This study does not research hybrid daylight transport systems, which combine an artificial lighting source with a natural lighting source to guide the illuminance through the transport element to the remote place.

In each of the papers of this dissertation, the corresponding limitations are argued, such as, for example, the limitation of a small office in the full-scale study. The reader is advised to check the appended scientific articles for the detailed limitations of each study part.

1.4. Thesis outline

This thesis presents an extended summary of all the research activities carried out during the four years of study. This PhD study consisted of a 75% PhD activity and 25% design activity at the company Norconsult. The research was divided into three research parts, resulting in five peer-reviewed scientific journal publications. The practician activity at the company over these four years provided the remarkable opportunity to verify the assumptions and results through design tasks.

Participation in the SHC IEA activity (through Task 61), as a voluntary activity, was a very stimulative forum for gaining knowledge and discussions with international experts within the field. IEA Task 61 resulted in many publications, among which, the author of this thesis contributed to three reports and two conference articles (David Geisler-Moroder, Bruno Bueno et al. 2019, Gentile, Osterhaus et al. 2019, Osterhaus, Gentile et al. 2019, Gentile, Osterhaus et al. 2021, Gentile, Osterhaus et al. 2021).

Additional contribution to the dissemination of the results of this study was done through two popular scientific articles in periodicals, an interview, and several lectures and presentations for architects, lighting designers, and electro-engineers, and students (listed under **Publications**, Other publications & Presentation and lectures, portal, and website presentations).

The goal of this thesis body was to provide a comprehensive summary of the development of this research and all the results of the published scientific works. The audience for this thesis is future scientists in sole- and cross-disciplinary arenas, such as architecture, physics, and environmental psychology. The most desirable audience for this thesis is current practitioners in the field of lighting and daylighting engineering and architecture as well as practitioners in the research and development of specific building technologies.

This PhD research is article-based, meaning that the parts of the research are structured and published as independent studies. The scientific articles are included in Appendix A, while a systematization of the four years' work is presented in the thesis body. Readers can consult the following summary to obtain information on the research flow, but a reading of the collection of appended papers is recommended for a more extensive understanding of the experimental settings and methods as well as the detailed results and discussions of each research part.

Chapter 1 introduces the topic of the study as well as its motivation and main objective. The multidisciplinarity and industrial framework for this research is also explained. The main body of the dissertation begins in **Chapter 2**, where an overview of the relevant disciplines and the theoretical basis upon which this study relies are presented. Here, the theories used in this PhD regarding light and daylight, electrical engineering, and sustainable building design are presented as well as the position of daylighting within the essential context of the study. A brief overview of the daylighting systems with DTSs are presented in this part as well.

Chapter 3 presents the knowledge gap in the current literature and a formulation of the research questions of the study. In **Chapter 4**, the research methodology of each study part is given along with a justification of the research's credibility.

The results from all parts of this research study are provided in **Chapter 5**, which is divided into four subchapters corresponding to each study activity. All supplementary data, such as the tables, graphs, and metric values, can be found in Papers 1–5. The study's main findings, limitations, and results and metrics are also described.

A discussion on the challenges, and potential for the application of the daylighting systems addressed in this research are presented in **Chapter 6.**

Finally, **Chapter 7** summarizes the achievements of the present dissertation and discusses possible directions for future work.

Appendix A contains the scientific papers (published or currently under review) that formed the basis for this dissertation.

2. Theoretical background of the research

The daylight assessment within this project involved several different disciplines. In general, research relied on the theories of light, which is a part of physics. Light and artificial lighting rely on the theory of photometry, with luminous flux, illuminance, and luminance as the basis. Photometry is a humanistic approach to physics where the measurement of a lighting flux is used to quantify the light perceived by the human eye. Especially for daylight considerations indoors, the application of the daylight provision, through daylight factor and daylight autonomy represent the basic assessment parameters. The daylight provided by the daylight systems relied on the concepts of reflection, refraction, internal refraction, and transmission law.

In addition to the basic theoretical background of the daylighting disciplines, there were other concepts used in this research. For instance, the theory of human vision and perception and the daylighting (lighting) role are discussed. Moreover, the daylighting position in sustainable development and passive building design represented the framework for this study.

2.1. Definition of light

Daylight is a completely natural phenomenon, with primarily physicists—but also philosophers and artists—having historically tried to define it. Scientifically, the concept of light is mainly based on two ideas: light is a part of the electromagnetic radiation from the sun, which, within the wavelength range that enables human vision at the same time contains, small energy packages called photons (quanta) that e.g., produce warmth for flora and fauna on Earth. These two concepts are called the 'wave theory' and 'photons theory' of light, respectively (Valberg 2007).

In both of these theories, the electromagnetic radiation can be measured. The electromagnetic waves can be measured by their wavelength in nanometres (nm), while photons are expressed in Joule (J) or kilowatt-hour (kWh) (as units of their energy content) (Arnkil, Fridell Anter et al. 2012).

Solar radiation within the wavelength range of 380 nm (violet light) and 760 nm (red light) is called light and is a stimulus of visual perception. Meanwhile, electromagnetic radiation bellow 380 nm is called ultraviolet light (radiation) (UV), while that above 760 nm is called infrared light (radiation) (IR) (Valberg 2007) (Fig. 7).

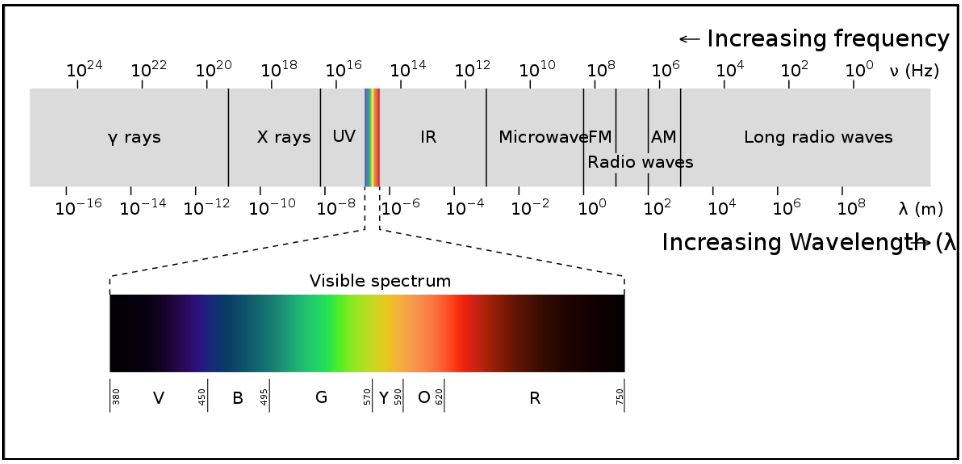

Figure 7 The electromagnetic spectrum with the visual light range [7]

Throughout history, there have been theories distinguishing light as a visual manifestation of radiant energy, which is then intimately related to the sensation of vision, and as a bond of radiant energy, i.e., something that can be measured beyond the scope of the human eye (Hopkinson, Petherbridge et al. 1966).

Light is considered a phenomenon that gives visibility to physical objects and spaces. It has been argued as based on the visual experience of one human being, and, as such, it is psychological—not absolute—and cannot be measured. The human eye can evaluate how bright or dark something is, but this 'measurements' is thus based on the spatial context of that object, which can be complex (Arnkil, Fridell Anter et al. 2012). The absolute correlation between the intensity of light as radiation and light in the perceptual sense has been challenging to establish. The main reason for this, according to Arnkil, Fridell Anter et al. (2012), is the sensitivity of the receptors (i.e., the rods and cones) in the eye. Rods are more sensitive to dim light conditions, while three types of cone receptors—S, M, and L, have slightly different peak sensitivity for light brighter than $3cd/m^2$ according to de Kort (2019) (Fig. 8a).

This distinction between the human (psychological) and purely physical aspect of light has been attempted using a psychophysical approach. Psychophysics theories concern the relationship between that which is physically measurable and that which is experienced by humans, with the fundamentals of *the sensory threshold* and *just noticeable difference (*Arnkil, Fridell Anter et al. (2012). A theoretical model for the human visual sensitivity to different wavelengths (referring to the energy of each light's wavelength) using a correlation curve called the V-lambda V(λ) curve has been established (Fig. 8b). This curve has been accepted by the CIE for use for both daylight and artificial light sources, and it forms the foundation of *photometry*. Photometry is a psychophysical approach in which the definitions of light are based on the electromagnetic radiation weighed against a theoretical model on the sensitivity (V(λ)) of the human visual system to radiation within the so-called visible spectrum.

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The photometric concept uses several units for measuring light, such as intensity and illuminance. This resulted in the development of corresponding measuring instruments, such as the spectrophotometer and lux meter, which measure radiation and weigh it against the V(λ) curve. Specifically, the photometric units of light are:

- *Luminous flux* (Φ) (measured in *lumens*) is a metric derived from radiant flux and refers to the light emitted from a light source by evaluating the radiation according to its action upon the CIE Photometric Standard Observer (definition by European Standard for Light and Lighting EN12665:2011 - 3.2.1).
- *Luminous intensity* (I) (measured in *cd = candela*), used for the light emitted from the light source in a given direction, is a quotient of the luminous flux leaving the source and propagated in the given direction, and having a defined element of solid angle (definition by European Standard for Light and Lighting EN12665:2011 - 3.2.2).
- *Illuminance* (E) (measured in lux as lum/m^2) at a point of a surface is a measurement of the photometric flux on a surface per unit area or the visible flux density (definition by European Standard for Light and Lighting EN12665:2011 - 3.2.10).
- *Luminance* (L) (measured in cd/m^2) describes the amount of light that is emitted from the light source or is reflected from a particular area, falling within a given solid angle (definition by European Standard for Light and Lighting EN12665:2011 - 3.2.3).

The V-lambda (Vλ) curve applies when the luminance levels are above 10 cd/m2—when the sensitivity of the cones are the highest. This is thus called photopic vision (in colour), with the (Vλ) curve peaking at 555 nm. When the luminance levels are below 0.0003 cd/m2, the rods in the eye are more sensitive and the V'-lambda (V'λ) applies. This is called the scotopic vision (black white) curve, and it peaks at 505 nm (Fig. 8b).

One of the concepts used in defining the lighting quality is glare. Human visual comfort under lit conditions can be hindered if the sensation of glare occurs. Glare occurs when an unsuitable distribution or range of luminance affects the human vision to produce discomfort or a reduction in the ability to see. Glare can occur by extreme contrasts in the luminance of the visual field. There are three types of glare conditions specifically: discomfort and disability glare are caused by the light source itself, while veiling describes the glare condition caused by luminance reflected from objects.

Two decades ago, non-visual sensitivity to light was discovered. A new group of receptors was found, the ipRCG receptors, which are located outside of the eye in the retino-hypothalamic tract. This finding happened after a hormonal secretion, dependent on the light spectrum in a specific range, was quantified in mice (Lucas, Freedman et al. 1999, Lucas, Douglas et al. 2001). The discovery of photopigments that regulate the secretion of melatonin and cortisone—directly responsible for the human circadian rhythm (wake-sleep cycle)—was conducted in a laboratory experiment studying individuals exposed to monochromatic light below 460 nm (Brainard, Hanifin et al. 2001, Thapan, Arendt et al. 2001). These studies were conducted within the field of chronobiology, which examines periodic (cyclic) phenomena in living organisms and their adaptation to solar- and lunar-related rhythms.

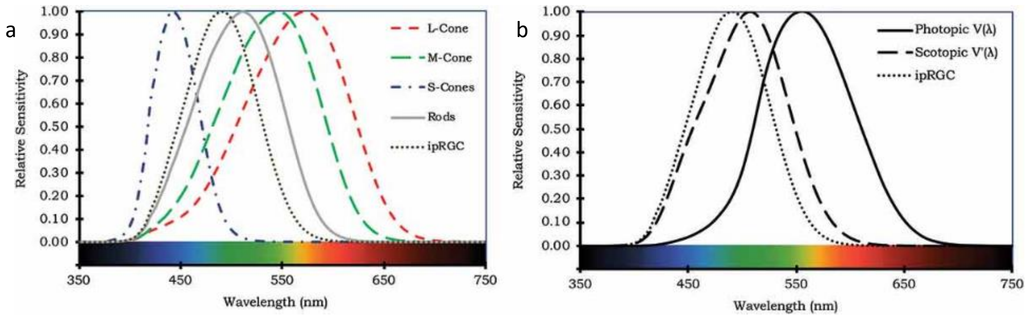

Figure 8 Relative sensitivity curves: (a) individual photoreceptors and (b) photopic sensitivity curve V(λ), scotopic sensitivity curve V'(λ), and, for comparison purposes, the ipRGC is also included, adopted from de Kort (2019)[8]

In recent years, research regarding the human circadian system (cyclic phenomena such as daylight and darkness) has been conducted inside neuropsycho-biology. A new sensory pathway for non-visual light has been established, with the threshold for this light within a certain wavelength range having been proposed. This 'melanopic light curve' is a new approach based on the electromagnetic radiation weighed against the retinal sensitivity (melatonin suppression model) or models concerning human non-visual sensitivity to light in the same manner as the V(λ) curve (Lucas, Peirson et al. 2014) (Fig. 8b). Melanopic light is assumed to possess a considerable stimulus for regulating not only circadian but also hormonal systems as well as behavioural systems.

2.2. Daylight

In this thesis, the theoretical background on daylight is further explained from the architectural point of view. There are several concepts used to describe daylight's effect on buildings. Starting from the sun's position regarding one object or location:

- The sun's altitude (αs) (solar elevation angle) is defined as the vertical angle between the line passing through the centre of the solar disc and the horizontal plane measured from the reference/observation point, as defined in the European Standard for Daylighting in Buildings EN17037:2018 (CEN 2018).
- The sun's azimuth (γs) (angle of the Sun's position) is defined as the horizontal angle between the vertical plane passing through the geographical north and the vertical plane passing through the centre of the solar disc and is measured clockwise from due north from 0° to 360°, as defined in the European Standard for Daylighting in Buildings EN17037:2018 (CEN 2018).

The experimental studies in this thesis were based in one location: Oslo; thus, the latitude of this location, 59°5'N, defined the solar altitude and azimuth used in the study. The

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characteristic solar altitude during the summer and winter solstice as well as the spring and autumn equinox was defined using solar chart tools available online. The same was applied for the solar azimuth regarding the time of day. The accurate solar altitude and azimuth were the basis for all parts of the current study. While the weather conditions of the study location have been said to be predominantly overcast, the solar altitude and azimuth were of great importance for the period when the weather conditions are clear and sunny; this is said to be for almost 40% of the year in Oslo.

In current architectural practice, the daylighting conditions indoors are estimated for daylight provision using mostly two approaches—daylight factor and daylight autonomy—as described in EN 17037 Daylighting in Buildings (CEN 2018). The most commonly used is the concept of daylight factor (DF), where the amount of daylight is measured for the worst sky luminance condition: an overcast sky.

- *Daylight factor* (DF) is the ratio of the illuminance at a point on a given plane in a room to the illuminance on a horizontal plane outdoors and due to an unobstructed hemisphere of this sky. The contribution of direct sunlight is excluded from both direct and indirect illuminances of a sky (as defined in European Standard for Light and Lighting, EN 12665:2011).

DF can be expressed using a split flux formula as a summation of the *direct sky component* and *externally and internally* reflected components (Hopkinson, Petherbridge et al. 1966) (Fig. 9). The sky component (SC) refers to the direct light on a point in the room from the region of the sky that is visible from that point. The externally reflected component (ERC) refers to the daylight reflected from external surfaces (e.g., shielding buildings), while the internally reflected component (IRC) refers to the light reflected from the indoor surfaces in the room.

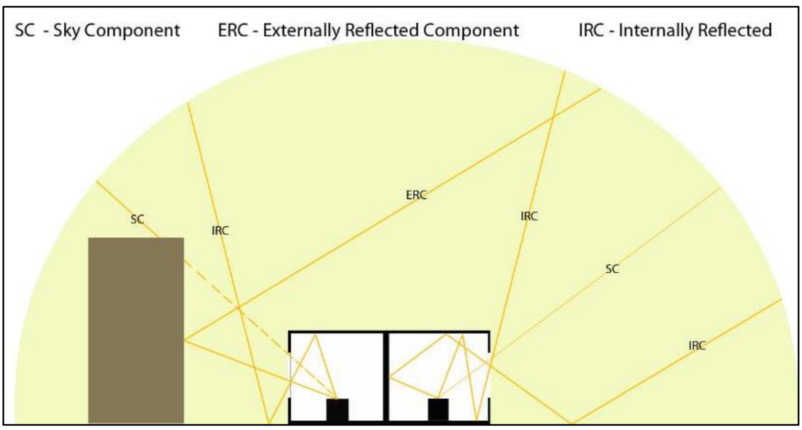

Figure 9 Daylight factor (DF) calculations, components of the split flux formula for the direct sky component (SC) and externally (ERC) and internally reflected component (IRC).

Depending on the building design and site context, if there are no objects present around the building, the ERC is not present, but, if there is a high obstruction in front of the windows, the SC might equal zero, and the ERC would, in that case, have much greater importance (Fig. 10) (Baker and Steemers 2002).

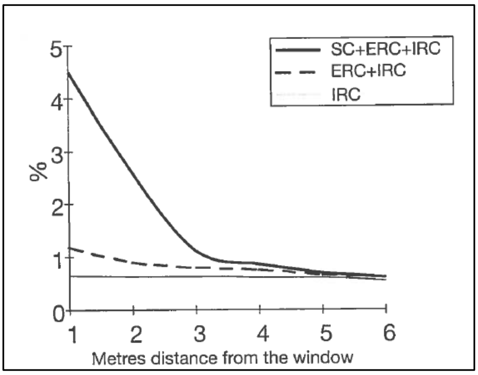

Figure 10 Relative contributions of daylight components (SC), externally reflected component (ERC) and internally reflected component (IRC) for a typical room with an external obstruction; adopted from Baker and Steemers (2002)[9].

The importance of the IRC for the total DF is argued to be high, as there is the highest possibility for control. The IRC depends on the reflectance of the interior objects (e.g., walls, floor, ceiling, furniture). Every surface has a reflection factor, which is the ratio of the reflected light to the incident light and depends on the colour and finish of the surface. Thus, the more reflective the ceiling, walls, or floors, the higher IRC. Fig. 11 illustrates how illuminance values for different areas in a room (distance from the window) depend on surface reflectance.

However, before the SC, ERC, or IRC approaches the measurement point in the room, they are all affected by the transmission properties of the window's glazing. The transmission factor is the ratio of the transmitted light through one transparent surface to the incident light. The percent of the light that is neither reflected nor transmitted is absorbed and transformed into heat.

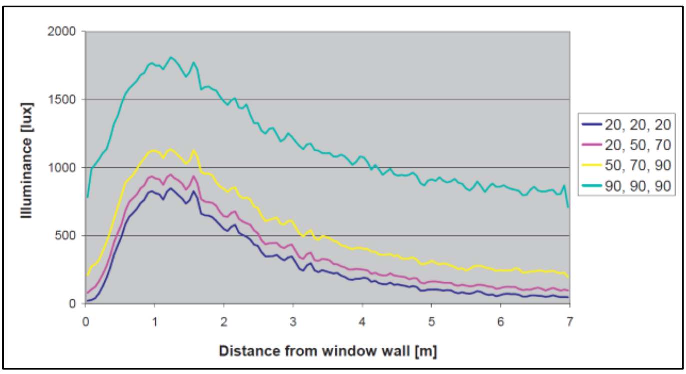

Figure 11 Average illuminance on the floor for different interior reflectance values (floor, walls, and ceiling) as a function of the distance from the window wall. Double glazing is present in the window openings, adopted from Kolås (2013)[10].

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[10] Used by permission. Permission to use the image granted by Tore Kolas on the 14th of February 2022.

The concept of the vertical daylight factor (VDF) for a façade is used during the initial phases of a project—where the layouts are not yet defined.

- *The vertical daylight factor* (VDF) is defined as the ratio of the total amount of daylight illuminance falling on a vertical surface of a building to the horizontal illuminance from a complete hemisphere of the sky (excluding direct sunlight). It takes into account the light coming directly from the sky as well as the reflected daylight from surrounding buildings and ground both above and below the horizon (Li, Cheung et al. 2009, Li, Cheung et al. 2009).

When considering the daylight metrics, any building is situated in some setting in a more or less urban area, where neighbouring objects represent the obstruction of the daylight availability. The building's protruding elements can also provide obstruction for particular rooms. The concepts of the horizon obstruction angle (αh) and zenith obstruction angle (αz) have been discussed by some authors (Arnesen, Kolås et al. 2011).

- The horizon obstruction angle (αh) is defined as the angular altitude of the top of the obstruction above the horizon measured from the window reference point in a section perpendicular to the façade.

- The zenith obstruction angle (αz) is defined as the angle of the obstruction subtended to the zenith from the window reference point in the vertical section perpendicular to the façade.

To estimate the daylight conditions in buildings, sky models (featuring pre-set luminance distribution values) are commonly used. There are 15 sky models that describe the sky luminance, ranging from homogeneously overcast, then, partly clear or sunny with a wide corona to a totally clear and sunny sky (Kittler, Darula et al. 1998). The most used models are *CIE standard overcast sky, uniform sky, and clear sky*. The sky model depends on the climate and latitude. The illumination under an overcast sky with a steep gradation and azimuthal uniformity varies depending on the sun's altitude (from 5,000 lux for low solar angle), while the illumination of the direct sun rays (for unobstructed sun) reaches its maximum when sun is in zenith, with over 100,000 lux (Hopkinson, Petherbridge et al. 1966). These are the standard theoretical values; in reality, higher values have been measured (Love and Navvab 1991).

Direct solar radiation or visible light as a ray is assumed to propagate in a perfectly parallel direction. The solar radiation is originally radial, but, because of the extreme distance between the sun and Earth, the sunlight rays reaching Earth's surface are adopted in parallel. Since the solar position varies during the day, the incident angle of sun rays on one specific area on the Earth varies. The intensity of the daylight thus depends on the incident angle and is described by Lambert's cosine law (Fig. 12).

- *Lambert's cosine law* describes the light intensity from an ideal diffusely source, observed on one surface as directly proportional to the cosine of the angle θ between the direction of the incident light and the surface normal $I_Q = I*\cos(\theta)$. Lambert's cosine law can be also used to calculate the illuminance (E) under the cosine angle from the normal.

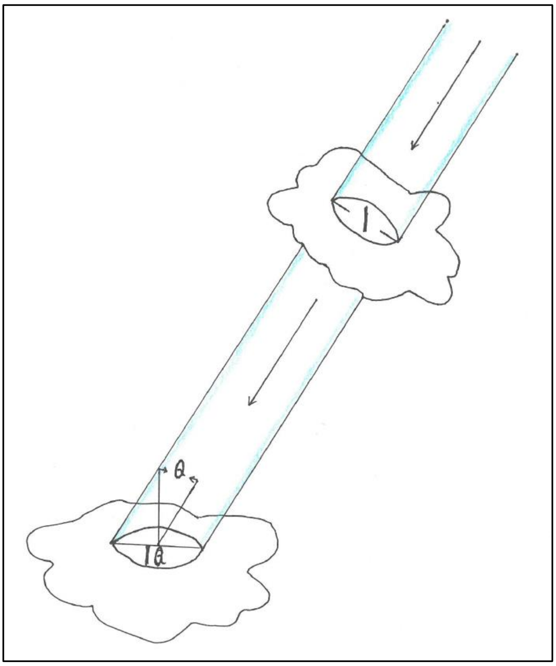


Figure 12 Illustration of Lambert's cosine law concept, $I_Q = I*\cos(\theta)$, for the Q angle between incident light and the surface normal

The concept of daylight factor has been criticized, because its prediction is statical and based on the lowest daylight condition—an overcast sky—while, nowadays, concepts regarding total building energy consumption require the dynamic forecasting of daylight conditions to reflect daylight in reality. Thus, climate-based daylight calculations (CBDC), which predict several various radiant or luminous values (e.g., irradiance, illuminance), are more desirable. CBDC uses sun and sky conditions derived from standardized annual meteorological datasets. According to Mardaljevic and Janes (2012), CBDC predicts absolute values (e.g., illuminance) based on geographically specific climate data followed by the fenestration orientation (i.e., accounting for the solar position and variable sky condition) in addition to the space's geometry and material properties.

Other useful metrics easily simulated with CBDC are daylight autonomy (DA) and sunlight exposure (SE). Particularly, DA is nowadays argued to be more appropriate than the DF for the evaluation of daylight provision.

- *Daylight autonomy* (DA) is defined as the percentage of 'occupied' times of the year when the minimum illuminance requirement at the sensor is met by daylight alone. This metric is quantified by combining both direct and diffuse radiation (Strømann-Andersen 2012).

- *Sunlight exposure* (SE) is the sum of the time (hours) (e.g., in a given day) within a given period during which the sun is above the actual horizon with a cloudless sky, which may be limited by permanent obstructions like mountains, buildings, etc. (European Standard of daylighting in Buildings EN 17037).

The other CBDC metrics found useful in predicting excessive sunlight are daylight glare metrics, such as the most used daylight glare index (DGI), but also, CIE glare index (CGI), unified glare rating (UGR), and daylight glare probability (DGP).

- *The daylight glare index* (DGI) is the evaluation of daylight glare from sources with non-uniform levels of luminance, such as windows, causing discomfort (Bellia, Cesarano et al. 2008). The DGI is often used as a threshold value for the operation of fenestration within in a building design with simulation tools.

It is assumed that the daylight through windows will more likely produce glare situations for the users of a space, since such daylight sources are often positioned on vertical walls (are in the visual field), while artificial lighting is usually mounted overhead. Some studies reported that illuminance incident value of windows that causes the sensation of glare discomfort is between Ev = 1250–1700 lux (Karlsen 2016).

In this research, the excessive glare from direct sunlight through the window was an important parameter. There are two perspectives on the issue of daylight glare that are essential to understand. The glare hinders people from seeing properly or brings about feelings of discomfort. The persistent glare that users cannot avoid brings about intolerable situations, forcing them to avoid the source of glare at all times. In this regard, these users would perceive the design of the space as inappropriate and dissatisfying for functional use. The other perspective of glare (excessive sunlight) is in the indoor climate. Glare is the result of direct solar radiation, which consists of solar heat as well, and when it occurs, the sun-shading devices will be closed to balance the indoor climate. Simulations, predictions of the indoor climate profile, and energy consumption during the year are dependent on glare, and, as long as glare is unpredictable, such simulations are not reliable. Both issues represent topics of this research. The indoor climate questions will be addressed more specifically in the chapter regarding the role of daylighting in passive building design.

2.3. Artificial light and lighting energy use

Artificial light refers to the lighting provided by an artificial light source. Since artificial lighting is a human artefact, it can be designed to completely answer the human visual need. A light source is always used in the luminaire, and usually a certain number of luminaires is used to achieve the recommended lighting across the space. Lighting recommendations are defined using photometric units and qualitative concepts per the standards described by the International Commission on Illumination (CIE) or, within Europe, the European Committee for Standardization (CEN). The horizontal, vertical, or cylindrical illuminance levels, as well as the uniformity levels, or glare limitations, are used in designing codes for artificial lighting. Each luminaire is thus designed for a certain position in the room in order to provide uniformity in the illuminance level in the entire rom. Lighting recommendations also refer to the possibility to control the light to use it reasonably and only when is needed; thus, lighting is controlled by a control system. The artificial light source is just a small component of a complex structure called artificial lighting, and, accordingly, the artificial lighting is also referred to as a 'lighting system' or 'lighting solution'.

Nowadays, the concept of the light source is in a transition period, with the old technology about to be completely replaced by new technology that is more energy-efficient. All light sources are characterized by their intensity, colour temperature, and spectral power distribution. Based on the chemical process that generates light inside the light source (i.e., bulb), all light sources are divided into three types: incandescent, discharge, and solid-state semiconductors (LEDs). Incandescent lamps produce light by heating a wolfram's filament until it glows, while discharge lamps produce light by ionizing a gas through electric discharge inside the light source. Meanwhile, LED light sources convert electrical energy directly into light via a phenomenon called electroluminescence.

LEDs are the most used light source on the market today. Beside their long lifetime (up to 100,000 hours) and a light efficiency up to 150 lm/W, nowadays, their miniaturity (small size) have made them attractive for use. It is easier to handle a small light source in luminaire design, but it can also be demanding to attenuate the light intensity from small point-like sources in some cases. The role of the luminaire is to provide electrical, mechanical, and thermal protection for the light source and to ensure the intended light distribution emitted from the source via reflectors, diffusors, or lenses.

The aforementioned photometric units apply to the artificial light source, but as artificial light has shown a certain deviation from natural light, new metrical units have been introduced.

- *The correlated colour temperature of the light* (CCT) provides information on the appearance of the colour of the light emitted by the light source by comparing it to the temperature of the black body that is heated. The temperature range of 2000 K to 3000 K will give the appearance of warmer, yellowish light; a 4000 K temperature indicates neutral white light; while higher temperatures (5000 K to 8000 K) give the appearance of cool, bluish light.
- *The colour rendering index* (CRI or Ra) is a quantitative measure of the capability of one artificial light source to reveal the colours of one object accurately in comparison with wide-spectrum daylight. The daylight colour rendering for a set of different dye samples is taken as a reference (100), while light sources, dependent on theirs spectral characteristics, are typically judged to have a CRI between 60 and 90.

Both the CCT and CRI measures were derived from a colour matching approach called colorimetry and used to quantify the appearance of the colour of the generated or reflected light based on the principle of the combination of the three main colours of light: red, green, and blue light (Valberg 2007). In Fig. 13, the spectral power intensity diagrams for daylight and LEDs of cold and warm colour are compared. The electromagnetic radiation visible to the human eye (wavelength between 380 nm and 780 nm), is, as mentioned in section 2.1., translated by the cones in the human eye to the sensation of colours. The spectral power distribution for each of the wavelengths is crucial for the CCT and CRI values of one light source. Deviation in the spectral power distribution of one artificial light source will affect its CRI when compared with daylighting.

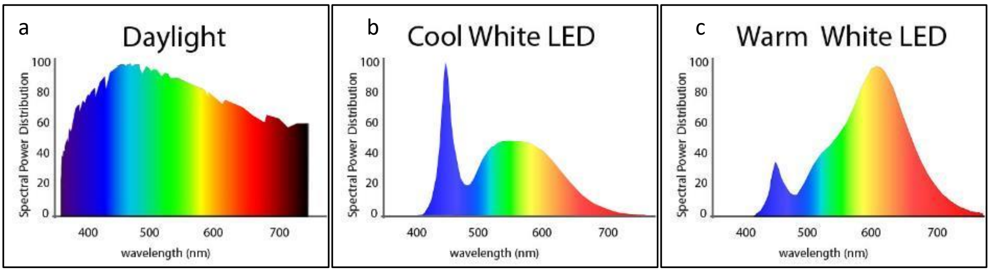


Figure 13 Spectral power intensity diagram for visible light recorded by Jeti specbos 2111 spectroradiometer a) daylight; b) LED of cold light; and c) LED of warm light

The light source is usually smaller than the task area in artificial lighting solutions. Thus, if the light source has an isotropic luminance, the illuminance on a task area is affected by Lambert's cosine law, as described in section 2.2. An important parameter for an artificial lighting solution is the distance between the light source and task surface. This relation is described by the inverse square law. As the task area moves away from the light source, the surface appears less lit. The inverse square law describes this effect using the approach of the widening (enlarging) of the light beam cone and thus the weakening of the light intensity with distance (Fig. 14).

- The inverse square law is noted as $Ev = Iv/d^2$, where Ev is the illuminance value on the surface, at distance (d) away from the light source, defined by the intensity value of Iv. This approach is only valid for a point-formed light sources, and with a minimum distance to the task of five times their size (Taylor 2000).

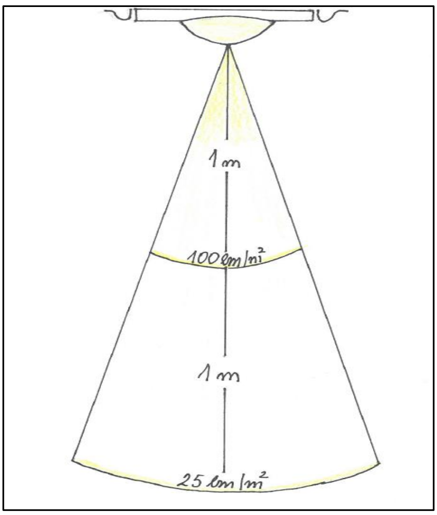


Figure 14 Illustration of the Inverse square law concept.

The recommendation for lighting uses photometry metrics to describe minimal quantitative and qualitative values for solutions. In Norway, the lighting standard NS/EN 12464-1 (2011), which is used for recommendations, states, for example, that the illuminance values of the horizontal working plane (along the desk height) in offices should be a minimum of 500 lux with a uniformity ratio of 0.6. The same standard prescribes the threshold values for the maximum glare from the luminaires and the minimum value for the CCT and CRI. These recommendations for lighting solutions also refer to energy-efficiency using several concepts.

- The light source efficacy is defined as 'the ratio of the total luminous flux emitted and the total power input' and is expressed in lumens per watt, lm/W.
- The system efficacy represents the power input given to the ballast or driver of the light source in addition to the light source's power input. For comparative purposes, the halogen source had an efficacy of 20 lm/W and a fluorescent light source 80–100 lm/W, while, nowadays, LEDs, have 100-150 lm/W.
- Luminaire efficacy is expressed via the light output ratio (LOR) as the ratio of the total luminous flux emitted out of the luminaire and total luminous flux emitted out of the light source, and it simply represents the efficiency of the luminaire (in percentage) to distribute the whole luminous flux from the light source. It can be divided into upward and downward light output ratios.

The energy consumption of lighting indicated a good opportunity for reduction when LED light sources came to the consumer market, as the light efficacy of the LED was foreseen to be up to the 200 lm/W in the future. However, the fact that LEDs were advertised as some exceptional discovery provoked a rebound effect (Herring 2006). The advertisements known as 'do not use any energy' and 'do not release any heat' have affected the increased use of lighting points in lighting solutions.

Moreover, as the LED light source was of a cooler light colour than the usual incandescent or halogen source, in its first years on the market, spaces lit by LEDs appeared colder and lacked ambiental characteristics. This provoked architects and interior designers to design interiors with warmer, darker colours, giving by this drastically poor basis for light distribution in the space. A darker interior has lower light reflections, bringing about the need for a higher light flux or more light sources. In all, the consumption of energy for artificial lighting was positively affected by the increasing efficiency of LEDs, but several other factors could overshadow the benefit.

The quantification of the yearly energy use for a lighting solution in one building is performed using a Lighting Energy Numerical Indicator (LENI) described by the European standard EN 15193:2007 Energy Performance of Buildings– Energy Requirements for Lighting. This LENI value is used in the calculation of the total energy need for a building or assessed against a maximum threshold value described in the standards.

The LENI value can be derived using two methods—either comprehensive or quick—both of which calculate the actual energy used in kilowatt-hours per square meter per year (kWh/m^2/year). The comprehensively detailed method uses parameters such as the usage of the examined room, zone, or building; the total installed lighting power; the annual operating hours during daytime and night-time; the type of control of the luminaries (automatic or manual); occupancy; and daylight availability. The quick method has been noted for overestimation problems, since it does not account for some of these parameters (e.g., the daylight availability and exploitation possibilities during the year).

An important fact in LENI calculation, which is also considered in the current thesis, is the operational hours of artificial lighting based on the availability of the usable daylighting. There are two parameters that describe the operational hours: the daylight operating hours (td), where daylight is present, and non-daylight operating hours (tn), where daylight is not present. The European Standard for Energy Performance of Buildings (EN 15193) does not offer an exact specification of the period of the day considered to 'daylight time' vs. 'non-daylight time'. According to Calistru, Pont et al. (2013), EN 15193 considers times with an average outside illuminance of 1000 lux or higher as daytime, and times under this value as non-daylight time. Some other studies have considered a solar altitude over 4° as a threshold for daylight time operational hour estimation (Yun, Kim et al. 2012). In the current study, a solar altitude over 5° was considered the threshold for daylight time.

2.4. Daylight position in the theory of the human visual system, perceptual system, and circadian system

An increased need for artificial lighting in buildings emerged after the industrial revolution, when most of the human activities moved from agricultural production toward manufacturing. Longer working days and production tracks brought about the necessity for human labour during the nights as well. This was also enabled by newly developed electric light sources. It was clear that electrical light sources can be a reliable source of light, and unavoidably, society began to arrange its activities around this possibility. So, nowadays, we face a modern era of humans spending 90% of their time inside, with almost all human activities based on the visual conditions enabled by artificial lighting.

Working consistently under electric lighting is believed to be harmful to one's health in the long term, while working in daylight, on the other hand, is believed to result in less stress and discomfort for the worker (Galasiu and Veitch 2006, Veitch and Galasiu 2012). Daylight is important for its quality, spectral composition, and variability. As some authors have argued, daylight is always desired in interior spaces, because it fulfils some basic human needs, such as seeing one's task and surrounding space, thus enabling visual performance, and also experiencing environmental stimulation, enabling visual perception (Lam 1986, Boubekri, Hull et al. 1991, Boyce 1998)

Human visual performance refers to a sensation of vision in human being and it is related to the amount of light that falls on the eyes. As explained in section 2.1, photopic and scotopic vision in human eye occur under the certain levels of luminance. According to Valberg (2007) there is also the mesopic vision which occurs in the luminance range from 0.001 to 3 cd/m2, and in which both the rods and cons are active.

Visual perception refers to an individual's perceptual impressions of a lit space, and it is thus dependent on the richness of the lit space regarding stimuli, as well as on the individual's visual experience. It has been argued that visual perception is better in environments lit by natural light (Hellinga 2013, Moscoso and Matusiak 2018, Knoop, Stefani et al. 2020). In this thesis, a partial aim was to examine how daylight delivered via an HLP would affect users' perceptual impression of a space.

Architects have always argued that daylight should be present in buildings due to its benefits in human health and wellbeing. Sun-path-defined daytime and seasonal changes are instilled in the human circadian rhythms of everyday activity and relaxation, creativity, and performance. However, since research on daylighting conducted by architects has not been documented using common scientific forms, it lacks the research tradition.

Not before some studies brought attention to daylighting, arguing on its effect on stimulation for the hormones melatonin and cortisone, the effect of daylighting on human health and wellbeing could not be scientifically proven. The consequences of the improper secretion of such hormones has been argued to result in distortion of the sleep-wake cycle, lethargy, and drowsiness; variation in body temperature; and, after a longer period of time, chronic fatigue and depression—influencing one's mood and sense of wellbeing; improper insulin production; the regulation of the kidneys and sex organs; and cancer (Baker and Steemers 2002, Veitch and Galasiu 2012).

The circadian approach to daylight could not be developed earlier because of the lack of technology to detect the phenomenon with reliability, such as certain instruments or chemical reactors. The lack of public attention, which is always a defining factor of science, and the lack of a research paradigm, i.e., a proper methodology, are historically argued to be the reasons for the slow development in one field. For comparison purposes, the energy crisis in the '80s brought increased attention and steady funding to studies of daylighting, with aims based on its energy-saving aspect.

Even after centuries of traditional architecture relying on daylighting, and, with new findings on daylighting's effects on the human circadian system, daylighting still has not attracted significant attention among investors in the building industry. Nowadays, a new approach to workers' health and wellbeing have been used to argue for better daylighting indoors through the use of certification systems such as BREEAM, LEED, and the WELL Building Standard. These certification systems are voluntary, but building owners are forced to use them to follow the trends in the property market. As a result, the labels (like BREEAM certified) were intended to ensure increased renting and market value for their buildings. History of science has witnessed the successfulness and implementation of one result via its applicability. It is expected that engaging the usefulness of a specific result will also increase public focus on it.

The other approach that indirectly argues for maximizing daylighting involves using the suggestions for so-called integrative lighting (human centric lighting [HCL]). The WELL Building Standard suggests recommendations for a melanopic lux (EML) of 150 to 250 EML, intended to bring about the equivalent reaction and proper functioning of the part of the circadian system dependent on daylight (Yuda, Ogasawara et al. 2017, Perez, Strother et al. 2018, Strik, Strik et al. 2018, Chinazzo, Chamilothori et al. 2020). It was argued that this level of melanopic lux is difficult to achieve, but the level of recommended lighting can be lower if the space has good daylighting.

This integrative daylighting and lighting approach is relatively young, lacking not only practical instruments and standards, but also its entirety. Its theoretical roots are diverse and rather different disciplines, such as physics, medicine, and biology. The combination with artificial lighting is perhaps an attempt to more quickly apply findings regarding the non-visual effects of natural light by using compound research and further implement it in the already-existing standards for artificial lighting. It will be necessary to develop a melanopic lux meter to aid the faster development of this discipline, but this will take years and new technologic progress, as were needed developing photometrical instruments in common use today (Kittler, Kocifaj et al. 2011).

2.5. Daylight position in passive building design theory

The aforementioned interest in daylighting as an energy-saving source began with the energy crises in the 1970s. With global attention directed at energy efficacy and carbon emission policy in the 1990s, the building policies began with the widespread idea that the potential to save energy rests, among others, in maximized daylighting (Mardaljevic and Janes 2012). The theories of passive building design that are the basis for the ZEB and ZEN concepts rely on this same idea.

Traditionally, daylight, as the originally only source of lighting, had been used to solve human visual needs in buildings. Consequently, the corresponding architectural building design responded to the nature of natural light (e.g., maximum intensity, incidence angle, and predominant solar path). The high ceilings and maximized window heights in both public and private buildings, or skylight and shed roofs in manufactural buildings, were solutions intended to obtain as much available daylight as possible. Daylight openings were designed in such a way that they allowed for direct usage of a diffuse skylight through the windows, while direct sunlight was supposed to be transformed into useful illumination by reflecting it on terraces, window sills, or walls (Fig 15). With time, due to socio-technical development and the availability of new artificial lighting sources that could provide total illumination, architectural building design has seen a weaker role of daylighting as the main criteria for the human visual need. Thus, a shift in building design, seen via decreasing window size, for example, produced less daylighting inside, and, consequently, the usage of artificial lighting increasing, which, in turn, increased energy consumption.

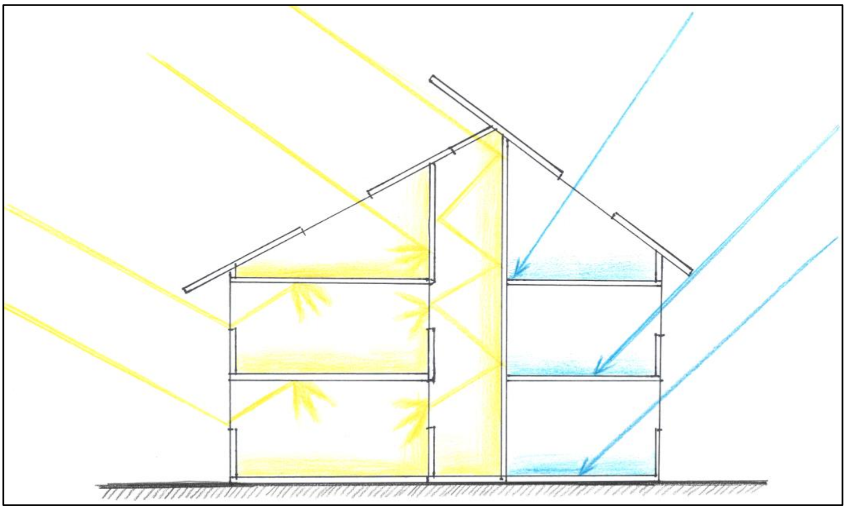


Figure 15 Illustration of daylighting design for passive building design, with yellow lines presenting sunlight rays, and blue lines presenting light rays from the sky.

Nowadays, the aim is to reverse this trend and reduce such energy use. Artificial lighting is much more convenient to control nowadays. For instance, artificial lighting can supply only the necessary recommended illumination for a visual task, which cannot be provided with daylighting. This can be a simple task if the buildings erected in the last three to four decades were not designed to not really support the maximized exploitation of available daylighting. For instance, the floor heights are usually small, as suspended ceilings are used to hide technical equipment (e.g., HVAC). This also decreased the window height significantly, especially toward the top of the window. The daylighting perimeter zone has thus been drastically decreased and can never be compared with traditional design buildings. In addition, as global economic growth has forced centralization, the most intensive development of commercial buildings has occurred in city centres, where an increased density is worsening the exterior daylighting conditions (Yeang and Powell 2007).

The context of daylight availability in urban areas is often lacking or diminished. A group of buildings in dense areas will influence outdoor daylight availability—or the *Urban Solar Microclimate* (USM)—around each other (Mardaljevic and Janes 2012). This will consequently influence the indoor daylight level. The USM depends on urban design, urban grid, and patterns in the urban texture, as argued by Strømann-Andersen and Sattrup (2011). According to DeKay (2010), it is the government's job to include regulations on the height to width ratio (H/W) and height to distance ratio (H/D)—also called *solar envelops* in urban design—and thus ensure the access of daylighting and sunlight for all buildings.

The density of an urban site is a critical parameter in regard to solar radiation, especially for passive or low-energy buildings. For example, in northern cities, the orientation of buildings is assumed to have a minor effect on the daylight availability due to the overcast sky uniformity for any solar azimuth. Nevertheless, an overcast sky is always brighter with an increasing solar altitude; thus, the height of obstruction in front of the building will have a great impact.

The concept of the previously discussed vertical daylight factor (VDF) is a useful indicator of the daylight availability in a dense urban area. According to some studies, the VDF was significantly reduced for obstructions higher than a H/D of 1.0 (height/distance ratio equal to an obstruction elevation angle of 45°) (Li, Cheung et al. 2009, Li, Cheung et al. 2009). According to Sattrup and Strømann-Andersen (2011), a similar obstruction ratio of H/D 1.0 showed a 85% increase in lighting energy demand (LENI) in offices compared to no obstructions at all. It is indicated that urban planning has the initial role of forming a strategy for good daylighting conditions intended to contribute to passive building design. It is clear that architectural design, later on during the design process, can just work out the daylighting conditions originally set by the urban grid and pattern.

Daylight distribution in interior depends on the reflection factor of the surfaces (floor, ceiling, walls). Darker walls inside will be a negative factor affecting good daylight distribution across the room. The same principles hold true for façade materials (urban fabrics) exterior (Strømann-Andersen 2012). Dark facades (or curtain walls) result in the poor distribution of daylighting among neighbouring buildings. In addition, glass facades present challenges in balancing the amount of necessary solar energy. This usually forces the closure of the sun-shading device of the building, which results in the increased use of artificial lighting. This increased use of artificial lighting will then increase the indoor temperature, leading to its increased operation for cooling and, thus, additional energy consumption.

Passive building design is nowadays introduced in many European countries through their national building regulations. In Norway, where this study was conducted, standards like Passive House standards (Criteria for passive houses and low energy Residential building (NS 3700:2013) and Criteria for passive houses and low energy Non-residential buildings (NS 3701:2012) are in the process of being implemented via a national building regulation called TEK17 (yielding). New building codes provide energy consumption constraints for new and refurbished developments. As a consequence, windows are designed with a minimum size and lower daylight transmission properties to preserve the thermal balance. In addition, the exterior walls have an increased thickness (the insulation layer is increased by 30%), reducing the window's open angle for daylight incidence (Houck 2015, Ulimoen, Karlsen et al. 2020).

The new European standard EN-17037 Daylight in Buildings introduces new metrics of good daylighting in the indoor space that will help designers take the right steps toward passive energy building design. One of these is the *spatial daylighting autonomy* (sDA)—calculated for an entire year—for the daylight hours (from sunrise to sunset) for a certain location. sDA has a requirement of 50% of daylight hours during the year, with a target illuminance of a minimum of 300 lux for 50% of the area and 100 lux for 95% of the area.

sDA can be calculated using climate-based daylighting simulation tools, and it is a good marker of the fulfilled daylighting threshold, especially for the occupancy period of a space (a typical office space is occupied between 7am and 5pm) (Mardaljevic 2013). The peak load for energy consumption in commercial buildings begins sharply at 7am and does not decrease before 5pm, while for example, the peak solar energy generation via photovoltaic (PV) cells follows the sun's altitude and occurs at the noon. Hence, in the mornings and afternoons, the demand for electricity for lighting is higher than the generation (Lindberg, Bakker et al. 2019). It is thus obvious that reliable daylight autonomy for buildings spaces, especially during the mornings and afternoons, could have an impact on energy use management when it comes to the peak load. According to Baloch, Shaikh et al. (2018), 20% of the world's energy consumption is used for lighting within buildings in general, while commercial buildings spend 40% of their energy consumption just on lighting (Kolås 2011).

In energy optimization theory, it is a basic idea that 'passive' design should be optimized first, meaning the minimization of heating and cooling loads and maximization of daylight. This is intended to reduce the energy demand, which is supplied by renewable energy to operate necessary active systems (Strømann-Andersen 2012). The role of daylighting in passive building design is understood through the decreased need for artificial lighting. Good daylighting is positioned at the bottom of the 'Kyoto Pyramid', meaning that designing daylighting is one of the starting points in building design, fig. 16.

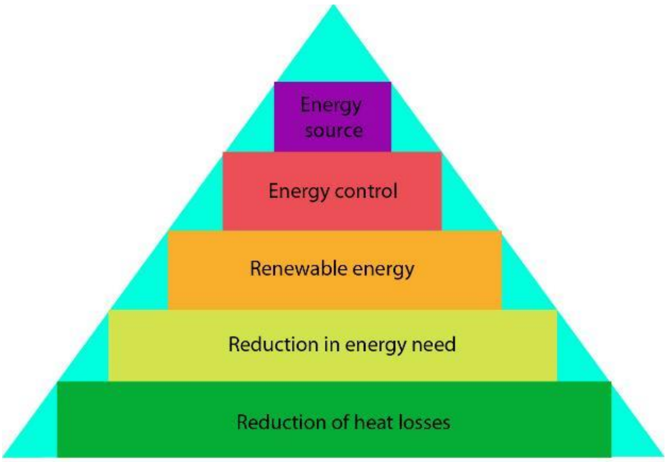


Figure 16 Illustration of good passive building design, a Kyoto Pyramid.

2.6. Sustainable building design and the need for new daylighting technology

A report by the European Commission found that approximately 40% of the total energy use in Europe goes directly to the operational use of buildings (EuropeanCommission 2010). In addition to the energy used for operation, buildings represent the energy used in the mining, processing, manufacturing, and transportation of the building materials as well as the energy consumed in the construction and decommissioning of the building. This energy, together with the energy used during the lifespan of a building, constitutes the life-cycle energy and emissions footprint (Li, Yang et al. 2013). One-third of CO2 emissions are from the building sector, indicating the energy reduction potential in improving the building stock.

In 2002, the European Union (EU) adopted the Energy Performance of Buildings Directive (EPBD). It consisted of a common aim of improving the energy efficiency of buildings, and, as Norway is a part of the European Economic Area (EEA), this aim was undertaken in Norway as well (Brekke, Isachsen et al. 2018). The EPBD required all new buildings to be of passive house standard by the year 2015; thus, two Norwegian standards were developed as mentioned in the previous chapter: NS 3700:2013 and NS 3701:2012. Parallel with the implementation of the passive house level, a nearly zero-energy building goal has been discussed as well.

A zero-energy building (net ZEB) should not be confused with a zero-emission building (ZEB). 'Zero emission buildings' refers to the balance of associated greenhouse gas equivalent emissions during the lifetime of a building. There are several levels of ZEB, including ZEB-EQ, ZEB-O, ZEB-OM, ZEB-COM, and ZEB-COME. Meanwhile, in a 'zero-energy building', the balance is defined as an annual balance between the energy imported from the energy grid and that exported to the energy grid, called the 'net ZEB'. This means that a net ZEB implies that the building produces the same amount of energy from renewable sources (e.g., PV, solar thermal collectors) as the energy needed for its operation (Sartori, Napolitano et al. 2012). The ZEB definitions also rely on annual analyses but feature the potential for shorter seasonal analyses (in the case of defining, e.g., just the winter or summer period) or a longer analysis period (usually 20 years, in the case of justifying a rentability period).

The ZEB standard does not yet exist in the same form as the Passive House standard. However, in Norway, the ZEB Research Centre, established within the NTNU, has delivered many different technical solutions for decreasing energy consumption, some of which particularly in regard to lighting energy use (Andresen 2009, Gustavsen 2009, Kolås 2011). The concepts of ZEB indicate that buildings must be connected to the energy grid and remain open to the prospect of the concept of zero (emission) energy neighbourhoods (ZENs), which is now followed by a research centre called FEM ZEN.

To succeed in delivering ZEB-projects, designers must apply energy-efficient design measures. Such measures have a significant influence on energy consumption in buildings and are intended for application during minor/major retrofits:

- working with building envelopes – thermal insulation, thermal mass, windows/glazing (including daylighting) and reflective/green roofs;
- working with internal conditions – indoor design conditions and internal heat loads (due to electric lighting and equipment/appliances);
- working with building services systems – HVAC (heating, ventilation and air conditioning), electrical services (including lighting), and vertical transportation (lifts and escalators).

It can be noted that improvements in daylighting and the careful design of artificial lighting are included in these measures. However, after one decade of active research on ZEB, it has been noted that implementation is slow and there is no consistency in design. There have been some disappointing reports of un-fulfilled ZEB concepts. Therefore, the research within FEM ZEN has nowadays focused on implementation phases. According to a report by Haase, Lolli et al. (2020), several challenges have been found, the following of which are important to the current research:

- a lack of consistent and standardized solutions suitable to new and different building standards used to achieve energy efficiency;
- disadvantages in technical solutions and lengthy processes regarding decisions;
- a lack of knowledge about the energy savings or profitability of a solution.

It is clear that the challenges affecting new technical solutions are related to inconsistency and shortcomings of current technology as well as a lack of knowledge and information on performance and rentability. This leads to the emergence of the need for more clear information about how the different energy-efficient technologies work in different climates, building functions, end-user schedules, or building contexts. Additional information for decision-makers regarding the importance of new technology on users' health and wellbeing. The author was aware of this necessity due to relevant practical experience, and this was the motivation for the initiation of this research study.

Besides these concrete conclusions, the general literature of socio-economy argues that a positive attitude toward energy and sustainability, and, in the end, the application of a new technology, need to be encouraged and maintained among the general public. The *social vision* in general public is the carrier of human behaviour, and a positive attitude of general public is needed for the acceptance and accomplishment of an *economic and environmental vision* (Li, Yang et al. 2013).

3. Knowledge gap, need for research, and research questions

The theoretical background addressed in the previous section provided the basic knowledge for this research. In the following part, the systematization of all daylight systems will be presented in order to lay the foundation for the narrow research topic and point out the knowledge gaps.

3.1. Daylighting systems: systematization and knowledge gap

As a consequence of the energy crisis in the 1970s and awareness regarding daylighting necessity, new optical materials and innovative daylighting systems were consequently developed (Johnson 1985). Daylighting systems suitable for the Scandinavian microclimate selected by Arnesen, Kolås et al. (2011) have shown improved daylighting conditions inside the room, but there are many disadvantages regarding solar gains and excessive sunlight. To facilitate good performance in the indoor climate, the function of sun-shading relies on the monitoring of solar radiation values, as noted by Galasiu and Veitch (2006). The method of using threshold values for the activation of sun-shading is too rigid to enable the highest daylighting at the same time as glare protection, and the daylight conditions inside are consequently worsening. The daylighting technologies that combine the benefits of daylighting and while managing its demerits can be noted as advanced in this regard.

IEA SHC Task 21 systematized all daylighting systems in *A Source Book on Daylighting Systems and Components* (Ruck, Aschehoug et al. 2000). The conclusions regarding the systems' applicability in different climates (through field studies) or daylight characteristics were presented as well as the disadvantages of these systems. The topic of this PhD study is advanced daylight systems— meaning they are innovative in some way, such as having a new approach to conveying daylight. Thus, the research focus on the daylight transport system and the literature review in the current research (Paper 1, (Obradovic and Matusiak 2019)) solely adresses this category. A brief overview of the other daylighting systems, as classified by IEA task 21, and the most relevant information will be presented here, as it forms the basis of the research.

The common feature for all daylighting systems is that they rely on the physics of light propagation, reflection, transmission, deflection, and refraction; hence, there are just new materials, or a new idea, that distinguish the advanced from traditional systems. This is true for so-called 'passive' systems. Active systems, are, on the other hand, power operated and use new technology.

According to Ruck, Aschehoug et al. (2000) and Kischkoweit-Lopin (2002), all daylighting systems can be divided into two groups according to their ability to shade excessive light and solar heat or guide it to deeper areas of the space:

The first group is called 'shading systems', as they completely or partly provide solar-shading and glare protection.

- Shading systems that provide diffuse skylight and block direct sunlight (Fig. 17).

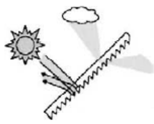
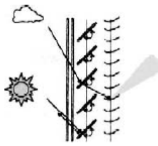
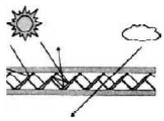
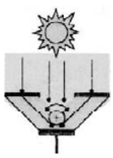
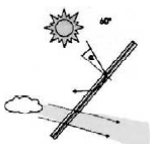
System		Climate	Attachment	Criteria for the choice of elements
Prismatic panels		All climates	Vertical windows, skylights	– Glare protection (D) – View outside (D) – Saving potential (artificial lighting) – Need for tracking (D) – Available
Prisms and venetian blinds		Temperate climates	Vertical windows	– Glare protection – Lightguiding into the depth of the room – Homogeneous illumi-nation – Saving potential (artificial lighting) – Available
Sun protecting mirror elements		Temperate climates	Skylights, glazed roofs	– Lightguiding into the depth of the room – Homogeneous illumi-nation – Saving potential (artificial lighting) – Available
Anidolic zenithal opening		Temperate climates	Skylights	– Glare protection – Homogeneous illumi-nation – Saving potential (artificial lighting) – Testing
Directional selective shading system with concentrating HOE		All climates	Vertical windows, skylights, glazed roofs	– Glare protection (D) – View outside – Saving potential (artificial lighting) – Need for tracking – Available
Transparent shading system with HOE based on total reflection (→ 4.2.3)		Temperate climates	Vertical windows, skylights, glazed roofs	– Glare protection (D) – View outside – Homogeneous illumi nation – Saving potential (artificial lighting) – Need for tracking – Available

Figure 17 Shading systems that primary using diffuse skylight, adopted from Kischkoweit-Lopin (2002)[11]

[11] Permission to use illustration granted by Elsevier, License number 5250070332945 https://s100.copyright.com/CustomerAdmin/PLF.jsp?ref=ca64375b-93e1-481f-904d-a798c4f9804d

- Shading systems that primarily use direct sunlight. They receive direct sunlight and redirect it onto the ceiling or above eye height (Fig. 18).

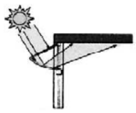
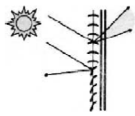
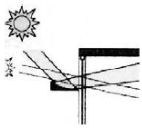
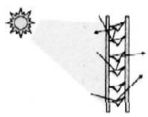
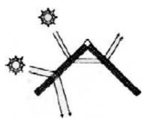
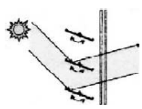
System	Climate	Attachment	Criteria for the choice of elements
Light guiding shade 	Hot climates, sunny skies	Vertical windows above eyeheight	– Glare protection – View outside – Lightguiding into the depth of the room (D) – Homogeneous illumination (D) – Saving potential (artificial lighting) (D) – Available
Louvers and blinds 	All climates	Vertical windows	– Glare protection – Lightguiding into the depth of the room – Homogeneous illumination – Need for tracking – Available
Lightshelf for redirection of sunlight 	All climates	Vertical windows	– View outside (D) – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available
Glazing with reflecting profiles (Okasolar) 	Temperate climates	Vertical windows, skylights	– View outside (D) – Glare protection (D) – Lightguiding into the depth of the room (D) – Homogeneous illumination (D) – Variable solar heat gain coefficient – Available
Skylight with Laser Cut Panels 	Hot climates, sunny skies, low latitudes	Skylights	– Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available
Turnable lamellas 	Temperate climates	Vertical windows, skylights	– Glare protection (D) – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Need for tracking – Available

Figure 18 Shading systems that primary use direct sunlight, adopted from Kischkoweit-Lopin (2002)[12]

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The other group is called 'optical systems' and they primarily redirect daylight and guide it to areas further from the window or skylight. Some of them also block direct sunlight and provide glare protection.

- Diffuse light guiding systems are designed to receive light from the zenithal part of the sky, which is much brighter than the horizon (for an overcast sky) (Fig. 19).

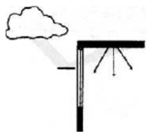
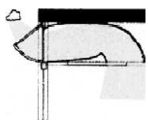
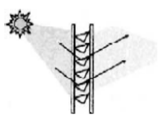
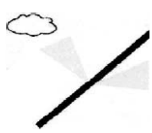
System		Climate	Attachment	Criteria for the choice of elements
Lightshelf		Temperate climates, cloudy skies	Vertical windows	– View outside – Lightguiding into the depth of the room (D) – Homogeneous illumination (D) – Saving potential (artificial lighting) (D) – Available
Anidolic Integrated System		Temperate climates	Vertical windows	– View outside – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available
Anidolic ceiling		Temperate climates, cloudy skies	Vertical facade above viewing window	– View outside – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Testing
Fish System		Temperate climates	Vertical windows	– Glare protection – View outside – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available
Zenith light guiding elements with Holographic Optical Elements		Temperate climates, cloudy skies	Vertical windows (especially in court-yards), sky-lights	– View outside – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available

Figure 19 Diffuse light guiding systems, adopted from Kischkoweit-Lopin (2002)[13]

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- Direct light guiding systems use direct sun light and discard excessive light, causing solar gains and glare issues inside the space. Their concept is to be used on a small part of the façade or window, called the daylighting part, while the view part of the window can be solved with a conventional shading system (Fig. 20).

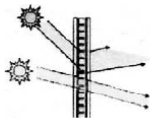
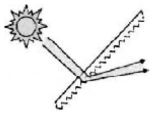
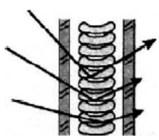
System		Climate	Attachment	Criteria for the choice of elements
Laser Cut Panel (LCP)		All climates	Vertical windows, skylights	– View outside (D) – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available
Prismatic panels		All climates	Vertical windows, skylights	– View outside (D) – Lightguiding into the depth of the room – Saving potential (artificial lighting) – Available
Holographic Optical Elements in the skylight		All climates	Skylights	– View outside – Homogeneous illumination – (artificial lighting) (artificial lighting) – Available
Light guiding glass		All climates	Vertical windows, skylights	– Glare protection – View outside – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available

Figure 20 Direct light guiding systems, adopted from Kischkoweit-Lopin (2002)[14]

- Scattering systems use direct sun light to scatter (diffuse) it to a more convenient lighting distribution. They do not provide shading from direct sunlight and can even prompt glare problems; therefore, they are used on skylights and not side windows (Fig. 21).

- Light guiding (transport) systems receive or collect daylight from outside and transport it through a light guiding element into rooms in the depth of the building. Light can be transported over long distances depending on the type of system and the nature of

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the collected light. If the same system is used for the transported artificial light when the daylight is lower, the system is noted as a hybrid light transport system (Fig. 22).

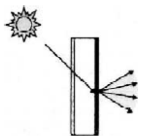
System		Climate	Attachment	Criteria for the choice of elements
Scattering systems (light diffusing glass, capillary glass, frosted glass)		All climates	Vertical windows, skylights	– Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available

Figure 21 Scattering systems, adopted from Kischkoweit-Lopin (2002)[15]

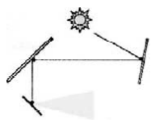
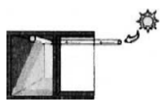
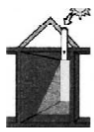
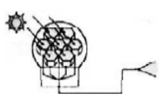
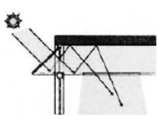
System		Climate	Attachment	Criteria for the choice of elements
Heliostat		All climates, sunny skies		– Lightguiding into the depth of the room – Saving potential (artificial lighting) – Need for tracking – Available
Light-Pipe		All climates, sunny skies		– Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available
Solar-Tube		All climates, sunny skies	Roof	– Lightguiding into the depth of the room – Saving potential (artificial lighting) – Available
Fibres		All climates, sunny skies		– Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Need for tracking – Available
Light guiding ceiling		Temperate climates, sunny skies		– Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Research and development

Figure 22 Light transport systems, adopted from Kischkoweit-Lopin (2002)[16]

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According to Kischkoweit-Lopin (2002), systems can be categorized according to their abilities to solve different issues. The ability of a system to provide shading and glare protection while still enabling outside view is a highly desirable feature for well-functioning human visual perception. Further, the ability to guide the light deeper into the room to provide an even illuminance distribution and the potential to save energy from artificial lighting are important in the context of building function and operation. Finally, the mode of light collection (the need for tracking), availability on the market, and profitability are sometimes unnecessarily rigorous criteria that can reject the system as unsuitable. Table 2 systematizes the parameters of performance that are necessary to consider when comparing the baseline solution, for example a window with a shading system, with an advanced daylighting system solution (Ruck, Aschehoug et al. 2000).

Table 2 Performance parameters characterising daylighting systems within the context of a building application, adopted from (Ruck, Aschehoug et al. 2000)[17].

Parameters		**Independent Variables**	
Visual comfort and performance	Illuminance	**Climate**	Daylight availability
	Distribution		
	Glare		Temperature
	Direction		
Visual amenity	Outside view	**Site**	Latitude
	Appearance		Local daylight availability
	Apparent brightness		Atmospheric conditions
	Colour		Exterior obstructions
	Privacy		Ground reflectance
	Social behaviour		
Thermal comfort		**Room**	Geometry
			Surface reflectance
Device characteristics		**Window**	Size
			Placement
			Orientation
			Daylighting system
			Shading system
Building energy use		**Lighting System**	
Lighting energy	Space conditioning energy	**Task**	Reading, writing
	Shading system		Self-illuminating equipment
	Peak demand		Occupancy schedule
Economy			
Codes and standards			
Construction and systems integration	Product data		
	Systems integration		
	User considerations		

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In the last two decades, prior to this PhD research, several studies evaluating daylighting systems for high-latitude areas have been performed at several Norwegian universities of architecture and civil engineering. The common aim was to address direct innovation possibilities and the adaptability of the systems to the Scandinavian solar microclimate. The daylight of atrium buildings and zenithal skylights was studied by Matusiak (1998). Then, the performance of several daylighting systems, such as prismatic panels and LCP panels mounted in front of the facades for side-lighted spaces, was studied by Arnesen (2003). Within the ZEB Research Centre, a report on daylighting and solar shading for high-latitude areas was systematized by Arnesen, Kolås et al. (2011). Venetian blinds were studied to develop the perfect configuration for direct sunlighting and shading (Kolås 2013). Later on, strategies for the control of solar shading were studied to determine the best design methodology (Karlsen, Heiselberg et al. 2016, Karlsen 2016). Moreover, window laser-cut panels were studied to improve daylighting indoors (Creda and Matusiak 2017, Matusiak 2017, Weibye and Matusiak 2019).

A research quite similar to the current study, which focuses on daylighting systems for improved illumination and energy-saving potential, was that performed by Arnesen (2003). This study was performed as a full-scale study at the exact location of the current study (Sandvika, near Oslo, at latitude 59°N). The test office in the study was equipped with a semi-transparent (inside) light shelf one meter in depth and mounted between a clerestory window (1.0 m2) and view window (2.2 m2). The whole-year monitoring showed that the illuminance in the middle and back part of the room was increased by 10–20% during the spring and autumn. However, the final conclusions were that there was no improvement in the daylight distribution in the room when looking at the whole-year situation. At very low sun angles, the internal light shelf did not shade or redirect direct sunlight.

Further, in the same study, prismatic panels were used in the same setting and mounted vertically between the two panes of the clerestory. Under clear, sunny-sky conditions during summer, the prismatic panels provided more uniform daylight distribution in the room than under overcast skies. The illuminance in the middle part of the room was increased by up to 30% and, in the back part of the room, by about 14%. However, compared with the reference room, the prismatic panels prevented direct sun from reaching the back part of the room. The final conclusions were that prismatic panels have limited application in climates with predominantly overcast-sky conditions.

This overview of studies performed in Norway indicates the necessity for further research. This PhD thesis departs from this point, aiming to study other advanced daylighting systems. According to the research addressing DTSs from the last two decades, there exists scientific evidence that the DTS may be particularly suitable for multistorey buildings in high-latitude areas (Vázquez-Moliní, González-Montes et al. 2009, Vázquez-Moliní, González-Montes et al. 2013, Nair, Ramamurthy et al. 2014, Nair, Ganesan et al. 2015, Alqudah, Stetieh et al. 2018, Mayhoub 2019). This comprised the starting point for the definition of the research aim and research questions of this study.

3.2. Need for research

This thesis aspires to further study the questions outlined above. In the last two decades, research using computer-based and field studies to examine traditional daylighting systems has shown that there are several shortcomings in the application of these systems in the Scandinavian microclimate (Arnesen 2003).

This PhD research is thus designed to generate more knowledge about the suitability of advanced daylighting systems, especially daylight transport systems (DTSs). The technology of DTSs has advanced in the last few years, with several products available on the global market. Some recent studies have shown that there is a certain potential for these systems to be used in high-latitude areas in particular settings.

The main challenges in energy-ambitious building projects lay partly in the lack of standardized products and insufficient evidence regarding performance. Stricter energy consumption policy for buildings will lead to an increased need for novel technology and reliable information. The energy-saving potential of artificial lighting has been shown to be quite low when it comes to an integrated solution with traditional daylighting systems in high-latitude areas (with a predominantly low solar altitude). However, none of the previously mentioned studies examined a field study of DTS in high-latitude areas, nor did they use a custom approach (with custom-made light distribution). Therefore, this PhD study examines the energy-saving potential via a field study using one of the most suitable DTSs.

The general assumption is that there exists a negative user attitude in regard to the visual perception of the daylight conditions indoors provided by the DTS. This PhD study aims to also examine the user's impression of daylighting by the DTS in a field study to find more evidence regarding this issue.

3.3. Research questions

This PhD study aims to answer the following research questions:

1. Which daylight transport systems have the greatest potential for use on the facades of buildings at high latitudes?
2. What is the amount of daylight delivered via an HLP to the task surface in the office in buildings at high latitudes, and is there an improvement potential if an LCP is used as a customized collector of the daylight at the HLP's entrance?
3. Does daylighting provision from the HLP improve the daylighting level at the back of the office compared to a reference situation without an HLP?
4. Is the energy use of the luminaires meant to provide the recommended light level reduced due to the application of the HLP and compared to the reference situation without an HLP?

5. Does noticeable daylighting provision from the HLP lead to a positive user perception of the space when compared to a situation without an HLP?

The methodology used to answer these research questions is described in the following chapter.

4. Research methodology

This PhD study features the combination of several formal disciplines and defined arts. In the beginning of this research, it was complex to find the affiliate institution for this research, but, finally, the research was settled under the Faculty of Architecture and Technology, which combines teaching and research methods for both science and the arts.

The subdisciplines relevant to this research—optics, building physics, daylighting, and lighting technology—traditionally have an already-developed research methodology. This is mostly objective, quantitative research, where numerical data is used for falsifying the hypothesis. While arts, skills, and practice, such as architectural design, interior design, or lighting design, do not have a developed methodology at the same level as that of physics, many centuries of architectural 'research' (e.g., performing via practice, in drawings, models, and, finally, realization) have not been documented using formal scientific methods. Thus, both architecture and daylighting design lack elements of a 'research methodology' (Mo 2003). Architecture was therefore never seen as a science, and, thus, it allows for the use of other research methods than strictly quantitative ones (e.g., human reflections about a certain issue and feedback on some experienced situations). Such methods are also reliable and valid methods for use to develop results. In the following chapters, the rationale for the selected methods for the research objectives will be justified.

4.1. Methodology in interdisciplinary research

This research as an entirety, as mentioned in the introduction, is mode 2 research. Traditionally, the methodology used in mode 2 is more versatile, than that in mode 1, which mostly consists of a quantitative approach. When research mode 2 employs several disciplines, it is reasonable to expect the necessity of more than one method. Sole-disciplinary research primarily focuses on justifying a hypothesis inside its research field. As argued by Lakatos (1968) and Kuhn (1971), the paradigms of the discipline that define the research program and methodology need to be considered, but they should not be limiting when the research is multidisciplinary. The paradigm through which one phenomenon is seen in a specific discipline is important and helps with falsifying a hypothesis. However, it is also necessary to acknowledge that the paradigm is the value that our 'field of search' has in that moment of the time, and it can evolve or suddenly change in the middle of one's research as a consequence of another study or results. As argued by Kuhn (1971), even our own research can highlight the facts of a new shifting paradigm in the research field. In such a case, the research needs to extend itself with a new paradigm and methodology. Historically, results from such research can be seen as a revolutionary, as they are changing a paradigm and moving a discipline forward.

Mode 2 research, as discussed in the introduction, has the aim of developing applicable results; thus, each part may need to apply a particular, customized methodology in order to falsify the hypotheses. A mixture of methodology could be needed to apply, for example, a mixed method where a qualitative-quantitative approach is used to collect qualitative data and then transform it into numerical values. For example, in the user survey part of this study, the main purpose was to understand human visual perception; thus, a qualitative approach was used. Then, later in the study, a quantitative method is used to analyse the causal relationship between some phenomena. Table 3 presents the methods used in the current study (i.e., a multidisciplinary mode 2 study).

Table 3 Parts of the current PhD study and the research methods used

Part of the study	**Paradigm**	**Research method**
Literature review	Pragmatism	Inductive, mixed-method reasoning
Experimental-scale model study	Post-positivism	Deductive, semi-empirical, true experimental, quantitative approach
Quantitative, full-scale field study	Post positivism	Retrospective causal-comparative, quantitative approach
Qualitative, user-survey study	Pragmatism	Mixed-method, explanatory correlational approach

Multidisciplinary research can appear non-systematized when it comes to the methodology, especially if it needs to apply both quantitative and qualitative methods. As the study by Apuke (2017) argued, while quantitative research always transforms an observed phenomena into numerical values for comparison via, e.g., statistical analysis, qualitative research usually collects data in a non-numerical form, such as texts, pictures, and videos. Then, the systematic searching, understanding, and categorizing of phenomena is used for analysis. According to Creswell and Creswell (2017), the quantitative approach to analysing data can be seen as a post-positivistic worldview, while the qualitative approach to understanding facts can be seen as a constructivist worldview. The compound of quantitative and qualitative approach is called a mixed method, and the corresponding research perspective or paradigm is usually a pragmatic worldview. The paradigm is, according to Creswell and Creswell (2017), nothing else than 'a basic set of beliefs that guide action'. Creswell and Creswell (2017) describe these three paradigms in the following manner:

- Post-positivism (positivistic, empirical) represents the traditional form of research, and it is usually used in quantitative research. The post-positivistic paradigm is always used when the research aim is to find the causes for certain events or vice versa. An example of this is an experimental approach, which always leans on the objective observations and measurement of the events.

- Social constructivism is a form of research usually used to understand an individual's opinion and impression of the world they live in, and it is mostly used in qualitative research. This paradigm is used to investigate the complexity of the individual's meaning-making of their surroundings. Constructivist researchers are also interested in the interaction among individuals and within the specific contexts in which people live and work. Social constructivism is used when individuals' or groups' historical and cultural settings are examined.

- Pragmatism is a paradigm that uses any approaches that help find the solution to a specific problem. The focus is not on a method but a research problem; thus, the actions and objectives in such research arises out of the problem itself. Mixed-methods research, which employs a pluralistic approach (several different approaches) in the overall methodology, uses the pragmatic paradigm. The pragmatic researcher deals with both quantitative and qualitative datasets and combines methods of both known quantitative and qualitative methods to develop their results.

Nowadays, mode 2 research activity almost exclusively uses a 'searchlight approach', meaning that a searchlight is specifically directed on a problem to find a solution. In contrast to the traditional 'bucket theory', where every experience and perception help accumulate knowledge, searchlight is seen also as clearly defined problem that will be focused on (Popper 1972). According to Popper (1972), in order to falsify our hypothesis, we need to have an observation which is planned and prepared, and that means that we also have an expectation of a result. Clearly defined problem helps identify the limits of the research, since multidisciplinary research can easily fall into widening the scope of the research. Popper argues that the researcher knows and expects the result in a certain domain and works to find answers needed in society at that time (Popper 1972). The focus of the research is on a problem that requires more knowledge to solve and answers within the context of that time.

The author of this study wanted to justify the study's analyses by considering a few elements from the feminist approach in science. According to Keller (1983), any step in a scientific process is influenced by the attitudes and personal values of the researcher. Thus, the authors' perspective on the specific problem studied in this PhD research can be seen through the lens of a feminist approach. It was the researcher's own desire to look into the problem that initiated this research through several approaches. The researcher's attitude regarding sustainable development, both energy efficiency of buildings, and care for people's health and wellbeing, came out of the researcher's understanding of the importance for all aspect of it. This demanded the researcher to switch roles from being an objective observer (or Robert Boyle's 'sceptical chemist') while performing the experimental study and analysing the data, to Dona Haraway's 'curious and committed investigator' while investigating solutions and possibilities (Haraway 1988).

Haraway's approach to diffractionism instead of reflectivism was used when defining the research questions, dividing the research into parts, and when describing the results. For Haraway, '*Diffraction is a mapping of the interference, not of replication, reflection, or reproduction*' (Haraway 1992). According to Haraway and Goodeve (2018), '*Diffraction patterns record the history of interaction, interference, reinforcement, difference*'. As observed by Udén (2018), Haraway states that diffraction is needed to observe interference—or, the diffractive principle allows for seeing how waves are superimposed to form lower or higher amplitudes. This means that, in this particular research, the effect of daylighting can be associated with multiple fields, such as energy, photometry, human satisfaction, human health, human wellbeing, lighting, and interior design. Diffractionism is thus demonstrated via multidimensional conclusions post findings, that touch different fields and disciplines inside architecture.

4.2. Research validity and reliability

Research *reliability* and *validity* are two of the most important concepts in scientific research. Their definition depends on the type of research being conducted. Research validity and reliability address different components of quantitative and qualitative studies also depending on the method used in the research approach. As mentioned above, this research consists of three parts, where, in the first part, inductive reasoning is used; in the second, a quantitative method; and, in the third, a quantitative and a mixed method is used in the two subparts of the study (Table 3).

According to Joppe (2000), *reliability* refers to the consistency of the results over a period of time or in the total population of a sample. The research instrument is reliable if the results of the study can be reproducible under a similar methodology over time and if the results are always stable. Further, Golafshani (2003) justifies the *validity* of a quantitative study method as a phenomenon that tells whether the research truly measures what it was intended to measure or how truthful the research results are. This refers to the precision of the measurements' credibility and the transferability of the measurements to results.

In the second part of the study, due to the laboratory setting, equipment, and nature of the method used, it was necessary to ensure reliability and validity. The reliability of the quantitative measurements could be threatened by systematic errors, particularly in the used equipment, the accuracy and the trustworthiness of the scale model, and the accuracy and cleanliness of the LCP samples. Reliability can be discussed regarding the artificial sunlight simulator, skylight simulator, and measuring instruments used. It was essential to ensure the stability of the supply voltage for the power operated equipment, the stabilization and cooling time of the lamps, an ambient temperature, and a maximum air-movement speed. To ensure measuring each instrument's precision, short-term repeatability tests should be performed prior to each measuring session. Calibrated illuminance meters, with a suitable measuring range for the purpose should be used. Further, the reliability resulting from the measuring action itself and the error factor caused by human handling of the equipment should be considered.

On the other hand, the validity of the laboratory measurements should be concerned if the methodology used to determine the results was really the most suitable. It could be discussed if the sunlight simulator in the daylight laboratory can be used to solely measure direct components of the daylight when it is known that the sunlight rays are not exclusively direct but instead consist of diffuse rays as well (to a very small extent). Further, it could be assessed whether the instruments that were used to measure the values were really the instruments that measure the physical phenomenon assessed in the study. The reliability and validity of the second part of the study (experimental laboratory study) are described in detail in Paper 2 and Paper 3 (included in Appendix A).

The third part of the study consisted of two subparts with different methodology: a quantitative and a mixed-methods approach. In the quantitative approach, standardized measurements were performed to developed datasets, which were further analysed. Thus, the reliability and validity concerns in the previous paragraphs apply to this part as well. When the test and reference models (periods) are established and validated within the rationale for the study, they intend to provide the validity for the monitoring of the observed phenomena. The validity of the design is important, and it is reliant on the researcher's knowledge and ability to recognize potential threats to the study's validity (e.g., if the change in the test model is really that which brings about the variation in the observed parameter, or it is due to some confounding factors).

In a mixed-methods approach, qualitative-quantitative datasets are developed and further analysed. Questions of reliability in qualitative studies are essential for the concept of such a study and can be discussed in terms of highlighting several issues. Justifying reliability in a qualitative study would be equal to justifying the quality of that study at all, and raising the question of whether the study is scientifically good. The other view is to check whether trustworthiness of the independent variables or questionnaires (test) is good. This is a crucial step in qualitative research, and it should always depend on the nature of the research and discipline. The variables in the user interview of the current study were defined as qualitative descriptors of the visual and perceptual qualities of the room. In Paper 4, included in Appendix. A, the trustworthiness of the variables used in the study are explained in greater detail.

In terms of validity in a qualitative research method, there are mainly two arguments. One group of scientists argues about the sufficiency to question the validity of the qualitative study. The other group believes that questioning the validity is essential for a qualitative study, but, when the validity is justified, it means that the research method is reliable as well. Creswell and Miller (2000), for example, suggested that validity is in direct relation to the researcher's perception of the study and their choice of paradigm assumption. In this matter, rigor is instead used as denoting the good validity.

In the current qualitative-quantitative study, statistical analysis and the level of significance were used to validate the overall result, which was developed by comparing the qualitative data to the quantitative data in the study. The reliability and validity for this qualitative-quantitative study will be discussed in greater detail in section 4.6.

Golafshani (2003) argued that both reliability and validity in the qualitative paradigm are contextualized with trustworthiness and rigor. These can be achieved by the researcher's own perspectives and ability to eliminate biases that may shape the results. Creswell and Miller (2000) suggested that providing a narrative summary of researcher's reflexivity on the research outcome can be included if the researcher thinks that justifying their role is important for the validity of the study.

4.3. Research method for the literature study

A literature study is a review of scholarly articles published for a topic of research; this PhD study addressed the review of the current state of knowledge regarding DTSs. A systematic review of the literature is used to find the answer. A literature review, as a research method, is usually used to develop an overview of the relevant background, and, if it is systematized and written, it can provide an indication of the relevant gaps in the field of research.

There are several ways to conduct literature research: First, any type of modern literature research uses the searchlight method, since the aim of the research is usually established and well-defined. This means that the aim of the research is important. The research question tells whether the literature review will be summarizing knowledge to examine the different themes addressed within the literature scope, such as in this PhD study. A literature review method is also usually used to review all known methods used to calculate, estimate, or predict some phenomenon or when the aim is to systematize all theory and examine the chronological development of a knowledge collection, as argued by McCombes (2019).

Depending on the aim, a literature review will use different methods to analyse the collection of literature. The research question for this (first) part of the study was to determine which of the daylight transport systems has the greatest potential to be used on the facades of buildings at high latitudes. The potential is defined as the possibility of the DTS to provide the highest amount of daylight (this can be quantified), and the most suitable visual environment (this can be estimated, using the qualitative method). Thus, the literature review in this research was, as discussed above, both *post-positivistic* when discussing the quantitative findings and *constructive* when discussing findings of a non-quantitative nature. Finally, the review was *pragmatical*, having a clearly defined problem aimed at investigating findings for buildings in high-latitude areas. The high-latitude areas are characterized by a low solar altitude and predominantly overcast skies. Thus, the review was focusing on findings about the overall efficiency and applicability of this technology for these specific micro-climatic conditions. This approach, when reviewing relevant sources to identify conclusions and generalizations on both quantitative and qualitative phenomena, is called an 'inductive' mixed-methods approach.

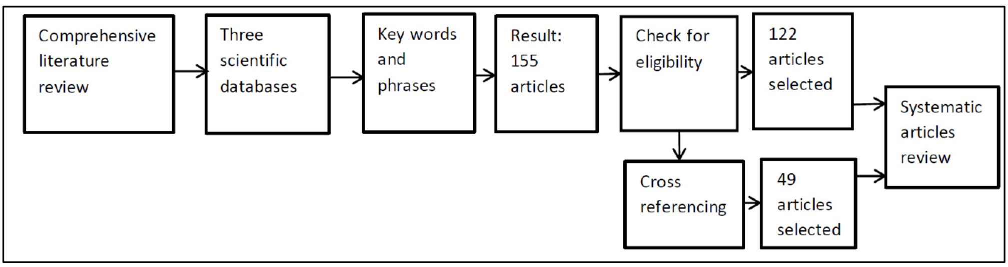

Figure 23 Strategy used for the literature review in this PhD study

The strategy used when performing a literature research study can be divided into the following steps (Fig. 23):

- Mapping of the scientific databases that contain scholarly sources relevant to the topic in this research. The databases Google Scholar, ScienceDirect, and Scopus were relevant for this research based on the research disciplines involved.

- Relevant keywords were used in the search engines to retrain the articles. The used keywords were: daylight, light, pipe, fibre, rod, and system; the key phrases were: lighting rod, fibre optical system, mirror light pipes, daylight shading system, daylight guiding system, and daylight transport system.
- The literature search originally resulted in 144 articles. All sources and topics addressed in these articles were evaluated. Then, 22 articles were excluded, with 122 selected as eligible.
- The period when the articles were published can be used to select the eligibility of the sources. Often, only the last two decades of sources are used in a literature review addressing a current state of the knowledge. In this review, the author wanted to review the historical development of the technology as well; thus, a time period filter was not used.
- Different themes that the articles address were identified within the literature review. In this review, the themes were: different principles of light collection (active and passive); or different transportation mediums, climates, and sky conditions; and/or the analytical modelling of light transport prediction; or products available on the market.

The review was outlined and structured to address themes found in the literature (Fig. 24). The findings were summarized, critically evaluated, and analysed. The results were synthesized in the given tables to provide a simple overview of the state of knowledge on the subject.

1. Introduction
2. Sun and sky conditions
3. Daylight transport systems
4. Analytical models and design adjusting for light transport systems
5. Development of market products
6. Discussion
7. Conclusions

Figure 24 Outline of the written systematized literature review of daylight transport system.

4.4. Research method for the experimental part of the study

The next step in the study had the objective of examining the light transmission efficiency of the HLP in the solar microclimate condition of the location of study. It was namely the findings from the literature review that pointed toward the HLP as the most suitable daylight transport system. In addition, laser cut panels (LCPs) were noted as a technology that could improve on the efficiency of the HLP, especially in delivering daylight deeper within the space at a low solar angle. Therefore, the objective was widened to also determine which LCP configuration (distance to width ratio [D/W] and tilt and rotating position) could most improve the light-pipe efficiency.

The assumptions of the study were (Fig. 25) that tilted LCPs (called T-) with horizontal straight cuts will deflect light from high-altitude angles, such as, for example, during the summer at noon. This would provide a higher light transmission efficiency for the light coming from sun when the altitude is high as well as for the skylight from the zenith. A pair of symmetrically rotated LCPs (called R-) with vertical cuts would deflect wide azimuth light and provide higher light transmission efficiency. Sunlight has such an azimuth angle in the morning and evening, especially during the summer half of the year.

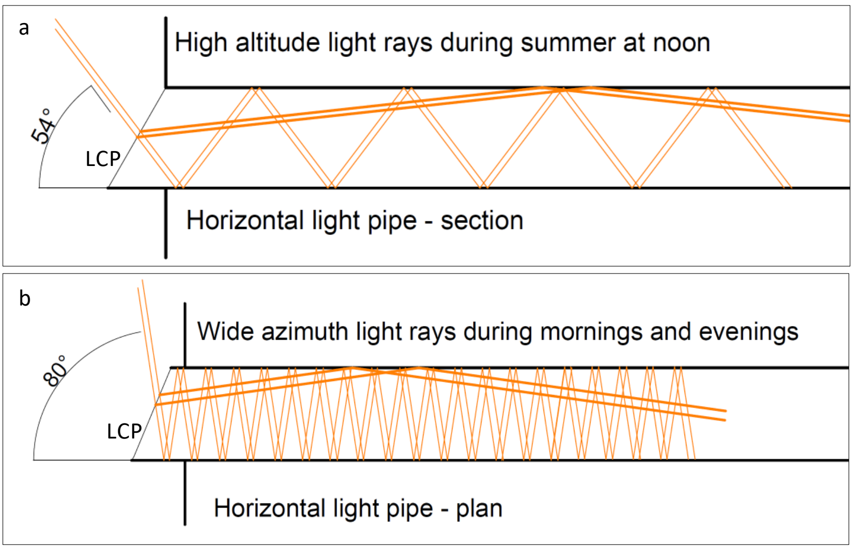

Figure 25 The principle of LCP at the entrance of the horizontal pipe. a) High-altitude light during summer at noon (vertical section through the wall); the thicker line denotes deflected light that has a preferable incident angle along the pipe's axis after deflection on a tilted LCP. b) Wide azimuth light in the mornings and evenings (horizontal section through the light pipe); the thicker line denotes deflected light that has a preferable incident angle after deflecting on a single rotated LCP.

In all, this part of the study took on a semi-empirical approach (Fig. 26). First, an experimental study employing a scale model and structured and validated data-collection in a daylight simulator was used to obtain quantitative datasets regarding the light transmission efficiency. A customized measuring matrix was developed to collect the data and link it with the temporal parameter, as the study aimed to express analyses for a whole year. A quantitative dataset was retrieved using a net-based database comprised of statistical values for daylighting conditions. Then, a theoretical model of an office was used to mathematically develop a situation through which the final metrics would be expressed. Finally, the collected datasets were analysed using a matrix for the temporal parameter and daylight autonomy (DA) model (expressed in hours).

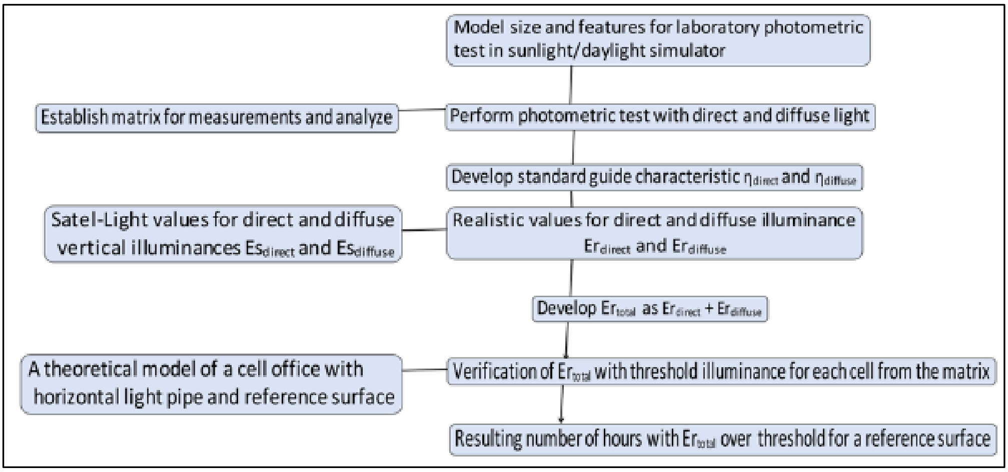

Figure 26 Flowchart for the semi-empirical method used in the second part of the study showing the protocol for estimating the light transmission efficiency of the horizontal light pipes and development of an applicable metric to validate the results against daylight recommendations.

Experimental methods used in daylighting studies

An experimental study deals with the process of supporting, rejecting, or validating a certain hypothesis in the study. According to Apuke (2017), experimental design must provide the conditions and guide the research in such a way to identify the relationships between the independent and dependent variables. Such an approach used in an experimental (quantitative) study is a deductive approach, meaning that the theory or hypothesis of something new is tested through empirical observations.

There exist several research designs to examine the light transmission of daylight transport systems. Some authors have used scale models under real-sky conditions to measure the illuminance values for light pipes (Garcia Hansen and Edmonds 2003, Baroncini, Boccia et al. 2010). Scale models under a real sky were also used to record light behaviour on laser cut panels (LCP) as a collector for light pipes (Garcia-Hansen and Edmonds 2015). Particularly, LCPs and the light deflection through them were studied using a scale model and under artificial daylight conditions using a sunlight simulator (Creda and Matusiak 2017, Weibye and Matusiak 2019). There are also authors that claim that use of experimental scale models for the purpose of examining the light transmission of light pipes is not appropriate and that precise analytical methods, applicable to both cloudy and cloudless sky conditions, should be used instead (Petržala, Kocifaj et al. 2018).

The specific aim of this PhD study was to examine the light transmission for a whole year, a feature lacking in all of the previously mentioned studies. Thus, the study design needed to provide the possibility of volume measurement. This immediately indicated that it would be impossible to perform such study outdoors by measuring real daylight because of the necessary time and resources. The aim of this research was to compare the efficiency of different LCP configurations (19 in total); thus, it was found necessary to employ highly controllable conditions of daylight intensity as well as solar altitude and azimuth. The only way to provide such conditions in the study was to use a daylight simulator.

In terms of the software calculations, as some authors have suggested, radiance-based daylight tools could be used to apply the whole-year approach. However, the aim of the study with testing the LCP, which has a complex geometry of ray deflection and, additionally, a mirror light tube with multi-interreflections inside, raised doubt in the researcher. Thus, the simulations were seen as unreliable for the study, and an approach using a scale model in the daylight simulator was chosen (Fig 27).

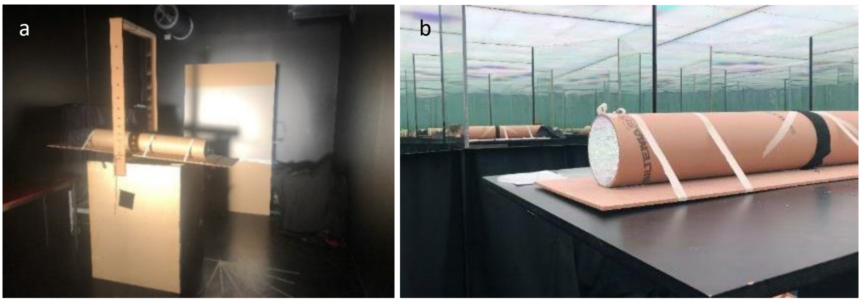

Figure 27 Experimental-scale model study in the daylight simulator: a) Scale model in the artificial sunlight simulator, b) Scale model in the overcast sky simulator.

Three types of experimental approaches are generally used: pre-experimental, true experimental, and quasi-experimental. According to Apuke (2017), the pre-experimental approach can be used to, for example, test the equipment or instruments. This approach should involve a minimum of one independent variable as a fixed value (i.e., does not vary). The true experimental design must be a systemic approach to collecting quantitative data. Such a design must provide a higher degree of control in the experiment, and it will produce a higher degree of validity. A true experimental design can also involve mathematical models in the analyses. The third model, which was not actually used in this research but is mentioned for comprehensiveness, is the quasi-experimental design. Such a design involves the non-random selection of study participants, which puts the validity of the experiment into question. This kind of design is usually used for a pilot study, where testing the protocol is the aim, and, according to De Young (2013), the quasi-experimental study is the first step towards providing validity for the main experiment.

The experimental approach of the current study led to a high level of control for the input variables as well as a systematic approach to collecting the data by using calibrated instrumentation. Thus, the experimental method in the current study is considered to be a true experimental approach.

Daylight simulators for daylight studies with scale models

Scale models of buildings are commonly used by architects and other building professionals. They are seen as simple technology that is easy to construct while enabling reliability in showing building volumes, situations, and relations to other surrounding objects. When building models are constructed in detail, they mirror almost the exact behaviour of daylight in real buildings. This is possible because of the size of the light wavelengths, which are extremely small (380–780 nanometres). According to Cannon-Brookes (1997), even models up to a 1:500 scale can be considered for daylighting examination. However, the scale of the model is rather guided by the level of detail needed, the ability to construct them accurately, and the real size of the object they represent. One disadvantage is that materials with textures are not convenient for use in a scale model of, for example, artificial light sources, due to the fact that they cannot be scaled (Baker, Fanchiotti et al. 2013).

In this study, a model of a HLP is used at a 1:2 scale. This was dictated by the size of the artificial sun and sky simulators in the daylight laboratory (the model could not be bigger than a 1:2 scale). The leading parameter for the model's scale was also the production of cuts on the LCPs examined in the study (the LCP samples could not be smaller).

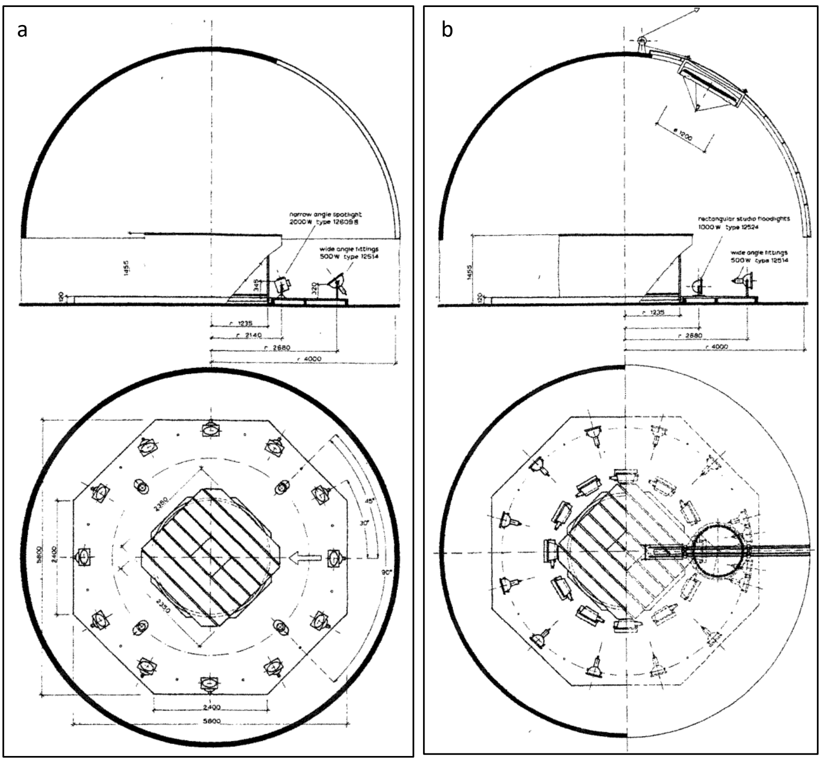

Figure 28 Illustration of a sky-dome simulator as well as the light arrangement for overcast sky luminance distribution and for clear sky luminance distribution; adopted from Kittler (1974)[18].

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The method for this research study included the usage of a daylight simulator. Several daylight simulator configurations have been known in the literature, the most frequently used of which is a 'mirror sky chamber' that simulates a CIE overcast sky. This type of simulator has a diffuse Lambertian light source as lighting ceiling and mirror walls where light from the ceiling is reflected (Kittler, Kocifaj et al. 2011). Then, for the simulation of overcast or clear sky luminance distributions, the sky dome (3–9 m diameter), made of a reflective opaque hemisphere (usually canvas), is used. The illumination is provided using uplight sources placed in the circular groove (Kittler 1974) (Fig. 28).

The only sky simulator that can produce any type of sky is a scanning sky simulator (Fig. 29). This simulator consists of a sixth of the vault (25 lamps), and the whole hemisphere is rebuilt by scanning the model in steps (145 light zones) (Aghemo, Pellegrino et al. 2008).

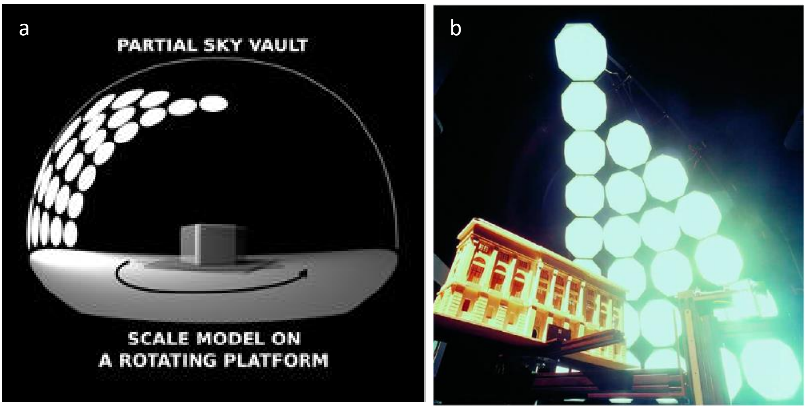

Figure 29 Scanning sky simulator. a) Illustration of virtual dome artificial sky[19]. b) The sky scanning simulator at the Daylighting Laboratory of the Politecnico di Torino adopted from Aghemo, Pellegrino et al. (2008)[20].

The experimental study in the daylight laboratory at NTNU

Due to the facilities available for the current study, i.e., the Daylighting Laboratory at NTNU, the experimentation was divided into two parts. A *static sunlight simulator* was used for the direct light measurements, and an *overcast sky simulator* was used for the diffuse light measurements.

The static artificial sun was composed of 70 halogen lamps fixed to a vertical metal plate and arranged in a hexagonal pattern (Fig. 30). The static sunlight simulator was situated in a corridor-like room, where the walls, ceiling, and floor were painted matte black to minimize

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interreflections and minimize scattering light on the model. Thus, the artificial sun provided near-parallel light beams (with a dispersion angle of 3°) when the model was positioned at a distance greater than 7 m from the sun. The scale model (light pipe) in the experiment was positioned 7.5 m from the artificial sun, ensuring an even illumination. The uniformity of the light perpendicular to the tube's entrance was measured prior to examination to check the reliability of the measurements. The resulting uniformity was 98%, which is explained in detail in Paper 2. This ensured the reliability of the measurements that could be affected by the validity of the method used (caused by a parallax issue in the daylight simulators).

A parallax issue can be explained as incorrect incident light (luminance pattern) from a light source due to the size of the sunlight/daylight simulator compared to the scale model. In reality, any light source, either the sun or a sky dome, is distant and large. In contrast, any building (or light pipe) is exceedingly small. This difference means that any opening/window in an actual building would receive equal light in terms of intensity and direction. However, in sunlight/daylight simulators, the light rays from the sun are not perfectly parallel or of equal intensity at all openings or across one large opening in the model. Under laboratory conditions, one sunlight simulator will never be large enough to minimize a parallax issue. It is also possible to account for a dimension of a scale model that is not small enough for comparison with real conditions. On the other hand, the scale model must be large enough to retain the details essential for light simulation, as mentioned above. If the model's entrance to the pipe is too large, the entrance surface will not receive an equal intensity of parallel sunlight rays from a sunlight simulator. Therefore, it is important to ensure that the tube entrance is located within the parallax-bounded volume of the space with the highest predicted accuracy (+/− 10%), as argued by Mardaljevic (2002).

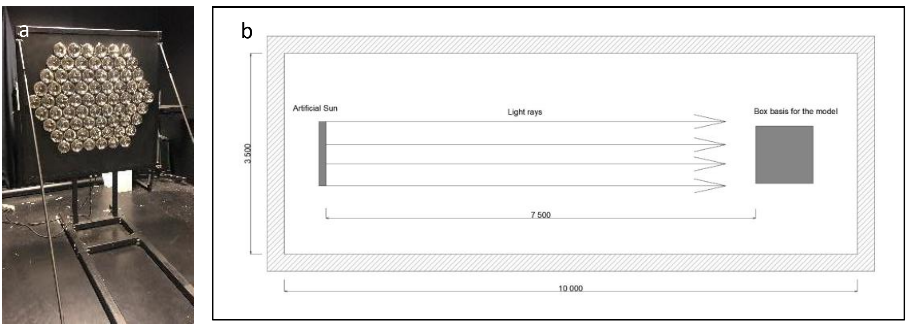

Figure 30 Artificial sunlight simulator in the daylight laboratory at NTNU, Faculty of Architecture and Design. a) Artificial sun setup. b) Sunlight simulator room, plan.

The laboratory measurements for the diffuse sky were performed using the overcast sky simulator, constructed as an octagonal mirror box where the luminance distribution refers to the CIE Standard Overcast Sky (Matusiak and Arnesen 2005) (Fig. 31). The simulator were originally constructed with a ceiling of translucent fabrics (an ideal Lambertian diffuser ceiling) and fluorescent light tubes, but was later replaced with translucent acrylic ceiling plates and LED light sources (Matusiak and Braczkowski 2014). The important parameter of one mirror-box simulators is the radius of the simulator. The simulator needs to be large enough to allow for models of reasonable size to be tested without causing parallax issues, as mentioned above. According to Lynes and Gilding (2000), the model (light entrance to the pipe) needs to be 10 times smaller than the radius of the simulator if the parallax error should hold under the +/−10% allowed error condition. This method applies only if the model is placed at the centre of the dome.

The height of the scale model in this study (the tube's entrance) was 150 mm—7.5% of the sky height in the mirror box (2000 mm). The parallax error was estimated to be somewhat higher than 10% for low altitude angles (0°–15°) but lower than 10% for altitude angles over 15°.

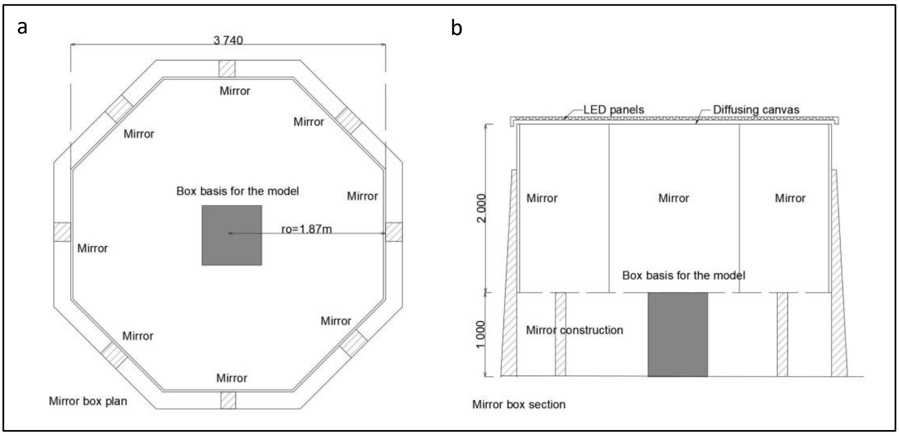

Figure 31 Artificial overcast sky simulator at NTNU, Faculty of Architecture and Design. a) Plan. b) Section.

The experimental part of the study provided just raw data, namely it resulted in the light transmission efficiency value, which represents a partial finding in this research but is applicable for further studies of LCPs and HLPs. The experimental study with the daylight simulator did not represent the real values of the sunlight and the skylight (the sunlight was not accounted for the reduction caused by the thicker atmosphere of the low solar altitude). Hence, the result was further used together with the real data (explained further in the text) to develop metrics analysed in the theoretical part of this semi-empirical study.

A temporal parameter in the study: Matrix of sun's altitude and azimuth

The aim of the study was to observe the whole-year daylight situation, meaning that the measurements of the daylight incident (on a pipe) had to be sorted based on some temporal parameter. The same parameter was intended for use when analysing the final data to link the final data to the different periods of the year (summer, spring, etc). The periods of the year and time were related to the sun's altitude and azimuth (not as seasons) (Fig. 32); thus, the temporal parameter was expressed via a matrix of the altitude/ azimuth positions of the sun (Table 4). This matrix is based on an HLP oriented to the south for a specific location (Oslo, Norway, 59°N); however, the protocol applies to any light pipe orientation (e.g., east and west or north for the southern hemisphere).

A matrix of points, each representing 5/10° of the sun's altitude and 15° of the sun's azimuth, was developed by dividing the field of the solar incident angles into as many planes as necessary to establish enough points of time. The matrix points also represent the testing positions; hence, they had to be easy to retrieve under laboratory conditions. Each measured value was saved in the respective cell.

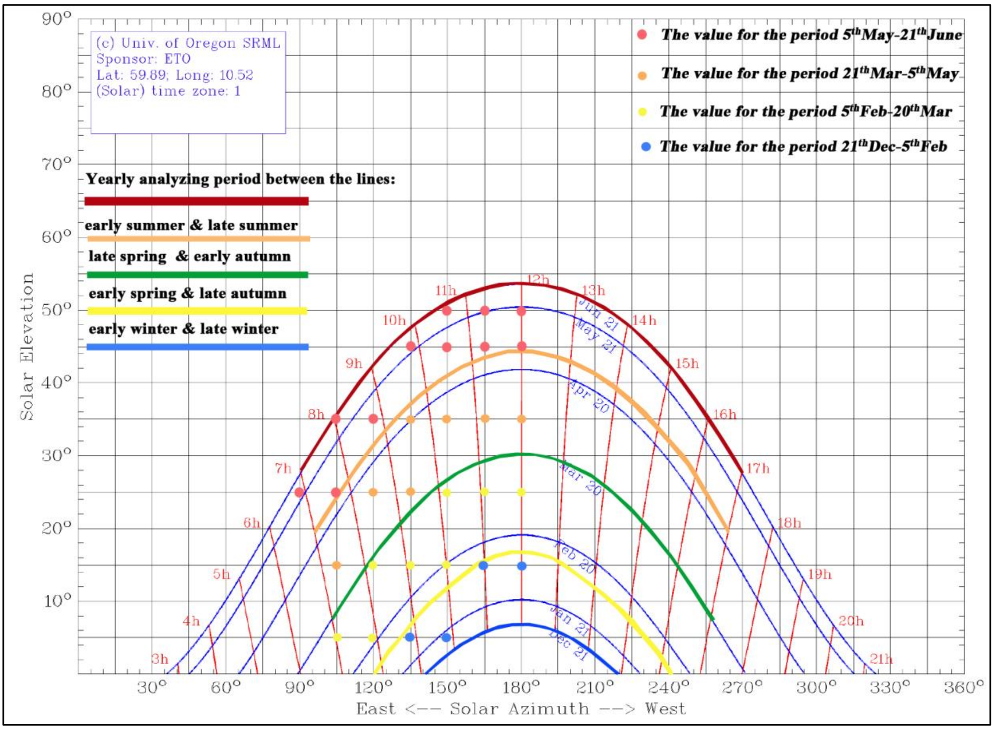

Figure 32 Solar chart for Oslo, Norway (59°53′ N, 10°31′ E), with the typical periods used in the analysis and a testing position corresponding to the testing matrix. Test points in colour represent typical analysis periods during the year: red-summer, orange-late spring or early autumn, yellow-early spring or late spring, and blue-winter.

As shown in Fig. 32, typical days (in terms of periods of the year) were determined based on differences in the solar altitude variation. There are four distinct periods in the year, each period being one-quarter of the total 365 days—or 91.25 days. Thus, for the *summer* and *winter*, it is taken the summer and winter solstice and counted 46 days back and forward (91.25 days divided by 2). For example, summer in this study starts on the 5th of May (through the 21st of June) and ends on the 5th of August. The spring and autumn periods have equal solar altitudes and are divided into two periods: *early spring* corresponding to *late autumn* and *late spring* corresponding to *early autumn*. This division was done to increase the precision, because the variations in the altitude through the spring/autumn are larger than those in the summer/winter. The total spring (or autumn) period was created by summing the data for early and late spring. The total result was developed by multiplying each typical period by the number of days in that period.

Table 4 Testing matrix for parametric laboratory study that refers to the solar chart for a south facade in Oslo. Test points in colour represent typical analysis period of the year.

50°					50	50	50	50	50				
45°				45	45	45	45	45	45	45			
35°		35	35	35	35	35	35	35	35	35	35	35	
25°	25	25	25	25	25	25	25	25	25	25	25	25	25
15°		15	15	15	15	15	15	15	15	15	15	15	
5°		5	5	5	5				5	5	5	5	
Altitude/ Azimuth	**90°**	**105°**	**120°**	**135°**	**150°**	**165°**	**180°**	195°	210°	225°	240°	255°	270°
*Summer								Not tested, assumed equal to the left side					
*Late spring or early autumn													
*Early spring or late autumn													
*Winter													

In order to link the daylight measurements with different altitude and azimuth values to the periods of the day, a matrix of the occupancy hours (7am–5pm) was developed based on Fig. 34. In Table 5, a matrix of the daily hours per period (summer, spring, etc.) is presented. This is a temporal parameter used to analyse the final data on the light provided by the HLP.

Table 5 Temporal matrix for daily hours per period of the year for a south facade in Oslo (59°53'N).

50°					10am-11am	11am-12pm	12am	12am-13pm	13pm-14pm				
45°				09am-10am	10am-11am	11am-12pm	12am	12am-13pm	13pm-14pm	14pm-15pm			
35°		08am-09am	08am-09am	09am-10am	10am-11am	11am-12pm	12am	12am-13pm	13pm-14pm	14pm-15pm	15pm-16pm	15pm-16pm	
25°	07am-08am	07am-08am	08am-09am	09am-10am	10am-11am	11am-12pm	12am	12am-13pm	13pm-14pm	14pm-15pm	15pm-16pm	16pm-17pm	16pm-17pm
15°		07am-08am	08am-09am	09am-10am	10am-11am	11am-12pm	12am	12am-13pm	13pm-14pm	14pm-15pm	15pm-16pm	16pm-17pm	
5°		07am-08am	08am-09am	09am-10am	10am-11am				13pm-14pm	14pm-15pm	15pm-16pm	16pm-17pm	
Altitude/ Azimuth	**90°**	**105°**	**120°**	**135°**	**150°**	**165°**	**180°**	195°	210°	225°	240°	255°	270°
***Summer**								**not tested, assumed equal as the left side**					
***Late spring or early autumn**													
***Early spring or late autumn**													
***Winter**													

Real daylight measurements, Satel-Light database

As initially mentioned, the second set of daylighting values were the values of a real measured direct and diffuse outdoor illuminance incident south-oriented façade located in Oslo (59°53'N). They were retained from the Satel-Light database (Satel-Light, 1998) based on the Meteosat Satellite images recorded over a five-year period and obtained every half hour.

The values of the direct and diffuse illuminances retained from Satel-Light were sorted by the months of the year and an hourly set provided in the report from the Satel-Light; hence, the values can be easily linked to the temporal matrix. In Table 6 and 7, the Satel-Light data for the direct and diffuse real measured illuminance used in the study are provided as sorted in the matrix.

Table 6 Satel-light data for direct vertical illuminance Es_{direct} (in lux) on the south façade of a theoretical office building in Oslo (retrieved from Satel-Light (2019)

50°					17100	20575	31000	20575	17100				
45°				12025	21575	25825	26900	25825	21575	12025			
35°		5650	8425	15100	21575	23775	25750	23775	21575	15100	8425	5650	
25°	350	3600	8425	14100	20100	15800	18000	15800	20100	14100	8425	3600	350
15°		2650	7675	5075	8450	11275	13100	11275	8450	5075	7675	2650	
5°		700	1825	2500	3325				3325	2500	1825	700	
Altitude/ Azimuth	**90°**	**105°**	**120°**	**135°**	**150°**	**165°**	**180°**	**195°**	**210°**	**225°**	**240°**	**255°**	**270°**

Table 7 Satel-light data for diffuse vertical illuminance, $Es_{diffuse}$ (in lux), on the south facade in Oslo (retrieved from Satel-Light (2019)

50°					17000	18650	19150	18650	17000				
45°				14425	17200	18900	19350	18900	17200	14425			
35°		8625	10850	14225	17200	13525	15025	13525	17200	14225	10850	8625	
25°	6000	7425	10850	8225	11350	8200	8800	8200	11350	8225	10850	7425	6000
15°		1750	4675	4075	6550	7300	7500	7300	6550	4075	4675	1750	
5°		200	400	1400	4250				4250	1400	400	200	
Altitude/ Azimuth	**90°**	**105°**	**120°**	**135°**	**150°**	**165°**	**180°**	**195°**	**210°**	**225°**	**240°**	**255°**	**270°**

The values from Satel-Light were then used together with the resultant light transmission efficiency values from the experimental measurements to develop the realistic values of daylight illuminance.

The method of combining direct and diffuse illuminance provided by the daylight simulator and real measured values can be argued as a simplification. The diffuse illuminance from the Satel-Light recordings also included the diffuse light from the direct sun (which was scattered in the atmosphere). At the same time, the direct illuminance from Satel-Light was reduced for this value. The CIE model of an overcast sky (enabled in the mirror-sky simulator used in the study) represents a worst-case luminance distribution compared to the realistic blue sky and does not include the diffuse illuminance from the direct sunlight. Clear skies feature a very bright area around the sun (called the corona). On the other hand, the light from the corona, which was included in the diffuse illuminance values from Satel-Light, will act quite similarly to the light from the sun, because the incidence angle of the light from the corona is similar to the incidence angle of the light from the sun. This means that the resulting direct illuminances at the exit of the tube would be even higher than presented (to a small extent).

As the results provided rather conservative results, the author concluded that the used approach maintained the necessary validity. Limiting the study to solely direct light examination would bring about a very high reduction in the resulting values, since diffuse illuminance is more than 50% of the direct illuminance for many positions of the sun, as shown in Tables 6 and 7.

Theoretical model of an office for analyses of daylight autonomy (in hours)

The last part of this semi-empirical research presents an analytical study of the daylight autonomy concept (expressed in hours) applied within a theoretical model of an office space where daylight is provided only via an HLP. Two cases were analysed. The HLP had an aspect ratio of 8 (2.4 m-long pipe) and 16 (4.8 m-long pipe), which corresponded to the theoretical model of the office space with 2 and 3 working places, respectively (Fig. 33). The illuminance on the pipe's exit was directed down to the reference surface by a curved reflector. The illuminance values of both the direct and diffuse light provided via the HLP were summed. They together represented the total illuminance, which was used to calculate the threshold values for each matrix cell. The illuminance values of 100 lux and 300 lux on the reference surface (working places) were taken as a threshold for verification. The illuminance values were developed using the inverse-square law. The final analyses included the temporal matrix to determine for how many hours in each period of the year the threshold was met. The calculations are described in detail in Paper 2, included in Appendix A.

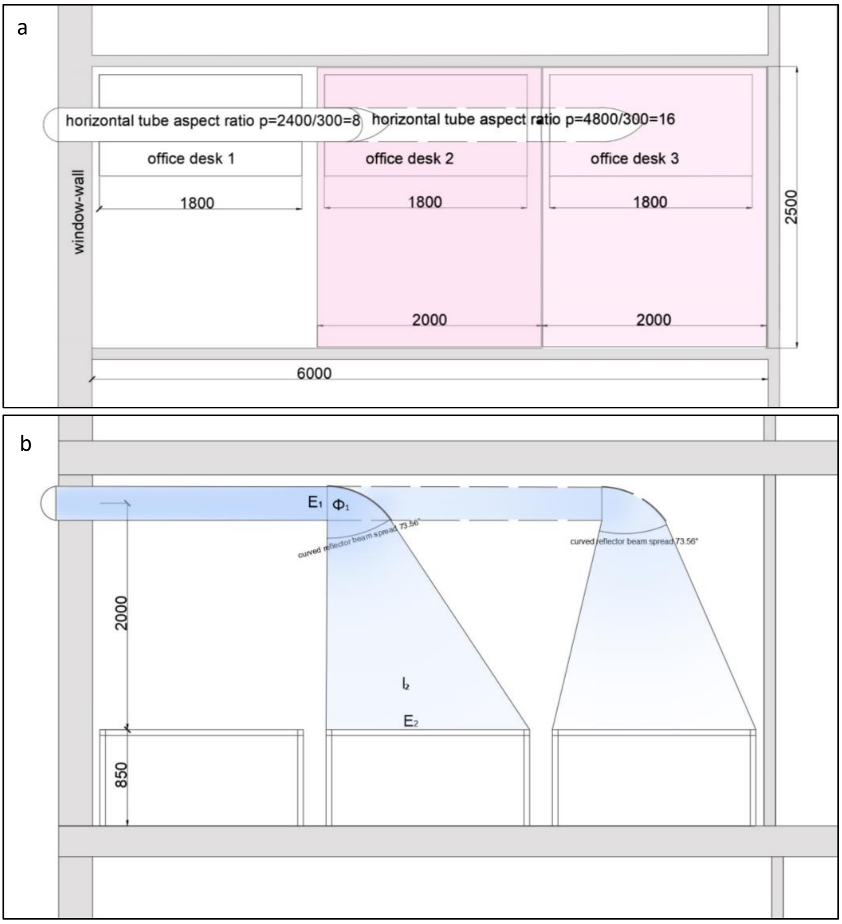

Figure 33 A typical office with the second and third working areas corresponding to a light pipe with an aspect ratio 8 and 16, respectively. a) Plan. b) Vertical section.

4.5. Research method for the full-scale field study

The next step in the study aimed to determine if the daylight in an office as provided by the HLP can affect the daylight provision and energy consumption. For this purpose, and as discussed above regarding experimental methods in daylighting studies, a full-scale experimental data-based study was performed. The full-scale study was thus designed to determine if daylighting provision from the HLP improved the daylight level in the back of the office compared to a situation without an HLP. The daylight via the HLP in the office was directed to the desk closest to the door by the application of a custom-designed reflector at the HLP's exit. The lighting energy use of the luminaire closest to the door (above the desk closest to the door) could thus be reduced as a consequence of the daylight supplemented by the HLP. Hence, the study aimed to examine this assumption as well. The study was designed to perform precise measurements using structured and validated data-collection instruments.

The full-scale test facility needed to be designed in a way to support a methodology that best-suited the study's aim. This test room was also used in the mixed-methods study regarding user opinions about the visual environment; thus, the design needed to be suitable for that study as well.

Experimental methods used to study the energy performance of buildings

The most common contemporary method for energy consumption estimation is using software simulation tools. Such tools can be used for a total building energy consumption, or the consumption of only one specific segment of the building (technical solution). These tools rely on building physics and thermodynamics theory and are quite complex nowadays. Still, many studies have reported an unreliability in the design predictions of modelling tools when compared with the measurement of energy performance in reality. A reason for this could be the threshold parameters used for certain protocols within the software. According to Strachan, Svehla et al. (2016), these protocols describe the regular building performance but can also describe other factors, such as occupant behaviour uncertainties or invalid equipment information. The validation of the modelling tools is often performed by inter-software comparative tests, where the input and output parameters (of the building performance model) are compared. However, this kind of validation does not provide real validation; it merely checks the software engines. True validation can be done by performing a full-scale experimental test, but the collection of high-quality experimental data via full-scale tests (often called 'living labs') is known to be time- and resource-demanding.

Since software-based studies lack reliability to a certain extent, and living labs are expensive, the *cell test* method can be considered a way to obtain reliable and valid empirical data. The cell test is a test where the 'cell', i.e., a room, is tested. Such tests regarding daylight conditions have been mostly performed as outdoor cell tests and without facilities to account for regular human occupancy. Thus, studies with such tests lacked occupant behaviour and opinion information.

In daylighting studies, depending on the parameters studied as well as the availability of already established reference (baseline) values, the experimentation may demand two identical cells. One of them is meant to be a reference, and the other will be a test, as argued by Ruck, Aschehoug et al. (2000). Studies by Zhang, Muneer et al. (2002) and Scartezzini and Courret (2002), which assessed the performance of light pipes and an anidolic ceiling respectively, used such experimental design with two identical cells. Table 8 presents an overview of the research design methods used to study energy or photometry in buildings, with summaries of the advantages and disadvantages of each.

Table 8 Research design methods commonly used in studies on buildings performance regarding photometry or energy consumption.

Experimental method	Advantages	Disadvantages	Availability
Software-based modelling	Full set of boundary conditions and parameters can be monitored	Lack accuracy and reliability	Inexpensive, available
Full-scale test cell (test and reference)	Limited number of conditions and parameters that can be monitored	Accurate in the limitations of the monitored phenomenon	Inexpensive, available
Full-scale tests (living labs)	Full set of boundary conditions and parameters can be monitored and tested	Accurate and reliable	Demanding in resources and time

The aim in this study was to observe a set of dependent parameters related to the values of other dependent and independent parameters. The independent parameters were the daylight conditions and, particularly, the daylight illuminance values under a clear and sunny sky. Thus, the solar altitude and azimuth were the parameters of importance. The resources for the study did not allow for establishing two test cells, so both the test and reference measurements were performed in the same room but in different periods. The two periods were chosen based on equality in a crucial parameter, the solar altitude and azimuth. The period from the 21st of June to 21st of December was used as the test period, and the 21st of December to the 21st of June was used as the reference period. The solar altitude variations within these two periods were equal, justifying the validity of the method chosen for establishing the test and reference periods in this full-scale experimental design. The analyses of the recorded data were performed for the selection of pair days (test and reference days) based on the equal altitude and daylighting profiles, fig. 34. This is in detail described in Paper 5, included in Appendix A.

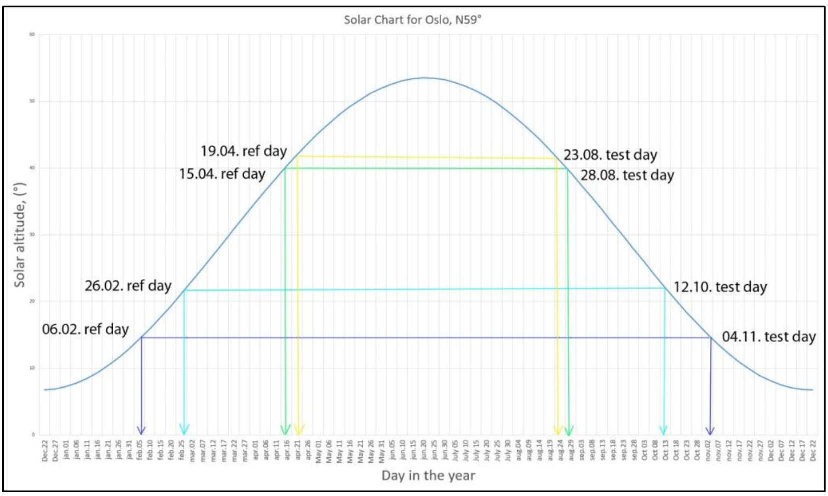

Figure 34 Selection of pair (test and reference) days, based on the equal solar altitude for the analyses

Design of a custom-made reflector in the full-scale test room

This study's aim was to introduce a novel method of light distribution from the light pipe's exit to the working area. Thus, the HLP installed in the test office was straight, without the typically used elbows (bends) to turn the light at the desirable point. Instead, a reflector was mounted at the HLP exit (Fig. 36). The reflector was custom-designed to catch all incoming daylight from the HLP and to direct it to the task surface (working area). A theoretical model of such an approach was used in the semi-empirical study described in the previous section.

When the HLP was first installed in the test office, the light output was observed for a half-year period (from winter 2019 to summer 2020) to understand the expected light distribution at different times of day and year. The daylight output pattern was visible on the wall adjacent to the pipe's exit. It was first observed that the light flux was not evenly spread (as it would have been if an opal diffuser had been used), but, instead, it was rather concentrated in a circular belt around the edges of the tube (Fig. 35). Around noon (during the winter months, when the sun reaches its highest altitude of around 6°, i.e., the closest to the auxiliary incident to the HLP), the circular belt of light observed on the wall was at its narrowest, with an approx. 10° distribution cone (Fig. 35a). In March, around 11am or 1pm, the circular belt appeared to be wider (Fig. 35b), while it was its widest at 10am or 2pm (Fig. 35c), with a distribution cone of approx. 30° from the HLP main axis. The visual judgement of the formed light image indicates that the light flux is very weak before 10am and after 2pm; therefore, only the light distribution cone between 10am and 2pm was used as a parameter in the reflector design.

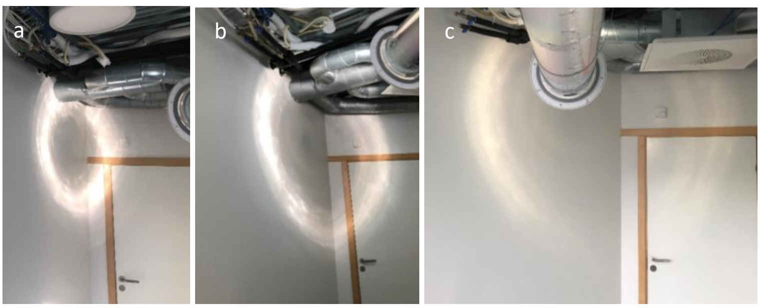

Figure 35 Circular belt formed by light output from the HLP with clear transparent diffuser on the adjacent wall (2 m-distance). a) in January at noon; b) in March around 11AM; c) in March around 2PM;

According to Kocifaj (2009), light pipes with a higher aspect ratio lack the directionality of concentrated light patches due to the sun's position according to the pipe's axis. Hence, it is acceptable to use the assumption of nearly equal light flux values along the pipe's circumference. The percentage of light output that is direct or diffuse was unknown in this study, and, therefore, just the angle of the light, predominantly direct light, was considered as the leading directionality of the light rays.

The initial assumption was that a convex mirror would be needed to 'diverge' (spread) the light rays from the source (the HLP) to the target (desk 2 and part of the wall in front of it), as the source was smaller than the target, but the angle (cone distribution) of the outcoming light rays from the HLP made it possible to use a concave mirror and still obtain the intended light coverage on the task area. The most useful reflector form would be a 3D, compound parabolic-formed reflector, as discussed by Chaves (2017). The time and resources of this study did not allow for fostering the skill to use a digital tool that could design such a reflector. It was therefore decided to design the reflector using 3D Autocad software, featuring forward raytracing from the HLP exit to the reflector surfaces and backward raytracing from the task area to the reflector surfaces. Such a method led to the establishment of a system of reflective surfaces that maps a given region of the source (HLP) to another region, the target, as described in Ries and Rabl (1995) (Fig. 37).

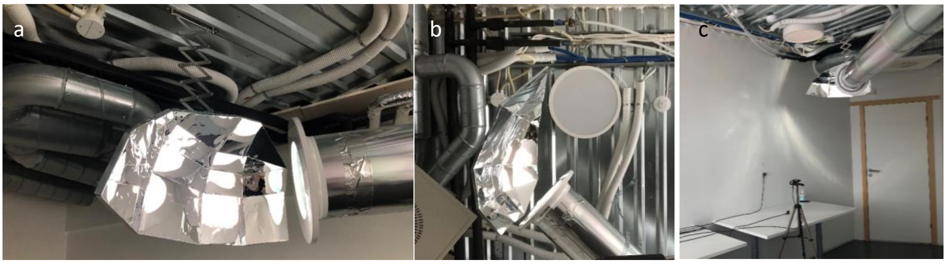

Figure 36 Custom-made reflector, the suspension is enabled by a scissor mechanism that allows for an easy adjustment in place (a); the ceiling view from the desk below the reflector shows how the HLP, reflector, and luminaire are positioned to avoid obstacles to the artificial lighting (b); the view from the corner of the test room; the light redirection is not total; there is a light patch on the wall from the lower left light flux belt (c).

In order to keep the number of reflector surfaces to a minimum to achieve the precise reflection and easy production of the reflector, it was decided to divide the reflector into a net of 4 X 4 parts (Figs. 37-38). The resulting system of reflective surfaces would then look like a multimirror and diverge the flux. The number of reflector surfaces would be 16, making it possible to construct under simple workshop conditions while keeping the manufacturing error low. The reflector was handcrafted out of lightweight aluminium sheets and manually layered using 3M-mirror folium with a 99% light reflectivity. The suspension of the reflector was enabled by a ceiling-mounted scissor mechanism (Fig 36a).

Some quality assurance steps assumed in the design were that the reflector must not pass into the light field of the luminaire and must not reflect the light from the luminaire (Fig. 36b). Further, in the case of nearly axillary rays extending out of the tube, it was important to check whether the rays reflected from the reflector did not trace back to the pipe. In general light rays coming out of the pipe hit the reflector surfaces straightforwardly, while the reflector’s concave form sends them crosswise further to the task surface – rays on the left side of the reflector go toward the right side of the task surface and vice versa (fig 37). The same principle happens with the rays on the upper and down-side of the reflector. Light rays coming from the upper part of the HLP hit straightforward the upper part of the reflector, to be further sent to the task surface area closest to the door; and light rays coming from the down part of the HLP hits straightforward the down part of the reflector, where they are further being sent to the task area closest to the window (fig 38).

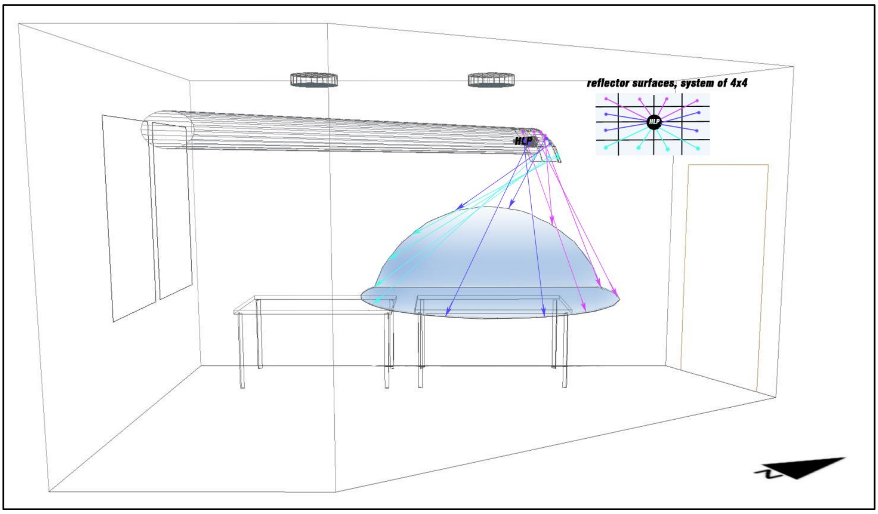

Figure 37 Side view of 3D model of the test office. A custom-made reflector for HLP light distribution receives the light rays from the HLP and reflects them onto the task surface. Light rays coming from the upper part of the HLP hits straightforward the upper part of the reflector, to be further send to the task surface area closest to the door; and light rays coming from the down part of the HLP hits straightforward the down part of the reflector, where they are further being sent to the task area closest to the window. The task surface is in the form of a circular plate covering a 1.2 m radius area, including desk 2 and the wall in front of it.

It was predicted that all reflected rays would fall within an area between 1.2 m from the centre of the table and spread over the imagined circular task surface (Figs. 37-38). The imagined circular task surface had a radius of 1.2m and covered the table and the wall in front of it. This approach, in which the light was cast radially creating a cone was chosen based on the concept of cubic illuminance being an important qualitative aspect of the illuminance quantity that determines the visual modelling in the space, as discussed by Cuttle (1997) and Cuttle (2013).

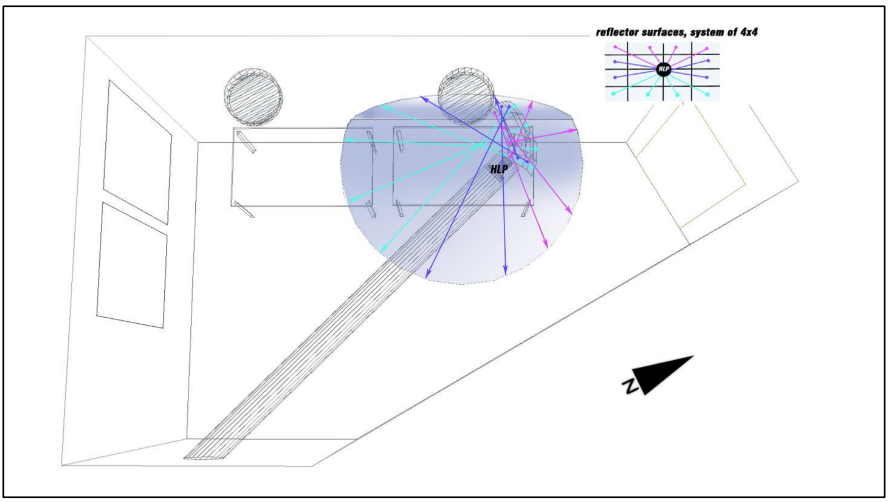

Figure 38 Top view of 3D model of the test office. A custom-made reflector for HLP light distribution receives the light rays from the HLP and reflects them onto the task surface. Light rays that come from the HLP and hits the reflector part closest to the wall, are being sent to the task surface area most far from the wall, and vice versa.

The performance of the custom-made reflector, in terms of light redirection to the imagined task surface, was tested performing an ad hoc measurement during the equinox, with darkened windows. The weather was clear and sunny and the outdoor vertical illuminance, incident HLP, was between 60 and 80Klux. The measurement revealed that the daylight is spread also on the desk closest to the window. This could have happened because of the white colour of the room surfaces and light interreflections on them. Between 200 and 300 lux was recorded by the three sensors connected to the desk closest to the door and up to 50 lux on the 2 sensors connected to the desk closest to the window. This ad hoc monitoring recordings are provided in Paper 5, included in Appendix A.

Full-scale test room in this study

The design of a full-scale experiment is a complex task. Due to the cost associated with such an experimental approach, it is necessary to design all aspects in detail prior to realization (building and installation). Since such studies often deal with some innovation, there are challenges not known in advance. A redesign brings unplanned costs and time delays to a study, and it is also associated with difficulties in replacement at the site. An overview of the steps used to design and perform this full-scale field study are systematized in Table 9.

Table 9 Steps of the full-scale test approach used in the current study.

Steps of full-scale experimental study	**Preparation**	**Experiment**
Set research question for the full-scale study	Set study objective (specifically for whole-year monitoring)	Whole-year monitoring
Set needs for the study (materials, etc.)	Room with windows, HLP and custom-made reflector, two workplaces, illuminance meters for outdoor and indoor illuminance monitoring, and energy meters for lighting energy use	
Choose and validate the study design	Two equal corresponding periods for test and reference experimentation	Monitoring is performed during the test and reference period
Design the experiment regarding the materials in the study	Decisions and installation regarding sun-shading strategy, artificial lighting, daylight linked control, HLP configuration, custom made reflector	The segment that is going to be examined, daylighting via HLP, is altered in the shift of the test to the reference period
Design the experiment regarding the monitoring equipment	Decisions regarding illuminance meters for outdoor and indoor illuminance monitoring and energy meters for lighting energy use	The decisions regarding monitoring equipment were kept equal under both periods
Check prior monitoring	Calibration and installation of the monitoring equipment, data acquisition system, and programs required	Data acquisition system was check regularly
Monitoring of both periods of the study		Visiting the full-scale room twice a week to observe daylighting conditions
Data collection		
Data analyses		

The full-scale test room was a two-person office on the top (6th) floor of a fully operative building at Norconsult Headquarters in Sandvika, Norway. The office originally had windows on its southwest and southeast walls, but the southeast window was removed, with a wall panel constructed instead. The horizontal daylight tube was installed 45° from the southeast wall (Fig. 39b). The aim was to allow for the placement of the tube's exit above the desk closest to the door (desk 2) as well as positioning the tube with a southern orientation.

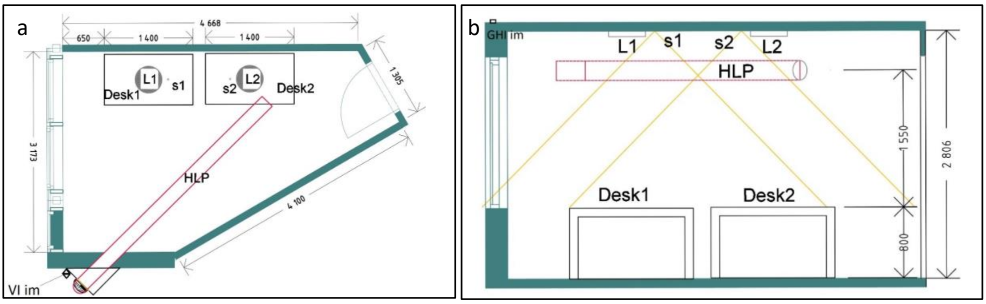

Figure 39 Full-scale test office. a) Plan of the test room; b) section the room: Desk 1 is closest to the window and desk 2 is closest to the door. The HLP exit is above desk 2. Desk 1 is to be lit by artificial lighting from luminaire 1 (L1), and desk 2 from luminaire 2 (L2). S1 is the DLC sensor connected to L1, and S2 is the sensor connected to L2. VI im is the outdoor vertical illuminance meter and the GHI im is the outdoor illuminance meter on the roof.

The artificial lighting system consisted of two luminaires, each of which had their own daylight sensor controlled by the daylight linked control (DLC) (Fig. 39b). The estimated LENI, using Dialux 4.13 software, was 12.76 kWh/m^{2}year. The calculation was based on a seven-day week and ten hours of occupancy, where just daylight dependency factors were employed. Monitoring of the energy consumption for those two luminaires was enabled using separate power meters (10–20 A) for each. The full-scale study was designed with a certain decision regarding the sun-shading strategy to account for glare-free space. Glare reduces visual comfort, making it an important parameter, not solely for the whole-year photometry and energy monitoring, but also for the user-survey study (described in the following section). A detail description and illustration of the artificial lighting system and configuration of the sun-shading system can be found in Paper 4 and Paper 5, both found in Appendix A.

Monitoring of the indoor illuminance was performed using 5 Ahlborn illuminance meters FL623VL and an Almemo logger to log the data on a PC. The CIE recommendation suggest using a grid point for photometry measurements; however, this is related to ad hoc measurements. Using only one illuminance meter per desk is recommended for continuous measurements, as argued by Kruisselbrink, Dangol et al. (2018) and Gentile, Dubois et al. (2016).

The illuminance meters were positioned to cover the horizontal illuminance on the desk closest to the window and desk closest to the door (0.8 m height) as well as the vertical illuminance on the wall in front of both desks (1.2 m height). The last one was positioned on a tripod to record the vertical illuminance at the eye level of the user of the desk closest to the door (Fig. 40, marked as Pim [1-5]). The placement of the illuminance meter coinciding with the luminaire position is not recommended, but, in this project, the same place was the target for the output of the daylight via the HLP; therefore, it was assumed to be the most suitable position. Moreover, because of the non-homogenous light, provided by the highly reflective reflector, the measurement of the light on the solely one position would be misleading, recordings from all illuminance meters will be taken in analyses.

Monitoring of the outdoor illuminance was performed via photosensors (Carlo Gavazzi lux sensors BSH-LUX-U). One sensor was placed vertically along the same south-oriented vertical plane as the tube's entrance dome to measure the vertical illuminance (VI) (Fig. 39a, marked as VI im), and the other was placed horizontally on the roof of the building (Fig. 39b, marked as GHI im) to measure the global horizontal illuminance (GHI). The measurement data was retrieved via a monitoring software UPW3 tool developed by Carlo Gavazzi.

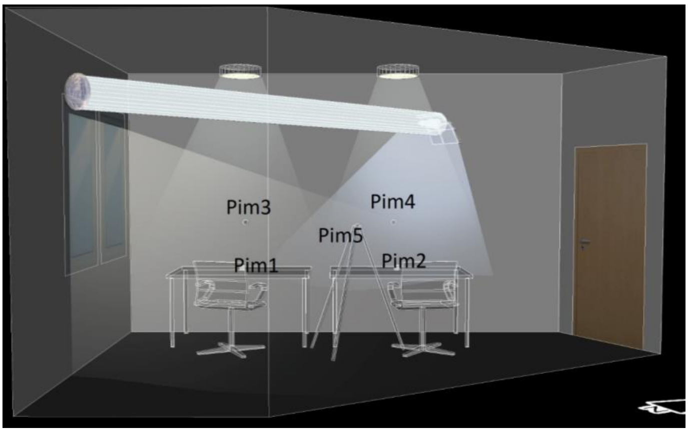

Figure 40 Full-scale test office model of the office with sources of illumination: window, HLP, and luminaires. Pim (1-5) show the position of the indoor illuminance meters

The monitoring procedure included measuring the indoor illuminance, outdoor illuminance, and energy consumption of the artificial lighting every minute from 7am to 5pm. This daily monitoring period was considered the 'occupancy hours' in this study. The parametric measurements were logged continually on a PC for a whole year throughout the aforementioned test and reference periods. Standard calibrated measuring equipment and validated data-collection instruments were used, which ensured the study reliability.

After the measuring data were collected and put in readable form, the analyses of compatible days were performed via hypothesis testing (applying statistical independent t-tests) and understanding their correlations and cause (via correlation statistics). This method is called a causal-comparative method, but, because the conclusions (e.g., relationships between them) are learned ex post facto, this used to be called a retrospective causal-comparative method, as mentioned by Gay, Mills et al. (2006). The retrospective analyses of the compared datasets of several (independent and dependent) variables provided ideas about their interrelationship. In simple terms, in ex post facto research, the researcher investigates a problem by studying the variables after they occur—with no control over them (Apuke 2017). Causal-comparative research is sometimes treated as a type of descriptive research, since it also describes conditions that already exist. A causal comparative study includes categorical independent and/or dependent variables, meaning that they can affect each other, even if they are actually different groups of variables.

4.6. Research method for the user survey in the full-scale study

The user survey study was performed in the full-scale test room described in the previous section. The objective of the user survey study was to examine users' perceptual impression of the daylight delivered via an HLP (and a custom-made reflector) on the working area. Thus, the user survey study used monitoring data on outdoor and indoor illuminance as independent variables in the study (Fig. 41). The test room was situated in a fully operative office building which gave the opportunity for employees in the building to participate in the user survey, thus, counteracting external validity questions regarding the group of participants.

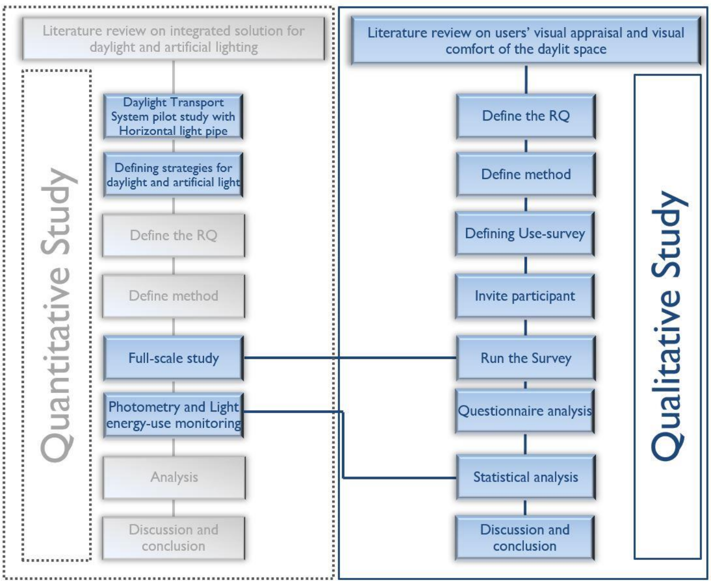

Figure 41 Methodology of the qualitative (user survey) study in the full-scale test office.

The external validity of such a full-scale study could refer also to whether the resulting findings could be applicable to some different settings of the study, such as space differing in size or wall colour, or a different research method. Other known research methods used for a user survey on perceptual impression include scale models and a virtual reality setting.

Experimental approaches for a user-survey study of visual environment

The starting point in each experimental design is to choose the method on the basis of that what is going to be examined. The user survey is about the examination of users' opinion and perceptions of an environment or setting and the surrounding conditions. Their environment is the input and independent variable upon which their opinion will depend. Thus, it is important that the examined environment in an experimental setting has all the features of the environment in reality.

The experimental settings developed for human environmental studies examining visual and perceptual conditions have usually been exposed to either real daylight or simulated conditions. The research approach with scale models (of test and reference box), where participants are meant to look and simultaneously notice differences in the observed parameters, has been performed by Arbab, Matusiak et al. (2017). A similar application of scale models was performed by Zaikina (2012) to examine the human perception of light levels in interiors with equiluminant colours. In the scale models used for human environmental studies the size of the scale model is an important parameter due to human vision performance, limitations of convergence, and the accommodations of the human eye.

Other methods used in environmental research have included the application of stereoscopic images of the visual condition of a space recorded via an HDR camera. The study by Moscoso and Matusiak (2018) used this approach to examine human preferences and aesthetical evaluation of interiors. The method of virtual reality offers the possibility to control the input parameters, which are, by nature, variable, and it is impossible to control them in reality. This method later on evolved into the application of virtual reality glasses, with which a recorded or simulated indoor environment was examined (Moscoso, Chamilothori et al. 2020, Moscoso, Chamilothori et al. 2021).

The current study aimed to examine user attitudes about daylighting via a specific daylighting system. In such studies, according to Ruck, Aschehoug et al. (2000), it is important to check if the performance of the examined daylighting system, and some crucial characteristic functions well, e.g., if the system does not produce negative issues regarding visual perception, visual adaptation, and visual comfort. It is also important to check if the light propagation, transmission, and reflection in the full-scale room function as expected.

According to Ruck, Aschehoug et al. (2000), full-scale test rooms are the best for examining visual performance. This is not just because photometric units can be measured (illuminance on the working surface), but the contrast between the object/background and visual comfort with luminance contrast (between task/background, illuminance uniformity) can be assessed. The scale models would not be able to provide this information due to the inability to scale down objects that are important in the luminous environment (fabric textures, the artificial lighting system).

Qualitative approach in the environmental study

Several studies have implemented user surveys in terms of visual impressions of a space regarding the daylight provided by a daylight transport system (Velds 2001, Al-Marwaee and Carter 2006, Carter and Al Marwaee 2009). Such studies have used interview in the form of a questionnaire as a method to collect data for the analyses. In these studies, the employees that regularly use the examined space were the participants in the user survey.

The reviewed literature on user survey studies in general has used mostly interview as an approach to collect users' opinions (Velds 2001, Mattsson 2015, Bellia, Fragliasso et al. 2017). Other known methods of studying environmental perception include observations and conclusions, such as *cognitive maps*, which is a method used in environmental psychology, or *personal space*, which is associated with environmental-social science.

The interview of this user survey study consisted of three parts. The first part, a reading test, and the second part, a colour test, were conducted during the preparation time in order for the participants to adjust to the lighting conditions. The third part involved a questionnaire with questions regarding their visual perception of the test room, such as the lighting quality attributes of the daylit space; statements regarding possible issues of visual comfort; and, after that, statements about the integration of daylight and artificial lighting. This third part involved a questionnaire with 46 questions divided into four parts of which: a) perception of the test office (the most important and relevant part of this study); and b) personal information, were used in this study, while c) the social and physical climate in the original workplace and d) the daylighting, sun-shading, and lighting conditions in the original sitting place for each participant, will be used in the future research.

The quality attributes used in the current study were first selected based on the research on the impact of window size and room reflectance on user perceptions (Moscoso and Matusiak 2015). The quality descriptors used in this study are listed, and according to Moscoso and Matusiak (2015) they present following:

- *Spaciousness* refers to if the room is experienced as wide, commodious, and spacious
- *Openness* refers to if the room has an open view free of obstruction
- *Pleasantness* refers to the feeling of pleasure, delight, or satisfaction, meaning that the room is experienced as nice and enjoyable
- *Excitement* refers to feeling like a room/space elicits active, positive conditions
- *Complexity (*used as *interesting)* refers to a room that is visually rich and has distinctive elements
- *Legibility* refers to the readability of the room and if it is easy to find one's way around the environment

The other quality descriptors used in the current study were *brightness* and *evenness* (used as *uniform*). They were chosen based on the concept of photometry and on the basis that most people working in offices under artificial lighting are familiar with these terms and their meaning. The application of these terms was justified within a Scandinavian study on colour and light (Arnkil, Fridell Anter et al. 2012).

The definition of a question or assumption in the questionnaire is an important task that justifies the validity of the study. In a qualitative study, both reliability and validity can be at risk if the parameters that the phenomenon is measured on are not suitable. The question asked needs to have the same meaning for each participant or be valid so that the participant's response gives a reliable answer. The validity and reliability in the qualitative research are described in section 4.2 and given in Paper 4.

The participants' answers to the question were collected using semantic differential rating scales based on a bipolar adjective of *agree/disagree*. Semantic differential scales were developed in the 1970s, and they have been used in many environmental studies regarding impressions of an architectural environment (Moscoso 2016). The concept of semantic differential scale is in the rating procedure, where a person is asked to give an evaluation on a scale of two (bipolar) extremes (e.g., extremely positive–extremely negative). Five-item scales and seven-item scales are most typically used. For this research, a five-point scale was established between the extremes of strongly disagree and strongly agree.

The steps of a semantic differential scale are assigned numerical values, 0 to 4 (in the case of this study), which are used to quantify the user opinion. Thus, the qualitative descriptors become measurable and can represent the variable in an experiment. This is the step that connects qualitative and quantitative approaches. In each experiment, there are two sets of variables, the independent variables, which are the phenomena that give input to the phenomenon that depends on them, and, the dependent variable, which the following effect is measured on. In one controllable experimental setting, the researcher will change and manipulate the independent variable and then measure the values of the dependent variable. Further analyses of this data will result in the relationship between the variables.

Quantification of the qualitative study findings

In experimental research, collected numerical data can be analysed using statistical analyses. Such analyses can help to obtain an accurate explanation of the relationship between independent and dependent phenomena, but this is of course dependent on the validity and reliability of the experiment itself, as argued by Creswell and Miller (2000) and Creswell and Creswell (2017). When it comes to the reliability of the statistical analyses, we can also review the reliability of the result. The reliability of the findings is based on the number of participants (the size of the sample) used in the study.

The statistical analyses used in the current research were chosen based on the research rationale and research aim. The different parameters based on the sample size and values, e.g., mean (M), standard deviation (SD) standard error (SE), and variation, are called descriptive statistics. Descriptive statistics analyses values for an individual variable.

Then, further, to analyse the relationship between the values of the different variables (both independent and dependent), inferential statistical analyses were used. Interferential analyses are those that establish the findings of a study based on the hypotheses.

In the current study, the t-test statistical test was used to compare the values on the mean (M) of two groups of participants that were divided into in the examination design (test and reference group). T-tests are usually used to test hypotheses and check if the groups differ from each other—in other words, if a difference between them really exists.

A correlation test is used to find if two or more variables in a sample have certain relationships and to what extent. The degree of relationships between variables is described by correlation coefficients. The correlation coefficients are expressed between +1.00 to -1.00, where a stronger relationship is characterized by a higher number (closer to 1.00). If the correlation is positive, the coefficient is positive; and vice versa. According to systematization given by Creswell and Creswell (2017), the type of correlational design used in this study is an *explanatory* design. An explanatory design is a research design where the conducted experiment seeks to determine to what extent one variable (independent) co-varies with another (dependent).

Mixed-methods approach

The overall approach for this user survey study was a combination of qualitative and quantitative methods; according Creswell and Creswell (2017) and Creswell (2021), this is called a mixed method. The experimental approach including the users' appraisal on an environmental setting, e.g., visual and perceptual conditions, characterizes this study as qualitative. The application of numerical data collected from the full-scale monitoring (during the user survey) characterizes this study as quantitative. The quantitative data was the independent variables, those affecting the dependent variables, the user's opinion. Both numerical variables (independent) and scale rating variables (dependent) were used in the statistical t-tests and the correlation analyses to test the hypotheses.

5. Results

The findings of all research activities within this PhD study are presented in the following subsections. The findings from the first part helped develop the activity of the next one (etc.) in the accordance with the research aim. The main research aim, as stated in the introduction, was to develop reliable evidence of the applicability potential of daylight transport systems in high-latitude areas. This potential is seen through increased daylight levels and energy saving of the artificial lighting, and improved user appraisal of the daylighting conditions in the office equipped with the daylight transport system.

5.1. Findings from the literature review

The first part of this research, as described in the methodology chapter, was a comprehensive literature review (section 4.3). The inductive reasoning approach was used to systematize the reviewed sources and find conclusions and generalizations. Within the literature review, different themes were identified, e.g., different principles in light collection (active and passive); different transportation mediums; the analytical modelling of the light transport prediction; and market available products. The information within these different themes was sorted and described.

The research question for the literature review was the following: Which of the advanced daylighting systems available on the market today has the greatest potential to be used on the facades of buildings at high latitudes? The *potential* can be discussed through the possibility of the DTS to provide the highest level of suitable daylight indoors. In the context of this study, high latitudes mean latitudes higher than 55 degrees, as several capitals (Oslo, Stockholm, Helsinki, Copenhagen) and other large towns (Bergen, Orebro) are located above this latitude.

According to the daylight conditions for the high-latitude locations, with the predominantly overcast sky providing diffuse light from the zenithal part of the sky and partly clear sky with a direct low angled sunlight that changes position, it could be concluded that the systems that can efficiently collect zenithal daylight and the variable position of direct sunlight should have strong *potential*. Table 10 shows the findings on the suitability of daylighting systems' components under a predominantly overcast sky and direct sunlight at a low solar altitude.

The anidolic collector showed the potential to collect diffuse light from the zenithal part of the sky dome, but it could also be custom-designed (according to the edge-ray principles) to suit other directions of light rays. LCPs with sloped cuts showed the potential to redirect a span of different light ray angles, which could be used for sun altitude and azimuth that variates through the day.

Table 10 Review of suitability of elements of daylight transport systems in predominantly overcast sky and direct sunlight at a low solar altitude

Daylight transport system	Directionality of transported light	Suitability for direct light and predominantly low solar altitude	Suitability for predominantly overcast sky
Collector			
Anidolic collector	Predominantly overcast and clear in temperate climates	Partly, if constructed according to edge rays for a low solar altitude	Excellent
Laser-cut panel	Predominantly clear in hot and temperate climates	Excellent	Partly, depending on a configuration and tilt of the panel
Compound parabolic concentrator	Predominantly overcast and clear in temperate climates	Excellent	Partly, depending on the form of the concentrator
Luminescent solar concentrator	Predominantly clear	Excellent, can be placed to align the incident angle	Bad
Fluorescent fibre solar concentrator	Predominantly clear	Excellent, can be placed to align the incident angle	Bad
Static light concentrator	Predominantly clear	Excellent, can be placed to align the incident angle	Bad
Heliostats	Predominantly clear	Excellent	Bad
Mirror sunlight system	Predominantly clear	Excellent	Bad
Fresnel lens concentrator	Predominantly clear	Excellent	Bad
Parabolic concentrator	Predominantly clear	Good, but positioning is problematic for building facade	Bad
Light transport element			
Vertical pipes	Diffuse and direct	bad	Excellent
Water-filled pipes	Direct	bad	Excellent
Double pipes	Diffuse and direct	Bad if vertical, but relatively good if horizontal	Excellent if vertical, bad if horizontal
Horizontal pipes	Diffuse and direct	good	Yes, if configured with anidolic collector
Horizontal ducts	Diffuse and direct	good	Yes, if suited with anidolic collector
Optical fibre	Direct	good	Bad
Optical rods	Direct and diffuse	Relatively good for short distance	Bad
Prismatic light guides	Direct	Relatively good	Bad
Lenses and mirrors system	Direct	Relatively good for short distance	Bad
Light distributors			
Prismatic, translucent diffuser	Diffuse	Yes, it reduces eventual excessive light	Partly, it decreases the efficacy of predominantly diffuse light
Lambertian, partly clear diffuser	Diffuse	Yes, it reduces eventual excessive light and increases transmission	Suitable, it partly decreases the efficacy of diffuse light
Crystal glass diffuser	Diffuse and direct	Partly, it can introduce excessive light and light diffraction	Suitable, it increases light transmission
Radial Fresnel lens	Direct	Partly, it can disperse excessive light	Partly, light dispersion can be uncontrollable
Anidolic emitter	Diffuse and direct	Partly, light emission depends on a surface finish	Excellent
Luminaire (spot or downlight)	Direct	Bad, it can introduce excessive light	Bad

Both vertical and horizontal light tubes could be used for daylight conditions in high latitude locations with specially tailored collectors. However, the application would depend on the building function and architecture. Fig. 42 shows the general principle of vertical and horizontal light pipe application. The vertical light pipes are suitable for low compact buildings, while the horizontal light pipes are suitable for a southern orientation in multilevel buildings.

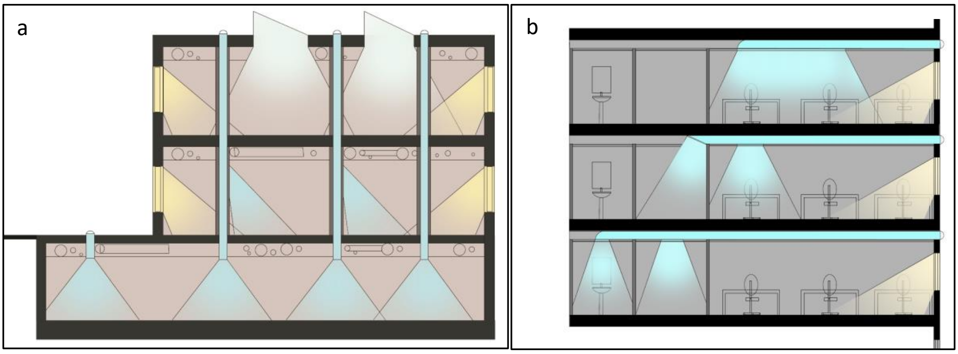

Figure 42 illustration of light pipe application in high litictude areas with predominantly overcast sky and low altitude sun. a) Vertical light pipes are suitable for low compact buildings. b) Horizontal light pipes are suitable for a south façade for multilevel buildings[21].

The literature review also resulted in an overview of the different available systems on the market and their light transmission efficacy. This overview is presented in Table 11. All systems are available in many configurations to suit new buildings or redevelopment. Solatube is efficient for both high and low solar altitudes because of its Reybender optics in the acrylic dome. Monodraught provides light redirection on a diamond dome with prismatic optics, while LightWay promises higher light transmittance through a Bohemia crystal glass dome. Solarspot has a clear acryl dome and relies on its Fresnel lens RIR deflector for low direct light, while Velux relies mostly on diffuse zenithal light collected through the skylight dome. A horizontal 'Adasy system' has shown high potential for use in a ceiling plenum.

Heliobus's daylighting shaft is simple and has a high potential for application, while Heliobus's light guide is a product that needs customization for each application. The Parans and Himawari systems show high efficacy under clear sky conditions, while, under non-clear sky conditions, they can be an alternative source. The Solux and Sundolier systems have historically only a few applications. Their large dimensions and the design shape of the collector and guide components make them unattractive for use on the building exterior.

For high latitude locations with predominantly overcast sky, Solatube could be used as a vertical system, and Solarspot, LightWay, and Adasy could be used as a vertical and horizontal system. The findings are illustrated in Table 11, and detailed findings and references to the literature sources can be found in the original article featuring the literature review, Paper 1, included in Appendix A.

[21] Permission to use images granted by Lyskultur on the 14th of February 2022.

Table 11 Certified daylight transport systems as market available products

Daylight transport system	Producer's site	Type of collector	Type of transport element	Type of distributer	Efficiency, light transmittance according to the producer
Solatube	https://www.solatube.com	Polycarbonate dome, clear or Reybender technology, and LightTracker™ Reflector	Straight and elbowed pipes Spectralight® Infinity tubing material	Prismatic and Fresnel lenses	81.3% for the dome; 99.7% Rf for tube
Solarspot	http://www.solarspot.it/en/home-res	Acrylic clear dome, RIR® Fresnel lens light funnel	Straight & elbowed pipes Vegalux® – anodized aluminium laminated with 3 m Daylighting DF2000MA film	Lambertian diffuser, prismatic, pearled	86% for the dome; 99.7% Rf for tube
Monodraught	https://www.monodraught.com/products/natural-lighting/sunpipe	Acrylic Diamond Dome with prismatic vertical on the circumference	Straight and elbowed pipes SUPER- SILVER mirror finished aluminium tube	Satin diffusers	84.3% for the dome; 98% Rf for tube
Velux	https://www.velux.com/products/sun-tunnels#underthesun	Dome like Skylight	Rigid and flexible Sun tunnels	EdgeGlow diffuser	Not available
LightWay	http://www.lightway.cz/english/	Acryl and bohemian crystal domes, parabolic-like mirror concentrator	Straight and elbowed, horizontal and vertical light pipes	Satin acryl diffuser and bohemian crystal diffusers	92% Tf for acryl dome 94% Tf for Crystal dome 98-99.8% Rf for tube
ADASY	https://www.eurekanetwork.org/project/id/3575 & https://lledogrupo.com/en/	Façade-mounted array of truncated compound parabolic concentrators (T-CPC)	Horizontal mirrored chamber	Prismatic diffusers	
Heliobus daylight shaft	https://www.heliobus.com/en/products/daylight-shaft/	Laminated safety glass cover	Highly reflective shaft for basement	Laminated glass	Not available
Heliobus® Light Guide	https://www.heliobus.com/en/products/daylight-engineering/	Mirror	Prismatic light pipe	Prismatic light emitter	420 lux for overcast sky of approx. 10000 lux
Parans	https://www.parans.com/products/parans-system-sp4-sunlight-collector/	Multiply Fresnel lenses collector	Optical fibre plastic	Spot luminaire, satin panel	100m length, 30 floors. 80% transmittance, energy-saving 20% north 46% south
Himawari	https://www.himawari-net.co.jp/e_page-index01.html	Fresnel lens honey-combed system	Large diameter quartz glass fibres	Spot luminaire	Up to 200 m, but 23% transmittance, after 2m length 500 lux indoors
Sundolier	http://www.designguide.com/products/70757/Sundolier	Mirror sunlight system	24'' hole – light pipe	Light distribution fixtures	Up to 3 floors
Solux by Bomin Solar Research	www.bomin-solar.de	Big single Fresnel lens	Liquid light guide	Luminaire	80-90% after 10 m length

Daylight transport systems are designed for sky and sun conditions for a specific location. Application in other locations brings decreasing transmittance efficacy, and the energy-saving potential is not certain. The findings from the literature review helped to select the most suitable system for high latitude areas for further examination in an empirical study. It was concluded that the horizontal light pipe (HLP) can be suitable in the case of façade application in a low solar altitude location, as it is more exposed to the direct rays of the sun. Sunlight has up to 10 times more light flux than daylight under an overcast sky. This indicates that the diameter of an HLP could be smaller compared to a vertical light pipe transporting diffuse light. The diameter of the vertical pipe is estimated according to diffuse daylight-overcast sky conditions, and, in realistic planning conditions, it would not be possible to apply it for more than three top floors of a building. The application in a multistorey building would then focus more on the HLP (Fig 42b). The application of an LCP could help the HLP increase the collection of (variable) direct sunlight flux in the case of wide solar azimuth variation (the case of the study location). This idea was previously demonstrated in the Australian study by applying the HLP in multilevel buildings and LCP that collects sunlight with wide altitude variations (Garcia Hansen, Edmonds et al. 2001). The decision was thus made to examine HLPs and LCPs in an experimental study as the next step.

5.2. Findings from the experimental-scale model study

The second part of the study had the objective of examining the light transmission efficiency of the horizontal light pipe (HLP) under the condition of low solar angles, the solar microclimate of the location of the study (Oslo). The potential of LCP application, as a collector for light rays at the entrance of the tube, was examined as well, and results were compared to the base case (HLP without an LCP). In this part of the study, two sets of findings were developed. The first findings regarded the light transmission efficiency for the HLP of an aspect ratio of 8 and for each LCP configuration tested in the experiment with a scale model. The light transmission efficiency was developed for separately direct and diffuse illuminance and expressed via the η, called the standard daylight characteristic in this study. The – η is the ratio of the measured output illuminance value and input illuminance value on the HLP. The second set of findings was in regard to the daylight autonomy (DA). This involved the further application of the first results (in form of coefficients) into metrical values based on the requirements of daylighting design practice.

The assumptions of the study were that tilted LCPs (here, called T-) with horizontal straight cuts will deflect the light from high-altitude angles and provide higher light transmission efficiency for the light with higher altitude, while the two symmetrically rotated LCPs (here, called R-) with vertical cuts will deflect wide azimuth (morning and evening) light and provide higher light transmission efficiency for the oblique light-incident angles. These assumptions were illustrated in section 4.4 (Fig. 25). Fig. 43 illustrates how the LCP samples could be applied in the tube’s dome under the assumption that they also can form a climate shell (without the need to use a glass dome). The angles shown in the figures are characterized by the configuration of each LCP sample. Coding of each LCP sample refers to the position (tilted or rotated), then second digit presents the distance of the cuts (D), and the last digit presents the angle of the tilt or rotation (fig. 43).

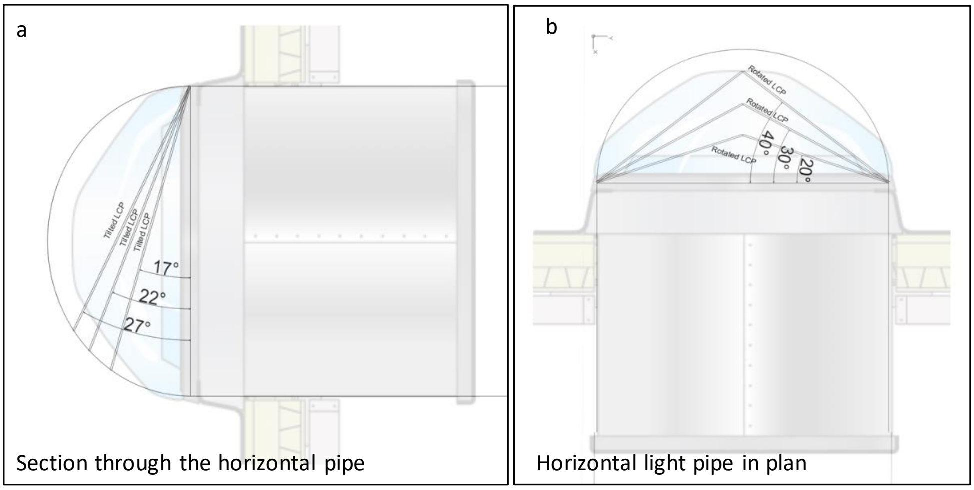

Figure 43 a) Tilt of LCP in an oval shape is limited by the shape of the dome. b) Rotation of symmetrically oriented LCP in half-oval shape is limited by height of the dome.

The first set of findings regarded the η (T-R) for each examined LCP configuration and its comparison with the base case. The η was developed for each cell of the temporal matrix, addressing specific sun's altitude /azimuth positions (explained in section 4.4). The summation of all – η (in all matrix cells) indicates the cumulative potential ($\eta_{cumulative}$) for each LCP configuration (Figs. 44-45). The findings were developed from the experimental measurements (thus separately for direct and diffuse illuminance) and refer to the tube with an aspect ratio of 8.

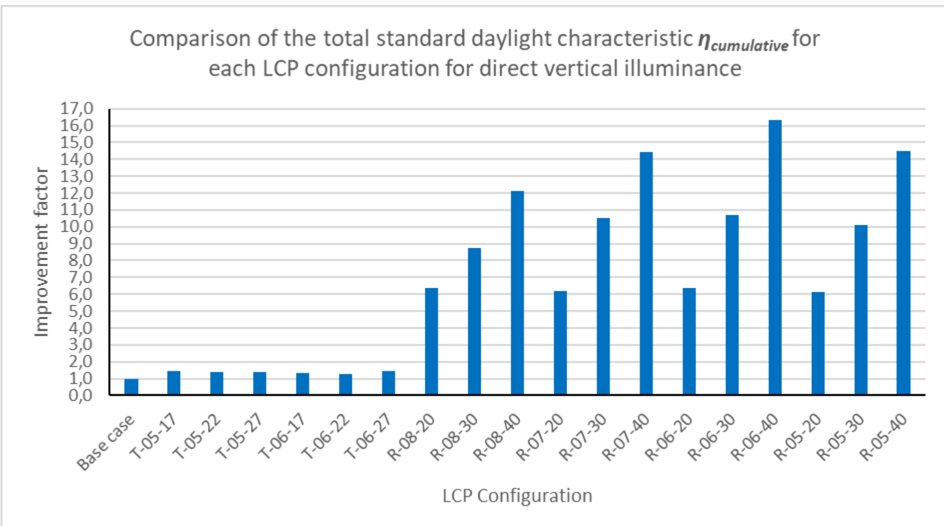

Figure 44. Comparison of the standard daylight characteristic $\eta_{cumulative}$ for each LCP configuration for direct illuminance (aspect ratio 8).

The standard daylight characteristic (***η***) for all R-LCP configurations increased from 6 to over 16 times for direct light when compared with the base case (Fig. 44). This meant that the light transmission efficiency was very much improved with the application of the rotated LCP samples (R). The T LCP configurations showed a slightly increased η of 1.46 times (46%). This indicates that the tilted LCP configurations increased the light transmission efficiency much less than the rotated ones for the direct incident light.

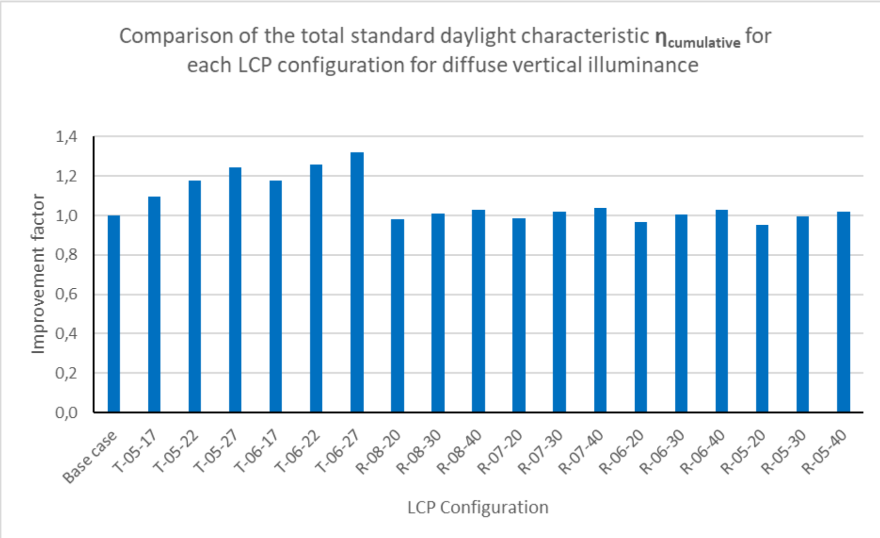

Figure 45 Comparison of the standard daylight characteristic $\eta_{cumulative}$ for each LCP configuration for diffuse illuminance (aspect ratio 8).

Fig. 45 shows that the highest increase in η for diffuse light occurs in the T LCP configurations (up to 1.32 times; 32%), while none of the R LCP configurations show any significant increase. This finding shows that the LCP as an optical collector is much more effective for the direct light rays of sunlight. The very high increase in η for the R samples in the direct light experiments can be explained through the difference between the extreme incident angles of the direct light, which are, in the case of altitude variability, 46°, and, in the case of azimuth angles, up 2 x 90°.

The second set of findings refers to the daylight autonomy (DA) of the theoretical model of the office space with 2 and 3 working areas. A comparison of the base case results for DA with each of the LCP configurations was performed as well in this part. Fig. 46 illustrates the theoretical model, where daylight is transported via the HLP deeper in the space and delivered to the task area by a custom-made reflector. The E_2 value shown in the figure is taken as a threshold value from the DA approach. DA_{100} and DA_{300} were used, meaning that 100 lux and 300 lux should be supplied at the task surface, respectively. The necessary threshold value of E1 (daylight supplement at the pipe's exit) was calculated using inverse square law (Fig. 46). The E1 threshold should be achieved by the Er_{total}, which is the result of the summation of Er_{direct} and $Er_{diffuse}$ for any testing configuration. The Er (for the base case and each LCP sample) was developed using the Satel-Light values of direct and diffuse illuminance, and the first set of findings (the light transmission efficiency), as described in section 4.4. The mathematical analyses of this approach are described in detail in the research article corresponding to this study, Paper 2, included in Appendix A.

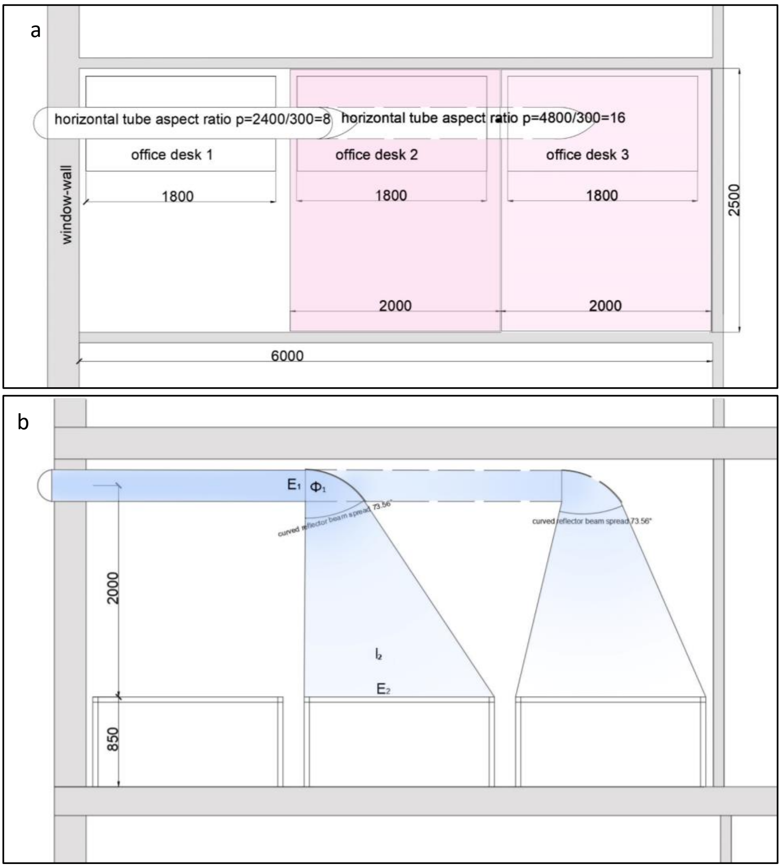

Figure 46 a) Plan and b) vertical section of a typical office (the second and third working areas in the office correspond to a light pipe with an aspect ratio of 8 and 16, respectively).

The results of the mathematical analyses for DA_{100} and DA_{300} for a tube aspect ratio of 8 and 16, developed as the daily and yearly DA, are presented in Figs. 47-50. The daily value refers to a typical day in one of the periods of the year, explained in section 4.4, while the yearly DA is a summation for all seasons.

The DA is presented in hours (instead of a percentage of time). This approach was chosen in order to compare the results within a defined occupancy time for a typical office building, which is from 7am to 5pm.

The findings of the analysis of DA_{100} for the aspect ratio of 8 (Fig. 47) show that the R-LCP configuration with a 40° (R-07-40) rotation produces the highest improvement in the total yearly DA hours (e.g., by up to 10%). The improvement in the DA, prolonged by nearly two hours, is mostly noticeable during the summer months.

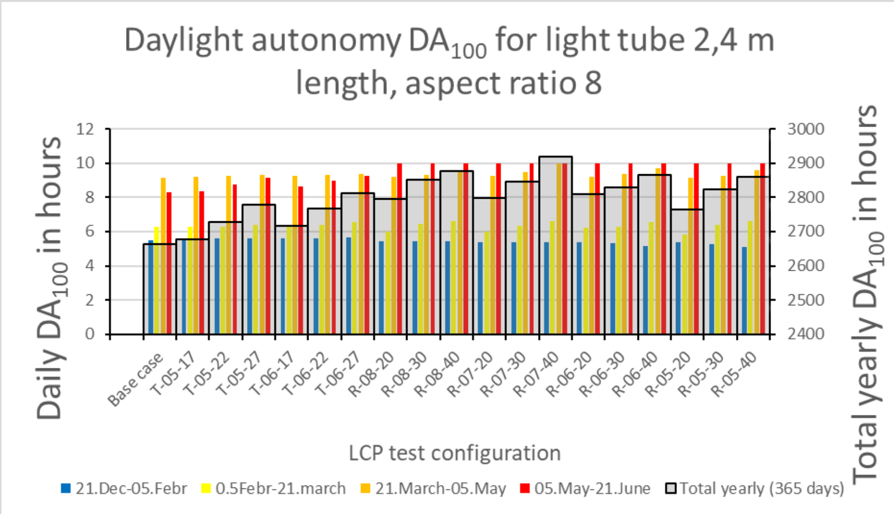

Figure 47 DA in hours for each LCP configuration when illuminance exceeds 100 lux on the reference surface, aspect ratio 8.

The findings from the analysis of the DA_{300} for the aspect ratio of 8 (Fig. 48) show that the increase in terms of the total yearly hours is highest for T-06-27, R-08-40, and R-07-40 (up to 19% longer yearly DA in hours). The highest improvement can be observed during the late spring: 1 hour and 20 minutes each day. It can be noted that all T configurations prolonged the DA_{300} during the early spring, especially T-06-27, up to 30 minutes. None of the R configurations showed improvements for the same period, and the reduction in the daily hours during the summer is noticeable for configurations R-05-40, R-05-30, R-06-40, and R-06-30, while the opposite is found in the late spring.

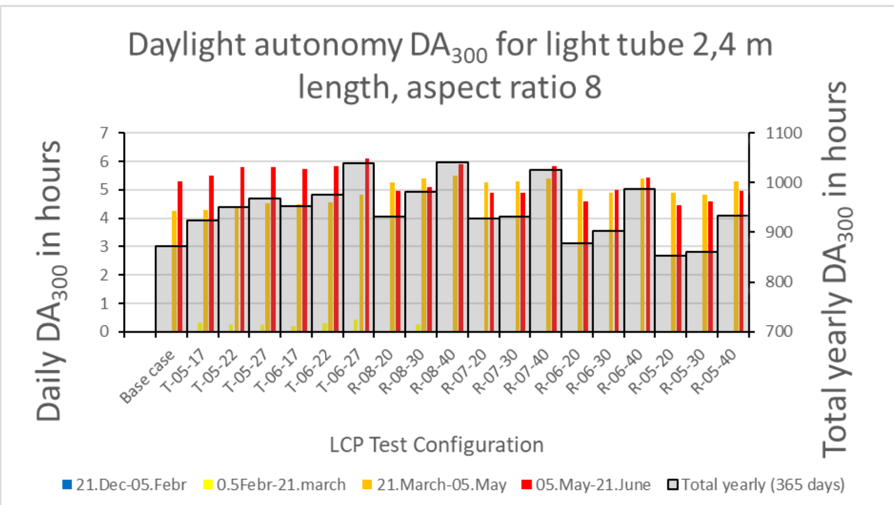

Figure 48 DA in hours for each LCP configuration when illuminance exceeds 300 lux on the reference surface, aspect ratio 8.

The findings for the tube with an aspect ratio of 16 showed a similar tendency. For DA_{100}, it is possible to expect 10 hours of daylight supplement during the summer using any of the rotated LCP configurations, which is one hour and 45 minutes longer than in the base case (Fig. 49). The total yearly improvement is most noticeable in the R-08-40 and R-07-40 configurations (up to 8.75% each).

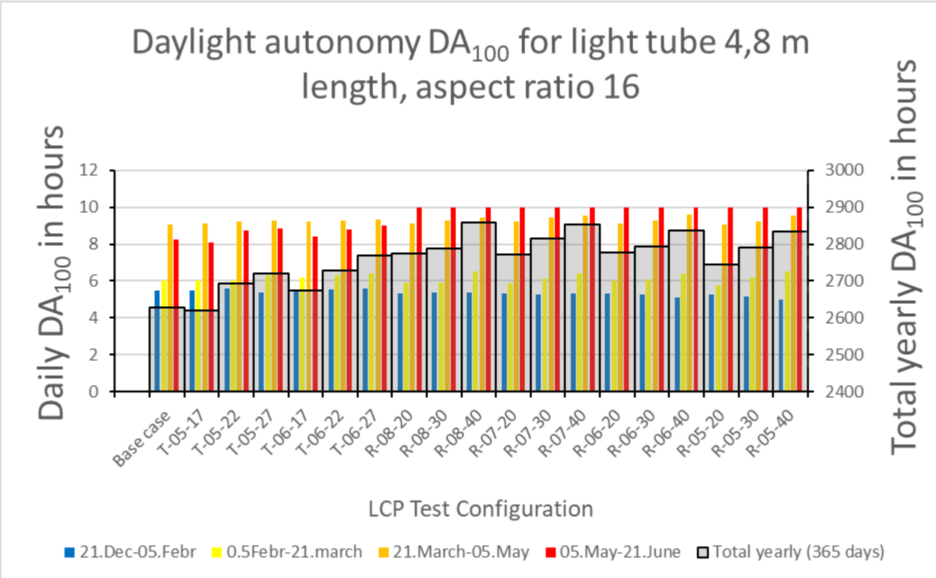

Figure 49. DA in hours for each LCP configuration when illuminance exceeds 100 lux on the reference surface, aspect ratio 16.

For DA_{300} (Fig. 50), the highest improvement in total yearly hours is observed for T-06-27, R-08-40, and R-07-40 (with up to 16%). Meanwhile, T-06-27 especially enables longer DA_{300} during the early spring. A reduction similar to that with the aspect ratio of 8 is noticeable for configurations R-05-40, R-05-30, R-06-40, and R-06-30. They contribute positively during the late spring but reduce the DA during the summer.

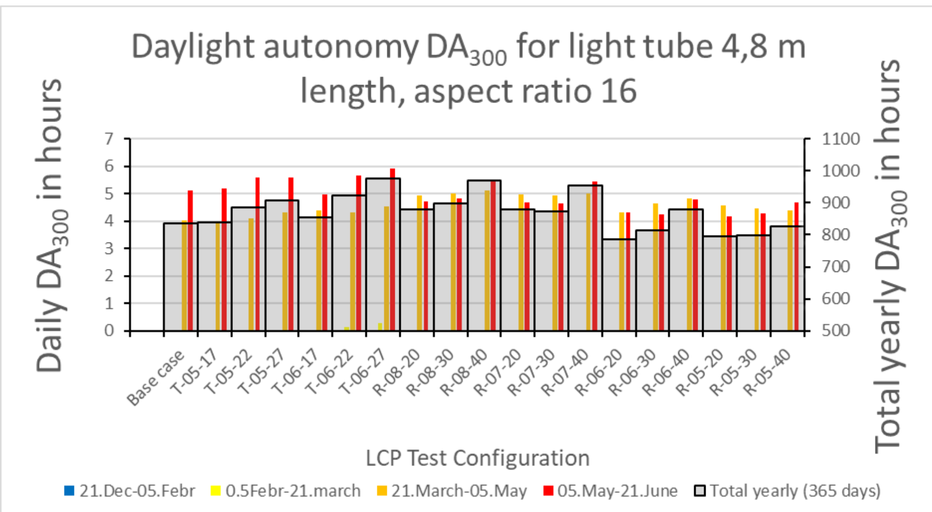

Figure 50. DA in hours for each LCP configuration when the illuminance exceeds 300 lux on the reference surface, aspect ratio 16.

The findings from this semi-empirical study also show that a two-fold increase of the light pipe's length (aspect ratio 8 to aspect ratio 16) brings about a reduction in the total yearly DA number of hours by about 6%. This information can be useful for a simple estimation of DA_{100} for pipes even longer than 4.8 m. The daily DA_{100} in hours still shows the possibility of 10 hours for 100 lux at a 4.5 m distance from the façade wall during the summer period. DA_{300} would be achieved for almost six hours during the same period. The total yearly DA_{300} for LCP configuration T-06-27 shows that the daylight requirements of the working place 4.5 m from the façade are fulfilled for 976 hours, which is almost half the regular total occupancy hours during the year.

The most important finding of this study for further work was the fact that even the base case of the HLP, without any LCPs at the entrance, enabled a minimum of five hours of daylight with 300 lux for both the 8 and 16 aspect ratios. The aspect ratio of 16 especially corresponded to an area where the window does not provide enough daylighting and electrical lighting needs to be used during all occupancy hours.

5.3. Findings from the full-scale field study

The field monitoring study, carried out as part of a full-scale study, assessed the monitoring of the indoor and outdoor illuminance and lighting energy use, as described in section 4.5. The analyses of the recorded illuminance values in the test and reference period were performed by inferential statistical analyses, while the analyses of the total lighting energy use for the two luminaires (L1 and L2) were performed by calculating the relative difference between the simulated LENI value for the lighting solution and the recorded LENI value.

To analyse the illuminance data, several sets of test and reference days in the study were selected and analysed. A corresponding pair of days for the TEST and REF periods was chosen according to their having equal solar altitude, as well as the daylighting conditions. A detailed explanation about the selection of these pairs of days can be found in the research article corresponding to this study, Paper 5. In the body of the thesis, just one example of the analysed pairs, illustrating the most common daylight conditions for the study (clear and sunny sky conditions, during the equinox time of the year) is described, and the reader is advised to review Paper 5 for other examples.

In the analyses of illuminance values, the independent data were a) the outdoor vertical illuminance incident pipe (VI) and global horizontal illuminance (GHI); and the dependent data were b) the indoor illuminance on the working areas in the test office (Desk 1 horizontal and vertical; and Desk 2 horizontal and vertical, and observer).

The findings from the photometry analyses during equinox for the TEST day 12.10.2020, and corresponding REF day 26.02.2021 are presented in Figs. 51-54. The illuminance meters (Pim1-5) recorded daylight provided by the window and daylight provided via the HLP (in the test period only), and artificial lighting. It was not possible to separate these two values (of daylight and artificial lighting). However, the values showing solely the artificial lighting levels on desk 1 and desk 2 were developed from the power consumption data for each of the luminaires (L1 and L2) individually, are presented as well. In figs. 51-52, entire occupancy period (daily recorded period) is presented for the TEST and REF day. It is possible to visually compare these two days in periods starting at 11 am, when equal daylight conditions occur, and the artificial lighting begins to dim to 0.

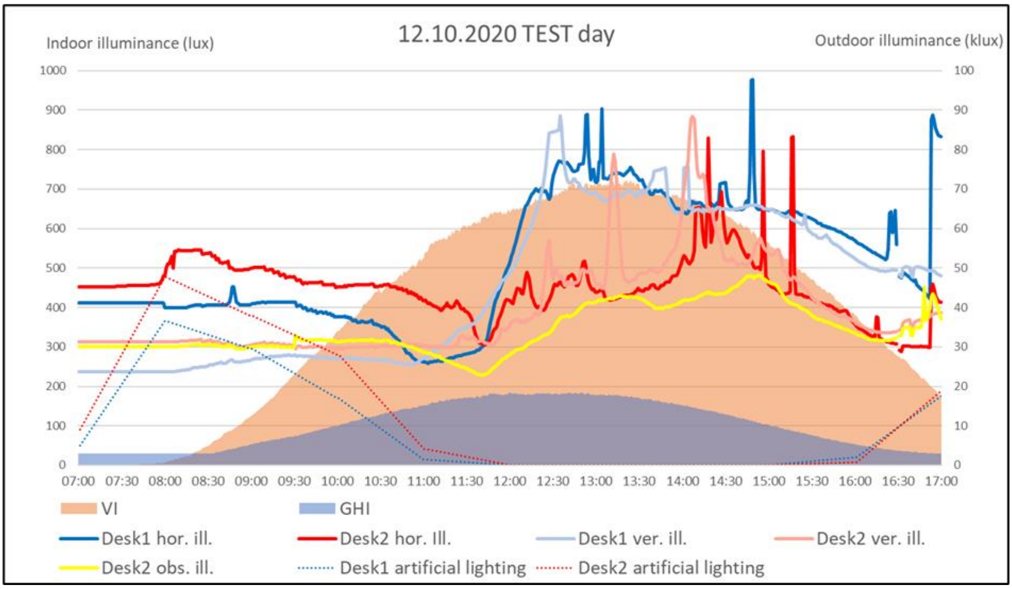

Figure 51 Recorded data for the TEST day. The areas show outdoor lighting conditions (VI and GHI) while bluish lines show illuminance recorded on the desk 1 and reddish lines show illuminance recorded on the desk 2. The blue and red dotted lines show the illuminance provided by the artificial lighting for desk 1 and desk 2, respectively.

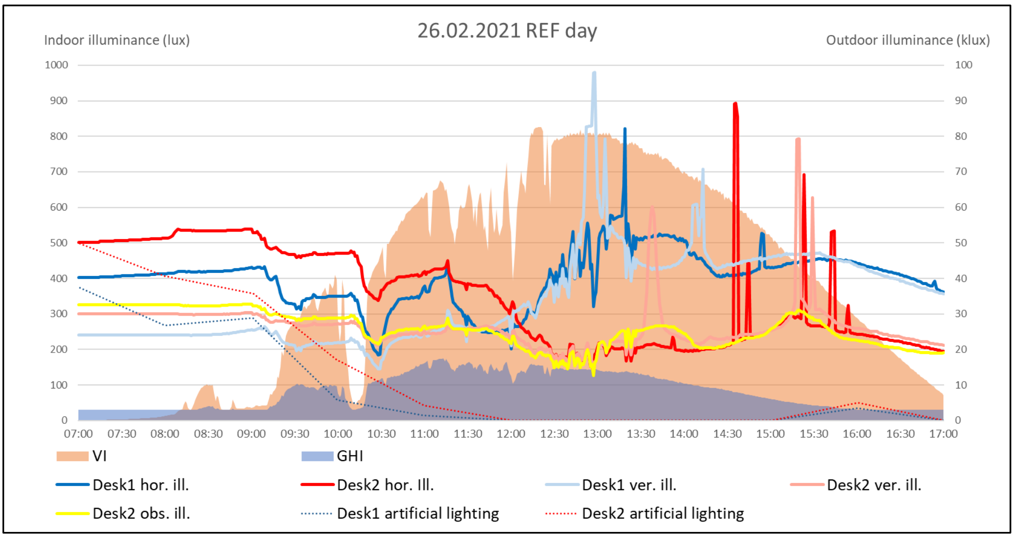

Figure 52 Recorded data for the REF day. The areas show outdoor lighting conditions (VI and GHI) while bluish lines show illuminance recorded on the desk 1 and reddish lines show illuminance recorded on the desk 2. The blue and re d dotted lines show the illuminance provided by the artificial lighting for desk 1 and desk 2, respectively.

For the TEST day (Fig. 51), the difference between the desk 2 horizontal illuminance (consisting of both daylighting and artificial lighting) and desk 2 artificial lighting is much higher than for the REF day. In the REF day (Fig. 52) the desk 2 horizontal illuminance follows the desk 1 horizontal illuminance until 12am, indicating that the values mostly depend on the artificial lighting but are also affected by sudden variations in the daylighting levels. After 12am, the sun moves from south to west and lights the windows, providing more daylight to desk 1 and, to a certain extent, desk 2. The desk 2 horizontal illuminance is under 200 lux for REF day (Fig. 52) and does not increase before 3pm, when the artificial lighting starts to increase. Meanwhile, in Fig. 51 (TEST day), the values of the desk 2 horizontal illuminance are above 400 lux during the same period, without any artificial lighting provided.

The almost twice higher level of desk 2 horizontal and vertical illuminances in the TEST day compared to the REF day was found to be due to the daylight supplement via HLP. In this TEST day, an increased level of desk 1 horizontal and vertical illuminance was recorded as well. This can be explained by the fact that the daylight supplemented via the HLP have been inter-reflected on the wall and directed to desk 1, as argued in chapter 4.5.

Further, it was found that, under the same daylight conditions for these two days, the luminaires behaved quite similarly as well. They seemed not dependent on the light level on the desks in the expected manner (Figs. 51–52). This indicates that the DLC sensors, which indirectly steer the luminaires, are much more affected by the light reflected from the sun-shading (slats) than by the illuminance level on the surfaces the sensors were intended to cover.

In order to confidently conclude on the difference of daylight provided by the HLP in TEST comparing to REF pair day, statistical analyses of the independent and dependent parameters, solely for the period when artificial lighting was dimmed to 0, have been performed using IBM SPSS statistics 27 software. An independent sample *t*-test, featuring a comparison between the Mean values of the independent variables with the Mean values of the dependent variables, in the test and reference day, data were used to draw a picture about the effect of the HLP presence during the test days. The analyses are presented in table 12. and the graph corresponding analyses is in fig. 53.

Table 12 Independent sample *t*-test analyses compare Mean values for the independent and dependent variables for the test day 12.10.2020 and ref day 26.02.2021

	Test day 12.10.2020			Ref day 26.02.2021					
	M	SD	SE	M	SD	SE	t	df	p
VI (Klux)	65.33	4.89	.31	71.02	9.520	.708	7.34*	251.16	**<.001**
GHI (Klux)	16.19	2.23	.14	11.73	2.774	.206	-17.70*	338.34	**<.001**
Desk1 hor. Ill.	603.14	178.41	11.49	446.49	86.297	6.414	-11.90*	365.52	**<.001**
Desk2 hor. Ill.	462.32	84.46	5.44	225.13	93.334	6.937	-26.90*	365.74	**<.001**
Desk1 ver. Ill.	599.05	152.84	9.84	462.35	120.876	8.985	-10.26*	418.86	**<.001**
Desk2 ver. Ill.	472.99	132.94	8.56	232.94	68.433	5.087	-24.10*	376.70	**<.001**
Desk2 obs. Ill.	367.58	77.68	5.00	215.89	33.664	2.502	-27.11*	346.17	**<.001**

*Levene's Test violated

In the independent sample *t*-test analyses (Table 12), Mean values of VI for test (12.10.2020) and reference (26.02.2021) days are 65.33 klux and 71.02 klux, respectively. Mean values of GHI for test and reference days are 16.19 klux and 11.73 klux, respectively. Thus, this pair of days has slightly lower VI and higher GHI values for test day compared with reference day. Recorded indoor illuminance values for the test and ref day show statistically significant difference (p = <.01) for all dependent parameters. Difference presented in the graph (fig. 53) show relative difference between Mean values of test and reference days (Test-Ref)/Ref), thus showing the improvement (in %) for the test comparing to the reference. The improvement of Mean values for Desk 2 horizontal Illuminance and Desk 2 vertical Illuminance is over 100%, while the improvement of Mean value for Desk 2 observer. Illuminance is 70% in case of test day.

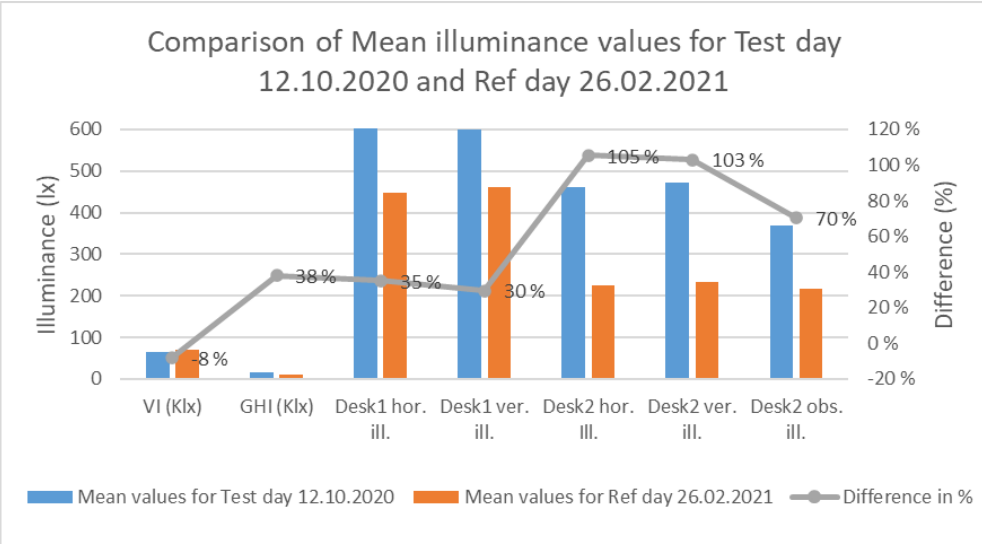

Figure 53 Comparison of Mean Illuminance values for the test and reference pair days which were recorded between 12 and 14:30 hours. VI and GHI are shown in Klux.

In the statistical analyses of correlation (point bi-serial correlation), all dependent variables (Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance) are used in correlation with binary nominal explanatory variable (Test= 1 and ref =0) to get the value of correlation coefficient. The result of biserial correlation is a coefficient R which is used to build a relation between the variables (R^2).

Table 13 Point bi-serial correlation test for the test day 12.10.2020 and the ref day 26.02.2021, and, Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance

Point biserial correlation between ref day 26.02.2021 (0) and test day 12.10.2020 (1)							
	VI	GHI	Desk1hor	Desk2hor	Desk1ver	Desk2ver	Desk2obs
Pearson Corr.	**-.363****	**.665****	**.469****	**.800****	**.436****	**.734****	**.768****
Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	<.001	<.001

Significance levels: * p<.05; ** p<.01. The analyses are based on n: 422.

In Table 13, point bi-serial correlation test for all independent and dependent variables show correlation strength based on the increase of the nominal parameter (0 for ref and 1 for test). Statistically significant correlation (p<.01) is shown for all dependent variables, meaning that the values were higher for test day (nominal parameter 1). The PBC coefficient is higher for the Desk 2 horizontal Illuminance (.800), Desk 2 vertical Illuminance (.734), and Desk 2 observer Illuminance (.768). The relation (R^2) regarding horizontal and vertical illuminance on the desk 2 for the test and ref day is also illustrated in figure 54.

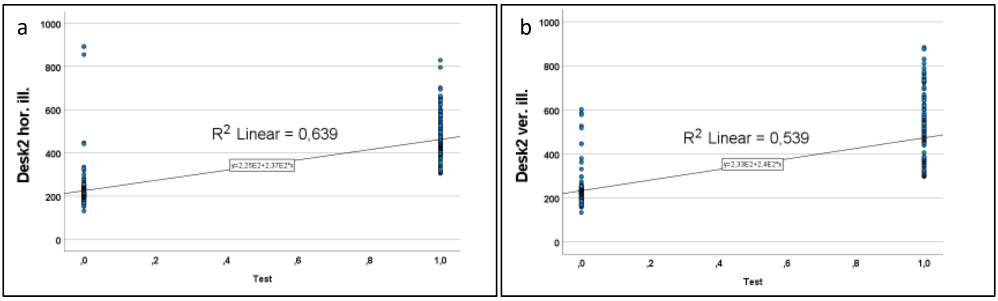

Figure 54 Point-biserial correlation coefficient show a relation between the values of desk 2 hor. Ill. (a), and Desk 2 ver. Ill. (b) for pair of days, ref (0) and test (1).

Some analyses of the lighting energy use of both luminaires indicated that the luminaires did not start at the same time, but they were rather affected by the daylight control signal, which was delayed for one of the luminaires. The delayed luminaire was the random one, not always the same, and not affected by any starting illuminance on the desk. This issue is noted as a 'dominant luminaire' case and is explained in the research article corresponding to this study, Paper 5.

As a result, the authors conclude that the collected data on the use of light energy for L1 and L2 in the test and reference period were strongly influenced by this phenomenon of the dominant lamp. Therefore, it was not possible to reliably conclude how much this phenomenon had an impact on the results of energy consumption in each of the study periods separately (test and reference), so the collected data on the monitoring of lighting energy consumption were unreliable and the authors decided not to report them by comparing the periods.

However, the authors can report total light energy consumption for solely test period. First, the calculated LENI for this test office, using Dialux 4.3 software, was 10.37 kWh/m^{2}year, as mentioned in section 4.5, and in detail explained in Paper 5, but the value of LENI based on the recorded light energy use for solely test period of the study was 5.79 kWh/m^{2}year, which can be argued as a direct effect of the daylighting via the HLP. The energy-saving potential could be then expressed as a relative difference between calculated and realistic situation, being ((10.37-5.79)/10.37) 44%.

It is important to acknowledge that the recommended light level (constant and stable target value of minimum 500lux) has not been always achieved in situations when DLC system was affected by daylight reflected from sun-shading, as discussed above. Such situations occurred during the days with clear and sunny weather, which is for the location of this study historically recorded to be about 30% of the daylight time. However, the monitored data and analyses of the pairs of days suggested, that in such situations, the illuminance values on the desks were around 400 lux (varying between 300 and 500 lux). Hence, the periods with artificial lighting under the recommended level (lacking approx. 100 lux) might have also contributed to lower energy use.

5.4. Findings from the user survey in the full-scale study

The qualitative part of the full-scale study implemented a user survey regarding the daylight conditions provided by the HLP. After the data was collected, as described in section 4.6, statistical and descriptive analyses were performed to determine causality and corelation. The analyses intended to answer the study aim, i.e., to find out whether a noticeable daylighting provision from the HLP onto the desk closest to the door led to a more positive perception of that working area as well as the room in general when compared with no daylighting supplement from the HLP.

The statistical analyses were performed using IBM SPSS statistics 27 software. An independent sample *t*-test, featuring a comparison between the test and reference group scores (collected using semantic differential scales) were analysed. The participants' group assignment was made post hoc, by analysing ''every minute loggings" (described in Paper 4, Appendix A). The participants in the test group had a noticeable amount of daylight delivered through the light pipe (on average, 70% (from 50% to 90%)) when they filled out the questionnaire, comparing to the reference participants (for which this number was 14%, while artificial lighting covered over 70%). The findings regarding the participant's visual experience and perceptual impressions are presented in Table 14. Statistically significant higher scoring in the test group was recorded for the attributes of the room being *pleasant, interesting*, and *exciting*.

Table 14 Independent sample *t*-test analyses comparing the scoring in the test and reference groups in terms of visual experience and perceptual impression of the test office.

1. How do you experience this room?	Test group			Reference group					
Attributes:	M	SD	SE	M	SD	SE	t	df	p
Bright	2.59	1.010	.194	2.74	1.214	.253	-0.466	48	0.643
Spacious	3.15	0.949	.183	2.78	1.126	.235	1.246	48	0.219
Open	2.89	0.801	.154	2.43	0.992	.207	1.791	48	0.080
Uniform	2.96	1.065	.222	2.64	1.217	.259	0.940	43	0.352
Pleasant	1.96	1.038	.204	1.30	1.063	.222	2.186	47	**0.034**
Interesting	2.37	1.275	.245	1.43	1.080	.225	2.771	48	**0.008**
Exciting	2.22	1.219	.235	1.35	1.027	.214	2.714	48	**0.009**
Legible	3.19	1.001	.193	2.95	1.046	.223	0.786	47	0.436

In Table 15, the findings for the questions regarding visual comfort, daylight dynamics, and the level of illuminance (daylight and artificial light together) are presented. Statistically significant higher scoring was recorded for statement 6b (*Satisfying level of artificial and daylight together in the entire room*) in the test group compared with the reference group.

Table 15 Independent sample *t*-test analyses comparing the scoring in the test and reference group regarding visual comfort and level of illuminance (daylight and artificial light together) in the test office.

	Test group			Reference group					
Questions from the survey	M	SD	SE	M	SD	SE	t	df	p
2. The daylight conditions in the room are satisfying	2.70	0.993	.191	2.26	1.251	.261	1.395	48	0.169
2a. Temporal changes of light have been noticed	1.40	1.506	.476	1.31	1.316	.365	0.157	21	0.877
3. No difficulties regarding the visibility of the task on the screen	3.15	0.989	.190	3.27	0.767	.164	-0.484	47	0.631
4. No reflections on the PC screen caused by the light	3.44	0.712	.142	3.33	0.913	.199	0.445	44	0.658
5. Difference between the colour of light were noticed	1.72	1.275	.255	2.05	1.468	.328	-0.807	43	0.424
6a. Satisfying level of artificial and daylight together at the workplace	2.96	1.020	.204	2.41	1.182	.252	1.716	45	0.093
6b. Satisfying level of artificial and daylight together in the entire room	2.88	0.927	.185	1.95	0.999	.213	3.293	45	**0.002**
6c. Satisfying level of artificial and daylight together on the screen	3.28	0.843	.169	3.05	1.117	.244	0.804	44	0.426

The second part of statistical analyses focused on the correlation between the variables of interest—E_{1Mean}, E_{2Mean}, E_{3Mean}, v-E_1, v-E_2 and v-E_3—and the scores given by the participants in the survey questions. The illuminance values of E_1 refers to the illuminance value on the test desk in the office; then, E_2 refers to the vertical outdoor illuminance incident tube, and E_3 refers to the global horizontal illuminance. These values were collected from the monitoring data in the full-scale test for each minute during the participant survey. The *Means* of this data as well as the V*ariation* in the values were calculated. Variation was calculated as a standard deviation of the value for each minutes (STDEV) divided by the *Mean* of the minutes' values.

The findings from the correlations analyses are shown in Table 16. Several statistically significant correlations for the independent values as well as visual experience and perceptual impression of the test room were found. For the mean value of the indoor illuminance on the test desk, E_{1Mean}, a statistically significant (negative) correlation was found for perceiving the room as *exciting* (Pearson's -0.308 [$p < .05$]). Then, for the mean value of the outdoor vertical illuminance incidence on the tube, E_{2Mean}, a statistically significant correlation was found for perceiving the room as *open* (Pearson's 0.298 [$p < .05$]), *pleasant* (Pearson's 0.332 [$p < .05$]), *interesting* (Pearson's 0.419 [$p < .01$]), and *exciting* (Pearson's 0.436 [$p < .01$]). Further, for the mean value of the outdoor global horizontal illuminance, E_{3Mean}, a statistically significant correlation was found for perceiving the room as *pleasant* (Pearson's 0.305 [$p < .05$]), *interesting* (Pearson's 0.341 [$p < .05$]), and *exciting* (Pearson's 0.372 [$p < .01$]).

Table 16 Correlation analyses between the E_{1Mean}, E_{2Mean}, E_{3Mean}, v-E_1, v-E_2 and v-E_3 and scores given by the participants in terms of their visual experience and perceptual impression in the test office.

1. How do you experience this room? Attributes		E_{1Mean}	E_{2Mean}	E_{3Mean}	v-E_1	v-E_2	v-E_3
Bright	Pearson Corr.	.141	-.055	-.063	-.234	-.266	-.180
	p value	.328	.706	.664	.101	.062	.212
Spacious	Pearson Corr.	-.122	.187	.060	.030	-.161	-.193
	p value	.398	.193	.679	.837	.264	.180
Open	Pearson Corr.	-.223	**.298***	.262	-.033	-.229	-.227
	p value	.119	.036	.066	.822	.109	.113
Uniform	Pearson Corr.	-.081	.126	.054	-.067	-.196	**-.330***
	p value	.598	.410	.724	.663	.198	.027
Pleasant	Pearson Corr.	-.281	**.332***	**.305***	-.014	**-.326***	-.281
	p value	.051	.020	.033	.923	.022	.050
Interesting	Pearson Corr.	-.147	**.419****	**.341***	.026	**-.392****	**-.318***
	p value	.309	.002	.015	.859	.005	.025
Exciting	Pearson Corr.	**-.308***	**.436****	**.372****	.065	**-.338***	**-.305***
	p value	.029	.002	.008	.652	.016	.032
Legible	Pearson Corr.	-.090	.132	.108	.009	-.169	-.267
	p value	.540	.367	.461	.950	-.246	.064
Significance levels: * $p < .05$; ** $p < .01$. The analyses are based on n = 45–50							

Table 17 Correlation analyses between E_{1Mean}, E_{2Mean}, E_{3Mean}, v-E_1, v-E_2 and v-E_3 and scores given by participants regarding visual comfort and level of illuminance (daylight and artificial light together) in the test office.

Questions from the survey		E_{1Mean}	E_{2Mean}	E_{3Mean}	v-E_1	v-E_2	v-E_3
2. The daylight conditions in the room are satisfying.	Pearson Corr.	.126	.043	-.029	.050	-.200	-.091
	p value	.382	.769	.841	.728	.163	.530
2a. Temporal changes in the light have been noticed.	Pearson Corr.	-.167	-.028	.032	.207	.028	.056
	p value	.446	.900	.884	.344	.901	.799
3. No difficulties regarding the visibility of the task on the screen.	Pearson Corr.	.106	-.143	-.092	-.021	.122	.135
	p value	.470	.326	.528	.885	.405	.356
4. No reflections on the PC screen caused by the light.	Pearson Corr.	.078	.089	.036	.008	.019	-.012
	p value	.607	.557	.813	.960	.898	.936
5. Difference between the colour of light was noticed.	Pearson Corr.	.019	-.212	-.147	.115	.254	.124
	p value	.899	.162	.335	.451	.092	.417
6a. Satisfying level of artificial and daylight together at the workplace.	Pearson Corr.	.059	.145	.051	.017	-.197	-.170
	p value	.693	.332	.734	.912	.184	.254
6b. Satisfying level of artificial and daylight together in the entire room.	Pearson Corr.	-.067	.268	.201	.192	-.231	-.101
	p value	.656	.069	.176	.196	.118	.501
6c. Satisfying level of artificial and daylight together on the screen.	Pearson Corr.	.018	.181	.181	.153	-.092	-.073
	p value	.906	.230	.230	.310	.544	.631
Significance levels: * $p < .05$; ** $p < .01$. The analyses are based on n = 23–50							

Further findings are regarding the independent variables of variation. For the variation in the outdoor illuminance value incident to the tube, v-E_2, a statistically significant (negative) correlation was found for perceiving the room as *pleasant* (Pearson's -0.326 [$p < .05$]), *interesting* (Pearson's -0.392 [$p < .01$]), and *exciting* (Pearson's -0.338 [$p < .05$]). Then, for the variation in the outdoor global horizontal illuminance, v-E_3, a statistically significant (negative) correlation was found for perceiving the room as *uniform* (Pearson's -0.330 [$p < .05$]), *interesting* (Pearson's -0.318 [$p < .05$]), and *exciting* (Pearson's -0.305 [$p < .05$]).

In terms of the correlation analyses between the variables of interest—E_{1Mean}, E_{2Mean}, E_{3Mean}, v-E_1, v-E_2 and v-E_3—and the scores regarding visual comfort, daylight dynamics, and the level of illuminance (daylight and artificial light together) in the test office, no statistically significant correlations were found. However, the analyses are shown in Table 17, to could draw a picture regarding results for some questions where significance (p) is approaching .05.

Further, the descriptive analyses, as described in section 4.6, were performed by computing the average values of the independent and dependent variables. Descriptive analyses provide easily understandable ideas about how the results are distributed, their relationships, and the correlations between them. Descriptive analyses in this study have shown compatible results with statistical inferential analyses.

The average score given by the participants in the test group when compared to the reference group in terms of the visual experience and perceptual impression of the test room indicated a more positive evaluation of the test room as *spacious*, *open*, *uniform*, and *legible* (Fig. 55). Even more evident positive evaluations can be seen for the finding of the test room as *pleasant*, *interesting*, and *exciting*. The *brightness* of the room was found to be rated higher by the reference group than the test group. This result can be explained by the level of illuminance on the desk (E_1), which, in the case of the higher daylighting supplement, was lower as a result of the light being re-directed from the slats against the DLC sensors and the fault signal given to the luminaires. This situation is explained in the research article corresponding to this study, Paper 4, included in Appendix A.

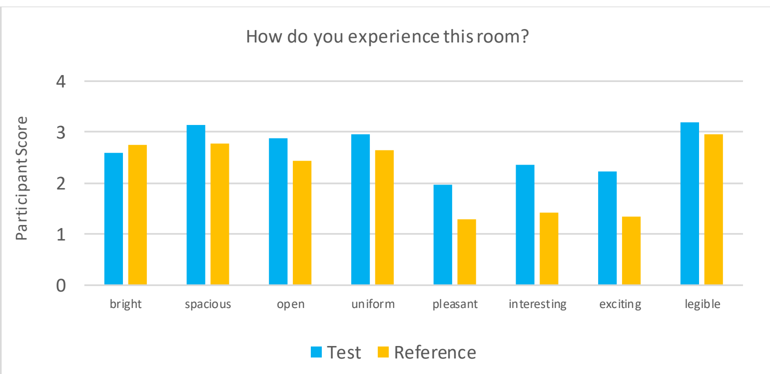

Figure 55 Average scores given by the participants in the TEST and REF groups in terms of their visual experience and perceptual impression of the room.

The participants' evaluation of the room's *pleasantness* was found to be relatively low in both groups. This might be an effect of the test room being too plain, lacking decorative elements (e.g., pictures, flowers) that are common in many workplaces; in addition, the suspended ceiling has been removed. The participants' sitting position was too close to the door, and they were lacking visual control over the office entrance. Humans prefer to have visual control over a space, such as having a direct view of its entrance at any time.

The participants' evaluation of whether the daylighting conditions were satisfying were found to be higher in the test group than in the reference group (Fig. 56). The underlying visual conditions' effect on the visual comfort in the room as a glare-free space could also be noted, as both groups evaluated the room above neutral scoring (which in this scale was 2). The average score regarding the light dynamics, which was evaluated in terms of whether temporal changes in the light were noticed, was found to be low (under 2). This result means that the participants did not notice the dynamics of the daylight.

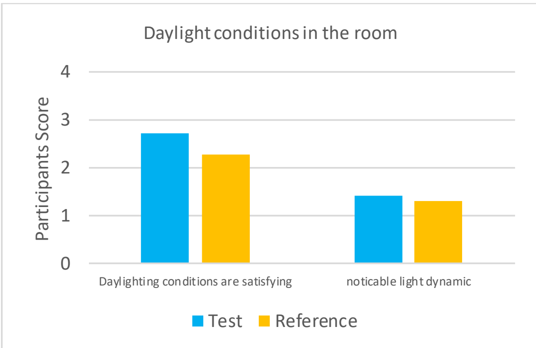

Figure 56 Average scores given by the participants in the TEST and REF groups for the daylight conditions and daylight dynamics in the room

Further findings were obtained regarding the average scores given by the participants for questions regarding visual comfort. These questions asked whether the participants experienced difficulties regarding the visibility of the task on the screen or observed reflections caused by the light as well as if they noticed a difference in colour of the light. The findings did not indicate any difference among the groups for these questions (Fig. 57).

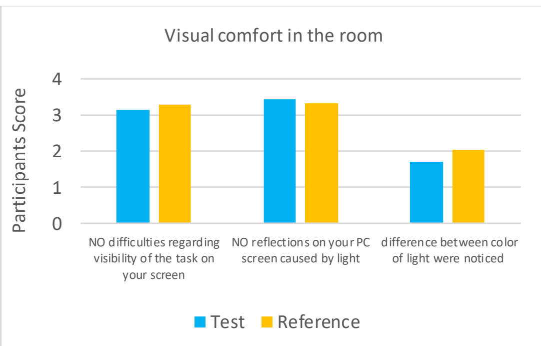

Figure 57 Average scores given by the TEST and REF groups in terms of their visual comfort in the test room

Other findings were obtained regarding the evaluation of the daylight and artificial light levels in the test room. There was a more generally positive assessment in the test group in regard to the light level in the workplace as well as in the entire room and on the PC screen (Fig. 58). The largest difference between the two groups was found to be in the assessment in regard to the light level (artificial and daylighting) in the entire room and at the workspace (desk 2).

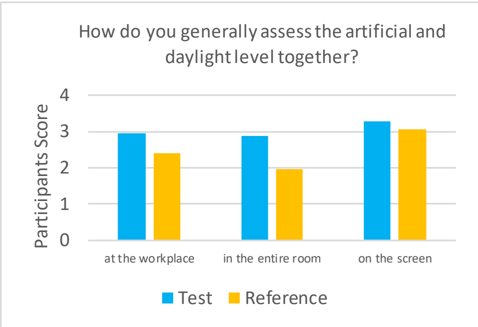

Figure 58 Average scores given by the TEST and REF groups in terms of the level of light (artificial and daylight together)

The findings from the open-ended questions from the user-survey revealed no commentary about the glare or excessive light in the test office. The fine-tuning of the sloping of the slats in the sun-shading system to 45 degrees proved to protect the participants from glare.

The systematized finding from the participants' responses to the open-ended question in the survey when the amount of the daylight via the pipe was clearly visible were positive when the light level on the desk was about 350 lux. On the other hand, when the level was 450 to 500 lux, under an overcast sky, and when the luminaires supplied the entire light, the participants' responses to the open-ended questions were more negative and critical. The participants comments can be found in the research article, Paper 4, describing the user survey study.

6. Discussion

This chapter will discuss topics not directly connected to any study part and not described in any of the scientific articles in this PhD research. The aim of this chapter is to provide information about the applicability of light pipes, as the daylight transport system examined in this PhD research, for newly designed or existing buildings in high-latitude areas.

6.1. Fire-, and sound-proofing; maintenance and the thermal properties of light pipes

One of the most important features for daylight transport systems, if applied in a building and aiming for preservation over time, is fire resistance. There exist common globally used regulations on fire resistance design in buildings, but each country has its own national regulations that projects must follow. Regulations are mostly described as a code requirement for: a) components to be fire resistant; and, b) fire compartments (cells) to be fire and smoke stoppable. They both must have a certain level of fire resistance expressed in hours. Each perforation (hole) of the fire compartments demands special fire protection for the elements that perforate the compartment. Light pipes can be one such element, because their design demands them to protract between several floors or a roof in the case of vertical light pipes or from the outdoor façade to the indoor space in the case of horizontal light pipes. Light pipes can weaken the fire design of a building, and some precautions (inhibition of fire and smoke passing through a light pipe system) need to be taken to protect the integrity of fire cells.

The fire resistance of a building's components can be established by, e.g., using special finishes; however, in the case of light pipes, the necessity to preserve optical properties does not allow for the usage of such finishes. Therefore, the fire resistance of the elements protracting and penetrating through fire-resistant walls, ceilings, or shafts can be established by using fire dampers, fire-resistant enclosures, or fire-resistant claddings, as described in the CIE173:2012, Technical Report Tubular daylight Guidance Systems (CIE 2012).

- Fire dampers are thermally actuated devices that need to be installed at the point of penetration of the light guide system into a fire cell. Fire dampers are activated by the detection of a rising temperature, and they will ensure no passage for flames or smoke.
- A fire-resistant enclosure refers to a fire-protected shaft that, in itself, is fire-resistant and transfers through several fire compartments. In case light guides are installed in it, they can go through several departments without additional fire resistan ce needed because it is in the protected shaft enclosure.

- Using a fire-resistant cladding in the form of the material of the light pipe or cladding around the light guide forms a protected shaft. However, this option is not available on the market at the present time.

The most common fire-protection solution used for light pipes nowadays is to provide fire separation between the two spaces through which the light pipe passes by insulating every joint, imperfection, and opening to ensure fire prevention.

The other feature of the daylight transport system that protracts through several floors or walls is that it must withstand a certain sound proofness. Lighting systems based on hollow mirrored pipes have empty, non-vacuumed space, which can transfer acoustic vibrations through themselves. The lightweight material used in the pipe element (aluminium) might additionally create such problems, as well as glass or polycarbonate used for a dome and diffuser, which are not particularly soundproof. The soundproof elements of buildings, like partition walls or doors and windows, are important for preserving the function of a building space. The minimization of the harmful effects of noise (sound waves of various frequencies) on people's central nervous system is important for the good functioning of brain cells to reduce overwork. The other effect that noise can have on humans is fatigue, lowered performance, and productivity. Therefore, light pipes are supposed to have similar soundproof features as other building components.

There have not been many studies examining the acoustic characteristics of light pipes. However, the recent study of Pleshkov, Bracale et al. (2021), which examined the sound-proofness of different light pipes (diff. aspect ratios) concluded on the possibility of their absorbing 20% of low-frequency sound waves and up to 85% in the medium- and high-frequency range of sound waves. These findings comply with the soundproof regulations on the noise levels in residential, administrative, and industrial buildings. The light pipe system examined in this study was manufactured by Solarspot International SRL. Further findings of the study included the diameter of the daylight tubes not affecting the transmission of sound waves of different frequencies through it; however, the difference of 5.8% was found for lower frequency sound waves, where the light pipes of a smaller diameter have better vibration resistance. A light guide with a diameter of 250 mm transmits 5.8% less low-frequency wave energy than a similar light guide with a diameter of 650 mm.

When it comes to the maintenance of light pipes, the maintenance factors are the common factors used in light transmission estimation methods. According to the Technical Report on Tubular Daylight Guidance Systems (CIE 2012), the dust collection that occurs on the outdoor mounted dome and on the indoor mounted diffuser are issues affecting maintenance factors. The dust collection indoors depends on the maintenance routines of the building (function) or space. The dust collection in residential, education, healthcare, or office buildings is simple to estimate. On the other hand, dust collection in factories, where some form of air pollutants or particles are present, can be an essential factor in light pipe dimensioning or necessary maintenance routines. The mirror layered tube is assumed to be enclosed by the dome and diffuser, but the hollow space inside is not vacuumed; hence, micro-dust can still enter the hollow space and collect on the mirrored surface. The reflective properties of the reflective layer would thus be reduced.

The question of the reduction of light transmission effectivity due to the dust collection on a light pipe's dome was addressed in a recent study by Mayhoub, Elqattan et al. (2021). The research was conducted on the weather conditions in arid climates due to the high dust saturation in the air. The study reported a dramatic reduction in the transmission efficacy of the zenithal pipes due to the dust collection on top of the dome. The air pollution in the Scandinavian climate is up to eight times lower than in the location of this study. However, dust collection on top of the dome is still possible in industrial and agricultural areas or near highly trafficked streets. A more frequent incidence of rain will remove the dust.

The study of Mayhoub, Elqattan et al. (2021) also reported a changes in the spectral composition of the daylight delivered via the light pipe due to the dust collection and reduced incidence of the light rays from the part of the sky dome where the dust collection was observed. This meant that the lower angled rays, which are also more reddish, will manage to preserve the transmission, while the light rays' incident from the zenith, which are more bluish, will be reduced due to the collected dust on top of the dome.

The thermal performance of tubular daylight guidance systems is a parameter used in the total net energy requirement for a building. In such calculations, two metrics commonly applied for windows, for example, can be used for light pipes as well. The thermal transmittance, described as the U value in W/m^{2}K, and the solar factor, described as *g* (solar heat gain coefficient, SHGC) in a steady-state are multiplicated with the surface exposed to the outdoors (m^2) to obtain the values of heat transfer. According to the Technical Report on Tubular Daylight Guidance Systems (CIE 2012), calculations using radiance have been performed for light pipes of a diameter of 250 mm and for different lengths ranging from 0.300 m to 3.0 m. The conclusion is that an uninsulated tube 3 m in length has a U value of 7.15 W/m^{2}K and a *g* value of 0.11, while for insulated tubes, the values are 5.56 W/m^{2}K and 0.13. The same values for windows of single and double glazing (Argon filling) are 5.6 W/m^{2}K and 0.87 and 1.6 W/m^{2}K and 0.30, respectively. The values for light pipes appear to be very high at first sight, but the size of the area exposed to outdoor conditions is much smaller for the light pipe compared to a standard window of, e.g., 1 m^2. The light pipes dome (opening in the façade or roof) has a surface area of 0.05 m^2 for a diameter of 250 mm, and, for example, a surface area of 0.33 m^2 for a tube with a diameter of 650 mm, as noted in the report (CIE 2012). The final conclusion within the report was that the light pipes have a low impact on the thermal balance of a building.

Several studies have recently addressed the thermal transmittance of light pipes (Šikula, Mohelníková et al. 2014), and thermal bridges (Šikula, Mohelníková et al. 2014, Pleshkov, Bracale et al. 2018), as these phenomena have been shown to be of importance when new building regulations (a highly thermally insulated building envelope, as in the Passive House standard) are applied. These studies show that longer and narrower pipes have lower thermal transmittance than those that are shorter and wider. This is due to the size and form of the air cavity, which is important for the development of the velocity of the airflow inside. Stronger air circulation brings about higher thermal loss and a higher risk of condensation on the surfaces connected to other building elements.

Light pipes with additional double or triple glass units inside, which act as an insulation element, have been shown to have a more uniform temperature profile. However, it is important to note that the additional glass unit reduces the light transmission efficiency. This is argued to be 28.5% for the triple glass unit, 20.1% for the double glass unit, and 10.6% in the case of a single glass unit (ASHRAE 2001). The temperatures on light pipe surfaces in connection to an insulated roof or wall, for example, are higher, and the risk of condensation is thus lower. A similar insulation effect can be enabled in the case of vertical light pipes installed in a loft if the light pipe is covered by an insulation layer (in case the loft is unheated). This will allow cold air in the pipe to preheat along its length (for longer pipes). If an uninsulated longer light pipe is installed in an insulated (heated) loft, the air within the pipe will be preheated by the surface being exposed to the warmer air.

6.2. Cost and value of daylight transport system application

The applicability of one technology in practice, especially a new one being considered as a standard solution, is dependent on its review for profitability. The profitability approach in the building industry is commonly expressed via cost-benefit analysis. While cost analyses are usually simple to perform, benefit analyses, especially for daylighting, have historically been very complex, since not all benefits can be expressed in parametrical values.

The value of delivering more daylight deeper in the space has been argued to be of great importance in regard to the psychological factors related to the fulfilment of basic human needs. The distinctive features of daylighting, as diurnal and spatial dynamics, ensure visually interesting conditions. The spectral composition of natural light provides the best perception of the colour, and, more importantly, it affects human health and wellbeing. Natural light gives a visual experience to the space by introducing a non-static 3D modelling. Daylight that comes from the side window has historically been argued by many authors to have another light geometry compared with the lighting provided by ceiling-mounted luminaires (Lam 1986, Boubekri 2008, Knoop, Stefani et al. 2020).

The importance of using a proper light reflector at the HLP's exit, which this study introduced (Paper 4 and 5), highlights this point. The monitoring of the indoor photometry in the full-scale office resulted in evidence that the levels of vertical and horizontal recorded light were nearly equal in the case of higher daylighting and lower artificial lighting, while, for higher artificial lighting and lower daylighting, the level of vertically recorded light was, as designed, much lower than the horizontal level. In Fig. 59, the monitoring data for the vertical and horizontal illuminances on the two desks are provided. During this example day, as illustrated in Fig. 59, during the period until approx. 12:30am, the weather was overcast, and the artificial lighting was dimmed up to full intensity, while, from 12:30, the weather became clear and sunny and the artificial lighting dimmed to zero.

The user -survey performed in the full-scale study resulted in statistically significant findings regarding the improved human appraisal of the visual appearance and daylighting conditions in this space (where the daylight was supplemented via a HLP and custom-made reflector). A human appraisal of a daylit space is an equally important dimension of the evaluation of a good daylighting solution. The human perception of space, especially daylight via DTSs, depends on a multitude of factors, not only the quantity and quality of the light. Psychological factors, like previous experiences and personal expectations, are important for the human perception and final attitude regarding the daylight delivered via DTSs. This study provided evidence that a custom-designed solution with a DTS led to a more positive human impression of a space.

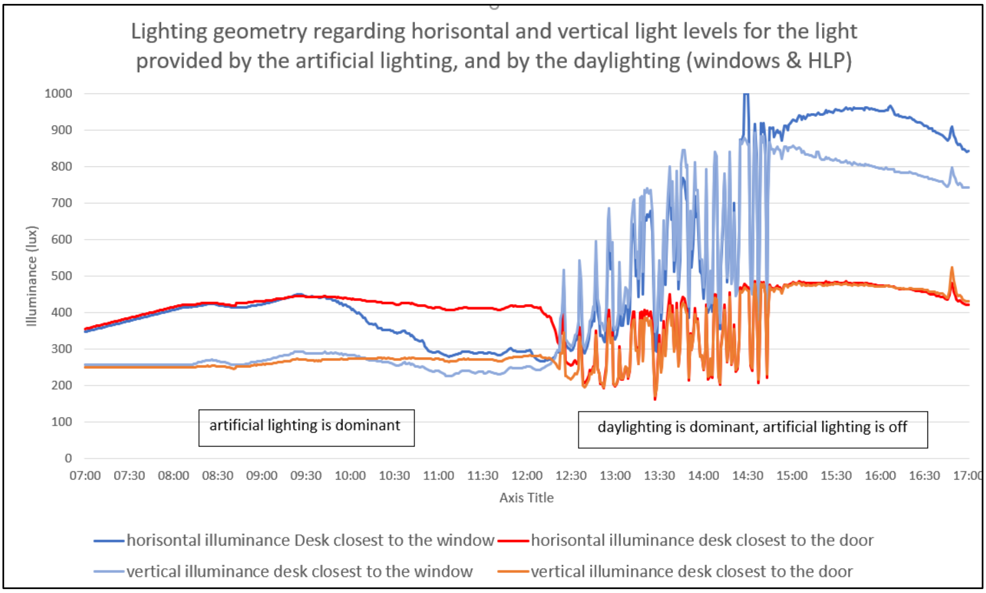

Figure 59 Illustration of light levels and relationship between horizontal and vertical light levels for the light provided by the artificial lighting and daylighting (side windows and HLP).

Some studies during the last two decades have tried to express the benefit of better lighting and daylighting via numerical values using a chain mechanism. One example is the perceptual chain mechanism, where better luminous conditions of the space will affect self-esteem and collegial respect among workers and, thus, lead to better collaboration and higher productivity (Galasiu and Veitch 2006, Veitch, Newsham et al. 2008, Veitch and Galasiu 2012, Veitch, Stokkermans et al. 2013). The other discussed chain mechanism is a circadian mechanism, where variable luminous conditions will ensure health and wellbeing for workers, lower sickness leave rates, and, thus, better productivity rate (Boyce, Veitch et al. 2006, Keis, Helbig et al. 2014). Figure 60 illustrates these linked mechanisms. Finally, the monetary value of improved luminous conditions from improved daylight could be measured in the company’s profitability through organizational performance and productivity if the corporative business models were statical, but they are not (Heschong, Wright et al. 2002, Heschong, Wright et al. 2002, Heschong 2002, Charles, Danforth et al. 2004). Every company has complex strategies even through a year as a time horizon. Business is dynamic, and many other activities within corporative strategies can affect the results.

Until a better paradigm for expressing the monetary value of improved daylighting is developed, the comparison of saved electrical energy for artificial light and the saved greenhouse gas emissions of an alternative solution can be used to argue about the rentability for application of DTS. Cost analyses can be developed by calculating the installation and operation costs of a standard (base case) solution as well as the solution with the daylighting transport system installed and then comparing the results. A simplified cost analysis without actualization of the investment is presented in Table 18. For a more general conclusion, several cases should be considered, but here, for example, the full-scale experimental office can be used, as it presents a standard office in a fully operative building. Energy-saving potential of 44%, as argued in chapter 5.3, is acknowledged by the author as a possible overestimation, due to the failure of the DLC system to enable threshold lighting; however, the value will be used as an example to demonstrate the cost analyses and rentability.

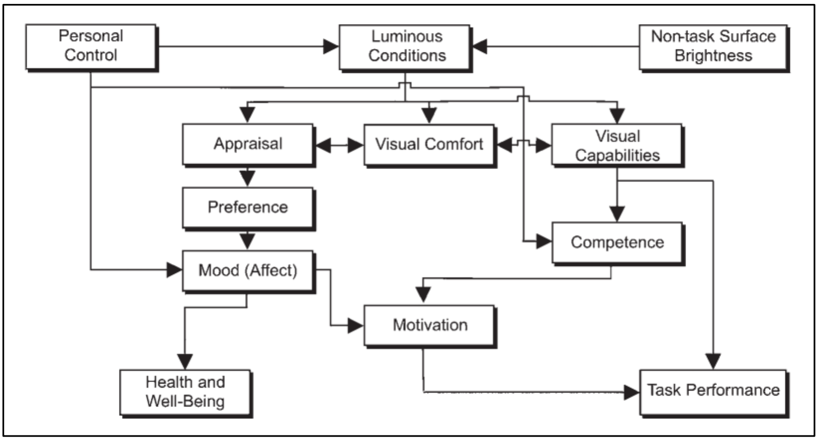

Figure 60 Linked mechanism hypothesized to link luminous conditions with health, well-being, and performance; adopted from Boyce, Veitch et al. (2006)[22].

The price for a lighting system (two luminaires of power 22 W, sensor, driver, and DALI) including the installation cost is 1,500 EUR, while HLP (4 m length) with the installation cost is 1,080 EUR. The findings from the energy-saving analyses of the full-scale study were that the alternative solution has the potential to save 44% of the energy of the artificial lighting for both luminaires. The price for electricity is quite variable nowadays, but, for the purpose of this relative comparison, the price for electricity, including the grid and taxes, is considered to be 0.2 EUR kW/h. The new regulations of grid prices in Norway state (according to Elvia, the Norwegian grid provider) that much higher prices will be charged during the day, from 6am-10pm, and the operational costs, thus, can look different. Today, with the forecast for the future cost of carbon emissions (Kikstra, Waidelich et al. 2021), the price of a CO_2 emission is estimated to be EUR 3/kg emissions. The inflation rate of 2% is taken in this calculation.

When calculating the investment and operational price, the profitability of the innovative solution (with the HLP) occurs in the 46st year. However, if the cost of CO_2 emissions for this standard and innovative solution is considered in the analyses, the profitability will be during the 5th year. The benefit of less CO_2 emissions on the global climate situation is not expressed.

[22] Used by permission. Permission is granted by Peter Boyce on the 16th of February 2022, and by National Research Council of Canada on the 25th of February 2022.

Is important to note from those analyses is that, with increasing electricity prices during the day (highest effectivity of HLP) and stricter carbon emissions, the profitability findings illustrated in Table 18 produce different results.

Table 18 Simplified cost benefit analysis of a standard and innovative (with HLP) solution in the full-scale test office

Rentability estimation for a full-scale study solution	**Standard solution, window and artificial lighting**	**New solution, window, artificial lighting and HLP**
Investment cost for the lighting solution including control luminaire with 0.022 kW power	1,500 EUR	1,500 EUR
Investment cost for HLP and a custom-made reflector		1,080 EUR
Operational hours during the year (10 hours * 7 days * 52 weeks); the alternative solution is adjusted for the findings (44%* reduction) in the full-scale field study	3640 hours	3640 hours * (100-44) % = 2038 hours
Annual operational cost for the solution (Norway 0,2 EUR/kWh electricity and grid cost) hours*nr of luminaires * luminaire power * electricity price	3640*2 * 0.022 * 0.2 EUR = 32 EUR	2038*2 * 0.022*0.2 EUR = 18 EUR
CO2 emissions – 1030 g/kWh-electricity	*3640 *2* 0.022 * 1030 g = 165 kg*	*2038*2 * 0.022* 1030 g = 92 kg*
Annual cost if CO2 emissions – price in 2021 was 3 EUR/kg	*165kg * 3 EUR = 495EUR*	*92 kg * 3 EUR = 277EUR*
Total cost investment and operation after 20 years installation + operation	1500 + 778 = 2278 EUR	1500+1080+437= 3017 EUR
Profitability occurs in the **46th year**		
Total cost investment, operation, and CO2 emissions after 20 years	*1500 + 778 + 12025= 14303 EUR*	*1500+1080+437+6730 =9747 EUR*
Profitability occurs during the **5th year**		
*The energy saving factor Is based on the relative difference between simulated and recorded value for LENI in the full-scale test office		

The building industry relies on economical profitability, and every new approach, seen as an addition to the standard solution, is seen through the lens of profitability. Some studies have shown that the willingness to invest in energy savings is higher if the reductions are monetarily higher (Oikonomou, Becchis et al. 2009). Investors and policymakers might not be concerned right now about issues that do not affect them directly, such as bills for electricity or the productivity rate of the company tenant of the space. However, this might change with within the context of time.

6.3. Applicability of the results and critical reflections

The potential for the integration of a daylight transport system (DTS) in a building can be discussed through several factors: outdoor daylight conditions and climate, building function and layout, and the integration of the daylight supplement via the DTS with the artificial lighting system and controls.

The process of designing daylight in buildings features several stages, starting from the building site and room orientation. The window should always be the primary source of daylighting, as it provides the view. Then, when good daylighting cannot be solved by the windows, daylighting systems and daylight transport systems can be used, as noted by (Ruck, Aschehoug et al. 2000). Table 19 shows the prerequisites for the process of designing good daylighting in buildings that should be taken in consideration.

Table 19 The process for designing daylighting in buildings; adopted from Ruck, Aschehoug et al. (2000)[23]

Daylighting design strategy steps			
Building	Daylighting availability	Latitude	
		Temperature	
		Sunshine probability	
	Obstruction		
	Building design scheme	Beam shaped	
		Courtyard/atria	
		Block	
		Nucleus	
Room	Relation to adjacent spaces	Autonomous	
		Borrowing light	
		Giving light	
		Interchanging light	
	Fenestration	Unilateral, sidelight	
		Unilateral, top-light	
		Multilateral, sidelight	
		Multilateral, sidelight and top-light	
	Proportion	Height to depth ratio	
Window	Design of facades and windows	Single design	
		Multiple design	Division within windows
			Division between windows
Daylighting systems	Function of system(s)	Single function	Protection from glare
			Solar shading
			Redirection
			Other functions
		Multiple function	Glare, shading, redirection
			Glare, solar shading
			Glare, redirection
			Shading, redirection

When designing daylighting solutions with a DTS, it is first essential to understand the local weather and solar microclimate at the building location. The weather conditions (predominantly the sky types through the year) give the first signals about what kind of DTS should be used. The predominant weather conditions are important when estimating the maximum performance of the system and, thus, dimensioning the system (quantity of tubes, for example). A building can feature a design with a primary system that works well under certain predominant sky conditions and another, secondar system that works well with other

[23] Permission granted by Pamela Murphy, SHC secretariat, on the 21th of February 2022. Permission to use information provided by IEA Terms and conditions: https://iea.blob.core.windows.net/assets/3bf6ce57-3df6-4639-bf60-d73ee8f017c0/IEA-Terms-April-2020.pdf

types of sky. Thus, all sky types that occur at the location should be discussed. The sun's altitude and azimuth (characteristic of the location of the building) are the most important parameters when it comes to the specification of the system in detail and designing its position within the building.

Solar radiation, such as in very hot (arid) or very cold (artic) climates, is important to consider because of the danger for heat transfer through the DTS. The thermal balance of the DTS used in buildings is argued to be high, but, in extremely high or low temperatures (outside the estimated conditions), this might be an issue where particular building design decisions are applied. An example of such design is a suggestion for horizontal light pipes located on the service side of a skyscraper building in Malaysia (Garcia Hansen, Edmonds et al. 2001). The idea was to enable daylighting in the deep inner space by guiding it first through the utility zone, which was oriented facing the west. The office space is oriented on the east side, while the utility zone on the west side is supposed to dampen the highest solar heat. In the same manner, in very cold climates, horizontal light pipes can be mounted on the ceiling plenum to guide the light. Then, the light pipes will be placed in a preheated area, and the heat loss or risk of condensation will be reduced.

DTSs, like light pipes, have been commercially available on the market for at least two decades. However, its number of applications is not high even in countries with predominantly clear and sunny skies, where the performance of daylighting via light pipes is not doubted. One may ask why, then, the application of light pipes does not proliferate in these countries? How can one expect that the application in countries with fewer sunny days would be better? The answer is in the so-called 'thermal delight', or the human preference for a thermal feeling based on experience. People in countries with hot climates associate an indoor space with a place where there can protect themselves from the hot weather outside and will not desire any more daylight, or direct sunlight, inside; on the contrary, they will appreciate dimmer, darker, ambient, cold-coloured lighting (Millet and Barrett 1996).

On the other hand, people living in cold climates associate indoor space with a place where they can be protected from the cold and would prefer ambient light similar to a warm sunlit place (Heschong 1979). A higher level of daylight inside will bring about a feeling of bright sunny weather outside, which can have a great positive effect on people in cold climates.

Moreover, the actuality of one DTS solution is also driven by the regulations and method used to rate the overall performance of the design, as noticed by (Ruck, Aschehoug et al. 2000); where different countries can put focus on different metrics, but they can also differ depending on their climate or building types and function. If an office building is located in a cold climate, lighting energy use will be important, and designers will be more eager to use alternative solutions. Hence, for buildings in hot climates, the balance in the thermal performance and reduction of thermal loads might be a priority, keeping designers reserved for any additional openings on the building and they're less likely to consider alternative solutions. The DTS has been proven to save lighting energy with an economic benefit present as well, but, in the end, the actuality for use lays in the overall strategy for the building performance.

Spaces like offices, schools, kindergartens, and physician and dentist offices have occupancy hours mostly from 7am to 6pm. These hours coincide with the daylight hours, except during the winter, when the daylighting hours are limited to 2-4 hours around noon. The use of daylighting might be reduced during the winter, yet it is still possible to achieve exploitation during the other ¾ of the year.

Other spaces like retail, public, cultural, and sports buildings have slightly postponed occupancy hours, such as from 10am to 8pm. Finally, hospitals, hotels, and some three-shift manufacturing industries have non-stop occupancy hours, with the exploitation of daylight during the daylight hours having even more potential. It is obvious that, even when daylight availability is reduced during the winter, it is equally increased during the summer.

It has been argued that the light power density (LPD) (W/m^2), of artificial lighting cannot be reduced in high-latitude areas due to the daylight absence during occupancy hours during the winter. LPD is one of the parameters for energy efficiency in buildings (Ryckaert, Lootens et al. 2010). With good daylight distribution in an indoor space, the operational hours for an artificial lighting solution can be reduced, which will reduce the total light energy consumption, expressed via lighting energy numerical indicator (LENI). LENI is included in the total energy consumption of one building, and it is equally important parameter.

Further, the application of the DTS in new buildings has to be coordinated with the space planning. The indoor space can be well-lit by unobstructed windows up to the so-called perimeter zone, which is estimated to be twice the height of the window (from the floor). This metric is nowadays unreliable, especially with new building regulations aiming for energy efficiency. Windows have gotten lower light transmission due to the higher thermal resistance. Walls are becoming thicker because of the thicker insulation layer, bringing about a reduction in the windows' open view. It is therefore reasonable to think that horizontal light pipes can be installed in such a way that the pipe's exit lines up with the edge of the perimeter sone. Deeper spaces can benefit even more, as the contrast of daylight delivered solely via (side) windows to these areas and the daylight delivered via the HLP will be even stronger (Fig. 61). Closed spaces within a building's core (stairs, bathrooms, service shafts) have a good potential for daylight supplement via an HLP as long as the distance from the facade is no longer than the DTS's design would suggest (the minimum aspect ratio of the pipe's length and diameter).

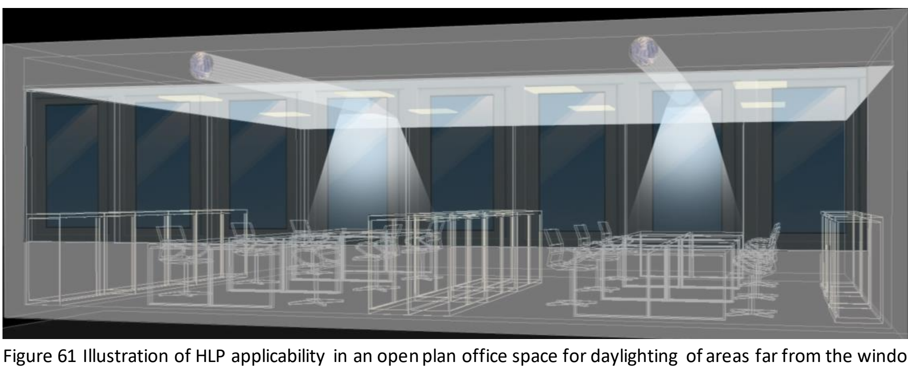

Figure 61 Illustration of HLP applicability in an open plan office space for daylighting of areas far from the windows

An issue related with DTS integration in building architecture is in connection with the layout design. Office buildings nowadays are designed with an open plan layout more often than with cell offices and partition walls. This is because of the concept of commercial buildings being rentable spaces of high flexibility in layout. The layouts often have columns as the only vertical elements in the space. If the most optimal design of daylighting via vertical light pipes would suggest a grid design, the space would thus need the installation of a number of vertical shafts, not only for the daylighting of one particular floor, but also for guiding the daylight from the roof to the lower floors. It can be challenging to get such design accepted, as shafts would reduce the rentable space of the floors. In these cases, vertical light pipes can be placed solely by the columns or used solely for a top floor.

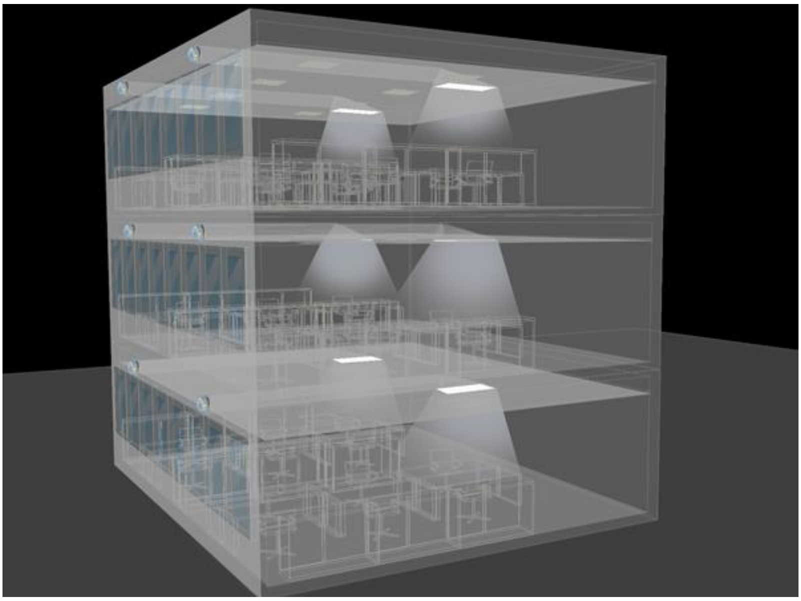

Figure 62 illustration of HLP applicability in a multilevel office building with application on a south oriented façade.

Horizontal light pipes are therefore argued to surpass this issue particularly in multilevel buildings, as they can be installed in the ceiling plenum, over the suspended ceiling (Fig. 62). The challenge of implementation is thus moved to the design concept of the facade and possibilities for perforation (according to the bearing system and height over the windows where the HLP needs to be placed). In this context, vertical light pipes protract to the roof and are thus less visible than their horizontal counterparts.

Based on the most optimal solution for the functionality of a daylighting system and its installation in a building, vertical light pipe systems would be suitable for compact buildings of up to three floors in height, where the inside space would benefit from natural light. Building types such as factories and those for industry, retail, and storage halls could use this solution. Kindergartens and educational buildings of up to three floors can also be included within this group. Horizontal light pipe systems are more suitable for multistorey buildings, where the solar conditions are such that the exposure to the south is without obstruction, and additionally, where the need for solar shading on these facades is foreseen. Office buildings, hospitals and non-compact education buildings would be suitable for horizontal light pipe solutions.

The reasonable question to ask would be if the application of horizontal light pipes where at least one, preferably the south facade of the building, needs to be without obstructions, is possible at all? Multilevel buildings are mostly erected in city centres, where it would be irrational to expect good sun conditions and desirable full sun exposure on the south facade. In the concept of ZEB design, energy independence is achieved by the building being ideally designed regarding exposure to the sun's rays. Such design presumes generally good insolation on the south-oriented façade. Furthermore, the concept of ZEN predicts a settlement or a group of buildings where each structure is designed in such a way that each enables and ensures the necessary conditions for its neighbouring buildings. This means that the buildings would not compete in getting exposure to the sun's rays, and the overall design of the settlement would be to regulate new developments to preserve these features. The future of HLP application thus rests in the future of the ZEB and ZEN concepts.

The proper integration of daylight in an indoor space and with artificial lighting through a light control system is essential for lighting energy saving. How light control equipment is designed and installed in a space may at first look like an easy task, but this is widely reported to be a very complex issue, especially in regard to lighting control based on the level of available daylighting. Light control systems with photosensors integrated in the ceiling to screen daylight levels on the working surface have been reported to not work as they should, because of the radical decrease in the daylight level from the side window and deeper in the space, and the sensors' 'visual field' (Kolås 2011). Higher latitude areas might need some special approach when it comes to light (daylight) control equipment. Low solar altitude daylight produces situations with excessive sunlight (luminance beyond sensor's threshold) that standard light control solutions are not capable of handling. This was also the conclusion in some studies dealing with daylight screening in areas at high latitudes (Arnesen 2003, Arnesen, Kolås et al. 2011, Kolås 2013).

The faster applicability of these systems can be also discussed through the idea of the systems' important usefulness, as mode 2 research argues (Hessels and Van Lente 2008). A research result has no understandable, acceptable, or applicable value if it is not from the social context of that time and place (Popper, 1972). It has also been suggested that the results of applied science, such as technological innovation are always very welcomed (Gieryn 1983). If energy-saving issues through cost and value analyses, as discussed in the previous section, do not provoke enthusiasm, the spectral composition of daylight (delivered deeper in the building space) should be the next path. The standardization of circadian light concepts might help, but this approach needs yet to be developed. Further, the aesthetics of the areas inside the building to be lit by daylight is one possibility, but, again, there are no such metrics that can measure the effect. Finally, the idea of enabling useful and rentable space deeper in the building and beyond the perimeter zone is directly addressable. Using the DTS, the inner space would be supplied by natural light each time the outdoor space has illuminance above a threshold value. It could never be said that it is the same as sitting next to a window, but it could be compared to sitting on the edge of the original perimeter zone. This is a kind of ‘trading zone approach’ introduced by Collins, Evans et al. (2007) to consider when the applicability and usefulness of the DTS are argued. The applicability lays in finding a commensurability, a common language to communicate with and be understood, similar to the Pidgin and Creole languages.

Society is a recipient of all scientific knowledge; thus, it is permanently under its influence. Society is, thus, in the long term, always moulded by all scientific research results, and, as such, provides a foundation and further context for the research results. In this context, the author has been working on the dissemination of the partial research results after each part of the study, to get closer to the ones that suppose to use them in practice (architects and lighting designers). The results have been published in periodicals in the form of popular scientific articles. Furthermore, the results have been conveyed at lectures for the students on Faculty of Stainable Architecture and Faculty of Lighting Design in Norway and, in the form of a presentation for practicing architects at the company that supported this research, Norconsult. The list of dissemination channels has been enclosed in the ‘Publications’ section.

6.4. Contribution to IEA task 61 subtask D

When this study started, that same year, the International Energy Agency (IEA SHC) office created a new task (Task 61, Annex 77) under the title ‘Integrated Solutions for Daylighting & Electric Lighting’. The International Energy Agency is an autonomous agency established in 1974 that carries out a comprehensive program of energy cooperation among 28 advanced economies. According to some reports, it was estimated that 20% of global electricity use is spent toward lighting needs (Waide and Tanishima 2006). With the world’s growing population and growing access to electricity (18% of the world’s population still does not have access to electricity), there is a risk that the global electricity demand will increase, even with the improved efficiency of lighting systems, if global and national policies are not changed (Gentile, Dubois et al. 2016). One of the aims of the IEA is to promote sustainable energy policies and environmental protection in a global context, particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.

In Task 61, 50-60 international experts and companies have been working to develop strategies that combine daylighting and appropriate lighting control systems, which will lead to improvements in energy-efficient lighting schemes. These solutions will be also offering the best lighting conditions for human beings. Task 61 was subdivided into four subtasks, of which subtask D hosted full-scale case studies. Some of the objectives for the subtask D were, e.g. to review the relation between user needs and user acceptance, and lighting energy use in buildings, then, to review lighting quality, non-visual effects, installation design, recommendations for energy regulations and building performance certificates. Finally, the objective was to discuss possibilities for robustness of integrated solutions for daylight and electric lighting, and to explain it using technical, ecological, and economical approach.

The full-scale office with the horizontal light pipe and custom-made reflector and the integrated daylight-electrical light solution was one of 20 case studies within this subtask. The general objectives for all case studies within the subtask were ad hoc or the long-term monitoring of the photometry of an integrated solution, lighting energy use, the circadian potential of an integrated lighting solution, and the user opinion of an integrated solution. The full-scale study in the current research offered long-term, whole-year monitoring of outdoor and indoor photometry and lighting energy as well as a user survey on the integrated solution. The full-scale case study report is published within the IEA SHC Report D3-D4, 'Integrating Daylighting and Lighting in Practice: Lessons Learned from International Case Studies' (Gentile, Osterhaus et al. 2021).

Participation in IEA Task 61 for the author of this thesis was a very useful experience, resulting in contributions in two conference papers and three reports, listed in the 'Publications' section.

7. Conclusions and future potential

Daylighting in buildings is one of the most essential elements of the space, enhancing not only human visual performance (necessary illuminance level for photopic and scotopic vision), but also perceptual impression (recognizing the space's forms, dimensions, and modelling), and, most importantly, providing basic conditions for preserving human health during a long-term stay in the space.

This thesis presents knowledge resulting from several research activities performed in the last four years within this PhD study. Information on the actuality of advanced daylight transport systems, like light pipes, in the Scandinavian area, was quite lacking when this research began. The widespread opinion was that the predominantly overcast sky in high latitudes areas is a poor foundation for the use of light pipes. However, while the weather might be overcast 70% of the time, still, 30% of the time the weather might be sunny. Even more, 30% of the time, low angled sunlight will disturb humans in the building, who will try to protect their visual comfort by closing the blinds, thus cutting off the daylight. The application of light pipes received attention in this situation. One light pipe could provide daylight inside the space at the same time blinds need to be closed. One standard window does not always manage to handle the situation with low angled sunlight. It is thus possible to view the light pipe as a 'daylighting solution' in addition to the window that will manage to provide daylight when the sun-shading of the window needs to be closed.

The literature of advanced DTS studies has mostly addressed sunny climates, but, to some extent, these studies were also performed under predominantly overcast sky areas similar to the location of this study: Norway. The initial part of this research was to conclude on systems that are the most suitable to provide functional lighting for buildings in high latitudes. The conclusion was that it is not possible to provide suggestions at once, and the suitability of each system according to predominant daylight condition needs to be a first step to consider. Also, every location has its own specific solar (daylight) microclimate that is affected by the settlement in the neighbourhood. Then, every building has unique layout solutions and room functions. It is not surprising that a decision could not be easily made by following the flowchart, but the decision should rather be designed in detail through the consideration of all prerequisites. One building could have several systems configurated depending on the orientation. Spaces oriented north could be designed with daylight transport systems for diffuse daylight, and spaces oriented south could rely on façade-mounted daylighting systems for direct sunlight. East and west building façades could rely on actively tracking the direct sunlight as well.

The systems reviewed in this paper deliver daylight deeper in the space than a usual window and thus increase the overall daylighting level and uniformity. The more extensive use of daylight in buildings through the application of such systems has many other benefits. The luminance across the room might be better balanced compared to the daylighting through side windows only. Visual comfort may be improved, since the luminance condition would change the glare conditions for a user. Seasonal and diurnal variation in the outdoor daylight would affect in dynamic of daylight intensity and daylight colour inside. These two features were considered beneficial characteristics of daylight that comes through the window, which, in the case of deeper distribution, could provide the same positive experience to spaces farther from the window.

In the second part of the research, the aim was to determine how efficient the HLP is in providing daylighting inside at the working area during the entire year. To manage this experimental trial, a customized measuring method was established with a matrix of different positions (representing the solar altitude and azimuth during the year) that, at the same time, presented the temporal parameter for the analyses (Paper 2 and 3). One of the findings from the first study suggested that this amount of daylight delivered via the HLP can even be improved if the LCP is used as a collector for incoming daylight.

The conclusions from the second, experimental part of the study (Paper 2) was that the illuminance levels inside the room at a 2.1 m and 4.5 m distance from the façade, corresponding to the second and third workplace from the window, can be increased by daylight being transported through a horizontal light pipe (HLP) with a static light deflecting panel, LCP, at the pipe's entrance. The conclusions from this study were that a horizontal light pipe, even without any LCP at the entrance, makes a significant positive contribution to daylighting deeper in the space, and that tilted LCPs work best under an overcast sky, while rotated LCPs work well with low angled sunlight. Tilted LCPs with horizontal cuts effectively deflect light at higher altitudes and increase the light transmittance (η) of the tube, but this is most significant during the winter, when most of the light predominantly comes from the zenithal part of the sky. In buildings where winter daylighting is highly beneficial for health and wellbeing, such as in healthcare facilities or schools, tilted LCPs with horizontal cuts could be a very valuable application. Two symmetrically rotated LCPs with vertical cuts increase the light transmittance (η) of the tube for morning and evening light, especially during the summer. As such, they could be even more attractive for buildings used during the evening.

The conclusions were that, for a light pipe with an aspect ratio 8, the DA_{300} was increased by up to 19% if the LCP configuration T-06-27 was used, and the highest improvement occurred during the late spring (an improvement of 1 h and 20 min each day). For the DA_{100}, the highest improvement (by up to 10%) was found when the LCP configuration R-07-40 was used. This improvement was most noticeable during the summer months, where, each day, the DA was prolonged by nearly two hours.

Further, for a light pipe with an aspect ratio of 16, the DA_{300} was improved by up to 16% if the LCP configuration T-06-27 was used, while, for DA_{100}, the most noticeable improvement was for the LCP configuration R-08-40 (up to 8.75%); it would be possible to expect a minimum of 10 h of daylight supplement during the summer, which is one hour and 45 min longer than in the base case. Analyses were made based for a maximum period of 10 hours (from 7am to 5pm), which indicates that, for a summer period, the improved daylighting might be even longer. The amount of daylight in the DA_{300} analyses for the HLP (aspect ratio 16) indicated that there is a high potential for daylight supplement for even longer pipes than those examined in this study.

The full-scale study offered multi-perspective (qualitative and quantitative) conclusions. The qualitative part of the research was performed as a user survey (interview) on the visual impressions of the daylit space when daylight was provided by the HLP (Paper 4). The interview consisted of qualitative descriptors and open questions about the visual and perceptual impressions of the daylight conditions in the office. Five-point bipolar semantic differential scales were used in the interview to collect the users' opinions. Statistical correlation and a t-test were used to analyse the results.

The paper concluded that the user impressions of the office were more positive when there was a noticeable daylight supplement from the HLP in the space, but the appraisal was negative for higher light variability in the both indoors and outdoors illuminance level. The conclusions from the independent sample t-test analyses were that there was an overall more positive evaluation of the room as pleasant, interesting, and exciting in the test group of participants. The test group was comprised of participants who had much higher daylight delivered through the HLP. The test group evaluated the daylight and artificial light conditions in the entire room more positively than the reference group.

The increase in the outdoor vertical illuminance incident light pipe had a statistically significant relationship with the increase in perceiving the room as open, pleasant, interesting, and exciting. There was also an increased positive evaluation for the room attributes of spacious, uniform, and legible with an increasing level of global horizontal illuminance outdoors.

Moreover, the conclusions from the analyses were that there was a statistically significant negative relationship between the variation in the vertical illuminance incident at the tube's entrance and the global horizontal illuminance and the participants' evaluation of the test room as uniform, pleasant, exciting, and interesting. The paper concluded that this occurred because of the inconsistent variation in the artificial light level, which was supposed to supplement the insufficient daylight level to achieve a recommended level in the office.

Furthermore, a significant negative relationship between the level of indoor illuminance and the participants' perception of the room as exciting was also found. However, this finding could be interpreted positively when it comes to the daylight solution with an HLP. The level of indoor illuminance was higher in cases when the DLC was not affected by the higher levels of outdoor daylight, which was reflected on the slats. This means that the higher level of indoor illuminance was strictly provided from the artificial light, which resulted in participants' negative impressions of the room in terms of it being exciting.

The other part of the full-scale study (Paper 5) was a field study based on recorded levels of daylight and artificial lighting provided on the two desks in the office and the lighting energy used for two luminaires supplying the two desks with artificial lighting when the daylighting was under the recommended threshold value. Two study periods were established based on equal solar altitude and azimuth conditions in the year: the test period with daylight via the HLP enabled and the reference period with daylight via the HLP disabled.

The main conclusion from statistical analyses of the independent values (vertical illuminance incident at the light pipe and global horizontal illuminance) and dependent values (measured indoor illuminances on the two desks) was that there is a noticeable daylighting delivered on the second desk coming from the HLP (and via the custom reflector). This value was found to be between 30 and over 100% higher than the value when daylight is supplemented solely by windows. During ad-hoc measurements at equinox, with darkened windows, the recorded values were found to be between 200 and 300lux on the desk 2, and up to 50 lux on the desk 1. The weather was clear and sunny, and the vertical illuminance incident HLP (VI) was between 60 and 80 Klux. The conclusions were also that this value could be expected between 10am and 2pm for this full-scale office (when the HLP is oriented against the south and without any obstacles in front).

The conclusion for the light energy saving potential was unfortunately not possible to develop due to the unreliability of recorded data. However, the light energy saving potential has been noticed comparing simulated and recorded values for lighting energy use (LENI) for solely test period. Difference between simulated and recorded values for energy consumption per year has been shown to be about 44% lower energy consumption.

The energy-saving potential argued above is present during the summer as well as during the winter and it varies according to the weather. The energy saving during the winter period is very important, as it is during the winter that the energy need of buildings in high latitude areas increases, and any reduction potential is thus of importance. Moreover, during the winter, when the low angled sun would induce the probability of excessive light (glare) in the space and total closure of the sun-shading, the solution with the HLP would enable daylight presence indoors to meet the human need for natural light.

The conclusions following the four years of work on this PhD study are as follows: The potential for advanced daylighting systems, such as horizontal light pipes, to be used for buildings in high latitude areas is good. Horizontal light pipes can even increase the usable daylight in climates with predominantly overcast skies if supplied with an LCP as a collector of the light. This can also be useful for buildings with exterior obstructions and, therefore, lower potential for daylighting via windows. Further, it increases the usable daylight when the weather is clear and sunny, because the direct sun rays are predominantly low, and the sun-shading would block them to protect the visual comfort indoors. The potential for the daylighting of windowless spaces, e.g., corridors, staircases, and other core rooms, by an HLP, is also foreseen based on the findings from investigations of this PhD.

The widespread belief about DTSs being too complex, unreliable, or not profitable has slowed the integration of such products in both new and renovation projects. The most major reason for this is the lack of real tactile and visual experience with these systems. There are not many such systems that are already implemented. In addition, the non-simplicity of the implementation of these systems rests in its design. It is easy for one architect to order a new product even when not seeing it, knowing that it will affect just a small part of the space around it, or for the lighting designer to choose a luminaire without seeing or holding it, because it will visually affect just a small part of the space, but daylighting systems affect the façade, building construction, ceiling layout, cooling-heating system, cold bridges, and visual experience of the room. Their general design involves electric lighting and shading controls, installation procedures, and the prediction of energy savings and costs.

7.1 Recommendation for further work

In this PhD research, the potential for further study lies in the examination of a full-scale test office that is equipped with a horizontal light pipe as a permanent daylighting solution. The potential for further research would rely on the design of a custom-made reflector to be adjusted to another research aim. The custom-made reflector in the current study was designed to cast all daylight on the task surface, as the user survey and field study aimed to analyse the daylight as functional light on the desk. In future work, a custom-designed reflector could be constructed to provide daylight from the HLP to another surface, e.g., solely the wall in front or a wall dividing the office from the corridor. Daylighting vertical surfaces much deeper in the building was argued to have a great impact on the human perceptual impression of the space as well as health and wellbeing of employees spending more time in these spots. In many buildings, rooms for gathering, meeting rooms, or kitchens are placed within the building core. These spaces could also be further topics for studying daylighting delivered via an HLP and custom-made reflector.

The findings of the user survey in the full-scale office only focused on the users' appraisal of one small office, where the effect of daylighting via an HLP was noticeable on the desk and the wall in front. The user appraisal might be different for an open-plan office, where users would have a much deeper view of the room and would be able to experience daylighting conditions in a much bigger space. Thus, future research could be performed in an open-plan offices with several HLP installed in the same way. The daylight via the HLP could be directed to the desks or other objects in the space.

As mentioned in the experimental study, the potential improvement in the daylight autonomy (DA_{300}) by using the LCP configuration T-06-27 as a light collector was up to 16% for a light pipe with an aspect ratio 16, the same aspect ratio as in the full-scale test office. It would then be reasonable to attempt this LCP configuration in a real case by applying it in the light pipe's dome in a full-scale study. In this case, this would complement the experimental laboratory test performed using a scale model of a light pipe while also providing a very valuable full-scale examination.

A suggestion for further work could also be an improvement suggestion for the issues noted during the monitoring in the full-scale field study, namely the reflection of the light (both sunlight and skylight) on the sun-shading slats in a position used in the study that caused interreflections for the daylight-linked sensors. In this context, another configuration of the slats or another type of sun-shading device could be used to overcome this issue.

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Appendix A

Scientific articles providing the basis for this PhD

1. Daylight Transport Systems for Buildings at High Latitudes, Biljana Obradovic, Barbara Szybinska Matusiak

2. Daylight autonomy improvement in buildings at high latitudes using horizontal light pipes and light-deflecting panels Biljana Obradovic, Barbara Szybinska Matusiak

3. A customized method for estimating light transmission efficiency of the horizontal light pipe via a temporal parameter with an example application using laser-cut panels as a collector, Biljana Obradovic, Barbara Szybinska Matusiak

4. The effect of a horizontal light pipe and a custom-made reflector on the user’s perceptual impression of the office room located at a high latitude, B. Obradovic, B. S. Matusiak, C. A. Klockner and S. Arbab

5. Illumination and lighting energy use in an office room equipped with a horizontal light pipe with a reflector, field study at a high latitude, B. Obradovic, B. S. Matusiak

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Daylight Transport Systems for Buildings at High Latitudes

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Abstract

This paper is a literature study of daylight transport systems aiming at selecting the most appropriate ones for application at high latitudes. It is limited to the systems that transport light at a long distance from the façade and distribute it either in the building core or at a rear place in a room adjacent to the façade. The literature is spanning from the 80s' to the present. It covers the theoretical background and development of the systems from their infancy, through technical development of the design elements and to the adaptation of the systems to different climatic conditions. Since the most literature comes from equatorial and tropical climate, a short contextualization with high latitudes climate is included. Findings are systematized and presented in tables for easier comparison of efficiency, visual comfort, design efficacy, maintenance need, cost and/or availability on the market, and energy-saving potential in different climates. Conclusions confirm that the daylight condition at the location is the main prerequisite when deciding on the type of collector while the building structure and room functionality are the basis for choosing the type of the transport element. Finally, the distribution element showed to be the key factor when discussing applicability in a functional space where the final success depends on human acceptance. This paper can be useful to get an overview of performance characteristics and application preferences of different daylight transport systems or just their components in daylight conditions at high latitudes.

1. Introduction

The demands for energy saving in newly constructed buildings, set by authorities, are systematically increasing. Nowadays there is a passive-house level for all the new buildings, but there have been many political signs about the demands for Zero-energy buildings (ZEB) starting from the year 2020, for residential and commercial buildings. This means that the building (or its site) must provide itself with energy.

Lighting can use just electrical energy while all the other technical systems can use some of the alternative sources that could be renewable or energy-efficient. Electrical energy demands for lighting in buildings could be solved with PV panels usually placed on the roof of the building. However, according to the Norwegian research project "Klima 2050", higher precipitation is expected in Scandinavia soon, because of climate changes. This implicates recommendations for the design of "green roofs". Green roofs help damper floodwater in cities and help reduce the load on the sewage system, thus allowing the design of lower capacity. This further means that it will no longer be possible for solar panels to be placed on roofs in the quantity that could solve all energy requirements. Moreover, it is also widely considered that PV panels are a ''renewable source of power to lighting, but this is wrong as they are just a convertor of the energy with extremely high CO_2 footprint [1]. That is why it is important to focus attention on finding a renewable alternative for lighting, for example by providing possibilities to the increased use of daylight. More daylight provided indoors could reduce energy demands for lighting.

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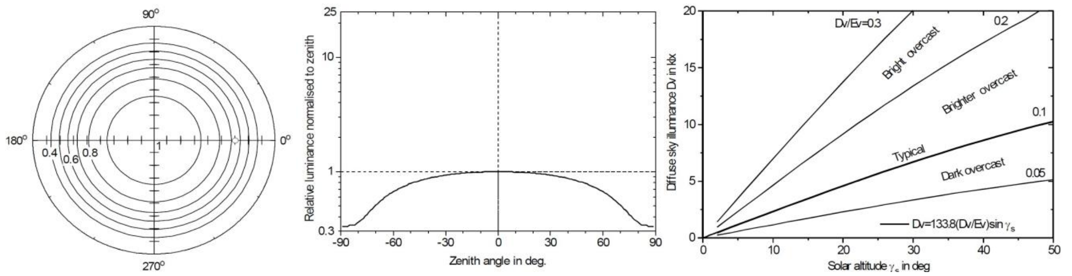
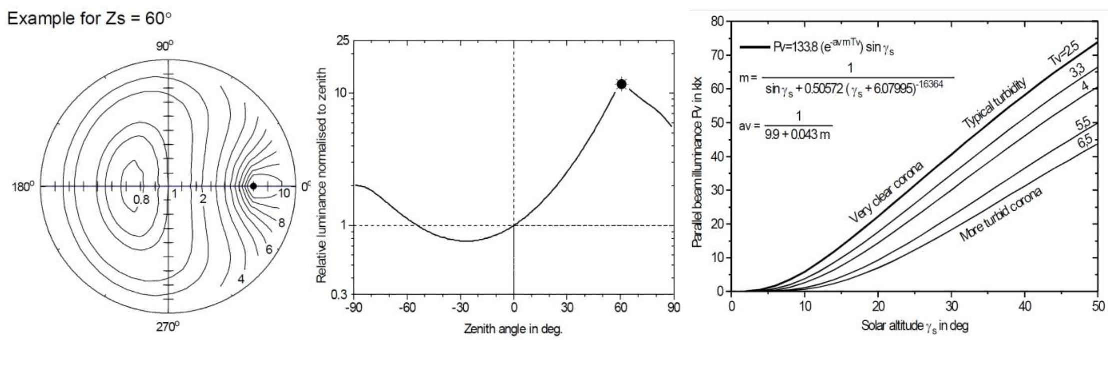
High latitude locations are characterized by low sun angles, and the necessity for sun-shading devices for visual and thermal comfort is strong [2-4]. Several studies addressing visual comfort in office buildings at high latitudes show the need for special attention when designing sun-shading devices, not only for low solar angles to balance daylighting and thermal load, but also for the unyielding need of users for manual control of sun-shading devices [5-8]. The practice and research have shown that user-controlled sun-shading devices are often the cause of radical reduction of daylight availability during the day, where daylight contribution through the window is, then, very much dependent on the weather conditions and a single-user personal judgment [9,10]. Daylight transport systems give the possibility to deliver daylight into the room independently on solar radiation control and could make daylight presence indoors more reliable. Any contribution to the daylighting in the deeper space is advantageous. In building cores and rooms without windows as low as 50 lux is a satisfactory level that makes significance for a feeling of daylight presence [11]. Prolonged daylight availability indoor could decrease energy demands for artificial lighting and increase the benefits to the human circadian system.



(a) (b) (c)

Fig. 1. Sky model I.1. Overcast sky with steep gradation and azimuthal uniformity, (**a**) Isoline graph e.g. Zs=60°, (**b**) Sky profile in solar meridian, (**c**) Probable diffuse horizontal illuminance Dv under this sky model [14].



(a) (b) (c)

Fig. 2. Sky model V4, very clear/unturbid sky with a clear solar corona, (**a**) Isoline graph for e.g. Zs=60°, (**b**) Sky profile in solar meridian, (**c**) Probable direct solar horizontal illuminance Pv under this sky model [14].

The primary goal of this literature review was to select daylighting systems suitable for buildings at high latitudes. In the context of this study, it means latitudes higher than 55 degrees. This is important since e.g. the office buildings use almost 40% of energy for lighting, other building types, as commercial or industry even more. The diurnal function for office buildings (9h-17h) corresponds very well with daylight hours. For winter months (the case of Oslo 59N) daylighting hours are from 09 h to 15 h, while for summer months, the daylighting hours are from 04 h to 23 h. This gives notice on systems' applicability for many other functions (e.g. industry, healthcare, sports and recreational buildings, and educational and cultural facilities). The last chapter brings a discussion about the results of the literature review and conclusions about applicability for high latitudes.

There are many benefits of using advanced daylighting systems. "*It increases usable daylight for climates with predominantly overcast skies, increases usable daylight for very sunny climates where control of direct sun is required, increases usable daylight for windows that are blocked by exterior obstructions and therefore have a restricted view of the sky, and Transport usable daylight to windowless spaces*" [12]. Specifically, deep plan offices, corridors, staircases and other core rooms that require lighting during the day can, without a doubt, benefit from advanced daylighting systems.

The potential of many of the daylight transport systems was scientifically proven, and they are mentioned in the overview of the daylighting technologies reviewed in the IEA task 21 [12,13].

2. Sun and sky conditions

Literature review reveals that the majority of studies were done in tropical and European maritime climate. The climate in tropical countries is characterized by high sunshine, high humidity, and very frequent cloudiness and rainfall. The exterior illuminance can rapidly decrease from 100000 lux to 20000 lux. High humidity brings light scattering in the atmosphere so even the clear sky has a considerable amount of diffuse light, about 20%. The average yearly sun hours are 2350, which is 55% of the maximum (4476 hours), according to Weather-and Climate site. Nevertheless, the percentage of sunny skies just passed 50%, the research on daylight transport systems in tropical areas mostly dealt with clear and sunny skies, while the studies in the European maritime region solely addressed the overcast sky. The conclusions given in the papers about the potential of application for different components in the high latitude regions, based on the research, are too general and more detailed ones need to be drawn based on realistic daylight conditions for almost every region.

Interestingly, in the rather low populated Northern Europe, three capitals (Oslo, Stockholm, and Helsinki) and other large towns (Bergen, Orebro) are located close to 60° N; giving motivation to study the potential for daylight harvesting at high latitudes, at least higher than 55°N (Copenhagen). The climate of the south part of Norway (58° – 62°) is classified as a humid continental climate. There are 1632 hours of sunlight per year (37.2% of day hours), which means on average 4:28h of sunlight per day. The remaining 62.8% of daylight hours are likely cloudy or with shade, haze or low sun intensity, according to the Norwegian Meteorological Institute. At midday, the sun is on average 30.5° above the horizon at Oslo (the lowest 7° in December and the highest 53° in June).

According to Satel Light data and Geophysical Institute, University of Bergen, Norway, predominantly overcast sky type, in the targeted area of 60° N, corresponds to the sky standard type I.1, while clear sunny sky conditions correspond to the sky standard V.4 [14]. When solar altitude is 10° for bright overcast sky (type I.1.), the exterior diffuse horizontal illuminance is 4650 lux, while for solar altitude 50° is 20500 lux, calculated from Dv=133,8×Dv/Ev sinα, Fig. 1 [14]. This result indicates the possible expected illuminance intensity and it helps to choose the right collector type and its design properties. When the solar altitude is 10° for clear sunny sky with very clear corona (type V.4; Tv 2,5), parallel normal illuminance Pv is 9468 lux, while for the solar altitude 30° it is 42000 lux, calculated from the Pv=133.8 $(ee^{-aaaaaaaaaa})$ sinα, Fig. 2 [14].

3. Daylight transport systems

The literature review covered scientifically studied components and available market systems. The review started with a repeated search in the following online data bases: Google Scholar, ScienceDirect and Scopus. The following keywords were used: daylight, light, pipe, fiber, rod, system, and phrases: lighting rod, fiber optical system, mirror light pipes, daylight shading system, daylight guiding system and daylight transport system. The literature search resulted in 144 articles, 22 of which were excluded and 122 were selected as eligible. Those articles gave the second set of articles via cross-referencing. The majority of second articles were older than two decades, but they were selected as eligible since they covered the innovation issues - patents or theoretical background of the main topic. Included patents also show that the first ideas of daylight transport in buildings were not solely initiated by the energy crisis but were triggered by the need for cheap and quick rebuild in the after-war period. The search was done in September 2018 and the updated search was done in September 2019. The review methodology is presented in Fig. 3.

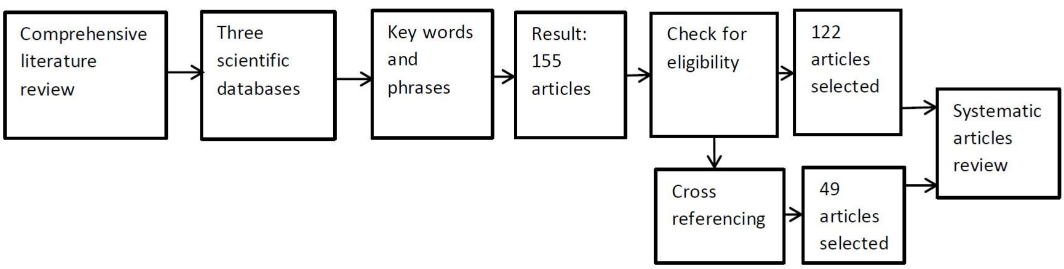


Fig. 3. The review methodology in stages.

A systematic review of the selected scientific articles showed that all light transport systems consist of three elements: a) a light collector, that collects diffuse and/or direct sunlight; b) a light transporting element, which allows light propagation inside itself; and c) a light distributor that extracts the light, and delivers it into the space [15]. An overview of the elements in the daylight transport system is presented in Fig. 4.

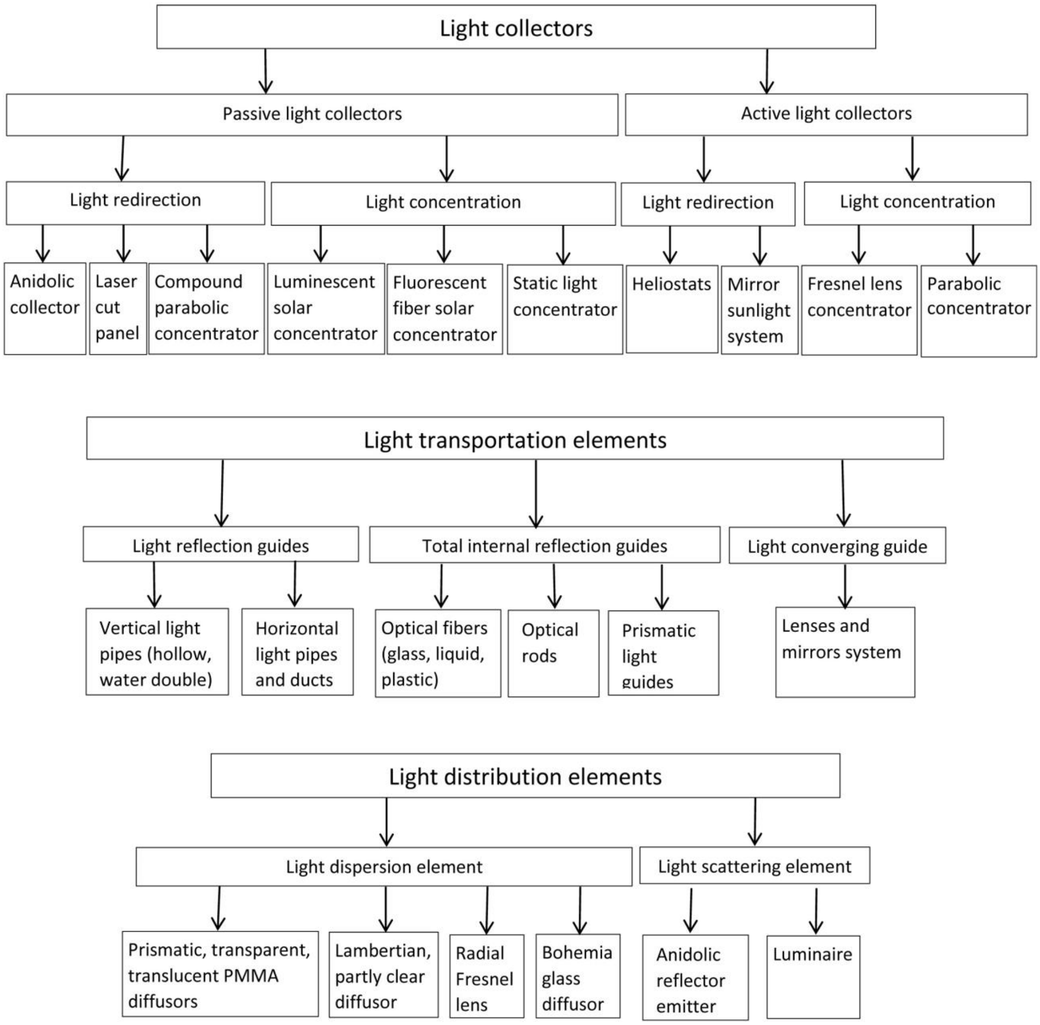


Fig. 4. Overview of the elements in the daylight transport system; blue and pink indicate often combined components.

3.1. Light collectors

A light collector aims to collect light and convey it to a specific point or direction. Light can be concentrated or redirected through passive or active light collectors. Passive light collectors are fixed in one position, usually the best-suited place according to design prerequisites, and they rely on predominantly light-incident conditions. Active light collectors rely on the highest light intensity source and its beam directionality. Active collectors have a fixed position in the place, but their light concentrator moves through a single or double axis and follows the direct normal component of the light source to efficiently convey the light.

3.1.1. Passive light collectors

Passive light collectors are fixed elements placed in a certain position outdoors to enhance light collection. Since their position is fixed, they mostly rely on the permanent light conditions, such as sky illuminance, and occasional direct sunlight incident on a collector's entrance. With the exception of flat glass [16] or dome [17,18] that (1) transmits light almost without changing its direction, the light is (2) reflected on an anidolic concentrator or hyperbolic concentrator [19], (3) refracted by the prismatic film in CPC [20], (4) deflected by laser cut panels (LCP), or (5) absorbed by a fluorescent fiber solar concentrator (FFSC) or a luminescent solar collector (LSC). Some active solar collectors were also studied with a fixed position (passive collection) [21,21].

3.1.1.1. Anidolic concentrator

This is a highly reflective element, composed as a compound parabolic concentrator (CPC), where the edge light rays' principle of acceptance sector is used [23]. It can be constructed as a 2D element, or as a 3D element rotating around its symmetry axis. Anidolic concentrator works on a non-imaging principle of light reflection, where all the incident light on an aperture entry (in the edge rays span as minimal-low to maximal high) is reflected and redirected towards the aperture's exit, Fig. 5 [24]. The concentrator was simulated for the CIE overcast sky and experimentally tested in winter weather conditions in Switzerland, where authors concluded that the admission sector of anidolic collector should match the visible part of the sky [25-27]. Experimental results show energy-saving potential of up to 31% compared to the reference room and additionally better visual comfort, improved uniformity and less contrast, as well as better results in human performance tests (string reading test according to Hygge and Löfberg, [28]) [29-31]. An asymmetric hyperbolic concentrator was developed based on non-imaging optics to contribute to the non-tracking solar applications. This design shows almost 100% of ray transmittivity for incident angles of up to 60°, and it could be used for collecting visible radiation too, Fig. 6 [19].

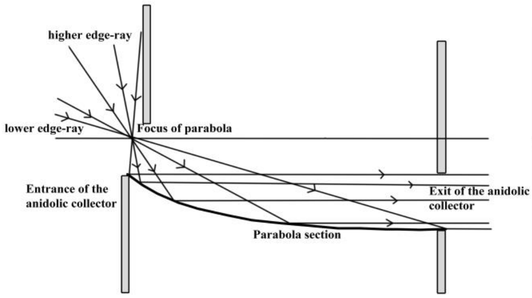


Fig. 5. Schematic view of an anidolic concentrator based on the edge-ray principle [27]

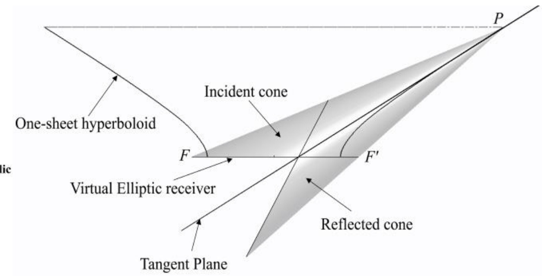


Fig. 6. Hyperbolic concentrator, incident-, and reflected- cone and tangent plane [19].

3.1.1.2. Laser-cut panel

Laser-cut panel (LCP) is a transparent acrylic panel with laser cuts which act as a reflection surfaces for light rays refracted inside the panel. The incident light on a panel is redirected as output light in the desired direction, according to the specific D/W (distance to width) configuration of the LCP [32-34]. It was proven that 90% of light is deflected, 8% of light is reflected from the panel, while 2% of light is passed through (undeflected), Fig. 7. For noninclined cuts, there is a unique incident light angle and D/W configurations that result in the highest light deflecting ratio Fig. 7(b), while for inclined cuts there is a span of incident angles for the same D/W configuration which results in the highest light deflecting ratio, Fig. 7 (c). Inclined cuts are thus more appropriate for variation in incident light angle, such as altitude variation during the day, because the output light-angles span will be more narrowed and suited to the aimed propagation in a desired angle. LCP is very effective in redirecting both direct and diffuse light if placed as a collector for the daylight transport system [35-37]. Simulated and proven studies were conducted for LCPs placed on the east and west side for horizontal light pipes in tropics [38,39]. It was also suggested that LCP can track the Sun's azimuthal movement to enhance light collection [35,40], still, the greatest usage for LCP is as a passive shading and daylight enhancer for windows since it provides the outside view [12,41,142].

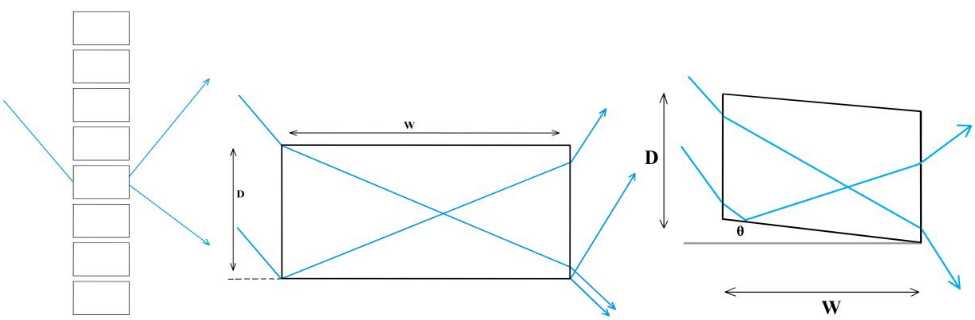


Fig. 7. (**a**) A laser-cut panel produced by dividing a clear acrylic sheet into rectangular elements with a laser cutter, (**b**) a fraction of light incident on an element is deflected by refraction and total internal reflection, and (**c**) light deflection through an inclined cut [32].

3.1.1.3. Compound parabolic concentrator

Modified compound parabolic concentrators were also studied to be integrated into the building south façade and to primarily collect direct sunlight. Compound parabolic concentrator lined with prismatic film has th e potential for light collection about 6 times higher than the Aluminum lined one, because of the light incident possibility also through the body of the concentrator [20]. Truncated CPC was developed as a rectangular array CPC collector in the ADASY daylighting system for the offices [43,44] Asymmetric lens-walled CPC was developed to concentrate solar radiation to increase incident energy on BiPV placed on the south façade Fig. 8 [45].

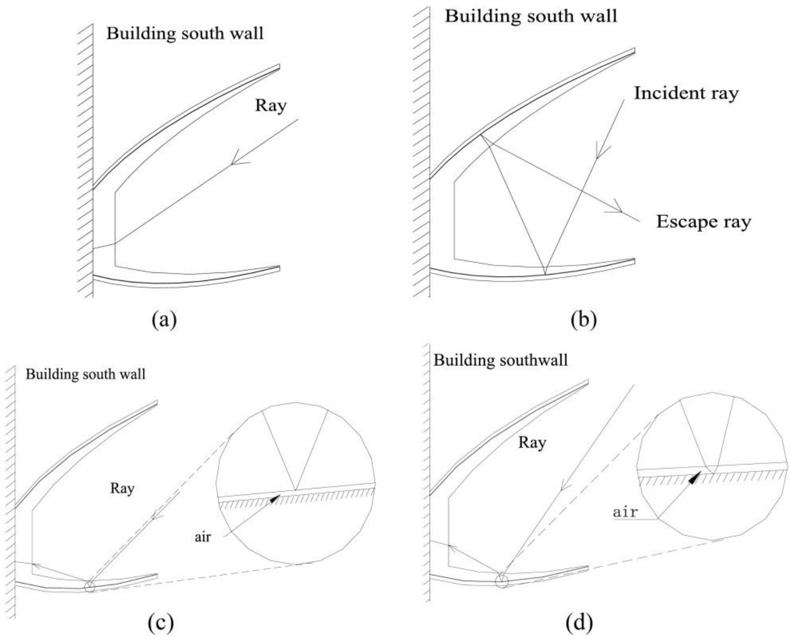
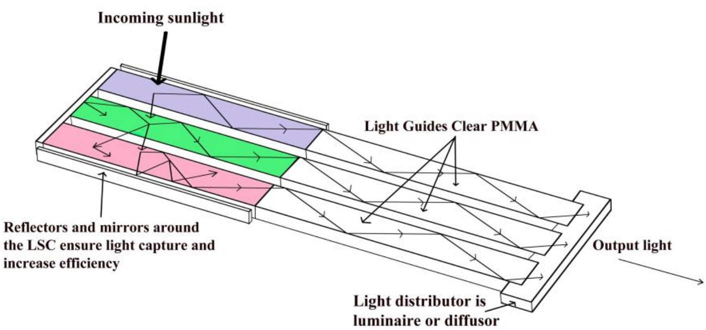


Fig. 8. (**a-d**) diagram of four kinds of ray paths in asymmetric lens-walled CPC [45].

3.1.1.4. Luminescent solar concentrator (LSC)

It was developed as a three color PMMA stack dyed in pink, green and violet luminescent dye. Luminescent quantum species absorb solar photons entering the stack and reemit them in random directions, where light propagation is secured by a total internal reflection inside the stack [46,47]. An experimental study, with prototype stack, 13.5 cm thick and 1.2 long, recorded 1000 lumen delivered output light from 100 000 lux of the exterior illumination. Since the system needs UV blocking to lengthen the lifetime of the violet dye, the luminous efficiency was increased up to 311 Lum/W, consequently, the output light color was white greenish [48]. This collector does not concentrate light to convey it to the transport element, but it is a collector and transporter in one, Fig. 9.



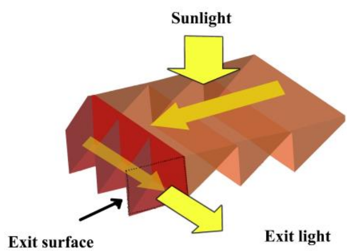


Fig. 9. Schematic of three-color LSC stack connected to light guides and luminaire [48]. **Fig. 10.** Sunlight path in a static light concentrator [50].

3.1.1.5. Fluorescent fiber solar concentrator (FFSC)

As LSC did not provide a solution for light concentration, an experimental study aiming at getting point-on-light concentration for fiber optics was conducted [49]. This collector consisted of 150 fibers of three luminescent colors (yellow, red and green), placed on a PMMA plate with a reflecting underlay to increase light absorption. Every fiber had quantum dots seeded in them to absorb solar photons and re-emit them with light propagation according to the total internal reflection inside the fibers. Point-on-light concentration was achieved at the end of the fibers where light transport fibers were connected by UV glue.

3.1.1.6. Static light concentrator

Static light concentrator was developed by a group of scientists in Taiwan, to collect, focus and direct light [50]. It is a combination of different prisms in array to create cascading units, Fig. 10. It was reported that, as a passive collector, it improved the total collected sunlight energy and that it could create a uniform light distribution.

3.1.2. Active light collector

Collectors that work on collecting the direct light beam are called active, based on a fact that they constantly track the source of direct light beam – the sun, for their best performance. Light is (1) collected and conveyed further to the transport element by light redirection, for heliostats, and mirror sunlight systems, and by (2) light concentration for Fresnel lens and parabolic concentrator. The tracking system for active light collector is the most important part, which works on a high degree of tracking accuracy to ensure system efficiency. The tracking computer adjusts the position using open or closed-loop algorithms and the sun tracking photosensors or satellite data for solar altitude and azimuth for a specific location [52]. Tracking systems are power-operated mechanical devices, which is why they easily wear off and they are expensive [22]. A single-axis passive tracker, which used solar thermal power to operate, was developed and studied [53].

3.1.2.1. Heliostats

Heliostats are single or multiple planar mirrors that track the sun's position by computer and reflect sunlight to redirect it into another optical element, lenses, mirrors or directly in the light tube. They have been used with the Fresnel lens in the Artelio project [54], and in a multistory office building in South Korea with the vertical mirror light pipe [51,55], Fig. 11. This collector type was used as a proposal for the staircase of the Semperlux building in Berlin to collect daylight and to guide it along with the prismatic hollow light guides [56]. Heliostat mirror is suggested for fiber optical systems for high latitudes location as sunlight redirecting and concentrating device placed on a south facade [57].

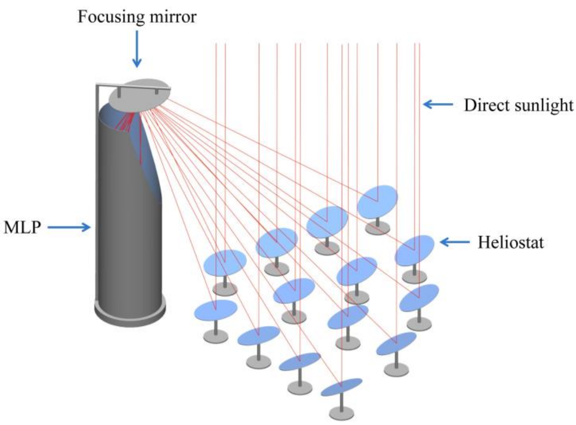


Fig. 11. Heliostats capturing and focusing sunlight into the mirror light pipe [51].

3.1.2.2. Mirror sunlight systems

Mirror sunlight systems usually consist of a single or several mirrors and are available from many different manufacturers. They are used to reflect and redirect sunlight into the spaces that sunlight never reaches, or where daylight level is very low because of too high obstacles. Kim and Kim reported an applied usage of those systems, known as Heliobus, Natulite, T-Soleil, Kuzelka, usually in dense city centers [58,59]. There were reported results on testing the different mirror sunlight systems to conclude on energy saving potential [58,60,61].

3.1.2.3. Fresnel lens concentrator

Fresnel lens, first developed in the 17th century, has been used in many forms with different optical principles for the concentration of solar energy [62]. In the form of a thin and lightweight lens it was developed by the Japanese inventor Dr. Mori, to be used as a light-concentrating lens for Himawari fiber optical system [63,64]. Fresnel lenses of different dimensions and shapes (square and circular) have been used mostly for concentrating direct sunlight into fiber bundles [65] or in a combination with funnel-like concentrators [66,153]; as a multi-lenses system [67,68] or to concentrate solar radiation into PV cells [69], Fig. 12.

The issue of uniform acceptance of concentrated light into the fiber bundle was treated using the secondary convex, biconvex, concavo-convex or plane-concave lens, to spread bundles of fiber and use them into separate locations [70,71]. Fresnel lens as a light concentrator generates the need to filter out heat from the concentrated radiation.

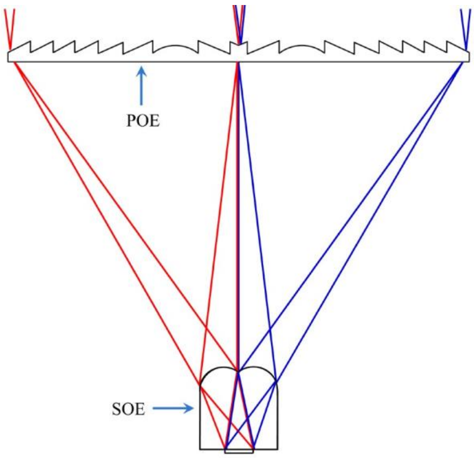


Fig. 12. Schematic showing the edge-ray mapping in an ideal Fresnel concentrator [69].

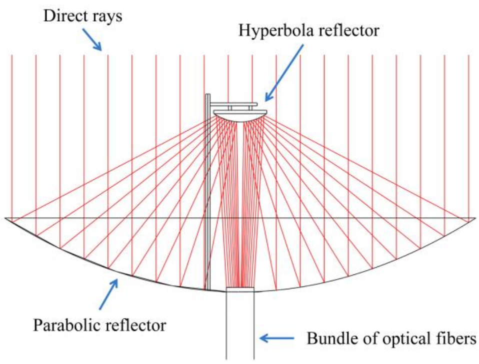


Fig. 13. Light concentrating principle in an ideal parabolic collector [71].

3.1.2.4. Parabolic concentrators

Parabolic concentrator for collection and focusing of light was first used in Fries's invention of the fiber-optical solar lighting system [72], but the origin of the parabolic collector dates from the antique where it was called ''burning mirror'', and was used to collect solar heat [73]. Parabolic concentrator is mostly used for fiber-optical systems as a primary optical element (POE) that focuses light into the secondary optical element (SOE) that is supposed to redirect the focused light into fiber and filter out UV and IR radiation, Fig. 13. The primary parabolic collector can be circular with a focus point [70,74], or rectangular, called parabolic trough, with a focus line [75,57,68]. Secondary optical element was a topic for many studies, where a convex ''cold'' or ''warm'' mirror was used [72,70]. Sapia studied special made cold mirror made of SiO2 and TiO2 [76].

3.2. Light transport element

The light transporting element guides light to a remote place where it is to be exported. Light propagates in the guide by (1) multiple specular reflection (mirror light pipe), (2) total internal reflection (solid guides made of PMMA, glass or liquid in form of optical fibers, rods, and hollow pipes), or (3) light convergence (system of lenses and mirrors).

3.2.1. Light reflection guide-pipes

They are defined as transporting devices used to distribute natural or artificial light into a remote space. In daylighting applications, they can also be called sun pipes, solar pipes, light or daylight pipes depending on their position in the building [77], Fig. 14 and 15. Those elements have a role to provide effective internal light reflection and are coated with highly reflective materials like silver, aluminum or 3M [78] and dielectric [79] films, which approach reflection of 99%. Light transmittance (efficiency) of the pipe depends on its Diameter to Length ratio called aspect ratio. It was reported that the optimal aspect ratio is up to 1/10, while its maximal value should be up to 1/20 [80]. The low aspect ratio increases the number of internal reflections and affects output light. It was recorded that silver coatings, after many interreflections, change light to reddish and more reminiscent to halogen light, while aluminum coating changes it to bluish and reminiscent to a fluorescent light source, while Ra- color rendering index was much higher for silver coating. Efficacy was in order 81% and 66% respectively [81]. To address designing and decision-making issues for usage of light pipes daylight penetration, factor (DPF) was developed and introduced to supplement to well-adopted daylight factor (DF) [82-84]. Recent experimental studies conducted worldwide, addressing the comparison of different light pipe configuration, lead to a conclusion on energy saving potential in many specific local solar climates [85-95].

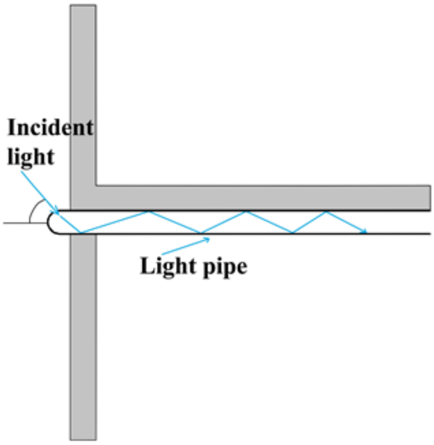


Fig. 14. Light guiding principle in horizontal light pipe.

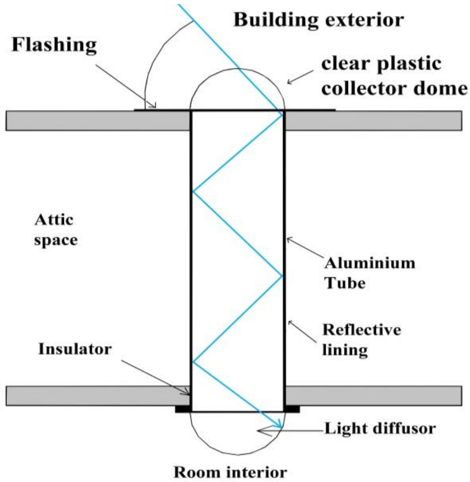


Fig. 15. Light guiding principle in vertical light pipe.

3.2.1.1. Vertical sun pipes

Vertical sun pipes are highly reflective hollow pipes and have been used to transport primary direct sunlight [77]. They are mostly tubular, i.e. with circular section [96-98], but other shapes have been studied as well; e.g. triangular [99] and rectangular [47,26]. Bended light pipes have been studied for both direct and diffuse light concluding that for the angled entrance part, accumulated yearly light output was higher than for the straight pipes due to the larger sun-facing area [100], but bends in pipes body inside the building should be avoided due to the increasing number of interreflections and decreasing efficiency [83,101,102]. Many theoretical and experimental studies addressed different pipe configurations aiming to find calculation models [103,95,104-111], resulting in more information on weather and design parameter dependence. Vertical light pipes give high and excessive luminous output when Sun's altitude and azimuth are nearly axillary and beam light propagates with minimal interreflections, while diffuse skylight gives uniform luminance with homogenous output during the daylight hours. It was recorded that daylight penetration factor for cloudy and clear sky was: 0,14% - 0,16% and 0,08 - 0,22% respectively [89]. This gives indications about the uniformity of the delivered light in the room and homogeneity of the light illuminances during the whole daylight period. Studies for overcast sky during winter, with 10 000 - 40 000 exterior lux, show up to 30% energy saving potential in a room with 350-500lux lighting demand [112-115].

Water filled light pipes were reported as efficient light guides with 20% light transmittance after 10m length. Due to the water's spectrally selective absorption of IR and the red part of the visible spectrum, the color of the light is bluish, and the luminous efficacy is 296lm/W because of IR and UV filtration [116].

Double light pipes were used for a building preservation case in architectural heritage. The double pipe consisted of an internal mirror pipe and the external transparent acryl tube for light deflection and transmission [117,118]. The authors studied luminance output for overcast and intermediate sky conditions concluding similar distribution of light in both cases, thanks to optical luminous film (OLF) used on the acryl tube, but drastically decreasing uniformity for increasing external illuminance.

Light pipe coated inside with dichroic material, which reflects 95% of visible light and transmits IR to the heat-generating component, was also studied [119]. This design showed the potential for the zenithal sun-pipes in hot climates in compound technology for natural ventilation since the extracted heat can help natural ventilation force.

3.2.1.2. Horizontal light pipes

Horizontal light pipes were first used to provide direct sunlight from the east and west in the tropics, because of the heat gain issues with vertical pipes [38,120-123,92]. They were also used to provide diffuse skylight in high latitude areas with predominantly overcast sky [124]. Horizontal light duct, with a rectangle section, was used as a custom-made solution in studies addressing anidolic collector and laser cut panels [37,38], or in studies dealing with light extraction elements [125,16,38]. Evaluations of analytical models for straight and bent horizontal light pipes were done to compare the results with experimental measurements [126,127]. The result was that the luminous efficiency of the horizontal pipes is dependent on its orientation to solar azimuth variation during the day or the year [120] and for solar altitude [39]. The study on energy savings for anidolic collector and horizontal light duct, for Singapore and UK, shows higher daylight autonomy and energy saving for overcast sky conditions (21% and 26%, respectively) then for the clear sky [128]. Similar studies showed up to 20% of energy-saving potential for direct light beams in Los Angeles [123,122].

3.2.2. Total internal reflection guides

Total internal reflection light guides convey the light that had an incident within a certain acceptance angle and that are reflected inside the guide on the boundary with the lower refractive medium. Transparent polycarbonate, acryl, glass, and different liquids were used as solid-state guides. A solid-state guide can be produced in different forms as fibers, rods, or it can take the form of a hollow pipe with walls of prismatic polycarbonate.

3.2.2.1. Optical fibers

Optical fibers rely on concentrated incident light, within acceptance angle (point-on-lite), to convey light with total internal reflection principle (TIR). Optical fiber consists of a core and cladding, where the higher refractive index of core comparing to cladding ensures total internal reflection of light in the fiber. The outer layer of cladding ensures the efficiency of the TIR by capturing the eventually scattered light. Each fiber has a flexible jacket, which has a reflective inner surface to protect fiber and ensure that light stays in it. Core is mostly produced of silica-based glass (SOF) or can be a mixture of highly purified liquids typically water and methanol and/or ethanol, but the most used is a synthetic polymer called polymethylmethacrylate or PMMA (POF) [129].

UV and IR radiation need to be filtered out because they can harm the optical fibers due to the low maximum operating temperature as 92.7 °C for POF and 120°C for liquid fibers. SOF has a much higher tolerance of 277°- 400°C, but this material has a great production cost and fragility, which makes it unpractical to use [57,130,131].

The incident light at the optical fiber cannot be completely transmitted, due to the material’s density, imperfection, and light absorption by core and cladding, and there is a light transmittance loss called attenuation (db/km or %/m). POF has the attenuation of 64, 73, and 130 dB/km for 520, 570, and 650 nm light respectively, which means that POF has lower transmittance for particularly orange light color (this is approximately 3% loss of luminous flux per 1-meter length of POF). SOF has very low attenuation for all wavelengths, and just as low as 0.2-dB/km at a wavelength of 1550-nanometers (nm). This makes the SOF the most efficient transmitter of the light and it can be used in the applications where light needs to be transported at a great distance [129]. It was recorded that light output using SOF was 4200K, Ra 98, while POF had 7000K, and Ra75 light output. Light transmittance on exterior 100 000lux after 20m fiber was 500lux for SOF and 400lux for POF [132]. Liquid core fibers have attenuation coefficients below 2-dB/m across for the visible spectrum, and very low for IR [133].

The coupling of fibers in branching showed significant light loss for which there were attempts to be solved by using a stepped coupler [50]. It was recorded that the index matching gel on the input fiber helps with light acceptance and uniformity [70,134].

Light acceptance into the fiber and its output were studied within the idea of stepped-thickness waveguide, which is an optical component, which redirects focused sunlight from the vertical direction to the horizontal direction, and it guides light to the attached optical fiber [135,136]. Modified optical fiber daylighting system (M-OFDS) for indoor lighting, with a collimated parabolic concentrator (CPC), attached to fiber and collimated end-part of the fiber, which emits a 5cm concentrated beam of light which propagates 30m in free space after leaving a fiber optical end [137,138] was also studied. This result could be used further to develop low diameter light pipes.

3.2.2.2. Optical rods

Optical rods were developed to be efficient in light transport and robust in form. They are made of transparent PMMA with different refractive index for core and cladding, Fig. 16. Light rods are sensitive to IR radiation, but they resist, and efficiently convey UV radiation. Similar to optical fibers, rods have its certain light incident acceptance angle for light to be transported by TIR, but comparing to fibers rods have a slightly manageable output issue, Fig. 17 [139]. Callow and Shao studied straight and bent light rods of 5mm diameter and 1000mm length, under the sunny and overcast sky, concluding that the luminous transmittance was between 47% and 64%, while the bend of 90° reduced rods transmittance by 20% [140,139].

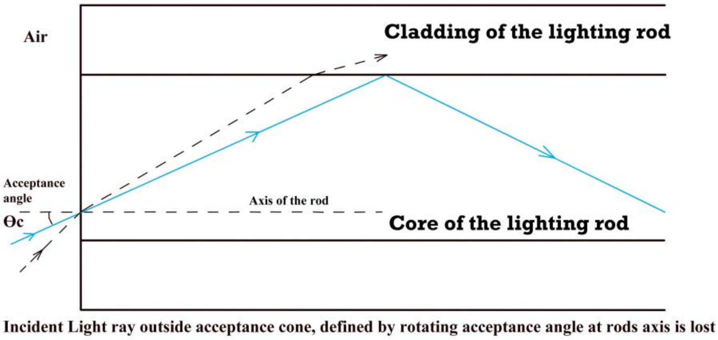


Fig. 16. Optical rod and light acceptance principle [76].

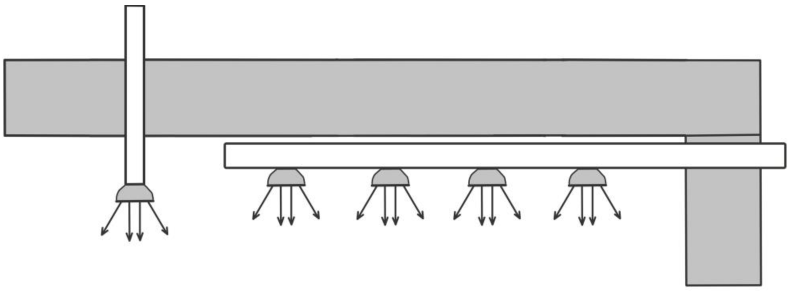


Fig. 17. Optical rods and possibilities for light emission [140].

3.2.2.3. Prismatic light guides

Prismatic light guides consist of one inner prismatic surface, coated with reflective coating on certain parts where the light reflects and propagates, and, one prismatic side where the light deflects and emits out of the guide, as in Conductalite prismatic emitter. If a prismatic guide is formed as a closed shape, as a hollow pipe, the emitted light is accepted again on the other side of the pipe and the light-guiding is continuous [141]. Light can be emitted along the guide, if the prismatic side is oriented outside [142,55]. High efficiency of the prismatic light guide used in the building core to convey and distribute daylight was reported in Heliobus and Artelio projects [56,143]. A recent study confirmed that the prismatic light pipes have higher light transmittance efficacy than mirror light pipes and that color rendering index and light color is constant CRI 99,7 and CCT6500 for the prismatic pipe comparing to the CRI 80-90 and CCT 3400-4400 for mirror light pipes which decrease with the distance [20].

3.2.2.4. Light converging guide

Light converging guidance relies on a light convergence between the precise arrangement of lenses and mirrors. System configuration depends on the lenses' focal distance. The physical construction around the lenses is not necessary but it is preferable because of the physical protection and dust maintenance, which can decrease system efficiency [141]. It is reported that the convergence system needs too much space and precise mounting, which makes it complicated to use [120]. The reported efficacy of one case application was 28%, due to the 13 lenses involved where each had a light transmittance of 92%, Fig. 18 [144].

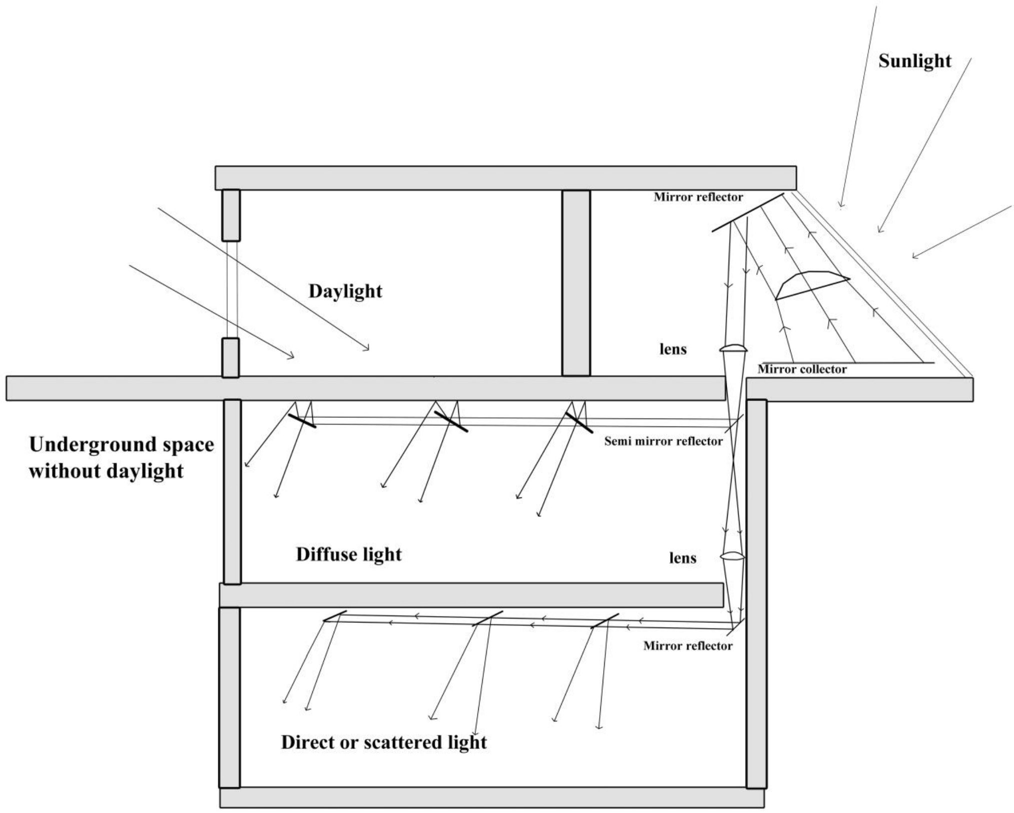


Fig. 18. The principle of light-converging guide in engineering building at the University of Minnesota [144].

3.3. Light distribution elements

Light distribution from the daylighting transport system is done by the light transmission and scattering through the emitters. Depending on the system's design idea there can be just one distribution point at the end [104,16], many distribution points along the light guide [142,155,43], or the distribution can happen continuously along the guide [145,146]. Light emitters are produced as circular or square (prismatic or transparent) PMMA diffusers, or as radial lenses (Fresnel) in a luminaire form. If light is transported by a wider guide, as light pipes or duct, diffusers are bigger, while for highly concentrated light from fibers, emitters are smaller, and in a spots or downlights form. Some studies were carried out to improve light uniformity [147].

Kocifaj worked to develop highly efficient, glare control diffuser, especially for the low solar altitude light, based on a fact that low incident light undergoes many interreflections in the tube with a low reflection angle. It consisted of a transparent glass on the outer part and a circular Lambertian diffuser in the center [104,105]. The same authors used continuous emitters as 6m thick transparent glazing and 5mm thick translucent glazing, with transmission factor 0.84 and 0.69 respectively. The issue of the output diffuser, as it is not a 100% transmissive and reflects light back into the pipe, was discussed in calculation models issue [125].

Emitters can be in form of a flat or an anidolic mirror element, placed at the end or along the light guide, to redirect light into the ceiling, walls or the working area [27,39], or to absorb light on a luminous gel and convey it further [39]. If a reflecting emitter is used, the glare issue needs to be handled carefully.

The emitters for concentrated light were often constructed as luminaires, which affect the beneficial feeling of transported daylight. Prismatic emitter with dot pattern screen was used to distribute light transported through fiber [65,50]. Luminaire-like emitters, made of crystal glass, were used as a light distributor for the LightWay light pipes, with producers promise for higher visual comfort.

Patterned or prismatic surface of the diffuser must be placed on the outside of the pipe, not inside the pipe, even though it is a preferable position due to the easier maintenance. Light is deflected and transmitted if it incidents on the flat side, while it mostly reflects back if it incidents on the prismatic side [80,18].

Light distributors are an understudied area, which needs special attention. As the last element in the daylight transport system and the only visible element in the indoor space, it has a responsibility and possibility to distribute light in the room and it affects the visual perception of light and the user's experience.

All reviewed components are systematized in Table 1, where columns present finished daylight transport systems and possible combination of light collectors and light distributors. Table 2 shows the overview of each component and their important characteristics to be widespread in the building industry.

Table 1. Most usual combination of light collectors and light distributors for a light transport element.

Possibilities of finished configuration of daylight transport systems						
Light Collector possibility	Anidolic collector LCP CPC Heliostats Mirror sunlight system	Anidolic CPC	CPC Static light concentrator	Heliostats Mirror sunlight system	Static light concentrator Fresnell lense concentrator Parabolic concentrator	Fluorescent/ Luminescent solar concentrator Fresnell lense concentrator Parabolic concentrator
Light transport element	Vertical light pipes (hollow, water, double)	Horizontal light pipes and ducts	Prismatic light guides	Lenses and mirrors system	Optical rods	Optical fibers (glass liquid, plastic)
Light Distributor possibility	Prismatic, transparent, translucent PMMA diffusors Lambertian, partly clear diffusor Bohemia glass diffusors	Prismatic, transparent, translucent PMMA diffusors Bohemia glass diffusors	Prismatic, transparent, translucent PMMA diffusors	Anidolic reflector emitter	Radial Fresnel lens Luminaire	Radial Fresnel lens Luminaire

Table 2. Review of elements in daylight transport systems.

Daylight transport system	**Mode of operation**	**Optical light principle**	**Light to light efficiency (light transmittance)**	**Easy of physical integration in the building**	**Maintenance**	**Cost**	**Availability**
Collector							
Anidolic collector [124,24,26,27,30,29, 31,153]	Passive	Light reflection	72% [124]	Robust need space	none	medium	Specially constructed and produced
Laser-cut panel [32,33,35,41,42]	Passive	Light deflection	Max 90% for custom (incident angles) LCP [32]	Light and compact, do not need additional space	none	low	Specially developed and produced
Compound parabolic concentrator [45] (dielectric prismatic film) [20]	Passive	Light reflection (total internal reflection)	Almost 1000% for edge ray light incident angles (up to 600%)	Light and compact, can be placed on sunexposed façade	none	Not specified	Specially developed and produced
Luminescent solar concentrator [46-48]	Passive	Light absorption, reemission and Total Internal reflection	6 – 10% for 1.2m concentrator length [49]	Need a small space	Need special care	medium	Research study

Fluorescent fiber solar concentrator [49]	Passive	Light absorption, reemission and Total Internal reflection	Very low [49]	Need a small space	Need special care	medium	Research study
Static light concentrator [50]	Passive	Light absorption and refraction on a prism	Up to 35% [50]	Concept phase	Need special care	medium	Research study
Heliostats [51,54,55]	Active	Light reflection	High, not defined	Need a lot of space	Need maintenance	high	Available, many producers
Mirror sunlight system [58-61]	Active	Light reflection	High, not defined [61]	Need space	Need maintenance	high	Available, many producers
Fresnel lens concentrator [63,64,68,69,154,74, 70,134]	Active	Light refraction on a prism	90 – 92% [144,64]	Robust or Compact but need space	Need maintenance	high	Available, many producers
Parabolic concentrator [70,72-75,68,76,22]	Active	Light reflection	Depending on many parameters	Robust Need space	Need maintenance	high	Available, many producers
Light transport element	**Light transport distance**						
Vertical pipes [77,8284,96,101,78,102]	D/L max 1/20	Light interreflection	Decreasing with length	Need vertical space	none	low	Available, many producers
Water-filled pipes [116]	6-8 m	Light absorption and scattering	20% after 10m [116]	Need vertical space	Special care	high	Research study
Double pipes [117,118]	3m	Light reflection and deflection	200lux delivered indoor for exterior 40Klux	Robust, Need space	cleaning	low	Case and Research study
Horizontal pipes [38,120-123,92]	7-8 m	Light interreflection	Decreasing with length, 300lux after 8m	Need space in the ceiling plenum	cleaning	low	Available a few producers, case concept
Horizontal ducts [37,38,124]	4-6m, up to 10m	Light interreflection	Decreasing with length	Need space in the ceiling plenum	cleaning	low	Specially constructed and produced
Optical fiber [68,75,76,130,155,132,156,157,129,57]	Up to 200m	Total internal reflection	Attenuation dependent	Compact, totally integrable	none	medium	Available, many producers
Optical rods [139]	1.2m studied	Total internal reflection	46-66% for 1.2m [139]	Compact and semiflexible	none	high	Research study
Prismatic light guides [141-143]	3-4 floors	Total internal reflection and light diffraction	20%	Need space		medium	Specially constructed and produced
Lenses and mirrors system [144]	3-4 floors	Light convergence and reflection	92% on each lens, 28% in total [144]	Robust, need place	Need special care	high	Specially constructed and produced
Light distributors	**Suitable for**						
Prismatic, translucent diffuser [125]	Light Pipe	Light diffraction	84% prismatic 69% translucent [125]	Compact, fit into ceiling	Dust cleaning	low	Available, many producers
Lambertian, partly clear diffuser [104,105]	Light pipe	Light diffraction and transmission	65% - 300% more than transparent glass	Compact, fit into ceiling	Dust cleaning	low	Research study

Crystal glass diffuser [158]	Light pipe	Light diffraction	94-95% light transmission	Usually formed as luminaire in different designs	None,selfcleaning	medium	Available
Radial Fresnel lens	Fiber	Diffraction of focused-concentrated light	90-92% light transmission	Compact, fit into ceiling	Dust cleaning	medium	Research study
Anidolic emitter [39]	Horizontal pipe and duct	Light reflection and scattering	70 - 99% depending on a finish reflectance	Robust, need space	Dust cleaning	medium	Research study
Luminaire (spot /downlight) [65,50]	Fiber	Light scattering	Depending on Luminaire Output Ratio (LOR)	Compact, fit into ceiling	Dust cleaning	medium	Available, many producers

4. Analytical models and design adjusting for light transport systems

Research studies addressing Light pipes aimed also to solve the issue of performance prediction for straight and bent light pipes. Design parameters as diameter, length, and optical properties of material and daylight directionality (sky types) were used to redevelop many different analytical methods and models [99,81,33,148]. To ease the design and decision-making process for light pipes, the concept of daylight penetration factor (DPF) was developed and experimentally validated [82-84]. DPF models predict the transmission of daylight (sky diffuse light + sunlight) through the light pipe system. A modified method for just overcast sky was introduced to be used for a simple design [78,102]. Carter also developed a simple method to determine the number of light pipes in the room [112]. Later he argued that in order to value DPF together with DF both methods should be considered for just overcast sky, as it is for DF [91,90]. HOLIGLIM analytical method, which uses ray tracing, backward ray-tracing and asymmetry parameters was developed for predicting light transmittance for straight and bent pipes [107,106,109,110]. HOLIGLIM was evaluated in light pipe studies for overcast and clear sky conditions [105,103]. A new analytical method, which analyzes the contribution of the direct and diffuse light separately was recently introduced [108].

Many computer-based simulation methods were developed and validated in building simulation tools [149]. Literature mentions the DOE-2 building energy simulation program, the SUPERLITE daylight analysis program, RADIANCE ray-tracing program, and recently Energy plus and CODYRUN [123,37,11,150,151].

Active collectors need solar tracking for the best working performance. The tracking system consists of two axes (or one axis) tracking, where the first actuator should align azimuth and the second one should align altitude/zenith angle. The tracking system needs an engine for the rotation that aligns the position using either a sensor for the highest solar radiation or the astronomical positioning system. Alignment tolerances are very tight (1 st. rad) and errors bring significant reductions in collection efficiency and system efficiency [129]. In order to minimize the alignment errors, tracking algorithms of open and closed-loop are used. Closed-loop algorithms are based on the feedback control principles, where parameters in the sensor are compared to give the info of the eventual fine-tuning the tracking position, while open-loop types of algorithms do not have this feedback information possibility and can result in 40-70% lower solar tracking efficiency [52,152]. It was recorded that azimuth axis tracker is more important than altitude because of the wider variating angle.

5. Development of market products

Since the first researches and scientific results, many finished and patented products have appeared on the market, coupling the over reviewed components by their optical properties. Sun-pipes and light-pipes were patented [159-162,98,97,163], manufactured and implemented widely. Fiber-optical daylight systems with the active [64,21,72] or passive [62,53] solar tracking, were patented and produced by different manufacturers [164,66]. Many studies were conducted addressing the light efficiency of those finished products [165,155,65]. An overview of daylighting systems on the market is presented in Table 3.

Some daylight transport systems were combined with electrical light sources to become hybrid daylight systems. The idea of combining natural and artificial light sources, and just one transport and emitter part was made mainly to have a better energy-saving control and to reduce the material and costs [166-168,65]. Studies showed that coupling losses can be up to 50% when a hybrid system is enabled for dual light source operation.

Table 3. Certified daylight transport systems as market available products, available to buy and install (not custom-made products for one case project).

Daylight transport system	Type of collector	Type of transport element	Type of distributer	Efficiency, light transmittance according to the producer
Solatube [169,170]	Polycarbonate dome, clear or Reybender technology, and LightTracker™ Reflector	Straight and elbowed pipes Spectralight® Infinity tubing material	Prismatic and Fresnel lenses	81.3% for the dome; 99.7% Rf for tube
Solarspot [98]	Acrylic clear dome, RIR® Fresnel lens light funnel	Straight and elbowed pipes Vegalux® – anodized aluminum laminated with 3m Daylighting DF2000MA film	Lambertian diffuser, prismatic, pearled	86% for the dome; 99.7% Rf for tube
Monodraught [100]	Acrylic Diamond Dome with prismatic vertical on the circumference	Straight and elbowed pipes SUPER-SILVER mirror finished aluminum tube	Satin diffusers	84.3% for the dome; 98% Rf for tube.
Velux [169,170]	Dome like Skylight	Rigid and flexible Sun tunnels	EdgeGlow diffuser	Not available
LightWay [158]	Acryl and bohemian crystal domes, parabolic like mirror concentrator	Straight and elbowed, horizontal and vertical light pipes	Satin acryl diffuser and bohemian crystal diffusers	92% Tf for acryl dome 94% Tf for Crystal dome 98-99.8% Rf for tube
ADASY [158]	Facade mounted array of truncated compound parabolic concentrators (TCPC)	Horizontal mirrored chamber	Prismatic diffusers	
Heliobus daylight shaft [171,58]	Laminated safety glass cover	Highly reflective shaft for basement	Laminated glass	Not available
Heliobus® Light Guide [58,171]	Mirror	Prismatic light pipe	Prismatic light emitter	420lux for overcast sky 10000 lux [171]
Parans [155]	Multiply Fresnel lenses collector	Optical fiber plastic	Spot luminaire, satin panel	100m length, 30 floors. 80% transmittance [165], energy-saving 20% north 46% south [155]
Himawari [142,64,63]	Fresnel lens honey-combed system	large diameter quartz glass fibers	Spot luminaire	Up to 200m, but 23% transmittance, after 2m length 500lux indoor
Sundolier [58,158]	Mirror sunlight system	24'' hole – light pipe	Light distribution fixtures	Up to 3 floors [59]
Solux by Bomin Solar Research [58,158]	Big single Fresnel lens	Liquid light guide	Luminaire	80-90% after 10m length [58]

6. Discussion

This comprehensive literature survey of daylight transport systems and their light conveying components show performance characteristics of each component, their limitations, and options for utilization.

Light collectors are designed to collect and redirect or concentrate direct or diffuse light depending on a light transport guide. Passive collectors cost less in production, running and maintenance than active collectors which also wear off easily, and need perpetual service. Passive collectors collect much less of exterior daylight flux than active collectors, which means that one active collector can serve a larger area than a passive collector. Because of the different light emission on the diffuser part, it is not possible to compare them to make investing or profitability comparison.

Anidolic collectors showed reliable applications for zenithal diffuse light collection for overcast conditions and could be customized to ensure direct sunlight redirection for every location (unique solar altitude variation). According to recorded energy saving potential, of ca. 25% for different locations, it can be concluded that an anidolic collector can be universally used to improve daylighting conditions in deep plan buildings. Specially designed Laser-cut panels can deflect a span of incident angles of direct light beams and transmit diffuse light from the sky, which qualifies them for usage in both clear and overcast sky conditions. Luminescent and fluorescent concentrators have shown low collecting efficacy, but their advantages are in physical adaptability in the aesthetical façade concept. Static light concentrators are in the concept phase but could be compared to the PV panels as they are flat, and if placed on a roof, do not violate building aesthetical concept.

Active light collectors are bigger elements, they are often placed on a roof in hot climates but could also need façade placement in temperate climates to collect direct sunlight. Heliostats and mirrors redirect direct light beam but only in little extend diffuse light. Fresnel lens and parabolic collector almost exclusively concentrate direct light. Tracking elements are mechanical components that use electrical energy, which needs to be considered in a total energy calculation. Active collectors are in general not suggested for predominantly overcast skies. However, literature suggests that heliostats on the south façade, for multistory buildings at high latitudes, could be more efficient for occasionally clear sky than horizontal light pipes for predominantly overcast skies.

Light transport guides as a mirror or prismatic pipes, water or double pipes need vertical or horizontal physical space, which dictates other technical systems and, to a smaller extent, building construction concepts. Mirror light pipes, supplied with customized collectors, have shown potential for daylight supplement in temperate and hot climates. Vertical light pipes could be used in single or double story buildings, while horizontal pipes could be used in multistory buildings. Light pipes convey direct and diffuse light, where daylight output from the pipe is more uniform, homogeneous, and discreet during the day when exterior light conditions are overcast than when they are clear sunny. Predominantly clear sky and direct light made high variations in the output light in terms of intensity and uniformity, while overcast sky and diffuse light did not show this problem, mainly because the light flux was lower and uniform by nature.

Fiber-optical light guides are flexible and of small diameter and could be protracted deeper in the buildings without the need for space. Silica-based fibers have higher light transmittance than plastic and liquid ones, but higher cost, too. Daylight output from the fiber can be problematic to spread since it comes from a very small section and it can variate as much as exterior light illuminance change, which makes it them difficult to design and problematic for user acceptance. Optical rods showed considerable light transmittance for diffuse and direct light, but the production cost and inflexibility labeled them as not attractive for use.

Light converging systems with lenses and mirrors remained on a few case solutions, as they showed high cost, and demand for space and maintenance, while light transmittance was low compared to other systems.

Light distribution elements, as the last component, are responsible for light spreading in the space, but also have high potential to manage the visual effect of light. However, this component is understudied and there have been just a few attempts to improve efficacy and control excessive light. Prismatic, translucent, and transparent plastic diffusers are used for light pipes, while spots and downlights are used for fiber optics. They are produced in a luminaire like form which affects the user's acceptance and opinion about the delivered daylight.

Research on tubular DTS gave several more components that can be combined than the research on fiber optical systems did, Table 1. The research in fiber optical DTS went into the direction of improving sun-tracking algorithm devices, and not much in the direction of the development of new component. Tubular DTS are also more applied and used in buildings than fiber optical DTS in spite of the implementation ease and flexibility of fibers [158]. This can indicate that the need for more building space for Tubular DTS was not such a great issue as the need for passive systems versus mechanical active systems.

Several daylight transport system reviews tried to define methodology on how to choose the best system for a specific building type, a room function or daylight conditions at the location. Cost and profitability analyses were also provided to ease the process of implementation by decision-makers. However, none of the researches so far has considered that if we aim at good integration between the daylighting system and artificial lighting, the artificial lighting, and control system should be redesigned as well. Additionally, to distribute daylight better in the space, space design, form and finishes could be adjusted and customized to reassure the expected daylighting effect. Only one single paper discusses ceiling form as curved, sloped, or chamfered for better daylight distribution from the anidolic ceiling [41] and another one discusses the mode of lighting controls for artificial lighting for better integration with daylighting systems under direct or diffuse daylight [93].

Daylight transport systems, as technical products, showed an increasing application tendency, but as they are designed to suit predominantly sky and sun conditions for a specific location, application in other locations brings decreasing transmittance efficacy and energy-saving potential is not certain. All systems are available in many configurations to suit new buildings or redevelopment. Solatube is efficient for both high and low solar altitudes because of its Reybender optics in dome. Monodraught provides light redirection on a diamond dome with prismatic optics, while LightWay promises higher light transmittance though Bohemia crystal glass dome. Solarspot has a clear acryl dome and relies on its Fresnel lens RIR deflector for low direct light, while Velux relies mostly on diffuse zenithal light collected through skylight dome. Horizontal Adasy system showed high potential for use in ceiling plenum. Heliobus's daylighting shaft is simple and has a high potential for applications, while Heliobus's light guide is more a special product. Parans and Himawari systems show high efficacy in clear sky conditions, while for nonclear sky conditions, they affect the profitability of the application. Solux and Sundolier systems had a few applications, but big dimensions and design shapes of the collector and guide components make them unattractive to use on the building exterior. For high latitudes locations with predominantly overcast sky, Solatube could be used as a vertical system, and Solarspot, LightWay and Adasy could be used as a vertical and horizontal system. For non-costal locations, between 55-65°N Parans system could be used if placed on the roof.

7. Conclusions

According to the daylight conditions for the high latitude locations, and the aim of this study (to address energy-saving potential for multi-storeyed buildings), it could be concluded that the systems that can efficiently collect zenithal daylight and variable position of direct sunlight should be used. Table 4 shows conclusions on suitability for each element in predominantly overcast sky and direct sunlight at low solar altitude. Anidolic collector showed the potential to collect diffuse light from the zenithal part of the sky dome, but it could be also custom-designed to suit other directions of light beams, according to the edge-ray principles. Laser-cut acryl panel with sloped cuts showed a possibility to redirect a span of light beam directions, which could be used for variating sun altitude and azimuth. Both vertical and horizontal light tubes, depending on the functionality and architecture of the building, could be used for daylight conditions in high latitude locations with specially tailored collectors.

Table 4. Review of suitability for elements of daylight transport systems in predominantly overcast sky and direct sunlight at a low solar altitude.

Daylight transport system	Directionality of transported light	Suitability for direct light and predominantly low solar altitude	Suitability for predominantly overcast sky
Collector			
Anidolic collector [27,153]	Predominantly overcast and clear in temperate climates	Partly, if constructed according to edge rays for low solar altitude	Excellent
Laser-cut panel [40,38,39,35]	Predominantly clear in hot and temperate climates	Excellent	Partly, depending on a configuration and the tilt of the panel
Compound parabolic concentrator [43-45]	Predominantly overcast and clear in temperate climates	Excellent	Partly, depending on a form of the concentrator
Luminescent solar concentrator [48]	Predominantly clear	Excellent, can be placed to align the incident angle	Bad
Fluorescent fiber solar concentrator [49]	Predominantly clear	Excellent, can be placed to align the incident angle	Bad
Static light concentrator [50]	Predominantly clear	Excellent, can be placed to align the incident angle	Bad
Heliostats [54,51,55]	Predominantly clear	Excellent	Bad
Mirror sunlight system [58-61]	Predominantly clear	Excellent	Bad
Fresnel lens concentrator [63,64,68,69,150,74,70,134]	Predominantly clear	Excellent	Bad
Parabolic concentrator [7274,70,68,76,22]	Predominantly clear	Good, but positioning is problematic for building facade	Bad
Light transport element			
Vertical pipes [77,83,101,102,40]	Diffuse and direct	bad	Excellent
Water-filled pipes [116]	Direct	bad	Excellent
Double pipes [117,118]	Diffuse and direct	Bad if vertical, but relatively good if horizontal	Excellent if vertical, bad if horizontal
Horizontal pipes [38,121,125,92]	Diffuse and direct	good	Yes, if suited with anidolic collector
Horizontal ducts [124,37,38]	Diffuse and direct	good	Yes, if suited with anidolic collector
Optical fiber [68,75,76,130,155,132,156,157,129,57]	Direct	good	Bad
Optical rods [139]	Direct and diffuse	Relatively good for short distance	Bad
Prismatic light guides [141-143,20]	Direct	Relatively good	Bad
Lenses and mirrors system [144]	Direct	Relatively good for short distance	Bad
Light distributors			
Prismatic, translucent diffuser [125]	Diffuse	Yes, it reduces eventual excessive light	Partly, it decreases the efficacy of predominantly diffuse light

Lambertian, partly clear diffuser [104,105]	Diffuse	Yes, it reduces eventual excessive light and increases transmission	Suitable, it partly decreases efficacy of diffuse light
Crystal glass diffuser [according to producer LightWay]	Diffuse and direct	Partly, it and can introduce excessive light and light diffraction	Suitable, it increases light transmission
Radial Fresnel lens	Direct	Partly, it can disperse the excessive light	Partly, light dispersion can be uncontrollable
Anidolic emitter [39]	Diffuse and direct	Partly, light emission depends on a surface finish	Excellent
Luminaire (spot or downlight) [65,50]	Direct	Bad, it can introduce excessive light	Bad

Systems reviewed in this paper deliver daylight deeper in the space than a usual window does and increase daylighting level and uniformity in total. More extensive use of daylight in buildings obtained through the application of the systems has many benefits. The daylight luminance uniformity across the room could be improved, comparing to the daylighting through the side windows only. Visual comfort would be better since the luminance condition will change glare conditions for a user. Seasonal and diurnal variation of exterior daylight will imply in light color and intensity dynamics inside. These two were qualified as beneficial characteristics of daylight that comes through the window, which, in case of deeper delivery spot, could extend the same positive feeling deeper in the space and far away from the window.
The literature survey showed light efficacy of the different components and light transmittance for the entire systems, which is summarized in Table 3. The accumulated supplement in daylight flux, during different weather conditions, season, or the entire year, was covered in many studies, resulting in energy saving potential for artificial lighting, too. The supplementary flux has been studied according to light demands in test rooms (very often offices) as 500lux in general, and conclusions were taken on this basis. Since studies were done mostly by architects, building engineers, or physicists, the lighting demands were only approximated. The real lighting demand according to standard and best lighting design practice is 500lux on a horizontal working area of 60×30cm, 300lux on a working desk and 200lux in the wider surroundings. If those prerequisites had been taken in the assumption the energy-saving potential would have been higher. Besides, the light controlling system for daylight supplement should be suitable for the predominantly daylight conditions as it was recorded that there are highest energy savings if the direct light is combined with on-off control, while diffuse light is combined with dimming.

The answer to the objective of this paper “which system is the most suitable for the buildings in high latitudes?” is more complex if we seek for the answer taken for typical office building and a general presumed predominantly daylight condition. There are very many types of building floor solutions, and room functions, orientation, settlement in the neighborhood. In addition, every location has its specific solar microclimate. It is, therefore, not surprising that decision could not be easily made by following the methodology, but it should rather be designed in detail through consideration of all prerequisites. It is not possible to generalize the good method for the choice of this ‘’technical component’’ and leave it to the architects to pick out. It is necessary to design a daylighting system together with the artificial lighting system and building spaces themselves. There should be an integrative design of building spaces and daylighting from the concept stage. One single building could have two or several system configurations depending on the orientation. Spaces oriented north could be designed with diffuse zenithal daylight transport systems, and spaces on the south could rely on a facade mounted direct sunlight daylighting systems, which either actively track suns altitude or passively rely on sunlight reflection. East and west façade could similarly actively track sunlight azimuthal movement or rely on passive light deflection.

The building industry nowadays aims to produce environmentfriendly materials, components, and equipment, so that they could have primacy on the market in more and more strict building standards. Daylight transport systems need to follow this vision in using environmentally friendly materials and to strive for low a CO_2 footprint.

Perception of, opinion about and satisfaction of daylight delivered through the daylighting systems depends on the nature of the distributed light inside. All the reviewed systems were constructed with diffusers that imitate a luminaire. This is probably because the producers of the systems wanted to have a finished product that they can put on a market as technical equipment while disregarding the primary aim of this application and that is to provide all the daylight beneficial features, and not just the light flux. This is probably the reason why user acceptance, and, in general, application breakthrough of those technologies has never happened.

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B. O. conceived and wrote the study, B.M. helped define the scope of the study, gave feedback on the contents of the paper and contributed by performing quality assurance and proofreading.

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Daylight autonomy improvement in buildings at high latitudes using horizontal light pipes and light-deflecting panels

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Abstract

Horizontal light pipes (HLP) have shown the potential to convey daylight deeper into buildings. The wide variation in incident angles of sunlight rays and the resulting numerous interreflections of light rays within the pipe are the main reasons for the limited light transmittance of such light pipes during certain daylight periods. This paper presents a research study on different configurations of acrylic laser-cut panels (LCP) applied at the entrance of horizontal pipes as light collectors to increase the transmittance of HLPs and improve daylight autonomy in spaces equipped with HLPs. This study required the development of a suitable methodology. The study begins with an experimental laboratory test of a HLP scale model to determine the light transmittance efficiency (standard daylight guide characteristic) of HLPs with several LCP configurations. The results from the laboratory test are combined with the statistical data for both the direct and diffuse illuminance on the vertical south-oriented surface (Satel-Light database) for the location selected for the analyses (Oslo, Norway). The analyses are discussed via the application of a theoretical model of an office space equipped with a HPL as well as through the concept of daylight autonomy (DA) in an indoor space. The paper shows that a certain static LCP configuration has the potential to increase DA_{100} and DA_{300} to 10% and 19%, respectively, at a 2.1 meter distance from the façade, and 8.75% and 16%, respectively, at a 4.5m distance. This paper also contributes to lighting science with its data on the light transmittance efficiency of each LCP configuration, which can be applicable in further research.

Keywords: Laser-cut panel (LCP), horizontal light pipe, daylight tube, daylight autonomy (DA), high latitude, low solar altitude, overcast sky.

Nomenclature:

T - Light transmission efficiency factor for light pipe and a certain light incident ray

TTE - Light transmission efficiency factor for light pipe for overcast sky conditions

L - Length of light pipe, meters

D_p - Diameter of light pipe, meters

p - Aspect ratio of light pipe (p = length/diameter of light pipe)

R - Reflectance factor of inner surface of light pipe

D/W - Distance-to-width ratio of Laser-Cut panel

Θ - Angle of the cuts on the Laser-Cut panel, degrees

Al, Az - Solar altitude and azimuth, degrees

αl, αz - Light incident angle of solar altitude and azimuth on certain surface, degrees

r_2 - Angle at which deflected light ray leaves the exit face of the Laser-cut panel, degrees

β - Tilt/rotating angle of LC-panel relative to pipe's entrance plane, degrees

$E_{direct}(ZERO)$, $E_{diffuse}(ZERO)$ - Direct or diffuse illuminance measured at the tube's entrance, lux

$E_{direct}(BaseCase)$, $E_{diffuse}(BaseCase)$ - Illuminance measured on the tube's exit without LCP configuration, lux

$E_{direct}(T\text{-}R^*)$, $E_{diffuse}(T\text{-}R^*)$ - Illuminance measured at the tube's exit for certain LCP configuration*, lux

Es_{direct}, $Es_{diffuse}$ - Direct or diffuse illuminance on a vertical south façade developed from the Satel-Light, lux

$Er_{direct}(T\text{-}R^*)$, $Er_{diffuse}(T\text{-}R^*)$ - Direct or diffuse real expected illuminance at the tube's exit for a certain LCP configuration*, lux

$\eta_{direct}(T\text{-}R^*)$, $\eta_{diffuse}(T\text{-}R^*)$ - Standard daylight guide characteristic for direct or diffuse light

Er (T-R*) - Total real expected illuminance at the tube's exit for a certain LCP configuration, lux

δ - Beam spread of the curved reflector at the exit of the light pipe in the theoretical model, degrees

Ω - Solid angle of the curved reflector at the exit of the light pipe in the theoretical model, steradian

P - Areal of the light pipe's exit in the theoretical model, square meters

E_1, E_2 - Required light illuminance on the light pipe's exit and the reference surface

Φ_1 - Required light flux at the light pipe's exit, lumen

I_2 - Required light intensity on the reference surface in a theoretical model, candela

A - Areal of the reference surface, square meters

d – Mounting height of the tube above the workplane, meters

* for all of the LCP configurations, see Tables 6 and 7.

1. Introduction

To fulfil new legislation requirements (such as *TEK17* or *NS3700* in Norway, where this study was conducted), buildings have become more compact, which results in spaces inside the buildings lacking natural light (Houck, 2015). This drawback has been noted, and some concepts of integrative lighting (light for the circadian rhythm) have been used to mitigate it; however, research and practice have still not come to a successful solution (Chinazzo et al., 2020; Perez et al., 2018; Yuda et al., 2017). The initial concept of finding a sustainable solution for the lack of daylight inside buildings has been additionally overshadowed by the decreasing costs of LED lighting (Herring, 2006).

Moreover, regulations on the daylight factor (D) are becoming stricter. A daylight factor demand of D_{mean} > 2% for permanently occupied rooms is becoming difficult to achieve, as buildings simultaneously follow stricter energy efficiency demands, with a 30% increase of wall thickness and a 25% decrease in the light transmission of window glazing (Ulimoen et al., 2020).

The new European standard, *EN-17037 Daylight in Buildings*, brings a requirement of 50% of daylight hours during the year, with daylight provision of a minimum of 300 lux for 50% of the area and 100 lux for 95% of the area (Mardaljevic et al., 2013). Daylight provision refers to the level of illuminance achieved across a fraction of a reference plane for a fraction of daylight hours. Daylight hours in this standard refers to the time from sunrise to sunset. This means at least six hours of 300 lux of daylight on average throughout the year, which occurs between 7 AM and 5 PM (the occupancy period of a typical office space).

As global economic growth forces centralization, the most intensive development of commercial buildings takes place in city centres, where high land prices lead to high-rise buildings. Multi-floor buildings have large facade areas that are predominantly made of glass and steel (Yeang and Powell, 2007). Glass facades, besides daylighting, provide unwanted glare and solar heat. Both research and post-occupancy reviews have shown that visual discomfort forces users to manually control sunscreens (Galasiu et al., 2004; Lindsay and Littlefair, 1992; Rea, 1984; Rubin et al., 1978). Especially in areas at higher latitudes, the conditions of clear sunny skies are not immediately connected with positive daylighting effects, since low solar altitude brings about glare and overheating issues. Automated sun-shading is, according to the practice in Scandinavia, pulled down and closed at a threshold of 43000 lux on a façade and not pulled up before illuminance decreases under 23000 lux (Christoffersen and Johnsen, 1999; Johnsen et al., 2011). Manually controlled sun-shading remains in a closed position much longer after the critical excessive light situation ends, usually until the user opens them again. A study by Reinhart (2004) showed that the initial daylight level in an office, at the time a user arrives, psychologically and physiologically determines their lighting comfort and need for electrical light. Such facts help note that low daylight level in an office, either as a result of the manual adjustment of sunscreens the previous day or the room's orientation and lack of sunlight, will increase the psychological need for a higher level of artificial light.

A literature review on daylight transport systems (DTS) revealed that light pipes can reduce the energy used for electrical lighting in commercial buildings at higher latitudes by up to 30% (Courret et al., 1998; Garcia Hansen and Edmonds, 2003; Kwok and Chung, 2008; Mayhoub, 2011; Obradovic and Matusiak, 2019). As electrical energy for lighting in commercial buildings in Norway accounts for 40% (Kolås, 2011) of total building energy used, the fact that a reduction of a 30% could give a total energy reduction of 12% is important. According to the Norwegian standard *SN/TS 3031:2016 Energy Performance of Buildings—Calculation of Energy Needs and Energy Supply* and the European standard *EN 15193-1:2017 Energy Performance of Buildings—Energy requirements for Lighting (Part 1: Specifications, Module M9)*, the maximum 145 kWh/m^2 per year is allowed for commercial buildings in energy class C, while the maximum of 115 kWh/m^2 enables energy class B. The stricter class is characterized by a 20% energy reduction, a significant part of which can be accomplished by reducing the need for electrical lighting.

The need for reliable and prolonged daylight autonomy, especially during the mornings and afternoons, is directly related to the energy requirements of buildings that rely on electrical energy generated from PV panels. The peak load for energy consumption in commercial buildings starts sharply at 7 AM and remains linear until 5 PM, while the peak of solar energy generation follows suns alignment with the south (Lindberg et al., 2019). Prolonged daylight autonomy could have an impact on the balance energy management of buildings in terms of the fact that 40% of the energy consumption in commercial buildings is used for artificial lighting.

Many post-occupancy reviews has shown that light controlling systems with light sensors integrated in the ceiling to screen daylight levels on the working surface do not work as they should. The reason for this is a drastical decrease of daylight level from the side window and deeper in the space (Kolås, 2011). Some recent studies conducted in higher latitude areas have proposed sun-screening and daylighting elements suitable to deal with low solar altitude issues (visual and thermal comfort simultaneously), but their implementation in real projects has been delayed and hindered by many decisions and issues (Arnesen et al., 2011; Kolås, 2013). If a certain daylighting transport system could convey daylighting at more balanced levels, this could help the controlling system have more reliable operation and would result in easier decision-making regarding the placement of lighting sensors.

Daylight transport elements, such as light pipes, can be layered with mirror folium, aluminium, or silver, with a reflectivity (R) of 99%. The total light transmittance of the pipe, T, is defined as a direct function of reflectivity, R, where L is the pipe's length, D_p is the pipe's diameter, and α is the plane light incident angle relative to the light pipe's axis (Eq. 1) (Zastrow and Wittwer, 1986, 1987). The light transmittance effectivity is in this case, beside the pipe's inner reflectance, highly dependent on the light incident angle.

$$T = R^{L \times tan\alpha \div D_p} \qquad (1)$$

Light rays with an axillary incident angle to the pipe's axis, where no light rays inter-reflect along the pipe, contribute the most to the light transmission efficiency. Any increase in the incident angle increases the number of interreflections, and the total light transmittance of the pipe decreases simply because the inner surface is not 100% reflective.

In order to solve the problem of unfavourable (oblique) incident angles, several studies have used approach with deflected incident light. Light deflection panels, in this case Laser-Cut panels (LCPs), can deflect the incident light and, in turn, change its propagation direction. LCPs have been adopted as an effective light redirecting element in architecture since the development of the theory of light deflection in 90's (Edmonds, 1993), but the original idea dates to the very late nineteenth century (Wadsworth, 1903).

A laser-cut panel is produced by making parallel laser cuts in a transparent acrylic panel (Fig. 1a), where each cut becomes a "light reflective mirror". Fig. 1c illustrates the deflection mechanism in the case of straight cuts. The definition of light deflection on LCP states that "light is deflected in a rectangular prismatic element by refraction, total internal reflection and refraction again'' and ''an array of prismatic elements forms a light deflecting panel called a Laser-Cut Panel (LCP)'' (Edmonds, 1993). Equations 2-4 explains how to calculate the outgoing angle of light, where the total angle through which the incident light is deflected is α_1+r_2 (see also Fig. 1d). For the Θ = 0° (angle of the cuts), the angle at which deflected light leaves the exit face, r_2, is the same as the angle of incidence on the panel, α_1. Edmond also explains that sloped laser-cuts have a higher deflecting factor for variating incident angles (span of angles) (Fig. 1d), but because of the technical impossibility of developing sloped cuts, there has not been any research addressing sloped cuts in the field of daylighting. The fraction of deflected light depends on the angle of incidence as well as the cut's distance-to-width ratio, D/W, which is defined with the help of a deflection factor (Fig. 1b).

$$\alpha_2 = r_1 - 2\Theta \qquad (2)$$

$$\text{Sin } \alpha_1 = \frac{\sin r_1}{\text{n}} \qquad (3)$$

$$r_2 = \sin^{-1}(n \times \sin(r_1 - 2\Theta) \qquad (4)$$

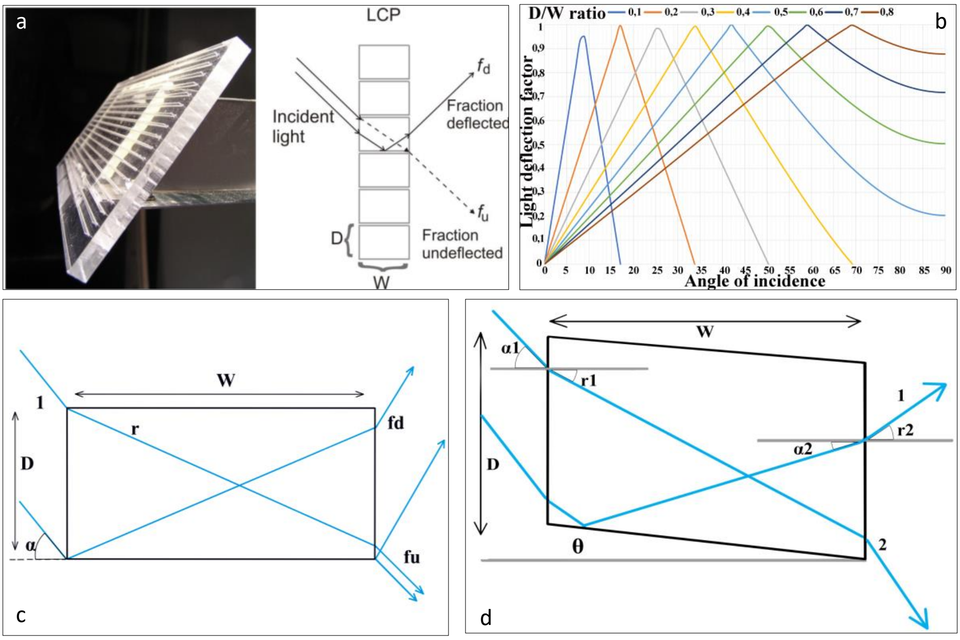

Figure 1. a) Laser-cut panel (Garcia Hansen et al., 2009); b) Light deflection factor for D/W ratios for Edmond's LCP design (Weibye and Matusiak, 2019) ;c) Light deflection principle in non-angled LCP; d) Light deflection principle in angled LCP

LCPs have been used to enhance daylight collection or control excessive sunlighting. They have been used in skylights, windows, and awnings, in order to deflect incoming light and send it toward the indoor ceiling or to deflect it back to the outdoor space and screen the indoor space of solar radiation during the hottest time of day or year (Arnesen et al., 2011; Creda and Matusiak, 2017; Edmonds, 2005; Edmonds and Pearce, 1999; Freewan, 2014; Kischkoweit-Lopin, 2002; Knoop et al., 2016; Labib, 2013; Ruck et al., 2000; Weibye and Matusiak, 2019). Such studies conclude on the same fact that LCPs have the potential to deflect or disperse direct sunlight, reducing the need for blinds in the case of excessive sunlight.

A vertical pipe equipped with a single-sheet-, gable-, or pyramid-formed LCP, and through the idea of rotation, has been introduced in several studies (Edmonds et al., 1995; Garcia-Hansen and Edmonds, 2015; Garcia Hansen et al., 2009; Kadir et al., 2019). A recent study with rotating deflecting sheets showed the improvement of illumination and the temporal uniformity of illuminance on the pipe's exit (Venturi et al., 2006). The study concluded that the LCP can be used as an alternative to heliostats and sun-tracking systems. Meanwhile, a research study with vertical light pipes and LCPs in different tilts showed that the tilt of a LCP should be strongly developed according to the south-north orientation (Nair et al., 2015).

Horizontally placed light pipes, situated in the ceiling plenum, have shown many advantages over vertical light pipes, especially in multi-floored buildings. Several researches in the last decade have also shown the potential in applying an LCP as a deflector for non-axillary rays on horizontal light pipes (Garcia Hansen and Edmonds, 2003; Garcia Hansen et al., 2001; Kwok and Chung, 2008). The main objective in such studies was to improve the light collection of high-altitude light during noon, since those researches have been performed in the tropical climates of lower latitude locations.

This study exclusively examines horizontal cylindrical light pipes, relying on the solar microclimate of high latitude areas. The study addresses a gap in the research on LCPs by examining double/symmetrically rotated panels with vertical cuts for handling the variating azimuth. Moreover, this study consists of experimental parametric measurements and the theoretical analysis of daylight autonomy reported in daily and yearly hours in the inner space 2.1 and 4.5 m distances from the façade wall.

The paper is structured as follows: First, the Introduction establishes the research objective. The research on a whole consists of two parts that are explained in Section 2: Methodology. The research uses a local solar microclimate for the analyses presented in Section 3: Outdoor Daylight Accessibility. The fourth and fifth chapters present the method of the experimental and theoretical part of the study. The results are presented and explained in Section 6. The Discussion chapter explains the results in general, justifies the research hypotheses and importance of the research, and the Conclusions chapter ends the study with the findings of the research. The paper is completed with Appendices A and B, which provide data on the experimental test applicable for further research, Appendix C, providing illustrations from the laboratory study, and Appendix D providing data on the uniformity of the direct light from the artificial sun at the Daylight laboratory at NTNU.

2. Methodology

The objective of the research is to determine how different LCP configurations (D/W, tilt, and rotating position) affect the light-pipe transmittance and to determine which configuration most improves the daylighting in the rear part of a typical office space. The assumptions of the study are that tilted LCPs with horizontal straight cuts will deflect the light from high-altitude angles and provide higher light transmission efficiency, while the two symmetrically rotated LCPs with vertical cuts will deflect wide azimuth, morning and evening light, and provide higher light transmission efficiency for unfavourable light incident angles. The assumptions are illustrated in Figures 2a and 2b. Here, thin lines represent the usual light propagation in the pipe, and the thicker lines represent the light deflected through an LCP in front of the pipe. In order to see the effect of each LCP configuration during the entire year, the concept of daylight autonomy is applied for a certain work area inside the standard office space. The study is a pilot study for a full-scale experiment planned for an office building near Oslo (59°53’ N, 10°31’ E), Norway, which location determined the solar altitude and azimuth applied in the study.

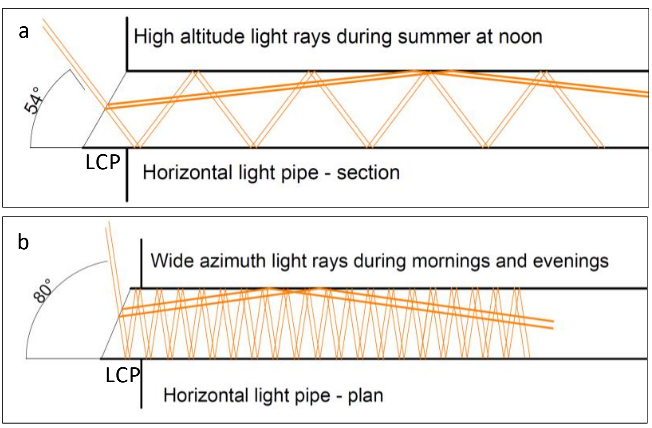

Figure 2. The principle of LCP on the entrance of the horizontal pipe (adopted from (Garcia Hansen et al., 2001) a) High-altitude light during summer at noon (section through the wall). Thicker line denotes deflected light that has preferable incident angle along the pipe’s axis after deflecting on a tilted LCP; b) wide azimuth light in the mornings and evenings (horizontal light pipe in plan). Thicker line denotes deflected light that has a preferable incident angle after deflecting on a single rotated LCP.

The first part of the research comprises a parametric measurement of illuminance at the end of the tube under the several LCP configurations at the tube's entrance. The laboratory tests were done for direct illuminance using an artificial sun and for diffuse illuminance using an artificial overcast sky at Faculty of Architecture and Design (NTNU). The experiment was performed on a model of a horizontal light pipe with an aspect ratio (length-to-diameter) of p = 1200/150 mm (8). The study used four different LCP configurations (D/W), combined with three tilts and three rotations, for each testing solar altitude and azimuth position. The configurations (dimensions and tilt/rotation) of the LCP sheets used in this study are explained in Section 4.1, while the measuring procedure is explained in Section 4.2. The experiment was carried out in the summer of 2019.

To establish the adequate testing positions, the matrix of 15° azimuth and 5°/10° altitude (Table 1), was developed based on the solar chart for Oslo (Fig 3). Due to the complexity and the size of the model, altitude 55° that corresponds best to highest altitude in Oslo (53°), could not be applied, instead the measurements were made with the altitude 50°.

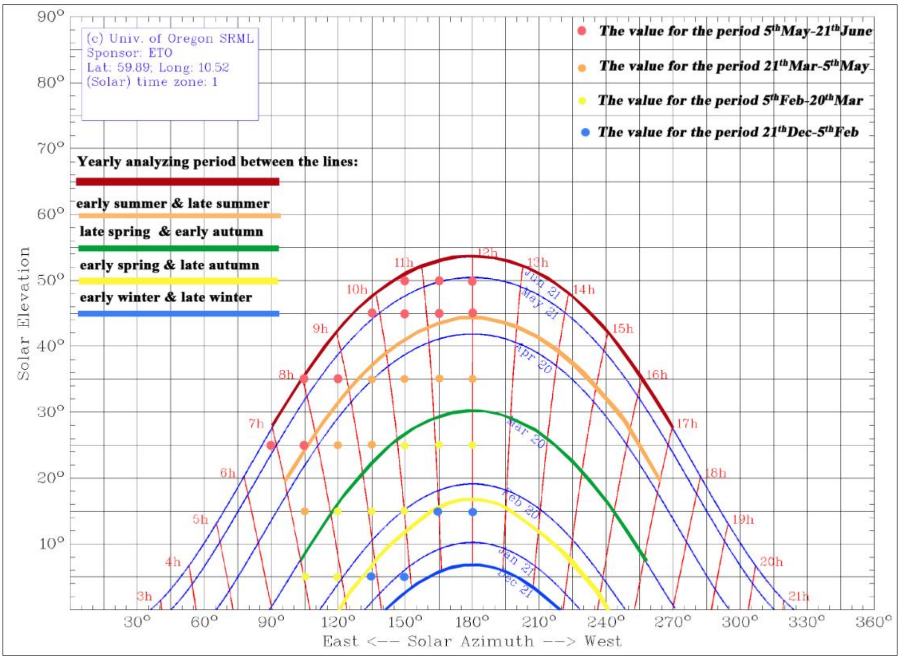

Figure 3. Solar chart for Oslo (59°53' N, 10°31' E), Norway, with typical periods used in the analysis and testing position corresponding to the testing matrix retrieved from (SRML, 2019). Test points in colour represent typical analysing period of the year: red-summer, orange-late spring or early autumn, yellow-early spring or late spring, blue-winter.

Table 1. Testing matrix for parametric laboratory study that refers to the solar chart for a south facade in Oslo. Test points in colour represent typical analysing period of the year: red-summer, orange-late spring or early autumn, yellow-early spring or late autumn, blue-winter.

50°					**50**	**50**	**50**	**50**	**50**				
45°				**45**	**45**	**45**	**45**	**45**	**45**	**45**			
35°		**35**	**35**	**35**	**35**	**35**	**35**	**35**	**35**	**35**	**35**	**35**	
25°	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**
15°		**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	
5°		**5**	**5**	**5**	**5**				**5**	**5**	**5**	**5**	
Altitude/ Azimuth	**90°**	**105°**	**120°**	**135°**	**150°**	**165°**	**180°**	195°	210°	225°	240°	255°	270°
								not tested, assumed equal as the left side					

After the measurements were taken, the transmittance efficiencies of the HPL of each LCP were calculated. The *CIE 173:2012 Tubular Daylight Guidance Systems* presented an approach to determine light transmittance efficacy called the ''standard daylight guide characteristics'' ***(η)*** (l'Eclairage, 2006). For each LCP configuration, the standard daylight guide characteristic ***η****(T-R)*, was found from the ratio of the illuminance measured at the tubes exit, E*(T-R),* and the illuminance measured at the tube's entrance, E*(ZERO),* applying the calculation for each measuring position from the matrix (Eq. 5).

$$\eta_{direct}(T-R) = E_{direct}(T-R) \div E_{direct}E(ZERO) \quad (5)$$

A similar calculation was done for the diffuse illuminance as well, and Fig. 4 presents the method used in the laboratory study. The results for the standard daylight guide characteristic *η(T-R)* of the direct and diffuse illuminance are presented in Appendices A and B, respectfully. This data can be used to develop illuminance data for several other locations at latitudes ≥ 59° N because of the maximum tested solar altitude 50°) by using the Satel-Light data of direct vertical and diffuse vertical illuminance for the particular location.

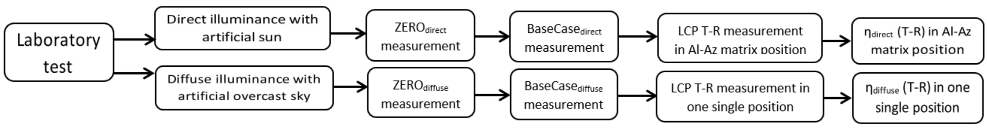

Figure 4. Method of parametric study and determination of the standard daylight guide characteristic η(T-R).

The second part of the research is a daylight autonomy analysis of the daylight supplement through the horizontal pipe in the theoretical model of an office space. As the first part of the study resulted in a standard daylight guide characteristic ***η****(T-R)* for a pipe with an aspect ratio of 8, the absolute illuminance values from a Satel-light database are used in order to develop real illuminance values for the pipe's exit. Satel-Light data for the direct and diffuse illuminance on a vertical, south-oriented façade in Oslo was used (Figure 5). Section 3 features the detailed procedure for the development of $E_{Sdirect}$ for a direct illuminance and $E_{Sdiffuse}$ for diffuse illuminance.

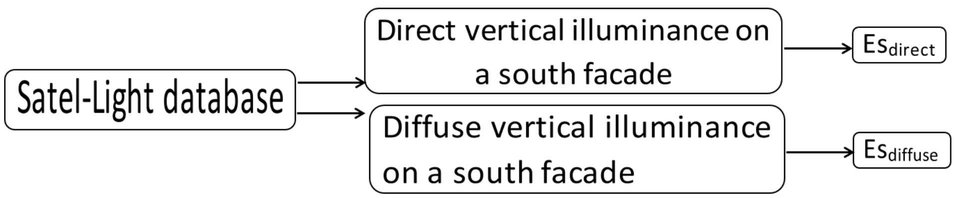

Figure 5. Method for the development of Satel-Light data, $E_{Sdirect}$ and $E_{Sdiffuse}$.

Real values for the illuminances at the tube's exit, Er_{direct} and $Er_{diffuse}$, were then developed by multiplying the standard daylight characteristic, ***η****(T-R)*, with the absolute illuminance values from the Satel-Light database*,* Es_{direct} and $Es_{diffuse}$ (Eq. 6). Eq. 6. is used for each LCP sample separately in each testing position from the matrix (Table 1).

$$Er_{direct}(T-R) = \eta_{direct}(T-R) \times Es_{direct} \quad (6)$$

The final Er_{total} is a result of the summation of Er_{direct} and $Er_{diffuse}$ for any testing configuration. Er_{total} is developed for the BaseCase (Eq. 7) as well as for each LCP configuration (Eq. 8).

$$Er_{total}(BaseCase) = Er_{direct}(BaseCase) + Er_{diffuse}(BaseCase) \quad (7)$$

$$Er_{total}(T-R) = Er_{direct}(T-R) + Er_{diffuse}(T-R) \quad (8)$$

Since the BaseCase test considered a completely open tube's entrance without any LCP and under the assumption that the entrance needs to be closed, the standard daylight guide characteristics (η) for the BaseCase were reduced by the standard light transmission factor for acryl (of 0,92).

In the theoretical model, the illuminance on the pipe's exit is directed down to the reference surface by a curved reflector. The theoretical model of the office space, the reflector, and the reference surfaces, together with the method for the calculation of illuminance on the reference surface, are explained in Section 5.

3. Outdoor daylight accessibility

The climate in Oslo is, in terms of the Köppen-Geiger classification, characterized by strong seasonality, snow, humidity, and warm summers (Dfb) (Kottek et al., 2006). According to historical weather recordings, there is a predominantly clear sky and sunlight for 37% daylight hours during the year, with the remaining 63% being predominantly overcast sky (Table 2).

Table 2. Sunlight hours for Oslo (retrieved from (Google, 2019)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average sunlight hours/day	01:27	02:56	04:54	06:04	07:30	08:08	07:03	05:54	04:36	02:48	01:22	00:48	04:28
Average daylight hours/day	06:50	09:05	11:46	14:35	17:09	18:40	17:58	15:38	12:51	10:03	07:29	06:02	12:00
Sunny/Cloudy daylight hours/day in %	22 /78	34 /66	43/57	43/57	45/55	44/56	40/60	39/61	37/63	29/71	19/81	14/86	37/63
Sun altitude at solar noon	10.3°	19.6°	30.4°	42°	50.3°	53.5°	50.5°	42.1°	30.7°	19.3°	10.1°	6.8°	30.5°

It is generally assumed that the predominant type of sky in Norway is overcast, but the 37% of daylight hours throughout the year should not be neglected, as clear sky and sunlight represent the highest potential for light collection in any solar microclimate. Most of these sunlight hours occur during the summer half-year, when the sun's altitude and azimuth also have the biggest variation during the day. The cumulative sunlight hours for the summer half-year is 248 hours, compared to 161 hours for the winter half-year. The Satel-Light recordings (Satel-Light, 1998), based on the Meteosat Satellite images and obtained every half hour, are used to generate data on the direct and diffuse illuminance on a vertical south-oriented surface.

The direct and diffuse vertical illuminances from the Satel-Light were developed by following the data matrix in this study (Table 1) to correspond with the specific altitude and azimuth positions for each hour given by the Satel-Light data. Table 3 shows data for the direct illuminance and Table 4 shows data for the diffuse illuminance on the vertical south-oriented surface.

Table 3. Satel-light data for direct vertical illuminance Es_{direct} (in lux) on the south façade of an theoretical office building in Oslo (retrieved from Satel-Light (2019))

50°					17100	20575	31000	20575	17100				
45°				12025	21575	25825	26900	25825	21575	12025			
35°		5650	8425	15100	21575	23775	25750	23775	21575	15100	8425	5650	
25°	350	3600	8425	14100	20100	15800	18000	15800	20100	14100	8425	3600	350
15°		2650	7675	5075	8450	11275	13100	11275	8450	5075	7675	2650	
5°		700	1825	2500	3325				3325	2500	1825	700	
Altitude/ Azimuth	**90°**	**105°**	**120°**	**135°**	**150°**	**165°**	**180°**	**195°**	**210°**	**225°**	**240°**	**255°**	**270°**

Table 4. Satel-light data for diffuse vertical illuminance, $Es_{diffuse}$ (in lux), on the south facade for Oslo (retrieved from Satel-Light (2019))

50°					17000	18650	19150	18650	17000				
45°				14425	17200	18900	19350	18900	17200	14425			
35°		8625	10850	14225	17200	13525	15025	13525	17200	14225	10850	8625	

25°	6000	7425	10850	8225	11350	8200	8800	8200	11350	8225	10850	7425	6000
15°		1750	4675	4075	6550	7300	7500	7300	6550	4075	4675	1750	
5°		200	400	1400	4250				4250	1400	400	200	
Altitude/ Azimuth	**90°**	**105°**	**120°**	**135°**	**150°**	**165°**	**180°**	**195°**	**210°**	**225°**	**240°**	**255°**	**270°**

Illuminances on tilted surfaces (both vertical- and south-oriented in this study) are, according to the Satel-Light knowledge facts, computed from irradiances on tilted surfaces using the diffuse and direct luminous efficacies of the horizontal irradiance. The values obtained from the Satel-Light for each hour for a certain month are, developed as the monthly mean of hourly values.

A limitation of this study is that the direct and diffuse light from the Satel-Light database presents values from the real sky condition with an unknown distribution of luminance on the sky. This means that the values for direct and diffuse illuminances do not come from a static sun or sky with predictable light intensity and distribution, upon which the laboratory test in the present study was conceived.

4. Experimental method for parametric measurements

4.1 Design basis

For the summer solstice in Oslo, Norway, the highest altitude of sun is 53.5° at 12:15 h (Fig 3). At 7 AM, the altitude is close to 25° (at Az 90°), and at 5 PM, the altitude is close to 30° (at Az 270°). The spring and autumn equinoxes are characterized by solar altitude between 5° and 30° and azimuth between 95° and 255° for the usual user-occupancy period (7 AM-5 PM). For the winter solstice, the highest altitude is 6.8°, the lowest altitude 0° is at 09:30 h (Az is 140°), and the second-lowest altitude 0° is at 15:00 h (for Az 220°). The angles are rounded to integers divisible by 5 for clarity.

The altitude variability is therefore 46.8° (53.5°– 6.8°), while the winter azimuth variability is 80° (for the first-lowest altitude 0°to the second-lowest 0°), and the summer azimuth variability is 180° (Fig. 3). This indicates that the variability in the azimuth angles should be the primary issue focused on in this study.

Table 5. Solar altitude and azimuth during the summer solstice, equinox, and winter solstice during typical occupancy hours

Season/solar altitude and azimuth	Altitude variation		Azimuth variations	
Time of the day	7 AM	12 AM	7 AM	5 PM
Summer solstice	25°	53°	90°	270°
Spring/autumn equinox	5°	30°	95°	255°
Winter solstice	0°	7°	140°	220°

According to the light deflection theory of the LCP, if the aim is to have deflected light leaving the LCP and propagating along the pipe's axis, the LCP tilt/rotation should be $\beta = \alpha/2$, where α is a light incident angle on an LCP in the vertical position (Fig. 6.). In the case of the summer solstice, $\alpha_{max}= 53.5°$, the tilting angle is $\beta = 26.75°$. Table 5 presents the extreme altitude and azimuth incident angles for the Oslo location, which occur during the typical occupancy period (7 AM-5 PM). If the LCP is tilted by angle β, then α-β becomes a *real* incident angle for the tilted LCP (Fig. 6.). In the case of strait cuts, Θ = 0°, as mentioned in the introduction, the *real* incident angle is $\alpha- \beta= \alpha- \alpha/2= \alpha/2$. The real incident angle α - β and the light deflecting factor (Fig 1b) should determine the LCP's D/W configuration.

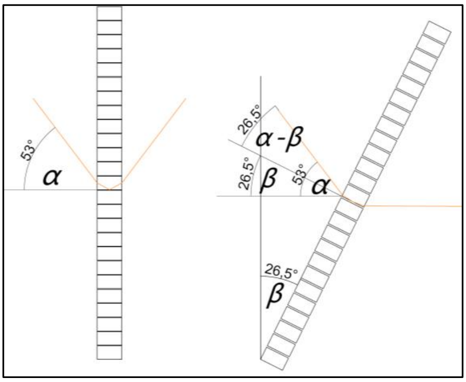

Figure. 6. Determination of real incident angle for the tilted LCP

4.1.1 Tilting LCP

For the light incident angle of 53.5°, and as can be seen in Fig. 1b, LCP D/W 0.3, tilted by *β = α/2 = 26.75°* will have almost 100% light deflection for the light incidence angle *α = 26.75°* relative to the LC panels. The angle through which the light would be deflected will be increased by the tilting angle of the LC panel *26.75°,* and the absolute outgoing angle will be 0° (deflecting angle 26.75°- tilting angle 26.75°)—relative to the pipes' s axis. The light will propagate an auxiliary within the tube without any interreflections, and the deflected light will be reduced just for the transmission factor of the acrylic panel (0,92).

For all incidence light falling between 53.5° to 26.75°, the fraction of deflected light will be reduced, and the fraction of directly transmitted light will be increased. For the incident light, exactly *α = 26.75°* light will be transmitted through the panel auxiliary at a transmission of 92%, while, for incidence light lower than 26.75° (October to February; Fig. 3), the light will be deflected through a much higher angle, which will increase the interreflections and reduce the light transmittance.

The principle of the tilting configuration that will best suit the light incidence angle during the summer solstice is presented in Fig. 7a along with that for the spring/autumn equinox in Fig. 7b and the winter solstice in Fig. 7c. See also Table 5 for altitude variations.

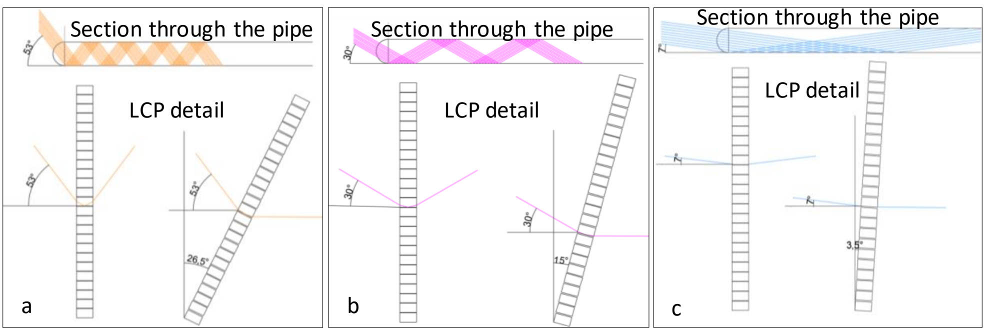

Fig. 7 The principle of light deflection for different altitude incident angles on a LCP with horizontal cuts; upper part of the illustration presents section through the horizontal pipe, and the lower part shows an enlarged section through the LC panel in the vertical and tilted positions; a) Tilted LCP that deflects summer sunlight well at the highest altitude; b) spring; and c) winter.

4.1.2 Rotating LCP

To manage the incident light with a non-preferable azimuthal angle, two symmetrically rotated LCPs with vertical cuts can be applied. They will deflect light rays with extreme azimuth angles and align them with the tube's axis (Fig 2b). Since the azimuthal variability is symmetrical from the south-oriented pipe's point of view (east/west), the LCP should consist of two identical panels, each angled on its side (Fig 8). In the case of the winter solstice sunrise, the altitude is 0° (at 09:30 h), and the Az is varying +- 40° (Table 5), the LCP with vertical cuts should be angled $\beta = \alpha z/2 = 20°$ in order to deflect the light auxiliary within the tube. In the case of the summer solstice, the solar azimuth ranges 90° to 270° from 7 AM- 5 PM. For $\alpha z = 90°$, the LCP rotating angle should be $\beta = \alpha z/2 = 45°$, and the real incident angle on an angled panel $\alpha z1 = \alpha z/2 = 45°$. For the incidence angle of an $\alpha z1 = 45°$, the LCP configuration of D/W 0.5 will provide the most effective deflection (Fig 1b). For $\alpha z1 \leq 40°$, the light will be deflected against the tube's walls, and the number of interreflections will increase, which will reduce the light transmittance.

The principle of the rotating configuration that will best suit the light incidence angle during the summer solstice is presented in Fig. 8a along with the spring/autumn equinox in Fig. 8b and the winter solstice in Fig. 8c.

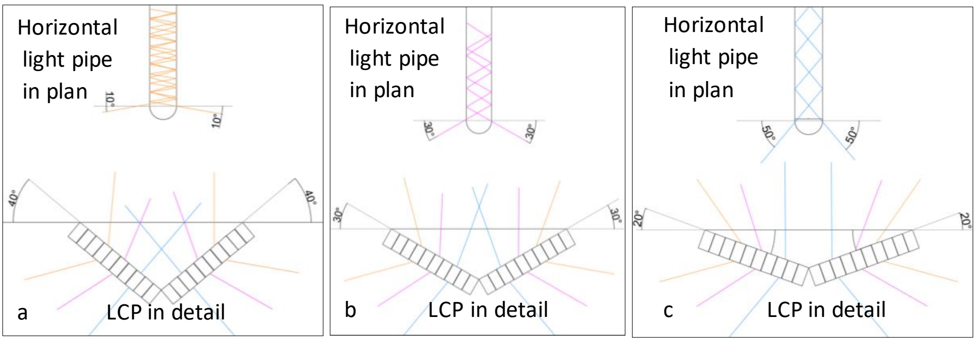

Fig. 8 The principle of light deflection for different azimuth incident angles on an LCP with vertical cuts; the upper part of illustration presents a plan through the horizontal pipe, and the lower part is an enlarged plan through two symmetrical LC panels in a rotated position; a) LCP configuration that deflects summer sunlight well (orange rays); b) LCP conf. that deflects spring sunlight well (pink rays); and c) LCP conf. that deflects winter sunlight well (blue rays).

4.1.3 LCP alternatives in the study

The proposed LCP configurations for variable altitudes and azimuth angles are presented in Tables 6 and 7. Due to the technical limitations of today's laser-cutting machines which cannot cut through acrylic plates thicker than 6mm, the D/W varies between 0.5 and 0.8. Each LCP configuration has its biggest potential (highest deflection factor) for just a certain incident angle (Fig. 1b), and the other incident angles will result in reduced deflected and increased transmitted light. Tables 6 and 7 present the theoretical approach to the specific configuration. Each of the proposed configurations of D/W and the tilting/rotating angle is expected to balance the differences of the light pipe transmittance under the variable light incidence angle.

Table 6. LCP test configurations: D/W, tilting angles, and deflection factor for a certain light incident angle relative to the pipe's axis

Testing configuration	D/W	Tilt	Deflection factor for an altitude incident angle		
ZERO	No LCP used - Sensors in the front of the tube	Measuring incident illuminance			
BaseCase	No LCP used - Sensors in the exit tube	Measuring output illuminance	34°	44°	54°
T-05-17	0.5	17°	0.50	0.65	0.88
T-05-22	0.5	22°	0.32	0.55	0.75
T-05-27	0.5	27°	0.20	0.45	0.65
T-06-17	0.6	17°	0.35	0.55	0.75
T-06-22	0.6	22°	0.25	0.45	0.65
T-06-27	0.6	27°	0.15	0.35	0.55

Table 7. LCP test configurations: D/W, rotating angles, and deflection factor for a certain light incident angle relative pipe's axis

Testing configuration	D/W	Rotating angle	Deflection factor for an azimuth incident angle		
Sample ZERO	No LCP used Sensors in the front of the tube	Measuring incident illuminance	90°/270°	80°/260°	70°/250°
BaseCase	No LCP used - Sensors in the exit tube	Measuring output illuminance			
R-08-20	0.8	20°	0.99	0.90	0.75
R-08-30	0.8	30°	0.90	0.75	0.60
R-08-40	0.8	40°	0.75	0.60	0.45
R-07-20	0.7	20°	0.85	0.99	0.85
R-07-30	0.7	30°	0.99	0.85	0.68
R-07-40	0.7	40°	0.85	0.68	0.50
R-06-20	0.6	20°	0.65	0.82	0.99
R-06-30	0.6	30°	0.82	0.99	0.80
R-06-40	0.6	40°	0.99	0.80	0.60
R-05-20	0.5	20°	0.40	0.58	0.80
R-05-30	0.5	30°	0.58	0.80	0.95
R-05-40	0.5	40°	0.80	0.95	0.70

4.2 Experimental setup

In this experiment, an acrylic panel 6 mm in thickness (Plexiglas® XT 0A770, Evonik Performance Materials GmbH) was used for the LC panels. This acrylic panel is completely clear, transparent, and with a light transmittance of 0,92 and refraction index of 1,491.

The main issue in LCP fabrication, even nowadays, is that laser cutters are not designed to cut through acrylic panels thicker than 6 mm. The thickness of the plate dictates the distance-to-width ratio (D/W), and very narrow cut distances can bring about melting problems. Laser cuts were therefore done as D/W 0.5, 0.6, 0.7, and 0.8, which, for a panel 6 mm in thickness, gives distances of 3.0 mm, 3.6 mm, 4.2 mm, and 4.8 mm, respectively (Fig 9).

During the design of the study, we considered a "climate envelope", which is necessary in real buildings to protect an indoor light pipe against the outdoor climate. The review of the commercial products on the market has shown that the most suitable and probable envelope shape would be a half-spherical dome (Figure 10). The limitations in LCP configurations are the result of this assesment. The panels for the tilt probe were oval (d1 = 150mm; d2 = d1/cos 45° = 212 mm), while, for the rotation probe, they were half-oval in shape (d1 = 150mm; d2/2 = d1/2*cos 45° = 106 mm). Figures 10a and b illustrate the issue of the dome's shape limiting the tilt/rotation of the LCP. The tube was 150 mm in diameter and 1200 mm in length and was made of pap. The aspect ratio of the tube was L/D 1200/150 = 8. The tube was coated with specular mirror folium with 99% reflectivity (Specular silver film DF2000MA, 3M).

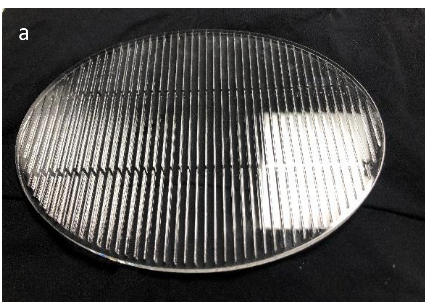

Figure 9. a) LCP in an oval shape for tilt probe; b) LCP in half-oval shape for azimuth probe

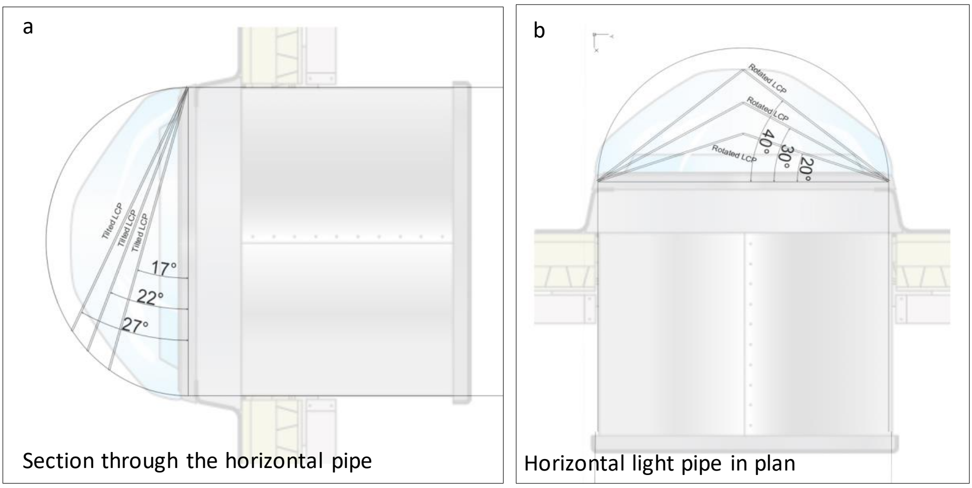

Figure 10. a) Tilt of LCP in an oval shape is limited by the shape of the dome; b) rotation of symmetrically oriented LCP in half-oval shape is limited by height of the dome.

Lighting simulations were performed in the Daylight laboratory at NTNU, Department of Architecture and Technology. For the direct light test, an artificial sun was used, which was composed of 70 halogen lamps with parabolic reflectors (50 W) fixed to a vertical metal plate and arranged in a hexagonal pattern. The artificial sun provides close to parallel light beams with a dispersion angle of 3°. It was situated in a corridor-like room enabling long enought distance from the sun to the models, (Fig. 11). The walls, ceiling, and floor were painted matte black to minimize interreflections in the room and scatter light on the model. The model (tube) was positioned at the 7.5 m distance from the artificial sun, which ensured very even illumination. Actually, the uniformity of the light from the artificial sun on the tube's entrance, measured in the perpendicular direction to the sun, is 98%. The data is taken from the measurements done for the alternative ZERO for altitude 5° and azimuth 180°. The illuminance uniformity data for all matrix positions is presented in appendix D.

The model was fixed on a box 1 m high so that the height of tube's entrance matched the centre of the artificial sun. For the altitude variation measurements, the model was tilted by lifting the back side on a vertical shelf, and azimuthal variation measurements were taken by rotating the box to align it with the angle grid on the floor. Testing positions were developed through the matrix of 5°, 15°, 25°, 35°, 45°, 50° for altitude, and 90°, 105°, 120°, 135°, 150°, 165°, 180° for azimuth (with the assumption that testing for azimuth 180° to 270° would be the same) (Table 1). The outermost azimuth angles, 90° and 270°, were taken from the vertical cut-off of the south façade and the user-occupancy hours, Table 5. Photos from the laboratory study are presented in Appendix C.

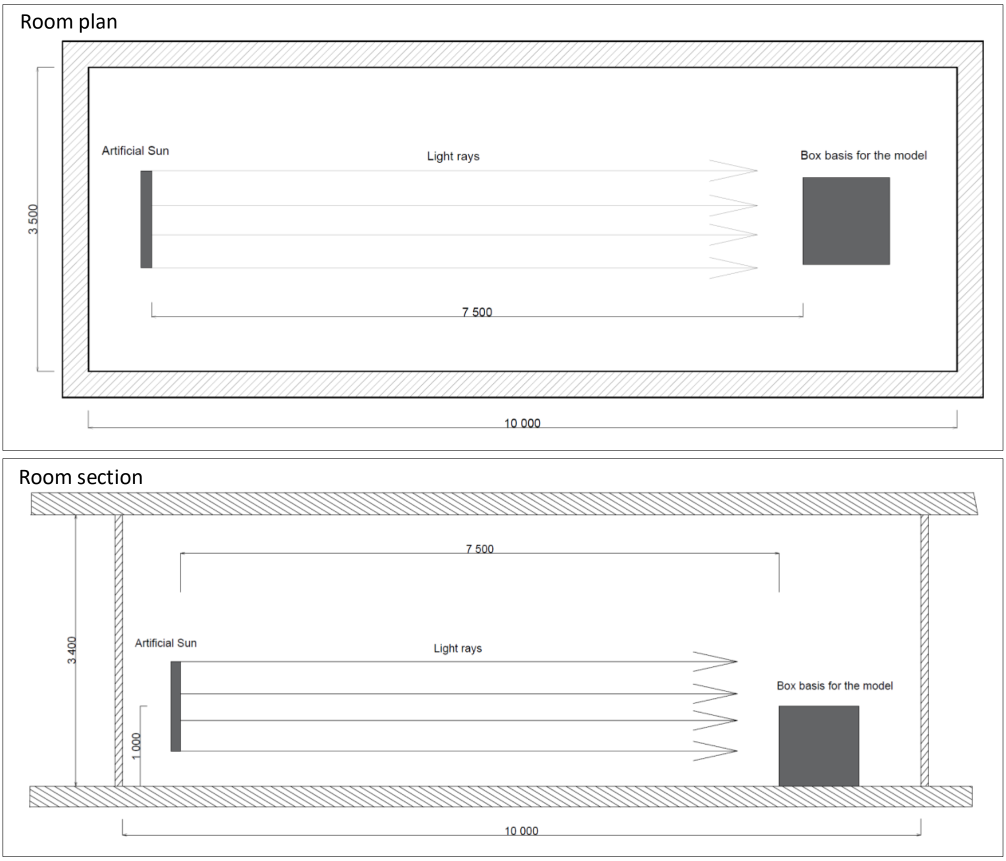

Figure 11. Artificial sun setup in Daylight laboratory at NTNU, Faculty of Architecture and Design, in plan (up) and section (down)

For the diffuse light experimental test, an artificial sky in the form of a mirror box at NTNU, Faculty of Architecture and Design, was used (Fig 12). The mirror box was originally developed between 2000–2003 with fluorescent tubes and a translucent fabric suspended between the tubes and mirrors. In 2012, the tubes were replaced by RGBW LED chips, and the fabric by translucent acrylic ceiling plates. The box is designed octagonal in plan. This ensures more even light distribution horizontally when compared to rectangular mirror boxes that have slightly lower luminances in the vertical corners than the mirror centres. An octagonal box gives users more flexibility regarding the rotation of the model, as it does not matter whether the daylight opening in the model is oriented toward a mirror centre (Matusiak and Arnesen, 2005; Matusiak and Braczkowski, 2014). As the height of the tube's entrance is 150 mm, which is a 7,5% of sky height in the mirror box (2000 mm), it can be estimated that the parallax error is somewhat higher than 10% for low altitude angles (0-15°). For the altitude angles over 15°, as discussed in Lynes and Gilding (2000), the parallax error is lower than 10%. The test model was fixed on the table located in the middle of the mirror box. The height of the table was adjusted to align with the lowest edge of the mirrors. The tube was placed in one single position, with the opening at the centre of the mirror box based on the fact that the overcast sky simulated in the artificial sky chamber was rotationally symmetrical—that is, its luminance distribution was not dependent on the azimuth angle. Photos from the laboratory study are presented in Appendix C.

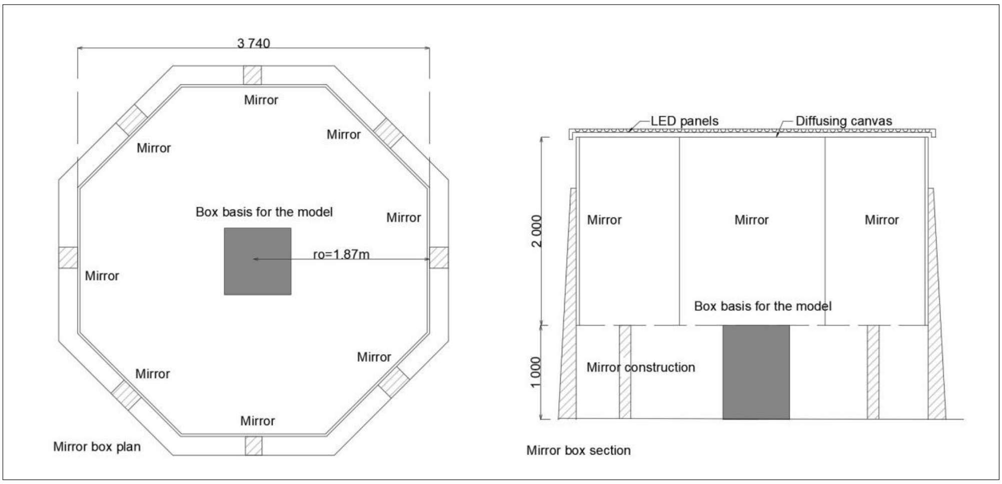

Figure 12. Mirror box for artificial overcast sky study at NTNU, Faculty of Architecture and Design, in plan (left) and section (right)

Lighting measurements were taken with five Almemo photosensors arranged in a cross on a circular surface, and the results were logged via Ahlborn logger and recorded via Almemo control software 6.0, fig. C3, Appendix C.

5. Theoretical method for the daylight autonomy analysis

As mentioned in Section 3, the resulting Er_{total} represents the illuminance at the pipe's exit for each position from the matrix and each LCP configuration. In order to analyse the result of Er_{total} for the typical period, the concept of daylight autonomy (DA) in an imaginative working space was employed, assuming that illuminance on the working area was provided just through the horizontal light pipe. As discussed in the introduction, the daylight provision through the especially south oriented windows, are very much dependent on users' individual opinions about visual comfort, which most often results in closed blinds for much longer periods than strictly necessary, as users tend to instantly react based on discomfort, forgetting to open the blinds when the discomfort has passed. This results in unreliable daylight supplement inside—even for working places closest to the window.

According to *EN17037:2018 Daylight in Buildings*, the recommendation for the ''minimum level'' target illuminance of 300 lux for 50% of reference surface area and 100 lux for 95% of a reference surface area; for the ''medium level'', a target illuminance of 500 lux for a 50% of reference surface and 300 lux for a 95% of reference surface; and, for a ''high level'', a target illuminance of 750 lux for a 50% of reference surface and 500 lux for a 95% of reference surface has to be fulfilled for a 50% of daylight hours. Following those recommendations (noting that the requirements for 50% of working surface in a room with window(s) in one wall is relevant only for the window zone), both a minimum level (DA_{100} for 95% of a ref. surface) and medium level (DA_{300} for a 95% of a ref. surface) are considered for a reference surface 0,85 m above the floor.

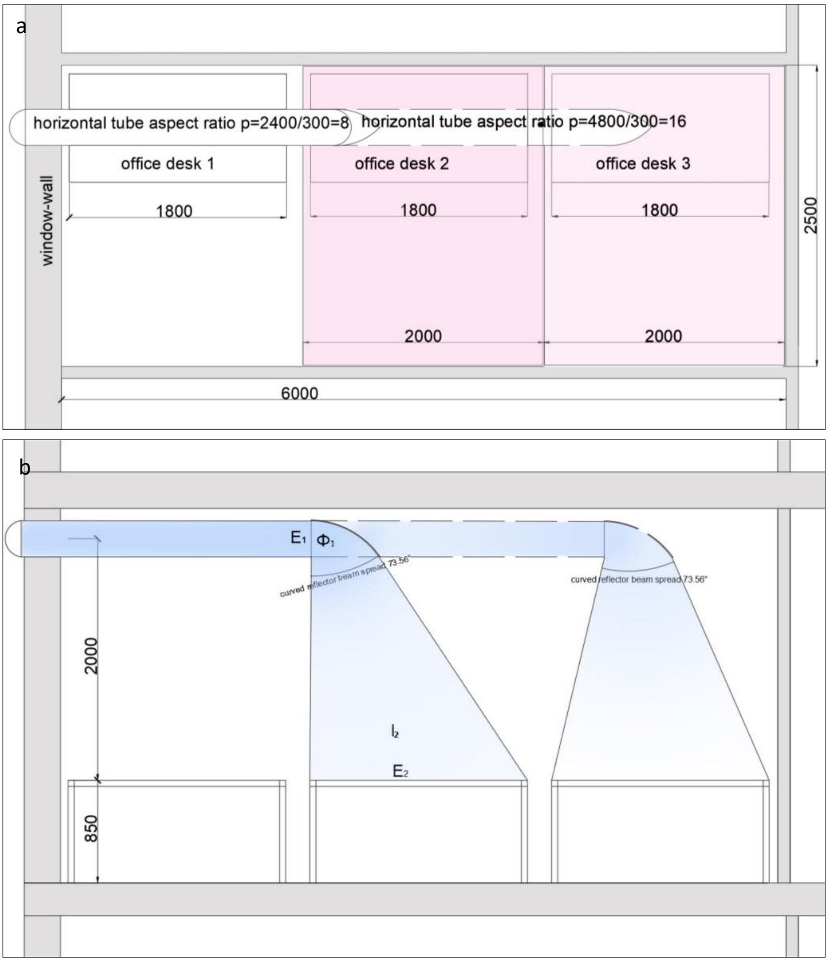

Figure 13. a) Plan and b) vertical section of a typical office (the second and third working areas in the office, correspond to a light pipe of aspect ratio 8 and 16, respectively).

The straight horizontal tube, of aspect ratios 8 and 16, is considered in the theoretical model of the office space. The tube of the aspect ratio 8 has a length of 2.4 m and a diameter of 30 cm, while the tube of aspect ratio 16 has a length of 4,8m and a diameter of 30 cm. Assuming a wall thickness of 30 cm, the tube's exit is 2.1 m from the wall inside in the first theoretical case and 4,5 m in the second, which corresponds to the second and third working area from the window (Fig 13). For the tube with an aspect ratio 8, the Er_{total} from the laboratory parametric study was used. For the tube with an aspect ratio 16, the tube transmission efficacy factor (TTE) described in CIE 173:2006 was used to estimate the transmission reduction on the basis of the increased length of the pipe (l'Eclairage, 2006). The approach of TTE was developed for vertical light pipes under an overcast sky, assuming that only light within a cone subtending an angle of 30° enters the tube. Under the circumstance of lacking a simple method for tube transmission efficacy estimation under other sky conditions, as well as a wider range of light incident angles, the TTE approach can be applied under the clear notice of an approximation. According to Table 2 (l'Eclairage, 2006), for a pipe reflectance at a min. of 0,995 and an aspect ratio of 8, the TTE is 0,97, and, for the aspect ratio of 16, it is 0,93. As the Er_{total} for the aspect ratio of 8 is already known (and is strongly dependent on LCP configurations), the Er_{total} for the aspect ratio of 16 will be calculated from the value of Er_{total} for the aspect ratio of 8 by reducing it for the difference factor of TTE_{16}/TTE_8 = 0,93/0,97 = 0,958.

It is considered that a certain portion of the light leaving the pipe is diffused and cannot be perfectly directed to the desired area (in this case, to a curved reflector explained further in the text). To account for this, the resulting illuminances on the pipe's exit, Er_{total}, is reduced by 10%. The mounting height of the tube above the workplane is d = 2 m (Fig.13). It is assumed that the daylight on the exit of the tube is reflected by the curved reflector of a high light reflectivity (99%), which features a beam spread covering the area corresponding to the reference surface A = 5 m^2, as it is supposed to be round. The solid angle (*Ω)* of the reflector is, in this case, 1,25 Sr (Eq. 9). The beam spread of the reflector is δ = 73.56° (Eq. 10).

$$\Omega = A \div d^2 \qquad (9)$$

$$\Omega = 2\pi\left(1 - \cos\frac{\delta}{2}\right) \qquad (10)$$

$$I_2 = E_2 \times d^2 \qquad (11)$$

$$\Phi_1 = \frac{I_2}{0.9 \times \Omega} \qquad (12)$$

If a threshold illuminance on the reference surface is E_2 (in this case, 100 lux and 300 lux), the threshold light intensity, I_2, is 400 cd and 1200 cd, respectively (Eq 11). However the inverse square low (Eq 11) can be used just for point sources where largest dimension of the source (here tube's exit) is not less than one fifth of the distance to the reference surface. The required light flux from the curved reflector, Φ_1, is dependent on the light beam spread but also the portion of light inevitably scattered outside the beam spread of the reflector and against the walls. It can be taken that this portion, for a room with light walls (reflectance > 70%) reflecting most of the diffuse light back to the reference surface is 10%. The required light flux, Φ_1, can be derived from Equation 12. In order to have a threshold value in lux to could compare with the results from the parametric study, E_1, is derived from Eqs. 13-14. The tube diameter (D_p) is 30 cm, and its exit surface (P_t) is 0.071 m^2. The required E_1-threshold value of DA_{100} is 7746 lux, and that of DA_{300} is 23239 lux.

$$P_t = \pi \times {D_p}^2 \qquad (13)$$

$$E_1 = \frac{\Phi_1}{P_t} \qquad (14)$$

The threshold values E_1 for DA_{100} and DA_{300} are used to determine the number of hours in the resulting Er_{total} for each LCP configuration. In the position matrix, typical analysing periods are determined from the position of the sun's altitude and azimuth. The typical analysing periods are winter, early spring/late autumn, late spring/early autumn, and summer. It can be noted from Fig. 3 that the depicted periods, with their characteristic Al and Az, will occur two times throughout one entire year.

6. Results

The results for the standard daylight guide characteristic *η(T-R)* (for direct and diffuse illuminance) for each LCP configuration and in each testing matrix position are presented in Appendices A and B.

In order to compare the standard daylight guide characteristic, - *η*, for each LCP configuration with the BaseCase, $\eta_{cumulative}$, (where *η* for a certain LCP configuration is aggregated) is presented in Figures 14 and 15 for direct and diffuse illuminance, respectively. The presented ***η****(T-R)* refers to the tube with aspect ratio of 8.

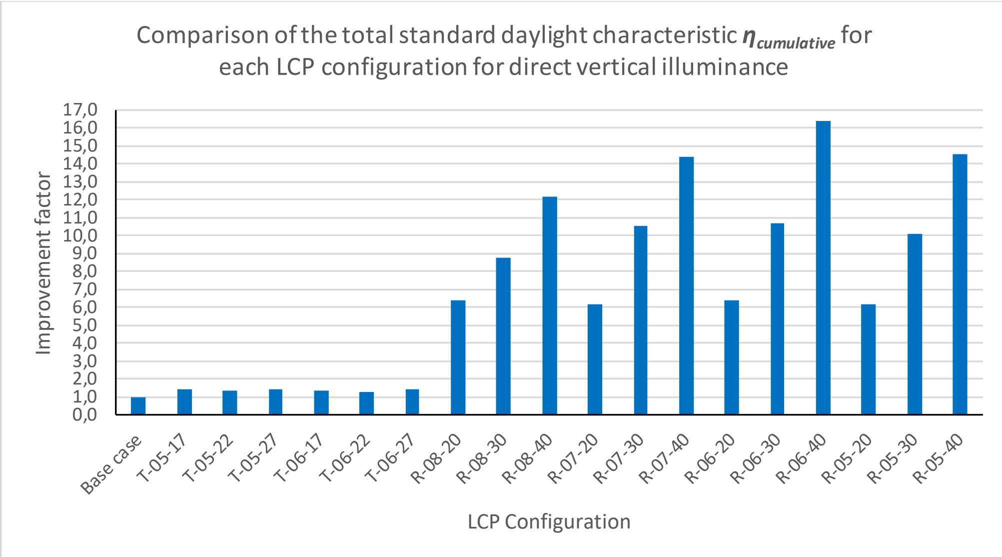

Figure 14. Comparison of the standard daylight characteristic $\eta_{cumulative}$ for each LCP conf. for direct vertical illuminance (aspect ratio 8).

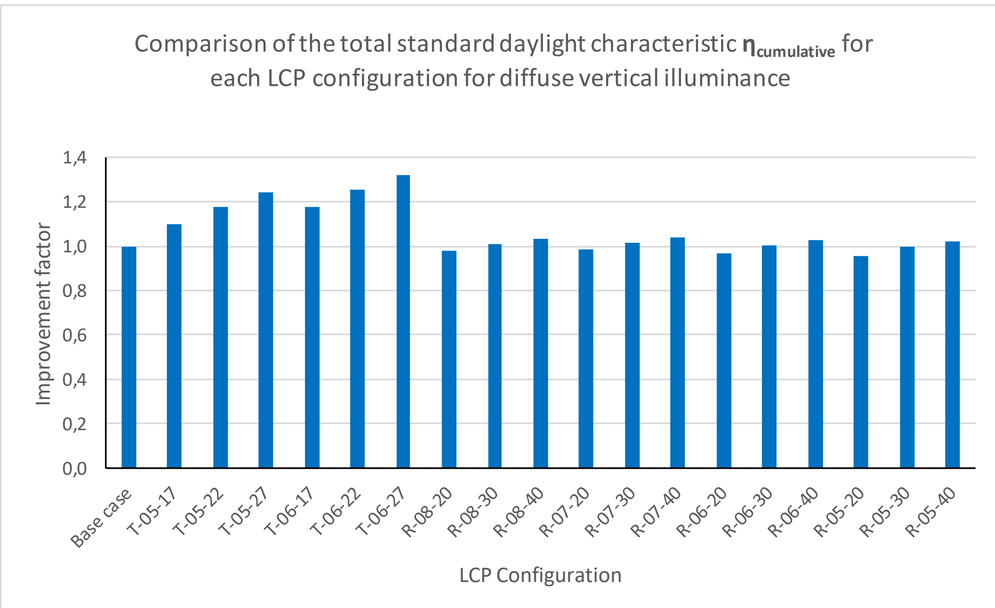

Figure 15. Comparison of the standard daylight characteristic $\eta_{cumulative}$ for each LCP conf. for diffuse vertical illuminance (aspect ratio 8).

The standard daylight guide characteristic (***η***) for all R-LCP configurations increased from 6 to over 16 times for direct light when compared with the BaseCase (Figure 14). The T LCP configurations show a slightly increased ***η***, with 1,46 times (46%). Figure 15 shows that the highest increase in ***η*** for diffuse light occurs in T LCP configurations— in fact, up to 1,32 times (32%), while none of the R LCP configurations show any significant increase. The very high increase in η for the R samples can be explained through the difference between the extreme incident angles, which are, in the case of altitude variability, 46° and, in the case of azimuth angles, up 2 x 90°. Some of the LCP configurations also have a very high deflection factor for some of the extreme azimuth angles (see Tables 6 and 7).

The final Er_{total}, as a result of the summation of Er_{direct} and $Er_{diffuse}$ for any testing configuration, was used to check if the threshold value (E_1) was achieved. The values are not presented in this study due to their non-universality, as they are only applicable to the Oslo-solar microclimate, but they are available upon request.

The results of DA_{100} and DA_{300} for a theoretical model of an office space with tube aspect ratios of 8 and 16 are analysed. The DA in this project is presented in hours (instead of a percentage of daytime) simply because this study addresses a typical office building with strictly defined occupancy time, that is from 7 AM to 5 PM. The time before and after is just not relevant.

The total yearly DA in hours can be calculated by multiplying daily DA of each period by the number of days in that period. As mentioned in the introduction, the solar position will take place twice during each analysing period throughout the year. There are 4 typical periods, and the number of days in each period is ¼ of the 365 days or 91.25 days. The total yearly daylight autonomy in hours is: DA_T = VinterDA$_d$*91.25 + EarlySpringDA$_d$*91.25 + LateSpringDA$_d$*91.25 + SummerDA$_d$*91.25.

Starting the analyses, the first issue to check was whether any of the LCP configurations decreased the DA when compared to the BaseCase. The values show that none of the LCP configuration decreased the DA_{100}, while the decrease was present for several R LCP configurations for DA_{300}. This is noticeable for both aspect ratios of 8 and 16.

The analysis of DA_{100} for the aspect ratio of 8 (Fig. 16) shows that the R-LCP configuration with a 40° rotation produces the highest improvement in total yearly DA hours by up to 10% for R-07-40. The improvement is mostly noticeable during the summer months, where, each day, the DA is prolonged by nearly two hours.

The analysis of the DA_{300} for the aspect ratio of 8 (Fig. 17) shows that the increase in terms of the total yearly hours is highest for T-06-27, R-08-40, and R-07-40 of up to 19% longer yearly DA in hours. The highest improvement happens during the late spring, with 1 hour and 20 minutes each day. It can be noted that all T configurations prolonged DA_{300} during the early spring up to 30 minutes in the case of T-06-27, while none of the R configurations showed improvements. The reduction in daily hours during the summer is also noticeable for configurations R-05-40, R-05-30 and R-06-40 and R-06-30, while they contribute to the DA positively during the late spring. This can be explained by total movement of light incident angle throughout the day, which in case of spring is not as wide as in case of summer, and the LCP R configurations that are rather successful in light transmission of the spring light rays than light deflection of the summer light rays.

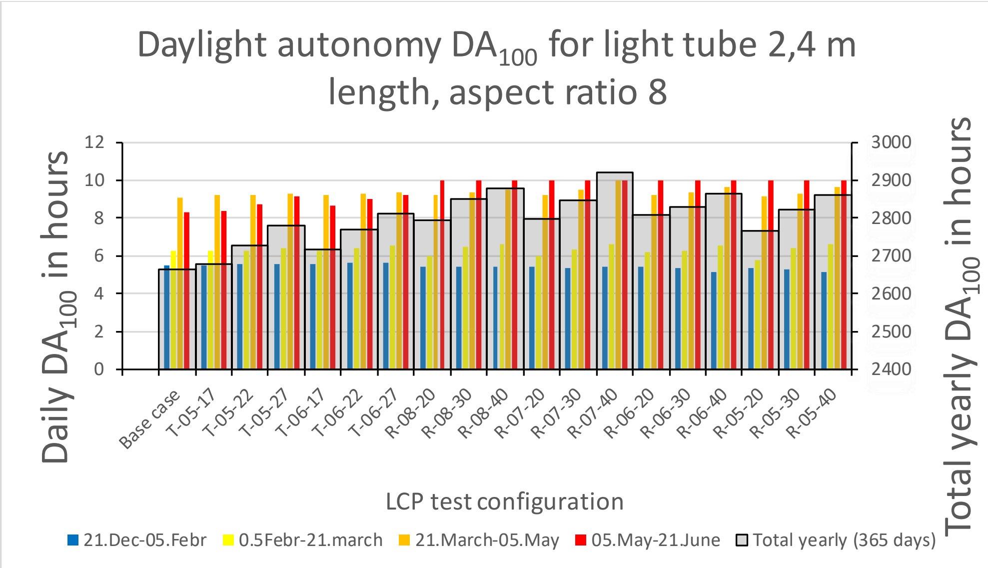

Figure 16. DA in hours for each LCP configuration when illuminance exceeds 100 lux on the reference surface, aspect ratio 8.

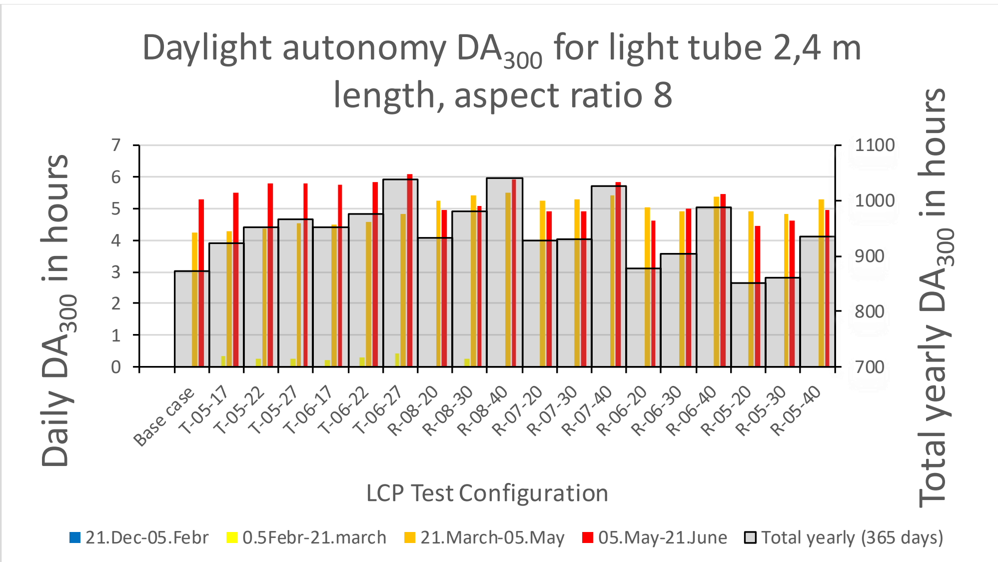

Figure 17. DA in hours for each LCP configuration when illuminance exceeds 300lux on the reference surface, aspect ratio 8.

The results for the tube with an aspect ratio of 16 show a similar tendency (Fig. 18 and 19). For DA_{100}, it is possible to expect 10 hours of daylight supplement during the summer using any of the rotated LCP configurations, which is one hour and 45 minutes longer than in the BaseCase. The total yearly improvement is most noticeable in the R-08-40 and R-07-40 configurations, with up to 8.75% each. For DA_{300}, the highest improvement in total yearly hours is noticeable for T-06-27, R-08-40, and R-07-40, with up to 16%. Meanwhile, T-06-27 especially enables longer visible DA_{300} during the early spring. A reduction similar to that with the aspect ratio of 8 is noticeable for configurations R-05-40, R-05-30, R-06-40, and R-06-30, to which they contribute during the late spring but prevent during the summer.

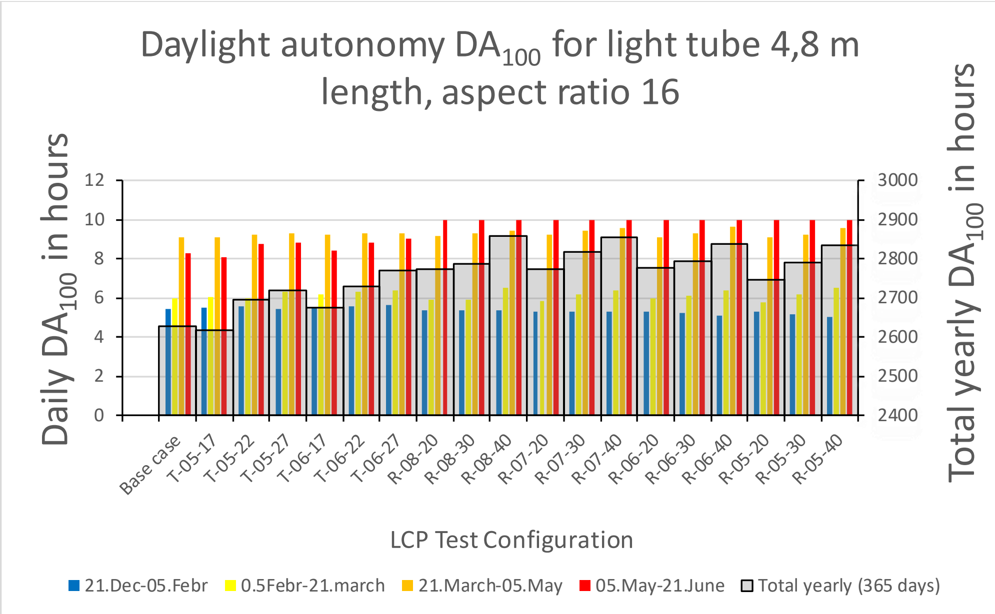

Figure 18. DA in hours for each LCP configuration when illuminance exceeds 100 lux on the reference surface, aspect ratio 16.

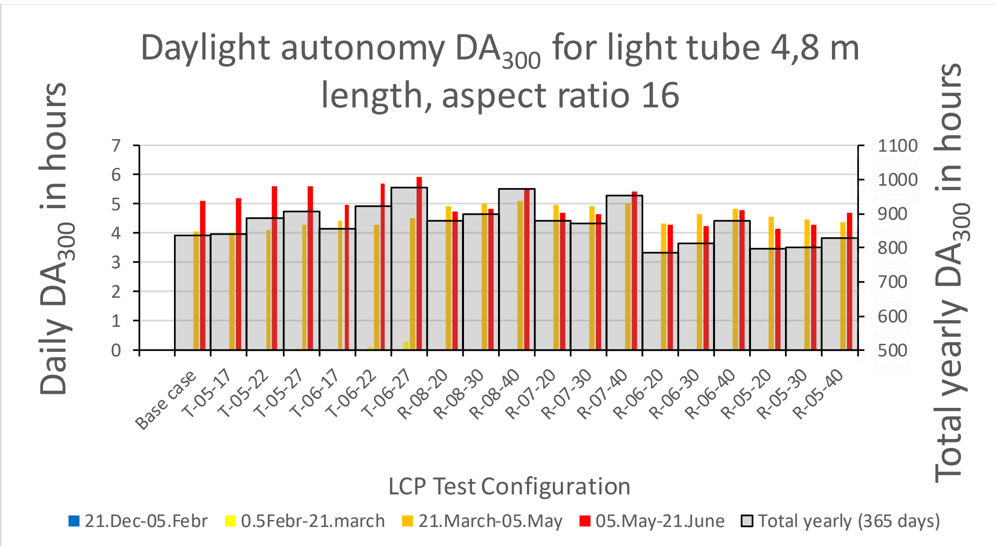

Figure 19. DA in hours for each LCP configuration when illuminance exceeds 300 lux on the reference surface, aspect ratio 16.

An analysis of the total yearly DA hours between a light pipe with an aspect ratio 8 versus 16 shows that there is a reduction in the number of hours for about 6%. This information can be useful for a simple estimation of DA for pipes even longer than 4.8 m. The daily DA_{100} in hours still shows the possibility of 10 hours of 100 lux at a 4.5m distance from the façade wall during the summer period. DA_{300} will be achieved for almost six hours during the same period. The total yearly DA_{300} for LCP configuration T-06-27 shows that the daylight requirements of the working place 4.5 m from the façade are fulfilled for 976 hours.

Tilted-LCP configurations should deflect high-altitude light well, which can take place during the summer at noon. This effect is noticeable in the results of Er, but, since all the LCP configurations give equal DA for the number of hours during the summer, the improvement is not as distinguishable as during the winter period. In the winter period, the portion of the diffuse light is much higher (in total) than the portion of the direct light; the fact that illuminance (either diffuse light in artificial sky or diffuse light from the Satel-Light) is increasing with altitude is reflected in the results.

The rotating LCP configurations give no indication of improvement during the winter, which was expected, and they also show a decrease during the early spring when compared with the BaseCase. An increase in DA hours for the R LCP is noticeable during the late spring and summer, which are associated with wide azimuth incident angles, but it appears that the D/W of the LCP is steering the potential.

Even the base base of the horizontal light pipe without any LCP on the entrance enables a minimum of five hours of 300 lux illuminance for both the 8 and 16 aspect ratios. The aspect ratio of 16 especially corresponds to the area where a window does not provide enough daylighting and electrical lighting needs to be used during all occupancy hours.

7. Discussion

User-controlled sun-shading devices are often the cause of a radical reduction in daylight availability during the day, with daylight contribution through the window then being very much dependent on the weather conditions and single-user behaviour. In general, users react instantly based on discomfort (glare or overheating) by closing sun-shading devices and are not that eager to open them again, which results in a much lower use of daylight than is theoretically possible. Automatically controlled sun-shading devices cause large and unpredictable changes in the luminous environment via switching between light and darkness. This paper shows that using a horizontal light pipe with a LCP can increase daylight autonomy in the indoor space of an office building and improve the reliability of daylight. More reliable daylighting in the indoor space will increase visual comfort and user satisfaction. In the mornings, daylight levels could be higher compared to a room with a side window. The highest improvement can be noted in the summer, and with the coincidence of the glare and thermal-load occurrence. The benefit of supplying the inner space with natural lighting becomes even more significant during the time when daylighting is drastically reduced by sunscreens.

It was discovered through the T and R LCP configurations tests that almost all T configurations work well with an overcast sky and R LCP configurations work well with sunlight. This fact could be used to design LCP configurations for north-oriented horizontal tubes. The portion of diffuse light on the north-oriented façade is undoubtedly higher in comparison to direct light, but direct light does still occur in the early mornings and evenings during the summer (Oslo, 59°N). Direct light on the north façade can appear when it is not needed (for commercial functions), but it can be quite appreciated during nightshift activity in industrial buildings. The T LCP configurations that show the highest improvements in diffuse light transmittance through the tube, (η), could be used to improve the performance of horizontal daylight tubes on the north facade. For the east and west oriented facades, a combination of tilted (T) LCPs against the north and rotated (R) LCPs against the south could be a successful solution, but this needs to be further tested.

By applying one single fixed solution, the full theoretical potential of LCP configurations cannot be utilized, but the possibility of the passive (user-operated) steering of the LC panel by rotating it along the tube's circumference could lead to greater DA improvements than that presented in this study. A season-dependent adjustment could be also applied.

As daylighting through the side window drastically decreases with distance from the facade, the extremely uneven lighting level affects the threshold sensitivity of the light controlling system and the possibility of reducing artificial lighting to conserve energy. This paper shows how the daylight level deeper in the space can be increased and produce balance across the entire room, which will also give more reliable data to light sensors and ensure lower energy use. The study demonstrates an improvement of 10% for DA_{100} and 19% for DA_{300} for the aspect ratio of 8, while 8.75% for DA_{100} and 16% for DA_{300} for the aspect ratio of 16 are shown on a yearly basis when compared to the BaseCase.

Limitations of the experiment included the following: the LCP samples were not perfectly cut due to the laser-cutter technology resulting in cuts with a chamfer on the LCP's frontside. There was also a possibility that some of the measurements had systematic errors caused by the manual handling of the model and LCP samples.

Also, a diffuse luminance distribution under the real sky, which depends on sun position and cloudiness, is different from the luminance distribution of diffuse light under an artificial sky at the Daylight laboratory at NTNU, which is a static simulator of a standard CIE overcast sky with a 1:3 luminance ratio (horizon:zenith) and rotational symmetry. To combine the standard daylight guide characteristics ($\boldsymbol{\eta}$) for diffuse light measured under the artificial sky with diffuse illuminance from Satel-Light is a simplification. Still, we posit that this simplification can be defended because it gives conservative rather than overoptimistic DA results. The CIE model of the overcast sky represents the worst case of luminance distribution compared to the blue sky with sun, which features a very bright area around the sun (called the corona). The light from the corona, which is included in the diffuse illuminance from Satel-Light, will behave quite similarly to the light from the sun, because the incidence angle of light from corona is close to the incidence angle of the light from the sun. The scenarios that function well with the direct light from sunlight will perform even better than presented in this study due to the additional contribution from the corona if the sky is clear around the sun (compared to the CIE-overcast sky). This means that improvements due to the diffuse light will be higher for the clear sky with sun than for the CIE overcast sky in the best scenarios.

8. Conclusion

This paper shows how the illuminance levels inside the room at a 2,1m and 4,5m distance from the façade can be increased by daylight being transported through a horizontal light pipe equipped with a static light deflecting panel, LCP, at the pipe's entrance. Two types of the LCPs were considered, T - tilted with horizontal cuts and R - rotated with vertical cuts

The study shows that a horizontal light pipe, even without any LCP on the entrance, makes a significant positive contribution to daylighting, and that T LCPs work best under an overcast sky and R LCPs work well with sunlight.

Tilted LCPs with horizontal cuts effectively deflect light of higher altitudes and increase light transmittance ($\boldsymbol{\eta}$) of the tube, but this is mostly significant during the winter, when most of the light is diffuse. In the buildings where winter daylighting is highly appreciated for health and wellbeing, as in healthcare facilities or in schools, the tilted LCPs with horizontal cuts could be a very valuable application.

During the summer, the light flux transported through the tube equipped with tilted LCPs was significantly higher than the minimum required illuminance at the tube exit, which indicates that the light could be conveyed at a longer distance.

Two symmetrically rotated LCPs with vertical cuts increase the light transmittance (***η***) of the tube for morning and evening light especially during the summer. As such, they could be even more attractive for buildings used also during evening. R LCPs showed no improvement in DA_{100} or DA_{300} during the winter.

The analysis of total yearly DA hours with minimum 100 lx (DA_{100}) shows similar results for both aspect ratios (8 and 16). The R-LCP configuration with a 40° rotation makes the highest improvement (up to 10% for aspect ratio 8). The improvement is mostly noticeable during the summer months, where the DA is prolonged by nearly two hours a day.

The analysis of the total yearly DA hours with minimum 300 lx (DA_{300}) for both aspect ratios shows that an increase of up to 19% is possible. The highest improvement (1 hour and 20 minutes a day for the 8 aspect ratio) happens during the late spring.

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Contributions: B.O. conceived and wrote the study; B.M. helped define the scope of the study and the methodology, gave feedback on the content of the paper, and contributed by performing quality assurance and proofreading.

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Appendix A: Standard daylight characteristic of LCP configuration for the direct vertical illuminance *ηdirect(T-R) = Edirect(T-R) / Edirect(ZERO)*

Table A.1 ***η*** BaseCase

50	0	0	0	0	0.68	0.83	0.85						
45	0	0	0.70	0.76	0.91	0.90	0.81						
35	0	0.35	0.84	1.00	0.85	0.87	0.83						
25	0.15	0.62	0.79	0.75	0.76	0.82	0.91						
15	0.36	0.61	0.74	1.07	0.96	0.94	0.87						
5	0.87	0.94	1.14	1.07	0.76	0.79	0.91						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.2 ***η*** T-05-17

50	0	0	0	0	0.75	0.83	0.93						
45	0	0	0.90	0.79	0.84	0.8	0.89						
35	0	0.53	0.76	0.87	0.78	0.89	0.88						
25	2.19	0.61	0.74	0.70	0.77	0.76	0.88						
15	2.44	0.66	0.68	0.96	0.88	0.89	0.82						
5	7.76	0.72	0.81	0.99	0.68	0.76	0.88						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.3 ***η*** T-05-22

50	0	0	0	0	0.76	0.87	0.96						
45	0	0	0.88	0.87	0.83	0.78	0.89						
35	0	0.56	0.78	0.88	0.79	0.89	0.87						
25	1.70	0.67	0.76	0.71	0.76	0.76	0.80						
15	2.45	0.69	0.69	0.88	0.86	0.85	0.79						
5	6.81	0.75	0.80	0.96	0.66	0.74	0.82						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.4 ***η*** T-05-27

50	0	0	0	0	0.73	0.88	1.00						
45	0	0	0.76	0.82	0.9	0.87	0.96						
35	0	0.52	0.74	0.87	0.79	0.84	0.9						
25	2.13	0.67	0.78	0.72	0.75	0.74	0.76						
15	2.24	0.72	0.71	0.93	0.85	0.81	0.76						
5	6.49	0.79	0.81	0.95	0.64	0.70	0.76						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.5 ***η*** T-06-17

50	0	0	0	0	0.77	0.9	0.97						
45	0	0	0.87	0.90	0.86	0.98	0.93						
35	0	0.57	0.80	0.89	0.79	0.88	0.87						
25	1.94	0.6	0.75	0.72	0.76	0.75	0.74						
15	1.97	0.64	0.68	0.96	0.91	0.82	0.84						
5	5.97	0.70	0.81	0.99	0.69	0.78	0.86						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.6 ***η*** T-06-22

50	0	0	0	0	0.77	0.85	1.0						
45	0	0	0.8	0.78	0.89	0.87	0.9						
35	0	0.55	0.76	0.87	0.77	0.87	0.87						
25	1.59	0.64	0.77	0.73	0.78	0.77	0.72						
15	1.88	0.68	0.68	0.95	0.9	0.79	0.8						
5	5.63	0.74	0.82	0.96	0.66	0.74	0.81						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.7 ***η*** T-06-27

50	0	0	0	0	0.77	0.89	0.95						
45	0	0	0.93	0.85	0.89	0.87	0.9						
35	0	0.8	0.76	0.87	0.77	0.88	0.83						
25	1.91	0.64	0.77	0.83	0.81	0.77	0.72						
15	1.88	0.77	0.74	0.95	0.9	0.79	0.8						
5	7.9	0.74	0.82	0.96	0.68	0.76	0.74						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.8 ***η*** R-08-20

50	0	0	0	0	0.63	0.71	0.73						
45	0	0	0.9	0.75	0.74	0.65	0.68						
35	0	0.88	0.73	0.78	0.71	0.81	0.81						
25	21.55	0.93	0.79	0.64	0.76	0.77	0.69						
15	43.30	0.96	0.67	0.89	0.95	0.83	0.83						
5	59.03	1.26	0.93	0.99	0.69	0.83	0.95						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.9 ***η*** R-08-30

50	0	0	0	0	0.67	0.72	0.72						
45	0	0	1.01	0.78	0.74	0.65	0.68						
35	0	1.5	0.73	0.78	0.71	0.82	0.74						
25	51.91	0.93	0.79	0.79	0.84	0.77	0.69						
15	43.30	1.35	0.88	0.89	0.95	0.83	0.83						
5	92.59	1.26	0.93	0.99	0.67	0.86	0.84						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.10 ***η*** R-08-40

50	0	0	0	0	0.70	0.70	0.83						
45	0	0	1.02	0.8	0.74	0.65	0.68						
35	0	1.73	0.73	0.78	0.71	0.72	0.62						
25	84.34	0.93	0.79	0.82	0.71	0.77	0.69						
15	43.30	1.76	0.95	0.89	0.95	0.83	0.83						
5	151.72	1.26	0.93	0.99	0.61	0.69	0.64						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.11 ***η*** R-07-20

50	0	0	0	0	0.56	0.63	0.73						
45	0	0	0.77	0.69	0.74	0.65	0.68						
35	0	0.87	0.83	0.74	0.74	0.80	0.80						
25	30.82	0.81	0.81	0.63	0.76	0.75	0.67						
15	32.20	1.14	0.66	0.87	0.83	0.82	0.82						
5	51.65	1.19	1.11	0.95	0.68	0.83	0.92						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.12 ***η*** R-07-30

50	0	0	0	0	0.59	0.67	0.70						
45	0	0	0.76	0.71	0.69	0.65	0.66						
35	0	1.27	0.80	0.76	0.68	0.75	0.74						
25	35.85	1.11	0.95	0.65	0.69	0.69	0.59						
15	61.17	1.51	0.79	0.94	0.75	0.77	0.77						
5	100.31	1.42	0.97	0.90	0.60	0.72	0.81						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.13 ***η*** R-07-40

50	0	0	0	0	0.66	0.72	0.64						
45	0	0	1.22	0.82	0.69	0.65	0.66						
35	0	1.75	0.8	0.76	0.68	0.69	0.63						
25	83.04	1.11	0.95	0.81	0.72	0.69	0.59						
15	61.17	1.9	0.94	0.94	0.75	0.77	0.77						
5	157.44	1.42	0.97	0.90	0.61	0.65	0.64						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.14 ***η*** R-06-20

50	0	0	0	0	0.59	0.67	0.71						
45	0	0	0.65	0.67	0.65	0.65	0.70						
35	0	0.86	0.78	0.73	0.69	0.79	0.78						
25	25.13	1.01	0.76	0.64	0.73	0.72	0.65						
15	25.47	0.97	0.68	1.02	0.92	0.80	0.85						
5	63.86	1.07	0.89	0.66	0.71	0.84	0.87						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.15 ***η*** R-06-30

50	0	0	0	0	0.58	0.61	0.67						
45	0	0	0.83	0.71	0.61	0.61	0.65						
35	0	1.26	0.86	0.68	0.61	0.71	0.74						
25	40.57	1.39	0.84	0.63	0.68	0.68	0.62						

15	51.29	1.33	0.75	0.91	0.79	0.72	0.80						
5	101.47	1.52	0.99	0.88	0.65	0.73	0.80						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.16 ***η*** R-06-40

50	0	0	0	0	0.60	0.58	0.56						
45	0	0	0.88	0.77	0.70	0.54	0.51						
35	0	1.60	0.87	0.80	0.64	0.61	0.58						
25	62.59	1.53	0.97	0.69	0.64	0.60	0.43						
15	80.32	2.02	0,90	0.97	0.81	0.58	0.64						
5	167.97	2.31	0.99	0.87	0.58	0.56	0.56						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.17 ***η*** R-05-20

50	0	0	0	0	0.52	0.64	0.67						
45	0	0	0.95	0.71	0.62	0.56	0.59						
35	0	1.12	0.81	0.67	0.65	0.65	0.67						
25	25.2	0.81	0.72	0.67	0.70	0.69	0.62						
15	24.67	0.92	0.67	0.90	0.81	0.75	0.86						
5	61.54	1.19	0.83	0.90	0.72	0.82	0.84						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.18 ***η*** R-05-30

50	0	0	0	0	0.57	0.57	0.63						
45	0	0	0.65	0.66	0.63	0.65	0.66						
35	0	0.79	0.85	0.70	0.69	0.75	0.75						
25	37.56	1.30	0.70	0.63	0.66	0.69	0.59						
15	39.88	1.35	0.8	0.99	0.79	0.65	0.79						
5	111.03	1.71	1.08	0.89	0.65	0.75	0.78						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Table A.19 ***η*** R-05-40

50	0	0	0	0	0.59	0.55	0.54						
45	0	0	0.87	0.74	0.69	0.52	0.52						
35	0	1.49	0.94	0.77	0.66	0.58	0.52						
25	48.8	1.65	0.9	0.69	0.64	0.52	0.45						
15	56.71	1.94	0.96	0.98	0.78	0.54	0.64						
5	168.92	2.12	1.00	0.92	0.6	0.55	0.54						
	90	105	120	135	150	165	180	195	210	225	240	255	270

Appendix B: Standard daylight characteristic of LCP configuration for diffuse vertical illuminance *ηdiffuse(T-R) = Ediffuse(T-R) / Ediffuse(ZERO)*

Table B.1 *ηdifusef(T-R)*

LCP configurations	*η*
BaseCase	0.85
T-05-17	0.93
T-05-22	1.00
T-05-27	1.06
T-06-17	1.00
T-06-22	1.07
T-06-27	1.12
R-08-20	0.83
R-08-30	0.86
R-80-40	0.88
R-07-20	0.84
R-07-30	0.87
R-07-40	0.88
R-06-20	0.82
R-06-30	0.85
R-06-40	0.87
R-05-20	0.81
R-05-30	0.85
R-05-40	0.87

Appendix C: Parametric laboratory study at the Daylight laboratory at NTNU

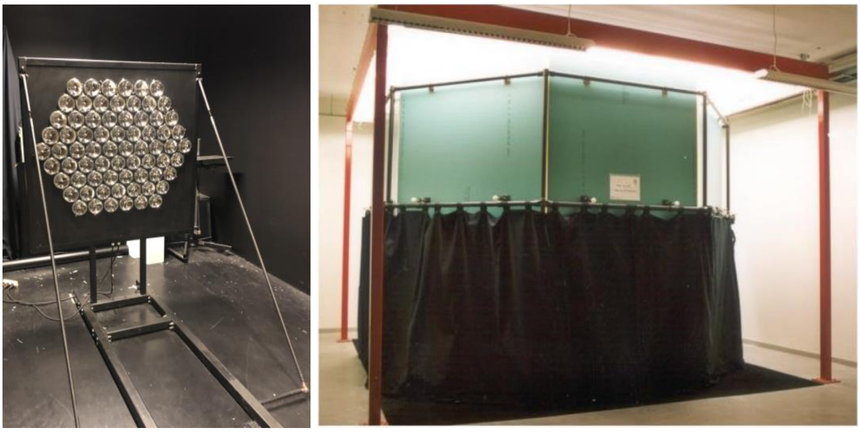

Figure C1. (Left) Artificial sun composed of 70 halogen lamps with parabolic reflectors (50W) fixed to a vertical metal plate and arranged in a hexagonal pattern; (right) artificial overcast sky in the form of octagonal mirror box

Figure C2. Model setup in the laboratory study with direct light (left) and diffuse light (right)

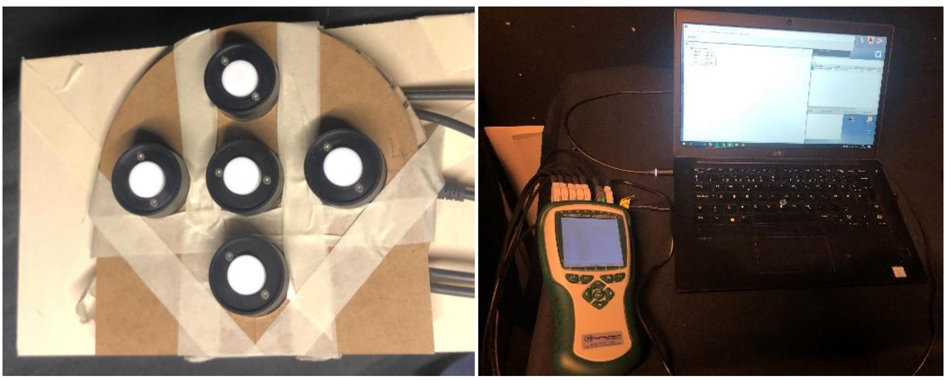

Figure C3. (left) Measurement instrument Almemo Ahlborn, with photosensors fixed on a circular plate and placed at the tube's exit; (right) logging of measuring data via Ahlborn Almemo logger and Almemo control 6.0 software

Figure C4 Laser-Cut panel T sample for tilt probe

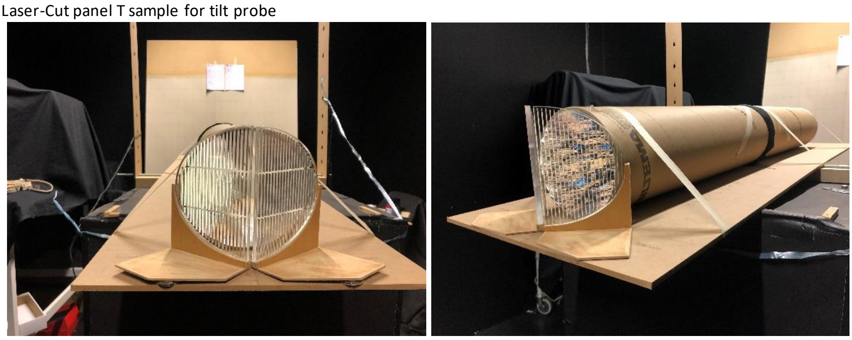

Figure C5 Lase-Cut panel R sample for rotated probe

Appendix D: Uniformity of the direct light from the artificial sun at the Daylight laboratory at NTNU

Table D.1. Uniformity of the direct light from the artificial sun for the direct light experimental test

altitude							
50°					0.93	0.95	0.95
45°				0.92	0.94	0.97	0.96
35°		0.85	0.91	0.94	0.96	0.97	0.97
25°		0.89	0.93	0.96	0.97	0.97	0.98
15°		0.88	0.95	0.96	0.94	0.98	0.98
5°		0.89	0.99	0.96	0.98	0.97	0.98
azimuth	90°	105°	120°	135°	150°	165°	180°

Method Article

A customised method for estimating light transmission efficiency of the horizontal light pipe via a temporal parameter with an example application using laser-cut panels as a collector

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ABSTRACT

The purpose of the study presented in this paper was to develop a customized method for estimating the transmission efficiency of a horizontal light pipe (HLP). The proposal is based on the established method and customized to encompass real incident daylight that horizontal light pipes could collect. Natural incident light is introduced using both direct and diffuse light sources through the temporal parameter of their altitude and azimuth. The temporal parameter is presented as a matrix model consisting of solar altitude and azimuth used in measurement and analysis. Because each location on Earth is characterized by a unique solar altitude and azimuth during the year, the proposed method establishes the measuring template, based on a specific location on Earth and applicable for the HLP. The methodology is supplemented with a theoretical model of an indoor space equipped with an HLP that can be used to analyse data and validate necessary threshold illuminance under real physical conditions. An example of an application of the customized method is demonstrated using a case of light collectors for the HLP light-deflecting panels, the laser-cut panel (LCP).

- *A method for predicting the transmission efficiency of the HLP for any location and any orientation on a building's façade.*
- *Estimation of transmission efficiency for the HLP implementing a temporal parameter through solar altitude and azimuth.*
- *Resulting data for transmission efficiency for the HLP using a template that is easily applicable for decision-making during a specific period of the year, season or the entire year.*

SPECIFICATIONS

Subject Area	Engineering
More specific subject area	*Improving daylighting techniques and technology to increase the energy efficiency of buildings and enhance daylighting in indoor space for health and wellbeing*
Method name	*Photometry method for horizontal light pipes and components, addressing real daylight condition;*
Name and reference of original method	''Method of photometry of Tubular Daylight Guidance systems and components'' in CIE Technical report 173:2012 Tubular daylight guidance systems
Resource availability	*Daylight Laboratory at NTNU, Department of Architecture and Technology; Satel-Light database at* http://www.satel-light.com/

Nomenclature

η - Light transmission efficiency

$\eta_{Light\ Guide}$, - light transmission efficiency for a light guide (light pipe)

$\eta_{Collector}$, - light transmission efficiency for a light collector

$\eta_{Diffuser}$, - light transmission efficiency for a light diffuser

Φ_o - light flux at the light pipe's entrance, lumen

Φ_1 - light flux at the light pipe's exit, lumen

Φ_2 - light flux at the light pipe's exit, pipe has collector or diffuser, lumen

E_{direct}(ZERO), $E_{diffuse}$(ZERO) - Direct or diffuse measured illuminance at the tube's entrance, lux

E_{direct}(BaseCase), $E_{diffuse}$(BaseCase) - Direct or diffuse measured illuminance at the tube's exit, lux

η_{direct}, $\eta_{diffuse}$ – Transmission efficiency for direct or diffuse light

Es_{direct}, $Es_{diffuse}$ - Direct or diffuse illuminance on a vertical south façade developed from the Satel-Light, lux

Er_{direct}, $Er_{diffuse}$ - Direct or diffuse real expected illuminance at the tube's exit, lux

Er_{total} - Total real expected illuminance at the tube's exit, lux

Al, Az - Solar altitude and azimuth, degrees

Background

A review of the literature on daylight transport systems (DTS) revealed that light pipes could reduce the energy used for electrical lighting in commercial buildings at high latitudes by up to 30% (Courret et al., 1998; Garcia Hansen and Edmonds, 2003; Kwok and Chung, 2008; Mayhoub, 2011). In particular, horizontal daylight tubes mounted in the ceiling plenum have been promoted as a successful solution for a deeper daylighting supplement in multi-storey commercial buildings in locations far north or south (Obradovic and Matusiak, 2019). Horizontally-mounted daylight tubes, unlike vertical light tubes, have a limited possibility to receive light from the zenithal part of the sky and will primarily base its light transmission efficiency on direct light from the sun. Locations far north or south are characterized by low solar altitude. Because the sun's position varies throughout the day, from morning in the east to evening in the west, the efficacy of the horizontal light tube varies in its ability to reach the maximum when light rays are aligned to the tube's longitudinal axis (central axis of light transmission). For buildings at high northern latitudes, the most successful orientation for horizontal tubes is to the south; this orientation coincides with the sun's longest exposure during the year (in winter the sunlight is accessible only from the south).

Light pipes are tubular hollow elements that can be layered with mirror folium, aluminium or silver. The tubes have a reflectivity (R) up to 99%. Light rays with an axillary incident angle, where light rays go straight along the pipe and do not inter-reflect with the pipe's internal surface, contribute the most to the efficiency of light transmission. Any deviation from the axillary incidence angle increases the number of interreflections, and the total light transmittance of the pipe decreases because the inner surface is not 100% reflective. That effect also means that light rays coming from the side, as with morning and evening sun rays for a south-oriented pipe, will intersect the tube entrance at sharp angles and produce numerous interreflections.

The method for estimating horizontal light pipe's efficiency has not been the focus of research in the field of daylighting. Several attempts to find an appropriate and precise method for calculation of light pipe efficiency have been made. However, all of the studies concluded with methods that considered static situations, either a large diffuse light source or a single light incident ray (Zhang, 2002; Zhang and Muneer, 2000; Zhang et al., 2002). The Commission Internationale de l'E´clairage's (CIE) Technical report ''Tubular Daylight Guidance Systems'' (CIE, 2012), includes methods to estimate light transmission efficiency only for vertical light pipes. As discussed, the most incident light to the vertical light pipes comes at the zenith. Consequently, the method assumed incident light from a large light source and relies on a specific minimum luminance of the sky (CIE, 2012). In this case, it was the CIE standard overcast sky with a luminance ratio of 3:1 from zenith to the horizon (Kittler et al., 1998). This ratio means there is much less diffuse light entering the horizontal pipe than the vertical pipe. This reduced light is the reason why the overall efficiency of the horizontal light pipes, compared to vertical pipes, is low. A result that relied just on an overcast sky induced a lack of interest in the horizontal position for the further research.

Nevertheless, the efficiency of horizontal light pipes may depend more on direct sunlight than on diffuse light from the sky. This is because the entrance to the tube can be directly exposed to low sunlight and result in much higher illuminance than any diffuse skylight can achieve. This higher illuminance aligned with the HLP is the case in the high latitudes of the northern or southern hemispheres.

The incident angle of the incoming light is defined by the sun's azimuth and altitude angles (Al and Az), which can be used as variables describing the temporal parameter. While the original method for estimating transmission did not consider time, the customized method is based on the time of day and the time of year.

The most common way to make a calculation for a period of time was using a simulation in which the period was the critical parameter, and the results showed the ''temporal behaviour'' of a ''tested system.'' In the last three decades, there have been few studies of horizontal light pipes. Some of them were published under the title ''simulations''. They only considered sunlight at a specific altitude/azimuth. No climate-based simulations that encompass the entire year or a specific period during the year have been conducted. The studies were conducted using either Radiance or Trace pro as the light calculation engine, and the model laser-cut panels (LCP) and horizontal light pipes (HLP) previously developed in either CAD (Kwok and Chung, 2008), Solidworks (Singh et al., 2020) or mathematical algorithms (Greenup et al., 2000; Labib, 2013). They resulted in data for a single day or a single sun position. The result was also reflected in the potential for improved daylighting and possible energy savings. However, none of the studies included calculations for an entire year. The likely reason for this was that such a simulation is time-consuming due to the huge number of light rays. Some latest studies considered laboratory scale model or model ''in situ'' for daylight estimation.

This paper aimed to fill the gap in the development of methodology for estimation of transmission efficacy of horizontal light pipes, and it is written based on a recently performed research study by the same authors ((Obradovic and Matusiak, 2020). The methodology proposed here can be used to estimate the efficiency of HLP with any entrance orientation. The same method can be used if the research aims to evaluate the efficiency of any custom-made collector that is sensitive to the incident sun angle, such as the LCP, Fresnel lens or anidolic collector. In addition, it shows how the obtained result should be used further to develop realistic data, that would be possible to expect in a repeatable full-scale study. The model for the resulting data can be easily applied to a period or the entire year.

The original CIE method is summarized in Section 1, while the customized approach is presented in Section 2. Since the result of such parametric laboratory study is limited to raw data on light transmission efficiency for direct as well as diffuse light conditions, it was necessary to connect them to the realistic daylight values. For this purpose, the information on diffuse and direct illuminance values from the Satel-light database was used. The original study used Oslo, Norway, as a test location. Section 3 presents the developed of the Satel Light data based on that location. Development of the real data is presented in Section 4. Section 5 describes the application of the real data via a theoretic model of an office space. Section 6 presents an example of a customized method for light transmission efficiency of the LCP as a light collector for the HLP. The protocol presented in this paper was developed through the original research study intended to demonstrate improvements to daylight autonomy using HLP and LCP for buildings in high latitudes (Obradovic and Matusiak, 2020). The protocol is described in a flowchart presented in Figure 1.

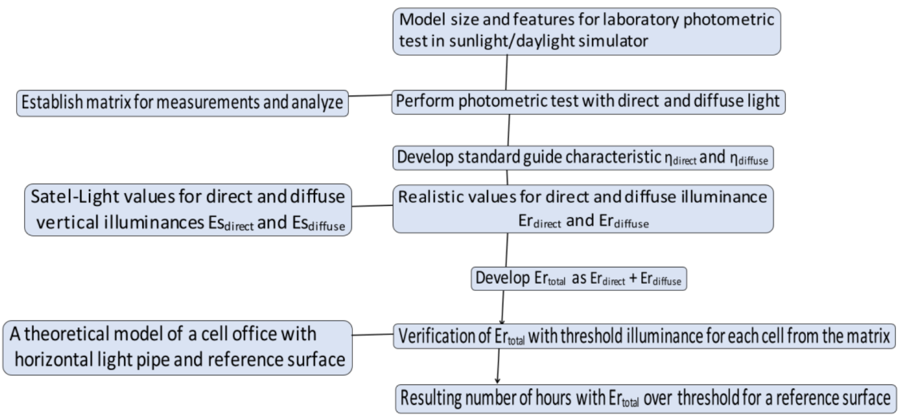

Figure 1. Flowchart for the proposed method with the protocol for estimating light transmission efficiency to the applicable real result.

1. The existing method for calculating the light transmission efficiency of light pipes

The CIE 173:2012 technical report: *Tubular Daylight Guidance Systems* presented an approach to determine light transmittance efficiency (η) for vertical light pipes (CIE, 2012). The photometric estimate can be made using a scale model of the light pipe, accompanied by a collector or diffuser, if desirable. The estimation method is described as ''a ratio of luminous flux at the tube's exit and luminous flux at the tube's entrance,'' (Eq. 1) in which illumination is provided by ''the diffuse light source placed near the tube's input window'' (Figure 2). The Φ_o represents the input illuminance, and Φ_{1out} represents exit illuminance. The light source is taken as a diffuse illuminance, coming from the zenithal sky (CIE overcast sky). The measuring protocol starts with the reference measurement and continues with the test measurement. The parameter that is evaluated is variated; in the case of tube length, the variable parameter is the length of the tube (Figure 2). In the case of the collector or diffusor efficiency, the reference measurements are made with no collector or diffusor, while the test measurement has the collector or diffusor (Figures 3 and 4). The transmission efficiency (η) for a specific pipe length is the ratio of outgoing illuminance and input illuminance for all assessed lengths (Eq. 1). For the transmission efficiency ($\eta_{Collector}$, $\eta_{Diffuser}$) of a light pipe equipped with collector or diffuser, the ratio is between the outgoing illuminance with the collector (diffuser) and outgoing illuminance without the collector (Eq. 2 and Eq. 3).

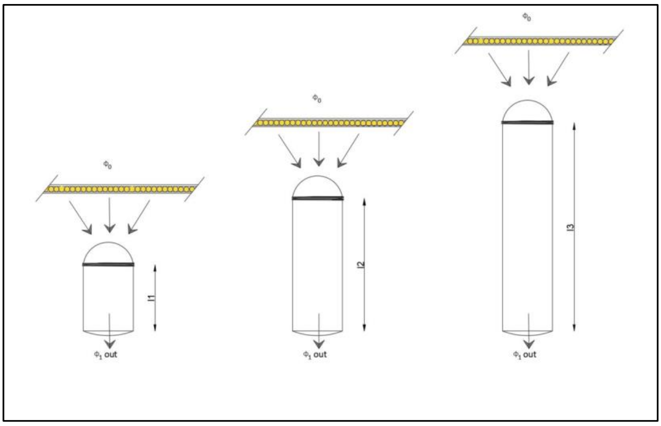

Figure 2. Light guide efficiency, adopted from (CIE, 2012), permission granted from CIE.

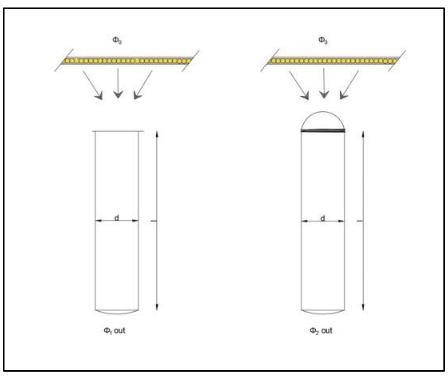

Figure 3. Collector efficiency, adopted from (CIE, 2012), permission granted from CIE.

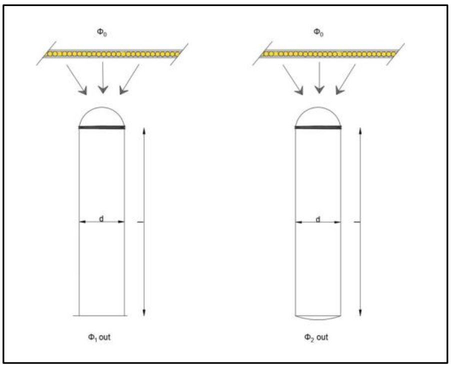

Figure 4. Output device (diffuser) efficiency, adopted from (CIE, 2012), permission granted from CIE.

$$\eta_{Light\ Guide} = \frac{\phi_1 out}{\phi_0} \times \frac{1}{\eta_{Collector}} \quad (1)$$

$$\eta_{Collector} = \frac{\phi_2\ out}{\phi_1\ out} \quad (2)$$

$$\eta_{Diffuser} = \frac{\phi_2\ out}{\phi_1\ out} \quad (3)$$

2. A customized method for calculating the light transmission efficacy of horizontal light pipes

Purpose of developing this customized method is to broaden the application of existing method on a horizontal light pipe, and to encompass all daylight conditions. The customized method is a laboratory measurement in Daylight simulator, where, two light sources are used to simulate the sun, and sky, separately. The efficiency of a horizontally-mounted light pipe is, as previously explained, in much higher extend influenced by the direct light coming from the sun than by diffuse light. The relation to the diffuse incident light is static and occurs with overcast skies or with diffuse (exterior and atmosphere reflected) light rays originating from direct sunlight. The light conditions that determine the light transmission efficiency of the HLP are variable; therefore, it is essential to verify efficacy using the full palette of light conditions. Variable light conditions can also be established using a temporal parameter because both direct and diffuse light conditions change with the time of the day and time of year. The proposed customized method considers lighting conditions using a temporally-related altitude-azimuth matrix. The method for developing the altitude-azimuth matrix is explained in Section 2a. The demands of the scale model study in the sunlight/daylight simulator facilities are presented in Section 2b. The protocol for the photometric measurement and methodology for the development of standard transmission efficiency for an HLP is described in Section 2c.

a) Development of temporal template using a matrix of altitude and azimuth

Photometric measurements must encompass a temporal parameter that is in direct relation to the sun's altitude and azimuth; they are used to establish the matrix also used as a template in photometric measurements. The protocol is based on an HLP oriented to the south; however, the protocol applies to any light pipe orientation (e.g., east and west or an orientation to the north for the southern hemisphere). Because the matrix points represent testing positions, they must be easy to retrieve under laboratory conditions. As shown in Figure 5, the testing position is chosen by developing analysis periods based on typical days in the year. For the summer and winter, it is taken the start/end date. The spring and autumn periods have similar solar altitudes and are divided into two periods, early spring corresponding to late autumn, and late spring corresponding to early autumn. This division is done to increase precision because the variations in altitude through spring/autumn are larger than summer/winter. Figure 5 shows the solar chart for a specific location (Oslo, Norway) from the original study (Obradovic and Matusiak, 2020) and a matrix of points, each representing 5/10° of the sun's altitude and 15° of the sun's azimuth. The matrix of the solar altitude and azimuth angles was developed by dividing the field of solar incident angles into as many planes as necessary to establish enough points of time. The outermost azimuth angles, 90° and 270° were based on the vertical cut-off of the south façade and the user-occupancy hours.

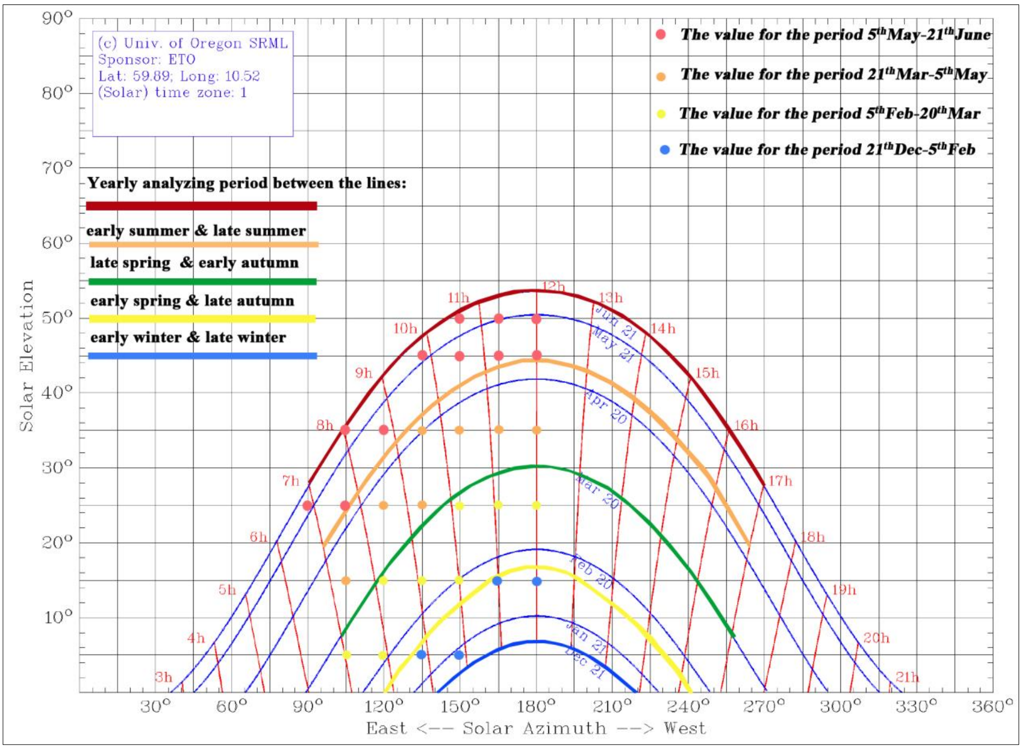

Figure 5. Solar chart for Oslo, Norway (59°53' N, 10°31' E) with typical periods used in the analysis and a testing position corresponding to the testing matrix (SRML, 2019). Test points in colour represent typical analysis periods during the year: red-summer, orange-late spring or early autumn, yellow-early spring or late spring and blue-winter.

Due to the complexity and the size of the model, when the method was first demonstrated, altitude 55°, which corresponded best to the highest altitude in Oslo (53°), could not be applied. Instead, the measurements were made at 50° (see Table 1). Test points in colour represent the typical analysis periods of the year: red-summer, orange-late spring or early autumn, yellow-early spring or late autumn and blue-winter. In Figure 5, the depicted periods, with their characteristic altitude and azimuth, occur two times per year. It is, therefore, easy to develop data for just one period, summer or winter, by multiplying the period by two. The spring (or autumn) period was created by summing data for early and late spring. The total yearly result is developed by multiplying each typical period by the number of days in that period. There are four distinct periods in the year, each period being ¼ of the 365 days or 91.25 days. Each cell in the resulting template contains an illuminance value on the pipe exits (see Section 4). The original study, Obradovic and Matusiak (2020), proposed a theoretical model for the analysis of that value (see Section 5).

Table 1. Testing matrix for the parametric laboratory study referencing the solar chart for a south facade in Oslo, Norway. Test points in colour represent typical analysis period of the year: red-summer, orange-late spring or early autumn, yellow-early spring or late autumn and blue-winter (Obradovic and Matusiak, 2020).

50°					**50**	**50**	**50**	**50**	**50**				
45°				**45**	**45**	**45**	**45**	**45**	**45**	**45**			
35°		**35**	**35**	**35**	**35**	**35**	**35**	**35**	**35**	**35**	**35**	**35**	
25°	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**	**25**
15°		**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	
5°		**5**	**5**	**5**	**5**				**5**	**5**	**5**	**5**	
Altitude/ Azimuth	**90°**	**105°**	**120°**	**135°**	**150°**	**165°**	**180°**	195°	210°	225°	240°	255°	270°
								not tested, assumed to be equal to the left side					

b) Scale model and laboratory facilities for the parametric measurements

A scale model of the horizontal tube to be used for photometric measurements was constructed. The original study was conducted using a model HLP with an aspect ratio (length-to-diameter) of p = 1200/150 mm, 8. It represented a 1:2 scale model as the most suitable light pipe module for office buildings. The dimensions of the model were considered in relation to the dimensions of the light simulator in which the photometric analysis was performed. The original study used the Daylight Laboratory at NTNU, Department of Architecture and Technology. The static sunlight source was used for the direct light study and a mirror box with a luminous ceiling was used for the diffuse light study. The distance between the light source and the model (in this case, the entrance of the horizontal light pipe) was the critical parameter because of the potential for a serious parallax error.

The parallax issue was explained as incorrect incident light (luminance pattern) from a light source because of the size of the sunlight/daylight simulator compared to the scale model. In reality, any light source, either the sun or a sky dome, is distant and large. By contrast, any building (or a light pipe) is exceedingly small. This difference means that any opening/window in the actual building would receive equal light in intensity and direction. However, in the sunlight/daylight simulators, light rays from the sun are not perfectly parallel or of equal intensity at all openings or across one large opening in the model. Under laboratory conditions, one sunlight simulator will never be large enough to minimise the parallax issue. It is also possible to account for a dimension of a scale model that cannot be small enough to be compared with real conditions. On the other hand, the scale model must be large enough to retain the details essential for light simulation and photometric measurements (Cannon-Brookes, 1997). If the model's entrance to the pipe is too big, the entrance surface will not receive an equal intensity of ''parallel'' sunlight rays from a sunlight simulator. Therefore, it is important to ensure that the tube entrance will be located in the parallax-bounded volume with the highest predicted accuracy (+/-10%) (Mardaljevic, 2002).

The original study was conducted in the Daylight Laboratory at NTNU. The direct sunlight facility there is in the form of a static artificial sun. The artificial sun is composed of 70 halogen lamps with parabolic reflectors (50 W) fixed to a vertical metal plate and arranged in a hexagonal pattern. The artificial sun provides near-parallel light beams with a dispersion angle of 3°. It was situated in a corridor-like room, enabling sufficient distance from the sun to the model (Figure 6). The walls, ceiling, and floor were painted matte black to minimize interreflections in the room and minimize scattering light on the model. The model (light pipe) was positioned 7.5 m from the artificial sun, ensuring even illumination. The uniformity of the light from the artificial sun on the tube's entrance, measured perpendicular to the sun, was 98%. The data were taken from measurements for the reference values, for altitude 5° and azimuth 180°. The model was secured to a box one meter high so that the height of the tube's entrance matched the centre of the artificial sun.

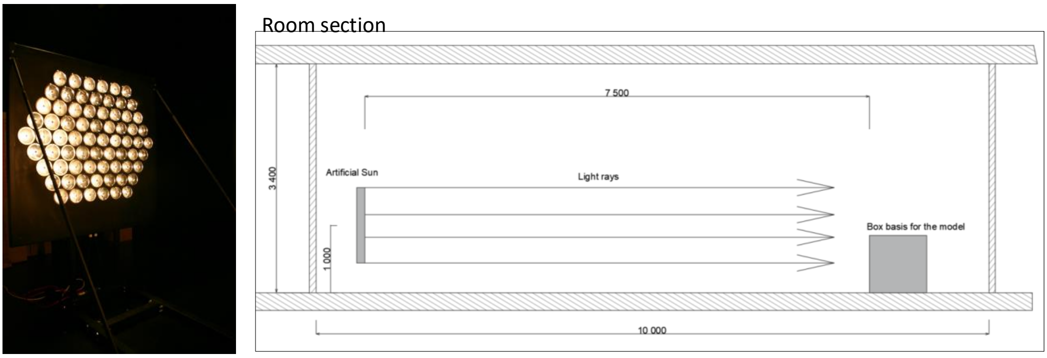

Figure 6. Artificial sun setup in the Daylight laboratory at NTNU, Faculty of Architecture and Design, photo of the artificial sun to the left and section of the room to the right (Obradovic and Matusiak, 2020).

The laboratory measurements for the diffuse sky were performed in the sky-dome simulator, where the dome luminance distribution refers to the CIE Standard Overcast Sky, in which the zenith luminance is three times that of the horizon. In such a sky-dome simulator, the radius of the dome was large enough to allow for the models of reasonable size to be tested without causing parallax. The model itself could not be too small and should allow for the details necessary to the light simulation (Cannon-Brookes, 1997). Therefore, to hold the parallax error under the +-10 %, the radius of the simulator should allow for a minimum 10 times the size of the model. As discussed in Lynes and Gilding (2000), this method applies only if the model is placed at the centre of the dome.

In the original study, the test with diffuse light was performed in an artificial sky in the form of a mirror box (Figure 7). The mirror box was initially developed between 2000 and 2003 with fluorescent tubes and a translucent fabric suspended between the tubes and mirrors. In 2012, the tubes were replaced by LED (RGBW) chips and the fabric by translucent acrylic ceiling plates. The box was octagonal, ensuring more even horizontal light distribution than rectangular mirror boxes with slightly lower luminance in the vertical corners than at the mirror centres. An octagonal box gives users more flexibility in the rotation of the model because it does not matter if the daylight opening in the model is oriented toward a mirror centre (Matusiak and Arnesen, 2005; Matusiak and Braczkowski, 2014).

Because the height of the tube's entrance is 150 mm, 7.5% of sky height in the mirror box (2000 mm), the parallax error was estimated to be somewhat higher than 10% for low altitude angles (0-15°). For altitude angles over 15°, the parallax error was lower than 10% (Lynes and Gilding, 2000). The test model was attached to the table located in the middle of the mirror box. The table height was adjusted to align with the lowest edge of the mirrors. The tube was placed with the opening at the centre of the mirror box. This location was based on the fact that the overcast sky simulated in the artificial sky chamber was rotationally symmetrical. That is, its luminance distribution was not dependent on the azimuth angle.

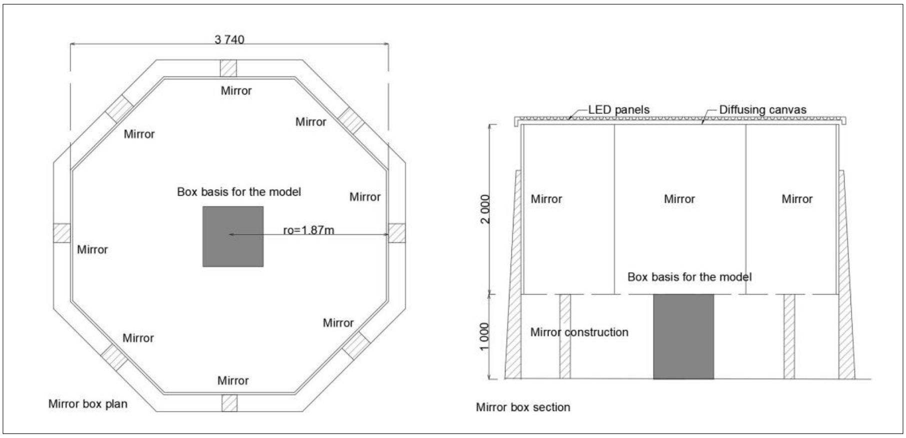

Figure 7. Mirror box for the artificial overcast sky study at NTNU, Faculty of Architecture and Design, in plan (left) and section (right) (Obradovic and Matusiak, 2020).

To obtain reliability of the photometric measurement in a laboratory conditions a certain level of accuracy is necessary to ensure, in all steps. First, it is essential to ensure a stability of supply voltage for the power operated light sources and illuminance meters. Requirements and operating conditions for the light source should be provided, e.g. stabilization and cooling time of the lamps, ambient temperature, and a maximum air-movement speed. To ensure measuring instrument's precision, short-term repeatability tests should be performed prior to each measuring session. Calibrated illuminance meters, with suitable measuring range for the purpose, should be used.

Since such laboratory tests can be long-lasting, but not all physical conditions in the laboratory are perfectly stable (dust), the accuracy of the obtained data and the reliability of the entire measurement should be strengthened by repeatability, by repeating one single measurement, for example, or all of them. If the measuring method is performed in only one laboratory, a repeatability test can be performed for part of the study, e.g. only for one alternative.

c) Laboratory measurements and calculation of the light transmission efficiency (η)

The empirical study was conducted on a scale model of the horizontal light pipe (HLP). The 1:2 scale model of the light pipe was 150 mm in diameter and 1200 mm long. This light pipe was the most common pipe module on the market; a 300 mm diameter pipe also suggested by the manufacturer for use in a single office. The pipe was coated with specular mirror folium with 99% reflectivity (Specular silver film DF2000MA, 3M). The pipe did not have a dome on the entrance or a diffuser on the exit because the original research aimed to study the collection efficiency of the LCP as a custom-made light collector. The assumption was that the LCP could be the ''dome'' or outside enclosure of the pipe. The diffuser was constructed in the shape of a curved reflector, a more efficient light distributor (see Obradovic and Matusiak (2020).

The model was attached to a box one m high so that the height of the tube's entrance matched the centre of the artificial sun or the lowest edge of the mirrors in artificial overcast sky.. For the altitude variation measurements (Table 1), the model was tilted by lifting the backside onto a special vertical shelf; azimuthal variation measurements were taken by rotating the box to align it with the angle grid on the floor. Lighting measurements were then taken with five Almemo photosensors arranged in a cross on a circular surface. The results were logged via an Ahlborn logger and recorded using Almemo control software 6.0 (Figure 8).

Figure 8. (left) Measurement instrument using Almemo Ahlborn, with photosensors fixed on a circular plate and placed at the tube's exit; (right) logging of measured data via Ahlborn Almemo logger and Almemo control 6.0 software.

The photometric test for direct light simulation was conducted in all matrix positions, while the diffuse light simulation was conducted for just one fixed position. The measurements were taken for the reference values, called ***ZERO,*** by placing the sensors in front of the tube's entrance, as well as for the test values, called ***BaseCase***, by placing the sensors on the tube's exit (Figure 9). This nomenclature was used in the original study, the aim of which was to test the efficiency of the LCP samples and BaseCase (where BaseCase presents ***none-LCP*** was then taken as a reference to compare it with). For each measuring position on the matrix, the light transmission efficiency, η_{direct}, was derived from the ratio of the illuminance (taken by the photosensors) on the tube's exit, E_{direct}(BaseCase)(Al/Az matrix), and the illuminance measured on the tube's entrance, E_{direct}(ZERO)(Al/Az matrix) (Eq. 4). The light transmission efficiency, $\eta_{diffuse}$, was found from the ratio of the illuminance on the tube's exit, $E_{diffuse}$(BaseCase)(static), and the illuminance measured on the tube's entrance, $E_{diffuse}$(ZERO)(static) (Eq. 5).

$$\eta_{direct}(Al/Az\ matrix) = E_{direct}(BaseCase) \div E_{direct}(ZERO) \tag{4}$$

$$\eta_{diffuse}(static) = E_{diffuse}(BaseCase) \div E_{diffuse}(ZERO) \tag{5}$$

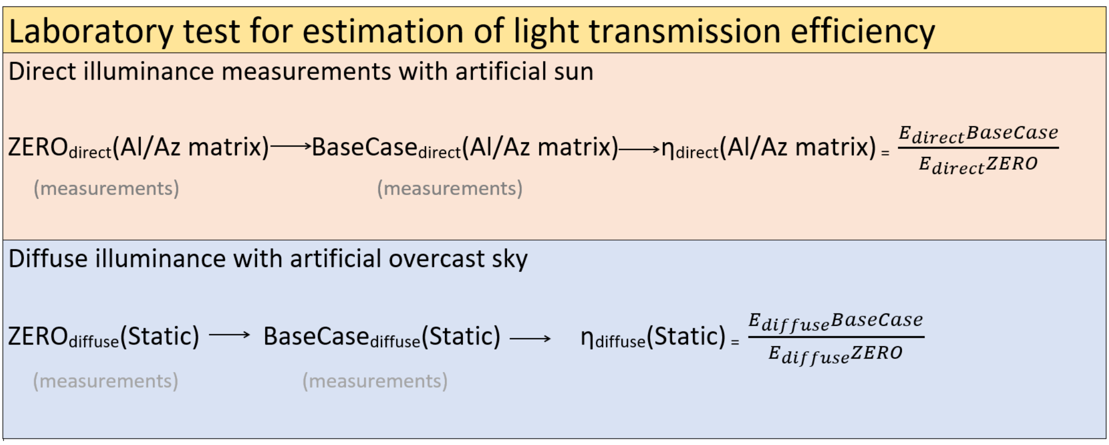

Figure 9. Parametric study method and findings of the light transmission efficiency η (for direct and diffuse).

3. Satel-Light database and real daylight accessibility

The resulting light transmission efficiency $\boldsymbol{\eta}_{direct}$ and $\boldsymbol{\eta}_{diffuse}$ are raw data which, under real conditions, would depend on natural sunlight/skylight conditions at a specific temporal point. In addition to the sun's altitude, the direct and diffuse light intensity depends substantially on the climate at the location and season of the year. For this purpose, statistical data on vertical illuminance for the chosen orientation can be retrieved from the Satel-Light database (Figure 10). The Satel-Light differentiates between direct and diffuse illuminance values and, in this case, offers the opportunity to estimate daylighting under real conditions. An hourly set provided with the data can be used, together with *solar chart table of changes* in the solar altitude and azimuth angles (for a typical month) to reference the values to the specific matrix cell Al*Az* (Section 2a). Each matrix cell could be referenced to a specific month and time.

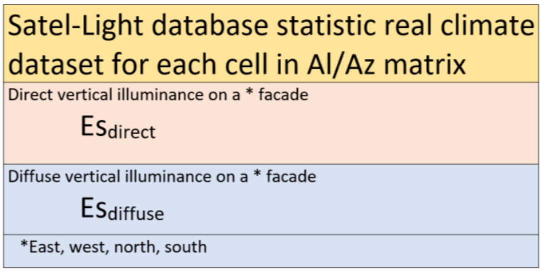

Figure 10. Method for the development of Satel-Light data, $E_{Sdirect}$ and $E_{Sdiffuse}$.

4. Development of performance indices using Satel-Light database

The values for direct and diffuse illuminances that occur in reality were used to develop indices of real illuminance values that could be realistically expected on the tube exit (Figure 11). Actual values of the illuminances on the tube's exit, Er_{direct} and $Er_{diffuse}$, were developed by multiplying the light transmission efficiency, η_{direct} and $\eta_{diffuse}$, and the illuminance values from the Satel-Light database, Es_{direct} and $Es_{diffuse}$ (Eq. 6 and Eq. 7). Final Er_{total} was a result of the summation of Er_{direct} and $Er_{diffuse}$ for any position from the matrix. For each position in the matrix, the Er_{total} gives the indices of the real expected illuminance on the tube's exit.

$$Er_{direct}(Al/Az\ matrix) = \eta_{direct}(Al/Az\ matrix) \times Es_{direct}(Al/Az\ matrix) \quad (6)$$

$$Er_{diffuse}(Al/Az\ matrix) = \eta_{diffuse}(Static) \times Es_{diffuse}(Al/Az\ matrix) \quad (7)$$

$$Er_{total}(BaseCase) = Er_{direct}(BaseCase) + Er_{diffuse}(BaseCase) \quad (8)$$

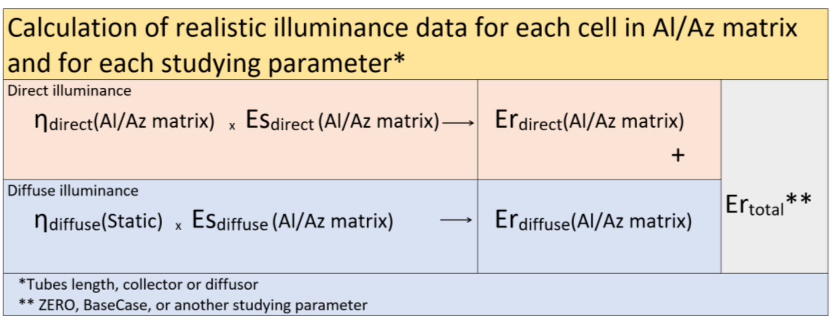

Figure 11. Procedure for developing the real illuminance values for direct and diffuse light and a resulting illuminance.

This paper is supplemented with the data from the original study for the Er_{total}; for the BaseCase, and examples of special collector (see also Section 6), in form of tilted (T) LCP and rotated (R) LCP (Tables 3, 4 and 5).

5. The application of real data via the theoretical office model

To analyse the results of Er_{total}, a theoretical concept of an imaginative working space was employed. The concept assumed that illuminance in the working area was provided only through the horizontal light pipe. The straight horizontal tube, with an aspect ratio of 8, was assessed in the theoretical model of the office space. The tube was 2.4 m long. Assuming a wall thickness of 30 cm, the tube's exit was 2.1 m from the facade wall, which corresponds to the second working area from the window. The reference illuminance of 300 lux on a reference surface was taken as a threshold for verification, and the necessary threshold illuminance value on the tube's exit was calculated using the inverse-square law. This threshold value was used to verify the Er_{total}, the real expected illuminance value for each cell from the template, to confirm whether the light pipe in that temporal position supplied room with enough light. For a detailed description of this calculation, please consult the original research paper: Daylight autonomy improvement in buildings at high latitudes using horizontal light pipes and light-deflecting panels, B. Obradovic and B. S. Matusiak, Solar Energy 2020 Vol. 208 Pages 493-514, DOI: https://doi.org/10.1016/j.solener.2020.07.074.

6. Example of an application: an estimate of light transmission efficiency for light deflecting panels as collectors for a horizontal light pipe.

The proposed customized method is applicable for estimating light transmission efficiency for several parameters in a horizontal light pipe in the same way as the original method suggests. The method can be used to establish the efficiency relationship between different pipe lengths, or the transmission efficiency of a light collector or light diffuser/distributor.

The research studies on horizontal light pipes often draw attention to improvement of the light collection issue. Even in the case of an highly reflective pipe, the increased inter-reflection of light rays reduces the output; the longer the pipe (deeper building), the higher the number of reflections. This issue occurs when incident light comes from oblique angles (e.g., morning or evening light from east and west for a south-oriented pipe). Therefore, the original study used light deflection panels, popularly known laser-cut panels (LCP) (Edmonds et al., 1995; Edmonds, 1993), to change the incident angle of incoming unfavourable light rays and direct them in parallel along the pipe's longitudinal (central propagation) axis. In this way, the LCP plays the role of a collector of incoming light.

In the original study, several LCP configurations were used. Some of them were tilted (T), and some were rotated (R). The transmission efficiency $\eta_{collector}$ for a one LCP configuration could be developed, (using steps from Section 1 and further) as a ratio of illuminance E (LCP configuration) and E (BaseCase) for each measuring point from the matrix in Section 2a. The (η) of only the LCP configuration as a collector (called T-R in the original study; please consult the original paper for more information on LCP configurations) could be developed separately for both direct and diffuse light, as proposed in equations 9 and 10.

$$\eta collector(T-R)_{direct}(Al/Az\ matrix) = E_{direct}(T-R) \div E_{direct}(BaseCase) \quad (9)$$

$$\eta collector(T-R)_{diffuse}(static) = E_{diffuse}(T-R) \div E_{diffuse}(BaseCase) \quad (10)$$

The resulting $\eta_{collector}$(T-R) for one LCP configuration in all matrix positions is just raw data, and the comparison between the collectors' performance in this phase can be made just between the single matrix cells. To evaluate the real expected illuminance, the $\eta_{collector}$(T-R) can be further used in steps 3, 4 and 5. In that case, however, it must be multiplied by the η_{direct} or $\eta_{diffuse}$ that describe the efficiency of the pipe (described in Section 1c).

This method is applicable for any collector the performance efficiency of which depends essentially on incident angles of light rays. In recent decades, research on horizontal light pipes also considered the anidolic collector in addition to the LCP (Molteni et al., 2001). The shape of the anidolic collector is described by a parabola through edge rays principles (Ries and Rabl, 1995; Welford and Winston, 1978). The anidolic collector for horizontal light pipes bases its efficiency on a zenithal skylight (Satel-light data for horizontal diffuse illuminance should be used); however, the curvature of the collector ensures that direct sunlight rays (from lowest to highest altitude) will be captured by the collector as well. The measuring matrix developed for specific altitude angles must, in the case of such collectors that are sensitive to incident angles, be developed with attention to those angles.

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Declaration of interests:

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

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Supplementary material: Er_{total} data-matrix from the original study (LCP as a collector of the horizontal light pipe oriented south and located in Oslo, Norway)

The examples of the Er_{total} matrix for the BaseCase and LCP configurations are presented in Tables 3, 4 and 5. The colours in the cells correspond to the periods described in Figure 5 (red-summer, orange-late spring or early autumn, yellow-early spring or late spring, blue-winter).

Table 3. BaseCase Er (lux) values

Altitude													
50°	0	0	0	0	23536	29704	38301	29704	23536	0	0	0	0
45°	0	0	13014	19244	30811	35319	34348	35319	30811	19244	0	0	0
35°	0	8358	14650	24426	29657	29035	30830	29035	29657	24426	14650	8358	0
25°	4638	7684	14312	15816	22508	17887	21455	17887	22508	15816	14312	7684	4638
15°	0	2803	8690	8007	12336	15158	15941	15158	12336	8007	8690	2803	0
5°	0	747	2182	3469	5532	9992	12511	9992	5532	3469	2182	747	0
Azimuth	90°	105°	120°	135°	150°	165°	180°	195°	210°	225°	240°	255°	270°

Table 4. LCP T-06-27 Er (lux) values

Altitude													
50°	0	0	0	0	28923	35198	45790	35198	28923	0	0	0	0
45°	0	0	0	23769	34591	39199	41350	39199	34591	23769	0	0	0
35°	0	12757	16676	26173	32323	32372	34447	32372	32323	26173	16676	12757	0
25°	6650	9573	16788	18870	26089	19246	20606	19246	26089	18870	16788	9573	6650
15°	0	3612	9845	8450	13420	15385	17042	15385	13420	8450	9845	3612	0
5°	0	668	1747	3579	6321	11373	12796	11383	6321	3579	1747	668	0
Azimuth	90°	105°	120°	135°	150°	165°	180°	195°	210°	225°	240°	255°	270°

Table 5. LCP T-05-20 Er (lux) values

Altitude													
50°	0	0	0	0	20440	25461	32776	25461	20440	0	0	0	0
45°	0	0	0	17631	24825	28913	30103	28913	24825	17631	0	0	0
35°	0	10291	14378	19864	25944	26006	28396	26006	25944	19864	14378	10291	0
25°	12320	8042	13355	14515	20958	15795	16538	15795	20958	14515	13355	8042	12320
15°	0	3463	8025	7071	10945	12983	15629	12983	10945	7071	8025	3463	0
5°	0	898	1648	3056	5260	9958	11670	9958	5260	3056	1648	898	0
Azimuth	90°	105°	120°	135°	150°	165°	180°	195°	210°	225°	240°	255°	270°

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The effect of a horizontal light pipe and a custom-made reflector on the user's perceptual impression of the office room located at a high latitude

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Abstract

This paper describes a qualitative study on user opinion of daylight supplementation via a horizontal light pipe (HLP) applied in a test office in a building located in southern Norway. The study is part of a full-scale long-term study analysing lighting energy consumption and the photometry of supplemented light. This study employs a custom-made reflector for daylight distribution via HLP to preserve the features of natural light, noted as the primary human association with daylight, and is, as such, first of its kind. The main research aim was to find out if noticeable daylighting provision from the HLP leads to a positive user perception of the space when compared to a situation without a HLP. The study collects user responses to a new illumination solution using a user-survey method based on exposure to the visual environment of an experimental office. Statistical correlation and a t-*test* were used to analyse the results. The paper concluded that the user appraisal of the office was more positive when there was a noticeable daylight supplement from the HLP in the space, but the appraisal was negative for the higher light variability in the illuminance level both indoors and outdoors. The conclusion serves as an additional argument for the implementation of the HLP in building design, besides its energy saving potential.

Keywords: Horizontal light pipe (HLP), daylight tube, full-scale, high latitudes, visual comfort, user opinion

Nomenclature

E_1 – Illuminance value on the test desk in the office, lux

E_2 – Vertical illuminance value incident to the tube's entrance, lux

E_3 – Global horizontal illuminance value, lux

E_{1Mean} – Mean value of the illuminance values on the test desk for the participant adjustment period, lux

E_{2Mean} – Mean value of the vertical illuminance values incident on the tube's entrance, for the participant adjustment period, lux

E_{3Mean} – Mean value of the global horizontal illuminance values, for the participant adjustment period, lux

v-E_1 – Variation of the illuminance values on the test desk in the office for the participant adjustment period, %

v-E_2 – Variation of the vertical illuminance values incident on the tube's entrance for the participant adjustment period, %

v-E_3 – Variation of the global horizontal illuminance values for the participant adjustment period, %

1. Introduction

This paper presents a qualitative study carried out as part of a full-scale study performed in an office equipped with a horizontal light pipe (HLP) in a high-latitude area in southern Norway. The full-scale office was designed with particular decisions regarding artificial lighting system, a sun-shading system, and a daylight-linked light control (DLC) system, to cover requirements for both qualitative and quantitative study. This paper focuses on qualitative features of the daylighting delivered by the HLP, while the results from the quantitative study will be reported in a subsequent dedicated publication.

Literature Review

Good daylighting can generate sustainable architecture that supports human physiological and psychological visual functions, as discussed by Boubekri (2008). Veitch, Bisegna et al. (2016) and Kruisselbrink, Dangol et al. (2018) argue about the function of human vision supported by the image-firming effect of light, and the function of the human circadian system (health and wellbeing) supported by the non-image-forming effect. Longer periods with natural light are an indisputably positive amenity to the built space as nowadays people spend as much as 90% of their time indoor, as discussed by Boyce, Hunter et al. (2003), and by Knoop, Stefani et al. (2020). Even in available daylight, the long hours humans spend indoors are not necessarily spent in areas adjacent to the building façade with available natural light but instead in areas far from windows. As one moves away from the window, the available daylighting decreases exponentially. To daylight a building's deeper areas, a daylight transport system (DTS) needs to be used. Horizontal daylight tubes (or light pipes) are passive DTSs that have proven by many studies to be efficient in delivering daylight to deeper areas of multistorey buildings (Garcia Hansen, Edmonds et al. 2001, Scartezzini and Courret 2004, Garcia-Hansen 2006, Duc Hien and Chirarattananon 2009, Nair, Ramamurthy et al. 2014, Daich, Zemmouri et al. 2017, Obradovic and Matusiak 2019, Obradovic and Matusiak 2020) besides increasing the illuminance levels and light uniformity of an entire room, the horizontal light pipe can reduce the room's front and rear areas' luminous contrast, which is associated with a room's perceived "gloominess", as discussed by Courret, Scartezzini et al. (1998), and Scartezzini and Courret (2002).

Humans experience a 20% higher light level (at the same lumen level) with daylight than with electrical lighting due to daylight's distinctive features, as argued by Boubekri (2008). Other authors, such as Fontoynont (2002) and Reinhart (2004), state that higher level of natural light in the office, especially in the mornings, prolong the period during which people avoid switching on the lights. Humans perceive artificial and natural lighting levels differently due to the "geometry of the natural lighting" as stated by Lam (1986). Daylight's higher horizontal component, which lights vertical surfaces, more effectively meets the human need for the good luminous design of a room or space. The dynamics of natural light in terms of its variability and the rhythm of change in light intensity are argued to be essential factors influencing the general human impression of a space. Daylight dynamics lead to improved visual performance, based on the fact that the nervous system is more attuned to noticing changes in the environment than steady states. argued by Heschong (1979). Therefore, it is considered more stimulating and leads to higher levels of arousal in people, as argued by (Kruisselbrink, Dangol et al. 2018). Further, some studies investigating the perceptual effects of both window size (Boubekri, Hull et al. 1991, Wang and Boubekri 2011, Moscoso, Chamilothori et al. 2020) and architectural design (Rockcastle, Ámundadóttir et al. 2017, Rockcastle 2017) have shown that varying sunlight intensity in a space, e.g., light patches, can bring about a more positive human experience with the space. when the patches are of a certain size and at a certain distance from the observer. Furthermore, the spread of the light was assumed as positive, because it would affect the peripheral area of the desk. Good peripheral light conditions are vital for the visual perception of a space, as argued by several authors (Mardaljevic, Heschong et al. 2009, Cuttle 2013, Gentile, Laike et al. 2016).

Issues of glare and people's interference with a glare control system are a known problem in regard to daylighting for improved energy efficiency. Studies addressing lighting energy-saving potential, have noted an unreliability of the resulting metrics of energy consumption, photometry, and visual comfort in situations with excessive sunlight (Lee, DiBartolomeo et al. 1999, Bellia, Pedace et al. 2014, Karlsen, Heiselberg et al. 2015, Karlsen, Heiselberg et al. 2016, Bellia, Fragliasso et al. 2017). The predicted (simulated) energy use for lighting, based on a daylighting availability model, has shown to be bellow realistic values, which is the result of unreliability in predicting human reactions to glare and their motivation to control it. The most common model for daylight linked control (DLC)—which is far from optimal and is assumed to be a compromised solution—involves completely closing the blinds when the daylight illuminance on the façade exceeds the predefined threshold, which results in artificial lights being switched on to their full level. This model has undermined many daylight and lighting control strategies, as stated by Bordass, Cohen et al. (2001). Moreover, a study by Velds (2001) found that a procedure considering human visual comfort generated reliable energy-savings; the amount of energy saving was relatively low, but more realistic because they took into account actual human reactions. The study is consistent with Christoffersen, Johnsen et al. (1998) and Veitch and Newsham (2000) who noted that lighting metrics alone cannot describe how humans perceive a room and its daylighting/lighting. The optimal method for such a human-environmental study would be to simultaneously perform photometrical measurements and a user opinion study because of the possibility of correlating users' answers with lighting conditions, as stated by Christoffersen, Johnsen et al. (1998) and Christoffersen and Wienold (2005).

The reliability of the results from such user survey studies has been debated, and the selection of "lighting quality descriptors" has been discussed several times in the last two decades (Veitch and Newsham 2000, Fontoynont, Dumortier et al. 2007). Recent studies by Moscoso and Matusiak (2015) and Moscoso, Chamilothori et al. (2020), focusing solely on human appraisal of the visual appearance of daylit spaces, selected the most suitable aesthetic attributes of the space, which are semantically correct, and provided results with high reliability in human-environmental studies. This study applies this selection of light quality descriptors in its evaluation of the test office in addition to questions regarding visual comfort, daylight dynamics, human satisfaction with the daylight conditions, and the integration of daylight with artificial light.

In the last two decades, studies on human reaction to daylit environments equipped with some special daylighting systems have been performed, concluding on issues that can decrease user satisfaction with daylighting systems (Velds 2001, Fontoynont 2002, Velds 2002, Al-Marwaee and Carter 2006). Several studies on particularly daylight tubes have considered the issue of the diffuser, which is an understudied element, specifically in this field (Kocifaj 2009, Kocifaj 2009, Mayhoub 2019, Obradovic and Matusiak 2019). Such studies have reported partial user dissatisfaction caused by light being delivered through a luminaire-like diffuser, which diminishes the essential connection of the delivered daylight with its original source. Even in the first pilot projects using DTSs from 40 years ago, the pointlessness in equipping the light pipe with a luminaire-like diffusor as a light distributor in the room was noted. While a significant amount of effort and resources have been given toward designing a collector and tube with a high light transmission efficiency, the distributor was completed with a standard light fixture.

The application of light pipes in Norway has been minimal, and no horizontal light pipes have been installed. Based on the knowledge presented above, it was decided for this study to introduce its own sun-shading strategy to support and preserve visual comfort, which will be described later on. Additionally, the authors noticed that other daylighting systems, such as the mirror system, which redistributes light into a space, retain the characteristic qualities of sunlight and suggest that this quality has to be preserved in any daylighting system. The greatest novelty of the study is a custom-made mirror reflector as a distributor of the light from the HLP in order to preserve the association of the daylight delivered via HLP with natural light.

This study's main objective was to evaluate the user's subjective appraisal of this office, which was daylit by a HLP in addition to windows. Therefore, it was designed to answer the following research question: Does significant daylighting provision from the HLP lead to a positive user perception of the space when compared to a situation with no daylight provision from a HLP. Statistical analysis of an independent sample *t*-test as well as correlative analyses were performed to determine the answer.

2. Method and procedure

This qualitative study is part of a full-scale research that investigates how daylight delivered through a HLP affects illuminance in specific areas in an office as well as the energy consumption for each luminaire installed to provide artificial lighting on two working areas during times with daylight shortages. The qualitative part was designed as a user survey consisting of a pre-test (oral reading test and colour vision test) and a questionnaire. The pre-test functioned as a visual adaptation to the test office and allowed participants to experience lighting conditions by reading a paper and attempting to discriminate colours. Independent parameters in the qualitative part of the study are parametric data from the study's quantitative part. Findings and analyses are thus based on nominal parameters obtained from the light metrics and then related to the subjective evaluation. This methodology is known as a mixed-methods approach, Fig. 1.

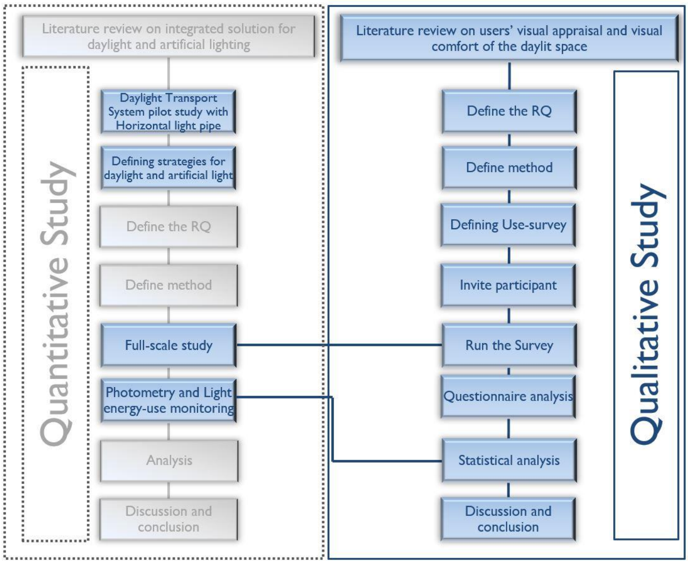

Fig. 1. Methodology of the qualitative part of the full-scale study

2.1 Experimental design: Full-scale test office

In a fully operative building at Norconsult Headquarters in Sandvika (59°.53'N, 10°.31'E), Norway, a two-person office on the top (6th) floor was used as a test room for one year. The office did not have as perfect of a form, size, or orientation as researchers would aim for in high-quality scientific studies, still, considering the limited time and available resources of the study, the office was considered the best choice (Fig. 2).

2.1.1 Test room

The office had an area of 13 m^2, and a height of 2.8 m after the suspended ceiling was removed. The finishes and colours of the room surfaces as well as the equipment inside were representative of offices in Nordic countries. The office had windows on its southeast and southwest walls; however, for the purpose of the experiment, the southeast window was covered with a wall panel, and the horizontal daylight tube was installed 45° from the wall (Fig.3). This was to allow for the placement of the tube's exit above the second work area, desk 2, without the use of any tube elbows (i.e., the tube was straight) as well as to position the tube with a southern orientation. The office was equipped with a few pieces of necessary furniture: two desks and two chairs (Fig. 5b).

Regarding the parametric part of the study, photometric and energy logging were performed every minute for one year, starting from 21 June, 2020, and also during the user survey. Indoor illuminance logging was performed using five photosensors placed to cover the horizontal illuminance on the first and second work areas (0.8 m height) and the vertical illuminance on a wall in front of the work areas (1.2 m height). The last photosensor was placed on a tripod to record the vertical illuminance at the eye level of the user of the second work area. Outdoor illuminance logging was provided via photosensors placed vertically along the same south-oriented vertical plane as the tube's entrance dome as well as via photosensors placed horizontally on the roof. The lighting energy consumption for every minute was measured using separate power meters (10–20 A) for each luminaire. The data was logged into a computer.

Fig. 2. Situation plan for the building at Norconsult Headquarters in Sandvika (59°.53’N, 10°.31’E), Norway, where full-scale test office is situated on the top (6th) floor

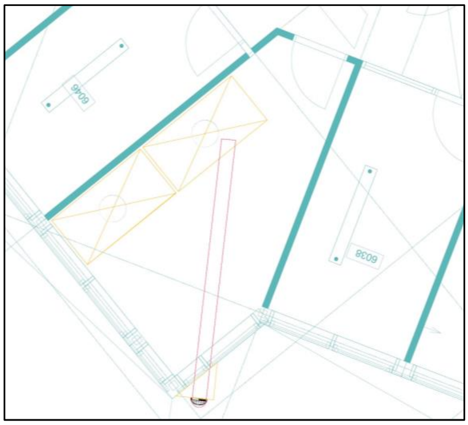

Fig. 3. Office plan, windows on the southwest wall, horizontal daylight tube (red lines) was installed 45° from the southeast wall, with entrance nearly oriented against south

2.1.2 Sun-shading strategy in the test office

As discussed in the introduction, a sun-shading strategy in the test office was developed to provide visual comfort at any time of the day and year. The sun-shading strategy was implemented to keep (manually controlled) the outdoor sun-shading slats partly open, with tilt angle for sunlighting cut-off 45°. In this way, the office was made glare-free, while a partial view is provided. Fig. 4 shows the view (visual conditions) from the entrance of the office (4a), from the desk 2 (4b), and from the desk 1 (4c).

The configuration of the slats tilt angle used here was based on the study by Kolås (2013), particularly at a low solar altitude. Kolås determined that, in the case of an intermediate sky (sun's altitude 30°, azimuth 45°, ground illuminance values of sunlight approx. 43,000 lux and skylight approx. 13,000 lux), this configuration can provide approximately 1200 lux for the first two metres from the window and half of this value, approximately 500 lux at 4 m distance from the window. The essential point here is that the light reflected from the slats is directed to the ceiling to be further re-directed to areas farther from the window. In the test office, the distances of 2 and 4 metres correspond to desk 1 and desk 2, and the reflectance of the slats, together with the ceiling reflectance, corresponded with those of the Kolås' study. Further, Kolås found that, under an overcast sky (ground illuminance value of approx. 11,000 lux), the same configuration can re-direct diffuse daylight to the ceiling; resulting in the illuminance at the middle of desk 1 slightly over 100 lux; and the illuminance at the middle of desk 2 approximately 60–70 lux.

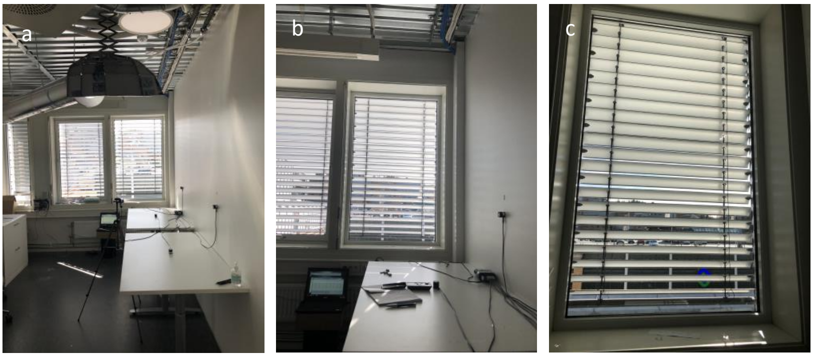

Fig. 4. Visual conditions in the full-scale test office using sun-shading strategy with slats tilt for sunlighting cut-off 45°: the observers view from the entrance of the office (4a), the observers view from the 2nd desk, closest to the door (4b) and the observers view from the 1st desk, closest to the window (4c)

2.1.3 Daylighting conditions in the office

Daylight in the office was provided by two windows facing southwest. The window glazing was a double glass (4-12Ar-4) with a light transmission factor of 0.8. The daylight calculations for the room were performed by applying the mentioned sun-shading strategy (section 2.1.2) using Dialux 4.3 software. The results are presented in appendix A. The calculations were done without accounting for daylight from the HLP. Results showed that, under an overcast sky, during equinox, 100 lux can be expected on the desk closest to the window and 50 lux on the desk closest to the door (app. A2). Under a clear, sunny sky during equinox at 12:00 h (sun altitude 30°, azimuth 180°) the values will be 350 lux on the desk closest to the window and 120 lux on the desk closest to the door (app. A1). These measurements were taken into consideration when performing the analyses. The results were very similar to those discussed in chapter 2.1.2 and found by Kolås (2013). The daylight factor calculated at the middle of the room, 0.8 m above the floor, was almost 1%, even though the sun-shading configuration described in 2.1.2 was applied (app. A3).

2.1.4 Horizontal light pipe in the test office

The horizontal light pipe used in this study was LW300 manufactured by LightWay. The most suitable light pipe configuration for the study should have been an aspect ratio of 12 (ratio of length to diameter), which was dictated by the necessary length of the pipe, 375 cm, and given a diameter of approximately 30 cm. However, due to the building's constructive issues, only a diameter of 22 cm could fit. These dimensions provided an aspect ratio of the installed light pipe of 17, which corresponded to a recent study done by the authors (Obradovic and Matusiak 2020). The light pipe's dome was manufactured of crystal glass, and had a light transmission factor of about 95% (test performed by the authors) (Fig. 5a), while light distributor was clear glass with a light transmission of 92%. The direction of the light down to the working area and the wall in front of it was provided by a custom-made reflector, designed by non-imaging optics rules (Chaves 2017) (Fig. 5b). Here, the aim was to redirect light to the working area while maintaining the qualitative features of the daylight (i.e., dynamics, variation, colour) that would be delivered through the HLP. The custom-made reflector was layered with a reflective mirror folium, product of 3M, which has a light reflectivity of 0.99. In the case of high daylight supplement through the pipe and in a period of 10 AM to 2 PM, the reflector provided delicate and balanced light patches both on the desk and on the wall (Fig. 5c).

The highest effectivity of daylight delivered via a pipe HLP oriented to the south, is, as argued in Obradovic and Matusiak (2020), when the sun's azimuth angle aligns with the pipe's longitudinal axis and up to a 30° incident angle. This coincided with the time period from 10 AM to 2 PM. During this period, in the case of clear, sunny conditions, the daylight delivered through the pipe was up to 330 lux on desk ''2''. Before and after this period, the daylight delivered via the pipe was of lower intensity, and, especially after 2 PM, when the sunlight incident was aligned with the window, the daylighting via the window (sun-shading strategy, section 2.1.2) was much higher than the daylight via the pipe.

Fig. 5. Light pipe mounted on the facade in the room and an adaptation element for angled mounting (5a); two working areas in the room (5b); light patches on the 2nd desk delivered from the HLP and via the custom-made reflector (5c)

2.1.5 Artificial lighting in the office

The artificial light in the test office consisted of two smaller ceiling-mounted luminaires. The luminaires provided 2700 lumen of light flux each, which enabled the required 500 lux of horizontal illuminance on both desks along with a uniformity of over 0.6, as specified in NS-EN 12464-1 (appendix B). The unified glare rate was under 19. The luminaires had a colour temperature of 4000 K and a colour rendering of Ra = 80. Each luminaire was connected to its own photosensor and programmed by a daylight-linked control system (DLC). Luminaires should supplement additional light levels when the daylight provided by the window and light pipe do not reach 500 lx. As discussed in section 2.1.2 and 2.1.3, the daylight coming through the window hit the two desks to different extents, while the daylight supplement from the light pipe was only directed toward the second desk.

The DLC system did not perform as expected due to the daylight reflection on the sun-shading slats (in tilt angle 45°) resulting in a partial re-direction of the light to the DLC sensors. This is the weakness of this study, and several similar studies reported the same problem, as mentioned in the introduction. Luminaires often receive incorrect information regarding the illuminance they need to provide; here, the illuminance on the tables from the artificial lighting varied greatly. The illuminance level on desk 2 (the user position in the survey) was as low as 230 lux in some situations. Moreover, 500 lux was only achieved under an overcast sky—given that the sensors were not affected at all. In all other situations, the DLC sensors were affected. Hence, the regulated artificial light was very low—far under the needed 500 lux. In most cases, artificial illuminance was equal to zero, and the illuminance level registered by the illuminance meter on the desk was only obtained from daylight—both daylight via the light pipe and daylight from the window (to a smaller extent). The illuminance on the test desk (desk "2"), E_{1Mean}, was one of the independent values in the statistical and descriptive analyses and was collected from the photometric loggings for each participant for the period they spent in the office before filling out the questionnaire.

2.2 Experimental design: User survey

The user-survey was conducted in September 2020 (between 10 AM and 3 PM), since the period for this study was purposely planned to be around the equinox (representing an average yearly daylighting condition).

2.2.1 Participants

The study involved 50 participants, most of whom were company employees recruited by an announcement on the company's website as well as—to a smaller extent—via social media. Participation in the study was voluntary and rewarded with colour-vision test results. The participants were aged 23–65 years (M = 37 and

SD = 12.2) and comprised of 26 males and 24 females. To avoid professional bias, participants without architectural or lighting engineering backgrounds were chosen. The user-survey design was approved by a human resources officer as well as the working environment committee of Norconsult after checking that ethical and privacy policies were not impaired.

2.2.2 User survey procedure

The participants had the opportunity to stay and work (on their own laptop) in the test office for half an hour prior to the survey. The participants sat at desk 2 in order to experience a working area far from the window and under the daylighting conditions from the light pipe (Fig. 6c). At the beginning of their participation, the participants received practical information regarding, i.e., the experimental protocol and the approximate duration of the experiment, and were asked to fill out a consent form. The user participation consisted of three parts: 1) a reading test, 2) a colour vision test, and 3) a questionnaire. The reading and colour tests were done during the preparation time in order for the participants to accommodate to the lighting conditions of the room. The additional function of the reading and colour tests was to obscure the main goal of the study, as mentioned in the introduction.

The first part of the pre-test was a Tambartun Oral Reading Test, developed by the Fosse (2001), in Norwegian, where the participants were asked to read two paragraphs aloud. The participants were informed that the first chart functioned as preparation and a way to familiarise them with the concept of Tambartun charts, while the second chart was the real test and the researcher was going to measure the time it took them to read the second chapter using a stopwatch. The Tambartun test concept made it suitable for usage in this study, as the functional equivalence of the elements upon which the test was built make it possible to compare reading ability of different participants under different physical conditions, such as under different light levels, as recently used in Matusiak, Fosse et al. (2009). Each chart consisted of 50 unrelated words (two- to six-letter words) chosen from the 300 most frequently used words in the Norwegian language. Thus, the reader could not base his or her reading on syntactic or semantic clues available in the text. Examples of the test can be provided upon request.

The second part of the pre-test was a colour vision test employing the Farnsworth-Munsell Hue 100 physical test (Fig. 6). The test was introduced in 1940s by Dean Farnsworth and is an easy-to-administer test and a highly effective method for evaluating an individual's ability to distinguish colors, as argued by Farnsworth (1957). It consists of a series of colored chips in which the color changes from one to the next in small steps. It includes four distinct rows of similar color hues, covering orange/magenta hues, yellow/green hues, blue/purple and purple/magenta hues. The test contains a pair of a fixed cap to serve as a reference and 25 removeable chips of distinct variations of each hue. The caps were mixed up and the task for participants was to arrange the chips in an order where the observer sees them fit, so that each chip is next to the color closest to it in appearance. The participants were informed about the typical two-minute duration needed to complete each of the four colour-sample plates, although they were told they could take more time if needed to ensure they were satisfied with the results. The participants spent an average of 8.6 minutes on this test, and the entire survey was designed to take half an hour. The test was performed "binocularly", because it was made only for vocational purposes (to give participants a chance to experience lighting conditions via reading the Tambartun test and discriminating between colours). The results of the colour vision test were sent to the participants after analysis, which was usually one day after their participation.

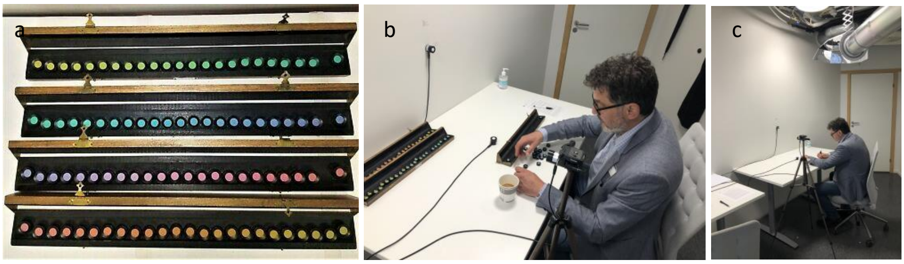

Fig. 6. Farnsworth-Munsell Hue 100 test physical model (6a); participant performing the test (6b); participant sitting at the desk closest to the door under daylight delivered from the HLP and via a custom-made reflector (6c)

The survey involved a questionnaire with 46 questions divided into four parts: perception of the test office (the most important and relevant part for this study), personal information, the social and physical climate in the original workplace and at the end, daylighting, sun-shading, and lighting conditions in the original sitting place evaluation. The questions were provided to the participants in the above order to avoid them being biased by their own workplace. The first part of the questionnaire included lighting quality attributes of a daylit space, as discussed in the introduction; statements regarding possible issues of visual comfort; and, after that, statements about the integration of daylight and artificial lighting. The questionnaire is available upon request.

The participants' appraisals in the questionnaire were collected using semantic differential rating scales based on a bipolar adjective of agree/disagree. For this research, a five-point scale was established between the extremes: strongly disagree, disagree, neutral, agree, and strongly agree. The second part of the questionnaire employed multiple -choice and open questions, while the last two parts were based on the same five-point bipolar semantic differential scales.

The majority of participants were Norwegians (80%), and the rest were of other nationalities, with compliance to participate in the study due to the socio-environmental acclimatization period being fulfilled, as discussed in the Lysgaard (1955) and Black and Mendenhall (1991). The questionnaire was translated into Norwegian in order to avoid any language barriers. For the three participants who did not speak Norwegian, the questionnaire was provided in English.

3. Results

Statistical and descriptive analysis was performed to determine whether a noticeable daylighting provision from the HLP onto the desk closest to the door led to a more positive perception of that working area as well as the room in general when compared with no daylighting supplement from the HLP. The participants were divided into two groups. These were comprised of 27 participants in the test group and 23 participants in the reference group. The group assignment was made post hoc, by analysing "every minute loggings" (described in section 2.1.1) for the indoor illuminance level on desk 2 (E_1), the outdoor illuminance on the tube's entrance (E_2), and the outdoor global horizontal illuminance (E_3) together with data regarding the energy consumption for the luminaire over desk 2. The participants in the test group had a noticeable amount of daylight delivered through the light pipe when they filled out the questionnaire's first page (addressing the test office conditions). This comprised, on average, 70% (from 50% to 90%) of the light on desk 2 that was delivered via the pipe, for the test participants and just 14% of the light for the reference participants. For comparison purposes, there were just 9.5% of the E_1 light level that came from the artificial light, for the test participants, while, for the reference participants, this range was over 70%.

The selection of the test/reference groups was validated via a theoretical estimation of the light transmission values using the light transmission efficiency of the HLP applied in the study. The noticeable daylight (minimum 50%) on the desk, delivered via the light pipe, would have a threshold value for the incident light at the pipe (E_2) around E_2 = 50,000 lux, based on the estimation described in Technical report 173, Tubular daylight guidance systems by CIE (2012). The test/reference participant selection, based on previously mentioned lighting energy consumption, matched this one.

The participants' reactions, impressions, and scores in response to the questionnaire were dependent on the E_1, E_2, and E_3 levels. The authors expected that a variation in these levels during their participation in the experiment (i.e. 45 min. adjustment period plus first part of the survey) would also affect the participants' reactions and scores. In terms of this, the illuminance values of E_1, E_2, and E_3 for each minute were collected, and the *Means* of these illuminances as well as the *Variation* in the values were calculated. Variation was calculated as a standard deviation of the minutes' values (STDEV), divided by the MEAN of the minutes' values. The means (E_{1Mean}, E_{2Mean}, and E_{3Mean}) and variations (v-E_1, v-E_2, and v-E_3) were further used in both the descriptive and statistical analyses as independent factors.

The dependent values in the analyses were the scores given by participants for each question. The five-point bipolar semantic differential scales were translated into nominal values from 0 to 4, which were defined as follows: strongly disagree (0), disagree (1), neutral (2), agree (3), and strongly agree (4).

3.1 Statistical analyses

The statistical analyses were performed using *IBM SPSS statistics 27* software. A comparison between the test and reference group scores regarding the test office was made using independent sample *t*-tests. Table 1 shows the results in regard to the participant's visual experience and perceptual impression (question 1) in both the test and reference group. Statistically significant higher scoring in the test group was recorded for the attributes *pleasant, interesting and exciting*. Table 2 shows the results for visual comfort, daylight dynamics, and the level of illuminance (daylight and artificial light together) (questions 2–6). Statistically significant higher scoring was recorded for statement 6b, *Satisfying level of artificial and daylight together in the entire room*, in the test group compared with the reference group.

1. How do you experience this room?	Test group			Reference group					
Attributes:	M	SD	SE	M	SD	SE	t	df	p
bright	2.59	1.010	.194	2.74	1.214	.253	-0.466	48	0.643
spacious	3.15	0.949	.183	2.78	1.126	.235	1.246	48	0.219
open	2.89	0.801	.154	2.43	0.992	.207	1.791	48	0.080
uniform	2.96	1.065	.222	2.64	1.217	.259	0.940	43	0.352
pleasant	1.96	1.038	.204	1.30	1.063	.222	2.186	47	**0.034**
interesting	2.37	1.275	.245	1.43	1.080	.225	2.771	48	**0.008**
exciting	2.22	1.219	.235	1.35	1.027	.214	2.714	48	**0.009**
legible	3.19	1.001	.193	2.95	1.046	.223	0.786	47	0.436

Table 1. Independent sample *t*-test analyses compare the scoring in the test and reference groups in terms of visual experience and perceptual impression of the test office.

Questions from the survey	Test group M	SD	SE	Reference group M	SD	SE	t	df	p
2. The daylight conditions in the room are satisfying	2.70	0.993	.191	2.26	1.251	.261	1.395	48	0.169
2a. Temporal changes of light have been noticed	1.40	1.506	.476	1.31	1.316	.365	0.157	21	0.877
3. No difficulties regarding the visibility of the task on the screen	3.15	0.989	.190	3.27	0.767	.164	-0.484	47	0.631
4. No reflections on the PC screen caused by the light	3.44	0.712	.142	3.33	0.913	.199	0.445	44	0.658
5. Difference between the colour of light were noticed	1.72	1.275	.255	2.05	1.468	.328	-0.807	43	0.424
6a. Satisfying level of artificial and daylight together at the workplace	2.96	1.020	.204	2.41	1.182	.252	1.716	45	0.093
6b. Satisfying level of artificial and daylight together in the entire room	2.88	0.927	.185	1.95	0.999	.213	3.293	45	**0.002**
6c. Satisfying level of artificial and daylight together on the screen	3.28	0.843	.169	3.05	1.117	.244	0.804	44	0.426

Table 2. Independent sample *t*-test analyses compare the scoring in the test and reference group regarding visual comfort and level of illuminance (daylight and artificial light together) in the test office.

Correlation analyses were computed for the variables of interest—E_{1Mean}, E_{2Mean}, E_{3Mean}, v-E_1, v-E_2 and v-E_3—and scores for survey questions 1–6 in order to check if there were any statistically significant correlations between the variables. Several statistically significant correlations for visual experience and perceptual impression of the test room were found (Table 3). For the mean value of the indoor illuminance on the test desk, E_{1Mean}, a statistically significant (negative) correlation was found for perceiving the room as *exciting* (Pearson's -0.308 [$p < .05$]). For the mean value of the outdoor vertical illuminance incidence on the tube, E_{2Mean}, a statistically significant correlation was found for perceiving the room as *open* (Pearson's 0.298 [$p < .05$]), *pleasant* (Pearson's 0.332 [$p < .05$]), *interesting* (Pearson's 0.419 [$p < .01$]), and *exciting* (Pearson's 0.436 [$p < .01$]). For the mean value of the outdoor global horizontal illuminance, E_{3Mean}, a statistically significant correlation was found for perceiving the room as *pleasant* (Pearson's 0.305 [$p < .05$]), *interesting* (Pearson's 0.341 [$p < .05$]), and *exciting* (Pearson's 0.372 [$p < .01$]). Graphs for the correlation analyses are enclosed in appendix C, Figs C1a-h. For the variation in the outdoor illuminance value incident to the tube, v-E_2, a statistically significant (negative) correlation was found for perceiving the room as *pleasant* (Pearson's -0.326 [$p < .05$]), *interesting* (Pearson's -0.392 [$p < .01$]), and *exciting* (Pearson's -0.338 [$p < .05$]). For the variation in the outdoor global horizontal illuminance, v-E_3, a statistically significant (negative) correlation was found for perceiving the room as *uniform* (Pearson's -0.330 [$p < .05$]), *interesting* (Pearson's -0.318 [$p < .05$]), and *exciting* (Pearson's -0.305 [$p < .05$]). Graphs for the correlation analyses are enclosed in appendix C, Figs C2a-h.

The authors did not find any statistically significant correlation between the — variables of interest—E_{1Mean}, E_{2Mean}, E_{3Mean}, v-E_1, v-E_2 and v-E_3 — and scores regarding visual comfort, daylight dynamics, and the level of illuminance (daylight and artificial light together) in the test office (Table 4).

1. How do you experience this room? Attributes		E_{1Mean}	E_{2Mean}	E_{3Mean}	v-E_1	v-E_2	v-E_3
bright	Pearson Corr.	.141	-.055	-.063	-.234	-.266	-.180
	P value	.328	.706	.664	.101	.062	.212
spacious	Pearson Corr.	-.122	.187	.060	.030	-.161	-.193
	P value	.398	.193	.679	.837	.264	.180
open	Pearson Corr.	-.223	**.298***	.262	-.033	-.229	-.227
	P value	.119	.036	.066	.822	.109	.113
uniform	Pearson Corr.	-.081	.126	.054	-.067	-.196	**-.330***
	P value	.598	.410	.724	.663	.198	.027
pleasant	Pearson Corr.	-.281	**.332***	**.305***	-.014	**-.326***	-.281
	P value	.051	.020	.033	.923	.022	.050
interesting	Pearson Corr.	-.147	**.419****	**.341***	.026	**-.392****	**-.318***
	P value	.309	.002	.015	.859	.005	.025
exciting	Pearson Corr.	**-.308***	**.436****	**.372****	.065	**-.338***	**-.305***
	P value	.029	.002	.008	.652	.016	.032
legible	Pearson Corr.	-.090	.132	.108	.009	-.169	-.267
	P value	.540	.367	.461	.950	-.246	.064
Significance levels: * $p < .05$; ** $p < .01$. The analyses are based on n: 45–50							

Table 3. Correlation analyses between the E_{1Mean}, E_{2Mean}, E_{3Mean}, v-E_1, v-E_2 and v-E_3 and scores given by participants for visual experience and perceptual impression in the test office.

Questions from the survey		E_{1Mean}	E_{2Mean}	E_{3Mean}	v-E_1	v-E_2	v-E_3
2. The daylight conditions in the room are satisfying	Pearson Corr.	.126	.043	-.029	.050	-.200	-.091
	P value	.382	.769	.841	.728	.163	.530
2a. Temporal changes in the light have been noticed	Pearson Corr.	-.167	-.028	.032	.207	.028	.056
	P value	.446	.900	.884	.344	.901	.799
3. No difficulties regarding the visibility of the task on the screen	Pearson Corr.	.106	-.143	-.092	-.021	.122	.135
	P value	.470	.326	.528	.885	.405	.356
4. No reflections on the PC screen caused by the light	Pearson Corr.	.078	.089	.036	.008	.019	-.012
	P value	.607	.557	.813	.960	.898	.936
5. Difference between the colour of light were noticed	Pearson Corr.	.019	-.212	-.147	.115	.254	.124
	P value	.899	.162	.335	.451	.092	.417
6a. Satisfying level of artificial and daylight together at the workplace	Pearson Corr.	.059	.145	.051	.017	-.197	-.170
	P value	.693	.332	.734	.912	.184	.254
6b. Satisfying level of artificial and daylight together in the entire room	Pearson Corr.	-.067	.268	.201	.192	-.231	-.101
	P value	.656	.069	.176	.196	.118	.501
6c. Satisfying level of artificial and daylight together on the screen	Pearson Corr.	.018	.181	.181	.153	-.092	-.073
	P value	.906	.230	.230	.310	.544	.631
Significance levels: * $p < .05$; ** $p < .01$. The analyses are based on n: 23–50							

Table 4. Correlation analyses between E_{1Mean}, E_{2Mean}, E_{3Mean}, v-E_1, v-E_2 and v-E_3 and scores given by participants regarding visual comfort and level of illuminance (daylight and artificial light together) in the test office

3.2 Descriptive analyses

The average score given by the participants in the test group in terms of the visual experience and perceptual impression of the test room indicated a more positive evaluation of the test room as *spacious*, *open*, *uniform*, and *legible* when compared to the reference group; this was even more evident for evaluations of the test room as *pleasant*, *interesting*, and *exciting* (Fig. 7). The *brightness* of the room was rated higher by the reference group than the test group. This result can be explained by the level of illuminance on the desk (E_1), which, in the case of the higher daylighting supplement, was lower as a result of the light being re-directed from the slats against the DLC sensors and the fault signal given to the luminaires. This situation is briefly explained in section 2.1.5.

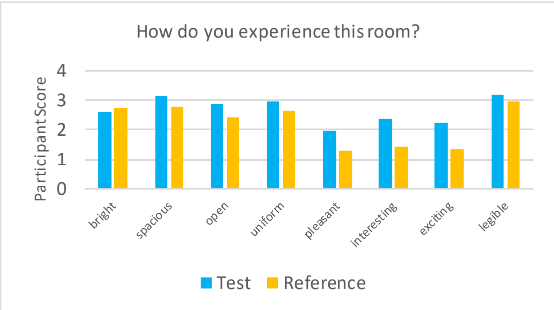

Fig. 7. Average scores given by the participants in the test and reference groups in terms of their visual experience and perceptual impression of the room.

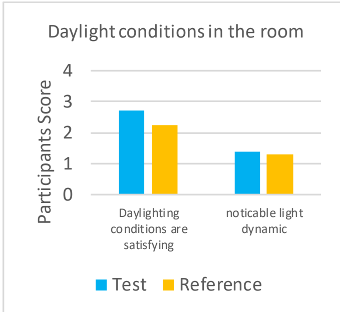

Fig. 8. Average scores given by the participants in the test and reference groups in terms of the daylight conditions and daylight dynamics in the room

The average scores given by the participants in their evaluation of whether the daylighting conditions were satisfying were higher in the test group than in the reference group (Fig. 8). The underlying visual conditions' effect on visual comfort in the room as a glare-free space could also be noted, as both groups evaluated the room above neutral (2). For the evaluation of the light dynamics, which was in terms of whether temporal changes in the light were noticed, the scores were low (under 2). This result indicates that the participants did not notice the dynamics of the daylight.

The average scores for questions regarding visual comfort were analysed. These questions asked whether the participants experience difficulties regarding the visibility of the task on the screen or observe reflections caused by the light; or if they noticed the difference in colour of the light. As previously discussed, the participants answered very positively (Fig. 9). No significant differences between the test and reference group were noted. This underly the issues widely discussed in the daylighting field regarding glare-free spaces.

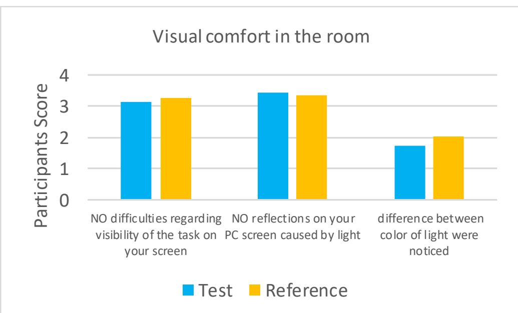

Fig. 9. Average scores given by the test and reference groups in terms of their visual comfort in the test room

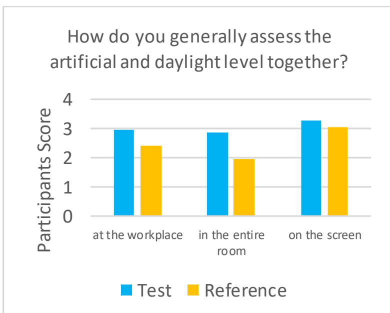

Fig 10. Average scores given by the test and reference groups in terms of the level of light (artificial and daylight together)

Evaluation of the test and reference group in regard to the daylight and artificial light levels indicated differences in the average scores. There was a more generally positive assessment in the test group in regard to the light level in the workplace as well as in the entire room and on the PC screen (Fig. 10). The largest difference in the assessment between the two groups was in regard to the light level (artificial and daylighting) in the entire room and at the workspace (desk 2).

In the evaluation of the participants' visual experience and perceptual impression of the test office, it was found that their scores slightly increased with their age. Furthermore, rated their visual experience and perceptual impression of the test office more positively than the males.

4. Discussion

Statistical and descriptive analyses show compatible results. While statistical analyses emphasize factors with an effect at a certain significant level, descriptive analyses provide easily understandable ideas about how results are distributed, relationships, and correlations between them.

The analyses confirm previously discussed issue that the sole use of photometric measurement (here illuminance) is an unreliable assessment tool for light condition qualification The light conditions in a space are created for human use. Human reactions to lighting have been historically marked as unreliable, but many studies have shown that human responses to light stimuli, sometimes noted as inexplicable, have logic under certain conditions. It is not easy to identify such conditions by comparing parametric measurements, but the human reaction can and, in the case of this study, did help in understanding such conditions. The authors' expectation of more positive participant reactions with an increasing variety in the daylight was disproven. This helped to shed light on this occurrence, and the authors put focus on finding how unbalanced light levels indoor are related to light levels outdoors. The variation in the daylight in the office here was supplemented (unplanned) by a non-attendant (wrongful and not balanced) level of artificial light, which, altogether, produced an uncomfortable situation for the participants, often known as "gloominess.

The participants' evaluation of the room's pleasantness was relatively low in both groups, which could have resulted from the room having been released of any possible decorative elements (pictures, flowers) that are common in many workplaces, in addition, the ceiling was removed. The participants' sitting position was too close to the door, without visual control over the office entrance. Humans prefer to have visual control over a space, such as having a direct view of the entrance at any time. This issue was discussed by several authors (Appleton 1984, Appleton 1988, Mumcu and Duuml 2010).

Daylight reflected on the slats and directed against the ceiling affected the DLC sensors, which resulted in incorrect information being given to the DLC system in its adjustment of the artificial light level. When under an overcast sky, the fade time for the DLC was not as unsuitable as when under a clear, sunny sky, under which the magnitude of the sun/sky luminance variation was much higher.

None of the participants complained about glare or excessive light in the test office. In situations where the level of light recorded by the illuminance meters on the desk was as low as 300 lux, higher daylighting spread in the room made the room appear pleasant, and participants commented that they noticed the light level was low but that it was comfortable to work. The fine-tuning of the sloping of the slats in the sun-shading system to 45 degrees proved to protect participants against glare.

Comments from the participants for the open ended question in the survey, when the light level on the desk was about 350 lux and the amount of the daylight via the pipe was noticeable: "It feels pleasant, and my eyes can relax"; "very unusual lighting: it feels simple/flat, but it is satisfying to work on the screen"; and "my 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."

Participants' comments when the level was 450 to 500 lux under an overcast sky and when the luminaires supplied the entire light included: "The corner towards the door is dark"; "the room and furniture/tables are white and uninspiring. Can probably seem a little cold in our climate"; "the room is somewhat monotonous and dull"; and "no colour dynamics. It keeps me awake, but I can get tired faster with exertion."

The crucial point here is that the aspect ratio of the used HLP, 17, could be used to supply daylight to the third workspace, as discussed in Obradovic and Matusiak (2020). This suggests that similar effects can be expected even much further from the window.

5. Conclusion

The research question raised at the beginning of this study, whether noticeable daylighting provision from the HLP leads to a more positive impression of the space compared to a situation without daylight provision via the HLP, can be answered using the findings from the statistical and descriptive analyses. The general conclusion is that the user appraisal of the office was more positive when there was a noticeable daylight supplement from the HLP in the space, but the appraisal was negative for the higher variability in the illuminance level both indoors and outdoors. The importance of this study lays in the user'-survey results and conclusions that will serve as an additional argument for implementation of the HLP in the building design, besides its energy saving potential.

The independent sample *t*-test showed that there was an overall more positive evaluation of the room as *pleasant*, *interesting*, and *exciting* in the test group which had significant light from the outside delivered through the HLP. The test group also evaluated the *daylight and artificial light conditions in the entire room* more positively than the reference group.

The increase in E_2 had a statistically significant relationship with the increase in perceiving the room as *open, pleasant*, *interesting*, and *exciting.* There was also an increased positive evaluation for the room attributes of *spacious*, *uniform* and *legible* with an increasing E3.

Unexpectedly, there was a statistically significant negative relationship between v-E_2 and v-E_3 and the participants' evaluation of the test room as *uniform*, *pleasant*, *exciting* and *interesting*. This can be explained by the inconsistent variation in the artificial light level, which was supposed to supplement the missing light level to achieve a recommended level in the office; however, this did not happen due to the daylight reflection on the slats and the false information given to DLC system.

Furthermore, there was a significant negative relationship between the level of indoor illuminance and the participants' perception of the room as *exciting*. The level of indoor illuminance was higher in cases when the DLC was not affected by the higher levels outdoor daylight reflected on the slats, which means that the higher level of indoor illuminance was strictly provided from the artificial light, which resulted in participants' negative impressions of the room in regard to it being "exciting".

The authors of this study had the opportunity to introduce a completely novel approach to distribute light from the light pipe, via a *custom-designed mirror reflector*. During this long-term study, it was observed that such a mirror reflector managed to provide visually clear and obvious sun patches, light sparkling, and sharp light variations on the desk under the pipe, which was directly associated with the variation in the natural light outside. The standard solution for a distributor provided by the manufacturer, opal, satin, or micro-prismatic diffuser, would never be able to produce those effects. Participants did not make any comments regarding the light sparkles on the desk.

Finally, this study has certain limitations: For instance, it is unknown whether the results can be generalized to spaces and offices of different sizes than the one used in this study. We assume that, in open-plan offices, in which the user has a deeper view of the space, the aspects of daylighting and lighting quality that are discussed in this paper will have an even higher significance in terms of user opinion. This assumption outlines a suggestion for further research.

Acknowledgement: This study was conducted as a part of a PhD-study at the Norwegian University of Science and Technology with Norconsult AS and the Norwegian Research Council's support. The concept of the full-scale test office was motivated by limited knowledge regarding daylighting by HLP in the form of image-forming lighting effects and non-imaging forming light effects on humans; potential in lighting energy reduction; and reference projects on HLP application in Norway. The authors hope the full-scale study results will fill the knowledge gap for architects, lighting designers, and investors by providing insight into the application possibilities of the HLP in buildings in Norway. Moreover, the authors are grateful to Per Fosse for supplying them with the Tambartun Oral Reading Test. We appreciate the sponsorship of the full-scale test office from Glamox along with the luminaires and photosensors as well as Carlo Gavazzi for the outdoor illuminance meters and controlling units. Last, the authors are grateful to Norconsult AS for the access to the test office for a whole year and the caretakers of the building for additional technical support.

Contributions

B.O. conceived and wrote the study; B.M. helped define the methodology, gave feedback on the paper's content, and contributed by performing quality assurance and proofreading. C.K. helped perform the statistical analysis and interpretation. S.A. helped prepare the user-survey, gave feedback on the content of the paper, and contributed by performing quality assurance and proofreading.

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Appendix A

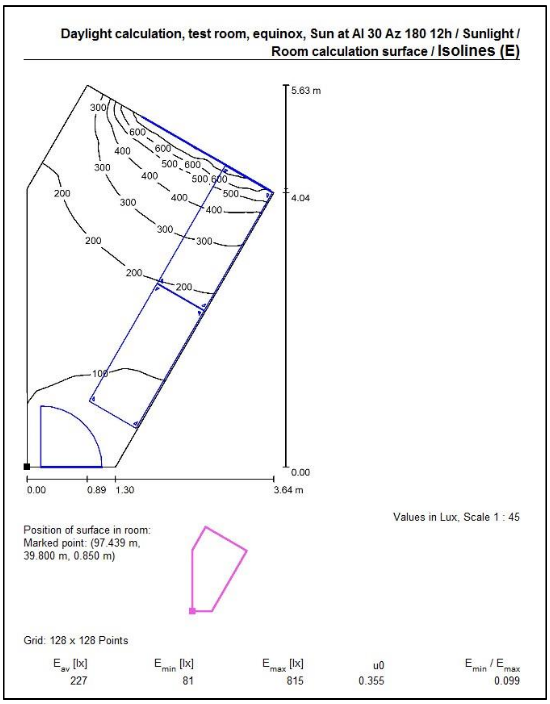


Fig. A1. Daylight calculation for equinox at 12:00 h under a clear sunny sky sun at Al 30° and Az 180°

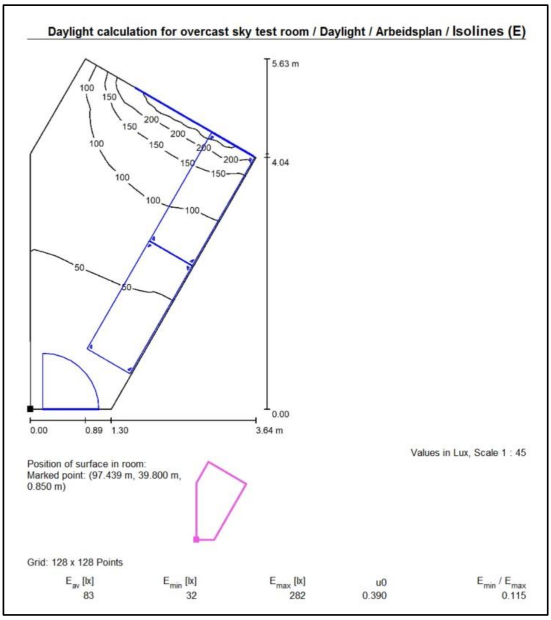


Fig. A2. Daylight calculation for equinox under an overcast sky

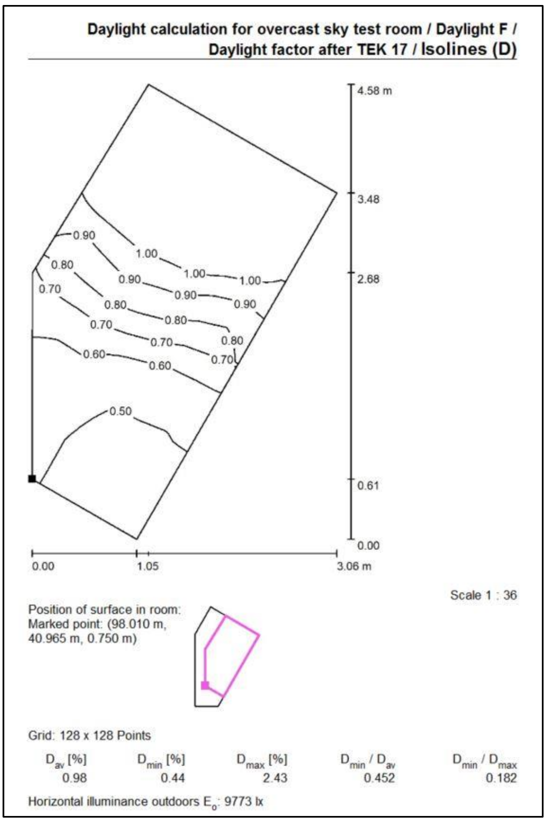
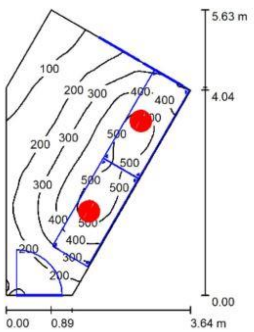


Fig. A3. Daylight calculation of the test room, daylight factor (Df) after TEK17 (Norwegian Technical standard)

Appendix B

Calculation of artificial lighting test room / Summary



Height of Room: 2.800 m, Mounting Height: 2.700 m, Maintenance factor: 1.00 — Values in Lux, Scale 1:73

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Arbeidsplan	/	290	67	539	0.231
Gulv	20	137	17	287	0.120
Tak	70	77	41	120	0.531
Walls (5)	50	129	15	826	/

Arbeidsplan:

Height:	0.850 m
Grid:	128 x 128 Points
Boundary Zone:	0.000 m

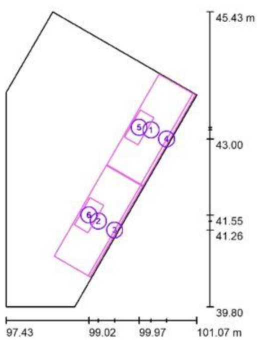
Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ (Luminaire) [lm]	Φ (Lamps) [lm]	P [W]
1	2	Glamox C90-S420 2800 840 MP (1.000)	2704	2704	22.0
			Total: 5408	Total: 5408	44.0

Specific connected load: 3.41 W/m² = 1.18 W/m²/100 lx (Ground area: 12.89 m²)

Fig. B1. Lighting calculation for the test room, artificial lighting

Calculation of artificial lighting test room / Calculation surfaces (results overview)



Scale 1 : 65

Calculation Surface List

No.	Designation	Type	Grid	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0	E_{min} / E_{max}
1	Horisontal calculation surface desk 1	perpendicular	32 x 16	459	295	534	0.644	0.553
2	Horisontal calculation surface desk 2	perpendicular	32 x 16	466	298	537	0.640	0.555
3	Vertical calculation surface desk 2	perpendicular	32 x 16	252	157	422	0.624	0.373
4	Vertical calculation surface desk 1	perpendicular	32 x 16	244	163	416	0.667	0.392
5	Task field 1	perpendicular	8 x 4	517	491	531	0.949	0.924
6	Task field 2	perpendicular	8 x 4	519	491	534	0.946	0.920

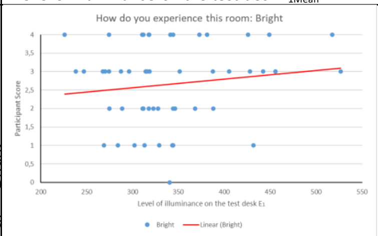
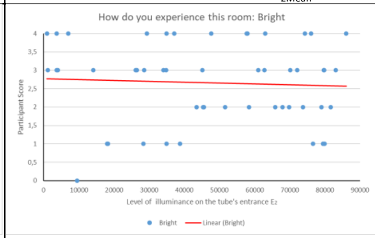
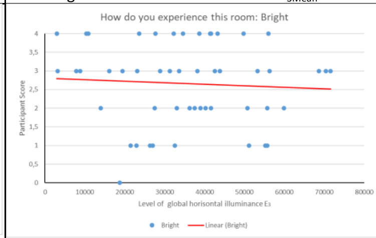
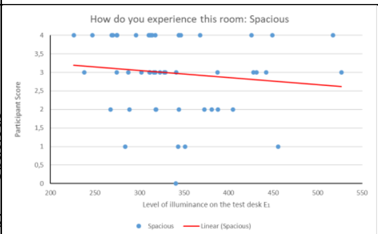
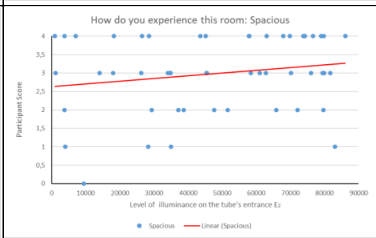
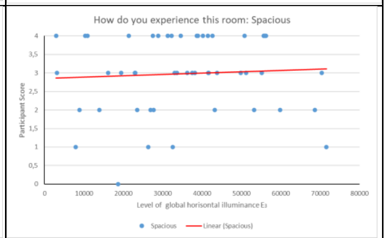
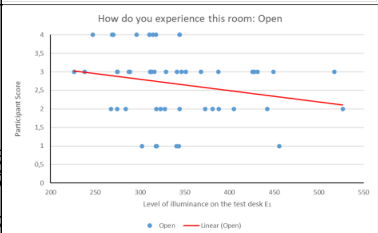
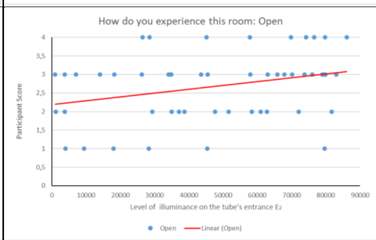
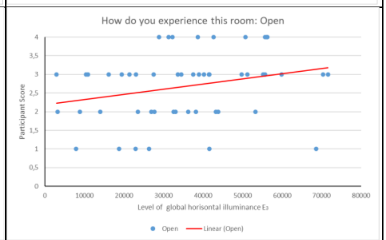
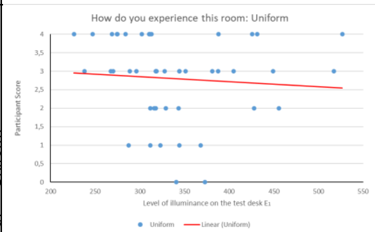
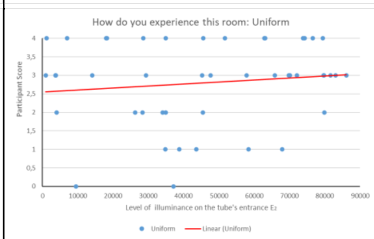
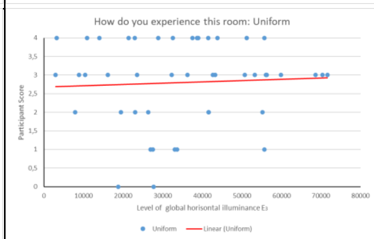
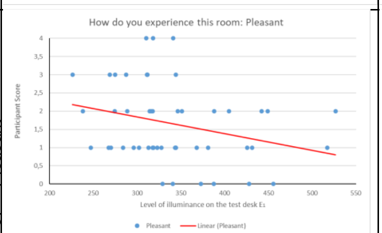
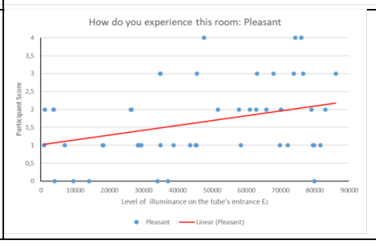
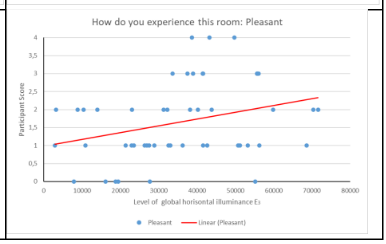
Summary of Results

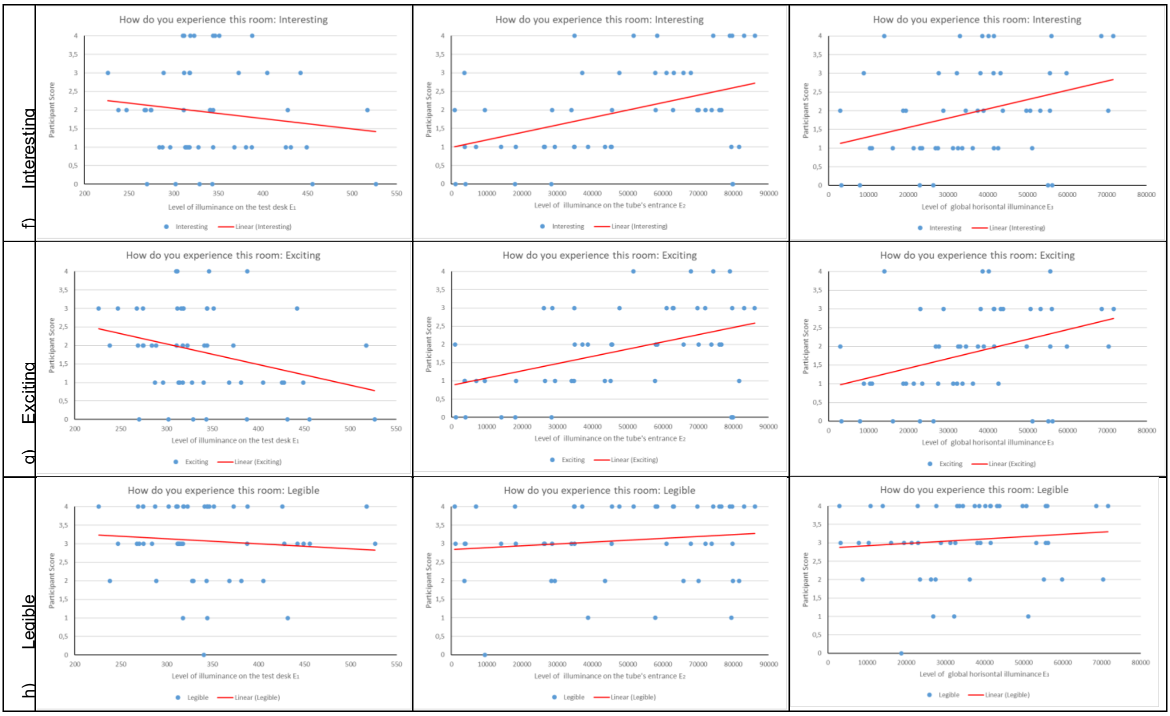
Type	Quantity	Average [lx]	Min [lx]	Max [lx]	u0	E_{min} / E_{max}
perpendicular	6	364	157	537	0.43	0.29

Fig. B2. Lighting calculation for the test room, artificial lighting on a relevant calculation surfaces

Appendix C

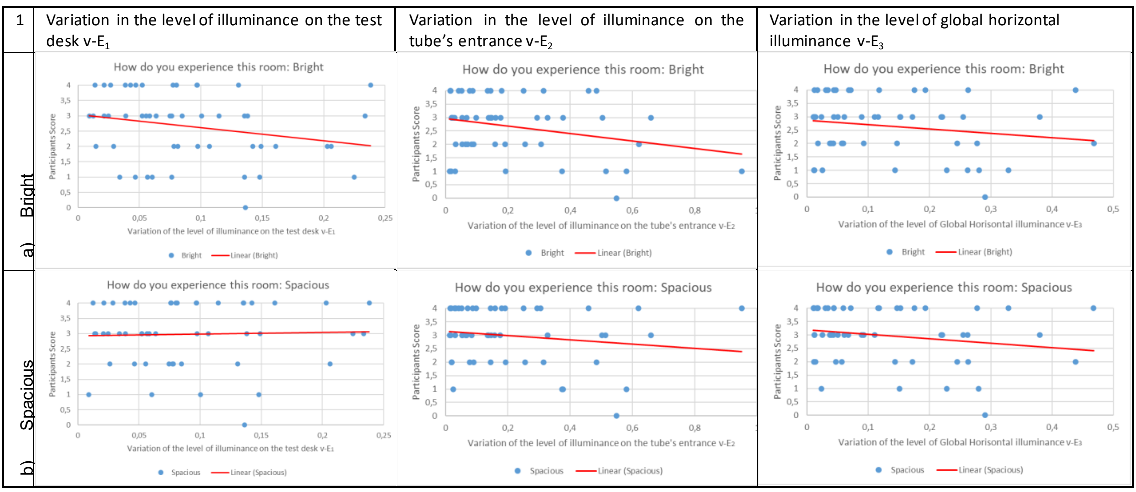
The analyses of participants' scores for the first question regarding the visual appearance and perceptual impression of all 50 participants according to the E_{1Mean}, E_{2Mean}, and E_{3Mean} values are illustrated in Figs. C1a–h. The evaluation was in agreement with that previously discussed in section 2.1.5. A reason for the increase in E_1 and how it is connected to the level of daylight delivered via the light pipe is explained in section 2.1.5.

1	Level of illuminance on the test desk E_{1Mean}	Level of illumin. on the tube's entr. E_{2Mean}	Level of global horizontal illuminance E_{3Mean}
a) Bright			
b) Spacious			
c) Open			
d) Uniform			
e) Pleasant			



Figs C1a-h. Participants' scores for different attributes related to visual appearance and perceptual impression of the test room based on E_{1Mean}, E_{2Mean}, and E_{3Mean}. In the evaluation of brightness, the participants' scores increased with the illuminance on the test desk (E1Mean), Fig. 11a, and slightly decreased as both the outdoor illuminance at the tube's entrance (E2Mean) and the global horizontal illuminance (E3Mean) increased. Figs. 11b–h show that, as E1Mean increased, the participants' scores decreased, and, as E2Mean and E3Mean increased, the scores increased for all other attributes related to visual appearance and perceptual impression (except brightness). This is clear in the evaluation of the room as a pleasant, interesting and exciting.

The analysis of participants' scores of the various attributes in terms of visual experience and perceptual impression of the test office was assessed in terms of the level of variation in the illuminance values (E_1, E_2 and E_3) v-E_1, v-E_2 and v-E_3.the graphs are presented in Figs C2a-h.



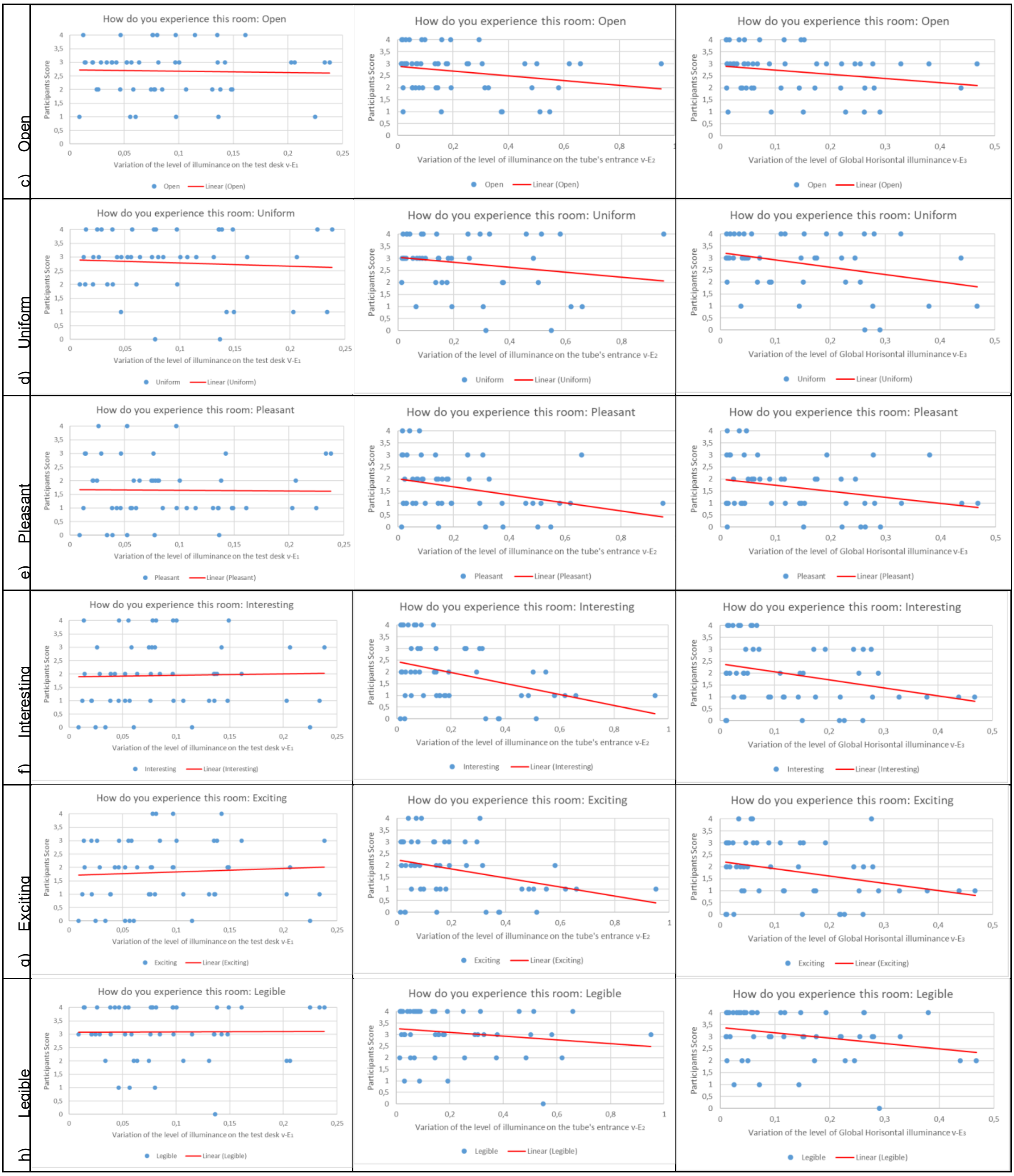


Fig C2a–h. Participant scores for the attributes related to visual experience and perceptual impression of the test office based on v-E_1, v-E_2 and v-E_3. Left column with figures show that the variation in the illuminance values on the desk (v-E1) did not have any visible correlation to the participants' scores—except in the case of the room's brightness. The higher v-E1 brought about lower scoring for the room as bright, as a higher variation is also correlated to higher outdoor illuminance conditions, E2 and E3. Higher daylight supplement, (unplanned) brought about higher variation in illuminance levels on desk 2 (v-E1), which participants evaluated negatively. The increasing variation in E2 and E3 was associated with lower participants scores (Figs D3a–h; middle and right) for all other evaluation attributes. This trend is especially noticeable for perceiving the room as pleasant, exciting, and interesting.

Illumination and lighting energy use in an office room equipped with a horizontal light pipe with a reflector, field study at a high latitude

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Abstract

This paper describes a field study of the Illumination and lighting energy use in a full-scale test office in a building located in southern Norway. Natural light is provided to the office via southwest-oriented windows and a horizontal light pipe (HLP) with a daylight entrance facing the south. The study is a full-scale field study, and it is a continuation of the recently published study addressing a scale model and a theoretical model. The novelty of this study is a custom-made reflector for the HLP's daylight distribution to preserve the features of natural light noted as the primary human association with daylight. The main research aim was to determine if the daylighting level in the back of the office was improved as a consequence of the daylighting provision from the HLP compared to a reference situation without a HLP as well as whether the lighting energy use for the artificial lighting system that was supposed to provide the recommended light level was reduced. This study includes monitoring of the outdoor and indoor illuminance levels as well as the energy consumption of the luminaires throughout the study's test period and a corresponding reference period. The recorded data were used to test hypothesis applying inferential statistical analyses. In conclusion, this paper reports an increased daylight level on the working area in the rear part of the office of approximately 200 to 300 lux during clear and sunny days at equinox. The increased daylight level on the working area near the window of approx. 50 lux was also recorded. These findings have important implications for energy balance in the Zero Energy Buildings (ZEB) and the 'peak load' for energy consumption.

Keywords: Horizontal light pipe (HLP), daylight tube, full-scale, high latitudes, illumination, photometry, artificial lighting energy use, LENI

Abbreviations

GHI – Global horizontal illuminance recorded during the test or reference period, lux

VI – Vertical illuminance on the tube's entrance recorded during the test or reference period, lux

DLC – Daylight-Linked Control

LENI – Lighting Energy Numerical Indicator

PBC – Point Biserial Correlation

1. Introduction

This paper presents a field monitoring study carried out as part of a full-scale study performed in an office equipped with a horizontal light pipe (HLP) in a high-latitude area in southern Norway. This full-scale study was developed following the semi empirical study, with a scale model of a HLP and a theoretical model of the office, recently reported in the article by Obradovic and Matusiak (2020). The present paper focuses on the quantitative features of the daylighting delivered by the HLP, illumination, and the lighting energy use of the artificial lighting solution. The qualitative analyses of this HLP solution in the full-scale office can be found in recently published study by Obradovic, Matusiak et al. (2021). This full-scale study was one of the case studies of IEA SHC Task 61, Subtask D, 'Integrated Solutions for Daylighting and Electric Lighting' (Amorim, Gentile et al. 2021).

Literature review

Artificial lighting represented almost 40% of the total energy use in commercial buildings in Scandinavia, as argued by Kolås (2011); however, since 2010, the evolving usage of LED light sources may have reduced this statistic depending on whether there has been no rebound effect caused by 'over-usage'. The most efficient way to save energy is to reduce the installed electrical power density (W/m^2) in the project's design phase, as stated by Ryckaert, Lootens et al. (2010) and Yun, Kim et al. (2012). Lighting design that aims for energy efficiency can develop lightings solutions based on a localized lighting rather than general, but such solutions lack flexibility. In the regions near the equator, the increased exploitation of daylight could lead to a reduction of installed power density as long as the building function coincides with the daylight hours, but this can be the case of a small number of functions, as most of the buildings operate also during the night (at least maintenance and cleaning). However, for high-latitude areas in the extreme north or south, the reduction of installed power density based on available daylighting is not feasible, due to the extremely short daylight period during the winter months. The fulfilment of the requirements for visual performance completely relies on artificial lighting. The only possibility to reduce energy consumption for lighting will be to focus on the periods throughout the year with abundant daylight. Therefore, the Lighting Energy Numerical Indicator (LENI), which presents the energy necessary for artificial lighting, is more suitable evaluation indicator than installed power density. Reducing the operating time of artificial lighting (included in LENI) through prolonged daylight availability (DA) is equally important, as stated by Tsangrassoulis, Kontadakis et al. (2017). For instance, Passive House Standards in Norway (NS 3700:2013; NS 3701:2012) set a LENI value threshold of a maximum of 12.5 kWh/m^2 per year, (e.g., for office buildings). The value is referred to the methodology described in the Norwegian standard for calculation of energy performance of buildings (NS3031), and, European standard for energy requirements for lighting (EN15193).

Boyce, Hunter et al. (2003) stated that, nowadays, people spend as much as 90% of their time indoors, and these long hours are not necessarily spent in areas near windows with available natural light but instead in areas far from windows. As an individual moves away from the window, the available daylighting decreases exponentially, as argued by Rosenfeld and Selkowitz (1977). Here, we notice the necessity to transport daylight beyond the daylit 'perimeter zone' to deeper areas within the building. To daylight a building's deeper areas, a daylight transport system (DTS) can be used, where, e.g., horizontal daylight tubes (or light pipes) are argued to be efficient in delivering daylight to deeper areas of multistorey buildings (Garcia Hansen, Edmonds et al. 2001, Scartezzini and Courret 2004, Duc Hien and Chirarattananon 2009, Daich, Zemmouri et al. 2017, Obradovic and Matusiak 2019, Obradovic and Matusiak 2020). The HLP can increase the illuminance levels of the rear part of the room, which results in better light uniformity and thus reduces the luminous contrast of the room's front and rear areas , as stated by Scartezzini and Courret (2002).

In terms of the prediction of energy savings, many studies have noted an unreliability in the resulting metrics of energy consumption, photometry, and visual comfort in situations with excessive sunlight (Bellia, Pedace et al. 2014, Karlsen, Heiselberg et al. 2015, Karlsen, Heiselberg et al. 2016, Bellia, Fragliasso et al. 2017). The predicted energy use of lighting in the projects, based on a daylighting availability model, used to be much lower than measured during the operation, which is the result of unreliability in predicting human reactions to glare and their motivation to control manually operated blinds. Blind closure results in switching on the lights to their maximum level.

The aim of the integration of daylight and artificial lighting is to minimize the energy consumption of lighting while ensuring adequate illumination. A key component of this integration is the daylight linked control system (DLC), which installation can be inappropriate even at the start. Several studies based on empirical settings concluded that discrepancies (e.g., insufficient illuminance at the work plane) occur due to the differences between the daylight supplement and measured lighting conditions indoors (Lee, DiBartolomeo et al. 1999, Galasiu, Atif et al. 2004). Systems are usually calibrated very conservatively to avoid user complaints or their overruling of the system, which undermines the energy-saving potential.

The DLC consists of three basic components: a photosensor, controller, and dimming unit. The photosensor requires careful positioning to limit the chance of collecting incorrect information stemming from variable luminance caused by veiling or sunlight patches on the surfaces the sensor covers. Direct sunlight reflected from the exterior ground or from the fenestration system (i.e., venetian blinds) and directed toward the sensors can directly interrupt the DLC. The partial shielding of the sensor can reduce the fluctuation of light, as discussed by Kim and Song (2007), but the other studies recorded that narrow-angled sensors increase the effect of a sudden illuminance level shift on the surface visible to the sensor (Mistrick and Sarkar 2005, Bellia, Fragliasso et al. 2016). Gentile, Dubois et al. (2015) suggested that slightly tilting these sensors, (e.g., 30°) against the wall could be a preferable solution. The control unit is usually steered by the controlling algorithm, which can be open loop, closed loop, and closed loop proportional. LED luminaires, nowadays, possess a linear dimming feature; thus, the provided artificial light is directly proportional to the luminaire’s used energy.

At the beginning of the development of the zenithal light pipe, more than two decades ago, the application was solely based in equatorial areas; thus, solving issues related to glare and excessive sunlight on the pipe’s exit brought about the application of Lambertian diffusor (Zhang, Muneer et al. 2002). Later on, authors studying light pipes under an overcast sky concluded that transparent closure at the light pipe exit should be used for those areas. Transparent closure still provides homogeneous light output for diffuse light input, and it preserves the light transmission efficiency in the case of direct sunlight, which, in areas with predominantly overcast skies, is a more desirable situation, as stated by Swift, Smith et al. (2006) and Jenkins, Zhang et al. (2005). Following those findings, the transparent closure was chosen in the present study. Additionally, a custom-made reflector was made to redirect the light flux to most desirable location, that is to the second desk from the window. User satisfaction with this solution was described in the qualitative part of this full-scale study which was recently published (Obradovic, Matusiak et al. 2021). The introduction of a custom-made reflector is the major novelty of this study.

The application of light pipes in Norway is in an early phase, with no HLPs installed thus far, thus, this study will contribute to the field regarding this latitude area. This study aims to answer the following primary research question: Does daylighting provision via the HLP lead to an increased level of daylight on the desk closest to the back part of the room (situated 4 m from the nearest window in the office), and does the lighting energy use of the luminaire meant to provide the recommended light level on this desk decrease under daylight conditions supplemented with a HLP in comparison to the situation without a HLP?

2. Method

This quantitative study is part of a full-scale research that investigates how daylight delivered through a HLP affects illuminance in an office as well as the energy consumption of each luminaire installed to provide artificial lighting on two working areas. The literature addressing full-scale tests where lighting conditions are examined propose the approach of having two modules, a test and a reference one (Ruck, Aschehoug et al. 2000). The variable luminance distribution of the skylight and sunlight are the main input conditions on which all other monitored conditions depend. As the resource limitations of this project did not allow two modules, an alternative rationale was developed. The highest daylight supplementation with the horizontal light pipe (HLP) will, in any case, happen when there is a clear and sunny sky, thus, the solar altitude and azimuth are the main parameters. Hence, if the two periods, test (summer to winter solstice) and reference (winter to summer solstice) have the same solar altitude and azimuth characteristics, the input parameters will satisfy the terms in sense of establishing the two similar testing periods instead of modules. The study was thus, divided into the test period with operable HLP, which was from 21 June to 21 December of 2020, and a reference period with non-operable HLP, which was from 21 December to 21 June of 2021. The cloudy weather conditions are expected to vary in those two periods, but it is the clear weather and unshaded sun that will establish the compatibility between the periods. The positive fact in the study is the level of control for the parameters of measurement (there is each minute recording of all monitored data, both outdoor and indoor illuminance, and lighting energy use). Hence, there is a full possibility to relate all monitored parameters to each other and between the test and reference periods, in order to have a full overview of validity. The collected data was used as independent and dependent parameters to study relationships. This methodology used in this study is known as a quantitative method using nominal parametric data.

2.1 Experimental design: Full-scale test office

In a fully operative building at Norconsult Headquarters in Sandvika (59°.53'N, 10°.31'E), Norway, a two-person office on the top (6th) floor was used as the test room for one year. The form, size, and orientation of the office were not perfect for the research purpose, but it satisfied the researchers' requirements after it was altered. In this study the daylight provided via HLP was analysed, but contrary to the previous study, Obradovic and Matusiak (2020), it was carried out in a real office with luminaires and sun shading systems equal as for the whole office building. Following the thought of testing a realistic situation, windows were not darkened and therefore the findings of the HLP's effect could be seen in relation to daylight supplied also via window. Hence, all recorded values of the indoor illuminance present the daylight supplement via HLP and windows together. The limitation of the study lies in that the pipe's exit was a bit close to the window, (3.5m in the perimeter daylighting sone).

2.1.1 Test room

The office had an area of 13 m^2 and a height of 2.8 m after its suspended ceiling was removed. The finishes and colours of the room's interior surfaces were representative of typical offices in Nordic countries. The office had two identical windows on its southwest walls. The horizontal daylight tube was installed 45° from the southeast wall (Fig. 1b), with the aim of allowing for the placement of the tube's exit above the second work area from the windows, 'desk 2', without any tube's bend (i.e., the tube was straight) as well as positioning the tube with a southern orientation (175°). The office was equipped with the minimum necessary furniture common for Nordic countries: two desks and two chairs (Fig.1c).

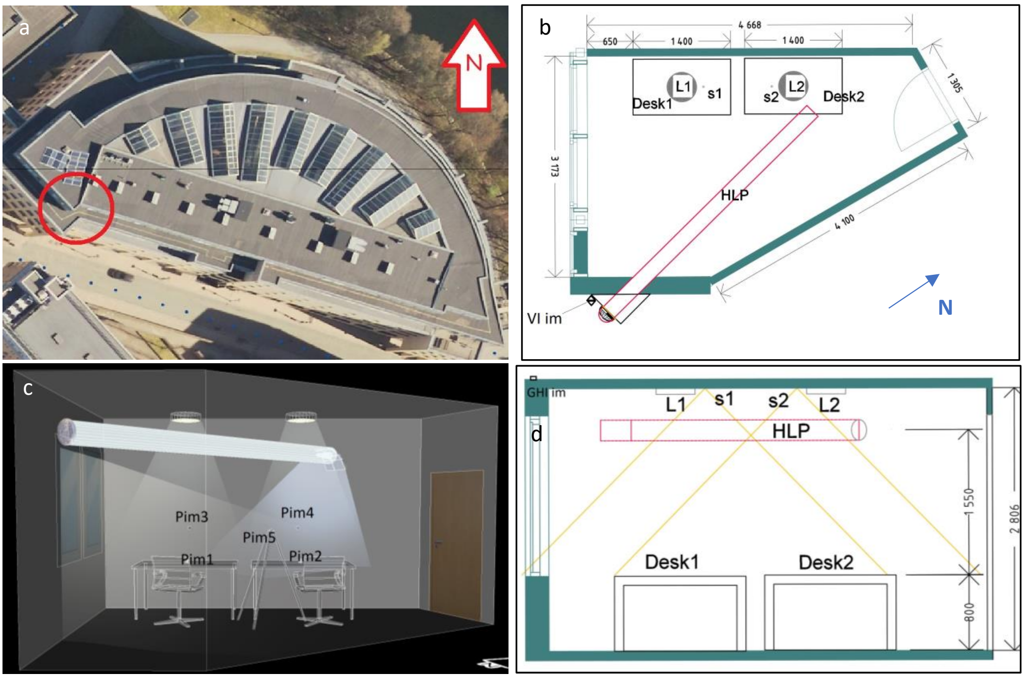

Fig. 1. Full-scale test office. a) Situation plan of the Norconsult Headquarters in Sandvika; b) plan of the test office, VI im is the outdoor vertical illuminance meter; c) model of the office with sources of illumination: window, HLP, and luminaires; Pim (1 to 5) show the position of the five indoor illuminance meters; d) section the room, Desk 1 is closest to the window and desk 2 is closest to the door. The HLP exit is near the desk 2 and the custom-designed reflector direct the daylight to the desk 2. Desk 1 is to be lit by artificial lighting from luminaire 1 (L1), and desk 2 from luminaire 2 (L2). S1 is the DLC sensor connected to L1, and S2 is the sensor connected to L2. GHI is the outdoor illuminance meter on the roof.

2.1.2 Sun-shading strategy in the test office

The sun-shading strategy was developed in the test office to provide visual comfort at any time of day and year, thus creating a glare-free space that would be reliable for the estimation of energy consumption and saving. The sun-shading strategy in the office consisted of keeping the outdoor sun-shading slats, which were manually controlled, partly open at a tilt angle 45° for a sunlight cut-off. The glare-free space ensured that situations with excessive sunlight would not occur at all, and the users' need to close the blinds completely would be prevented. Figure 2 presents the view (visual conditions) from the entrance of the office (2a), from Desk 2 (2b), and from Desk 1 (2c).

The outdoor venetian blinds had curved slats (8 cm width and 1 cm thick) and were positioned within a frame. The distance between slats was 8 cm. The sun-shading slats were made of semi-specular white aluminium. The configuration of the slats' angle (partly open at a tilt angle 45° for a sunlight cut-off) was based on the study by Kolås (2013) that was performed for the same location as the present study.

2.1.3 Daylighting conditions in the office

Daylight in the office was provided by two windows facing southwest. The daylight calculations (using Dialux 4.3 software) for the room were performed by applying the aforementioned sun-shading strategy (section 2.1.2) to check what would be reasonable to expect for the daylight supplementation on the two desks in the office. These calculations were done without accounting for the daylight from the HLP. Results were reported in the appendix A1 in the qualitative part of this full-scale study which was recently published (Obradovic, Matusiak et al. 2021). Under a clear, sunny sky during equinox at 12:00 h (sun's altitude of 30°, azimuth of 180°), the values would be 350 lux on the desk 1, closest to the window, and 120 lux on the desk 2, closest to the door.

Fig. 2. Visual conditions with the sun-shading strategy: from the entrance to the office (a); from desk 2, closest to the door (b); from desk 1, closest to the window (c)

2.1.4 Horizontal light pipe in the test office

The HLP used in this study was the LW300 manufactured by LightWay company. Due to the building's constructive issues, the maximum diameter of a pipe that could be applied was 22 cm. Dictated by the aim of the study, to have a pipe's exit near desk 2, the necessary length of the pipe was 375 cm. These dimensions provided an aspect ratio of the installed light pipe of 17, which corresponded to a semi-empirical study recently done by the authors (Obradovic and Matusiak 2020). The reflection factor of the inner surface of the pipe is 99.8% according to the manufacturer. The light pipe's dome had a diameter of 26 cm, was manufactured out of crystal glass, and had a light transmission factor of about 95% (test performed by the authors) (Fig. 3a). The light distributor, that is the element of the light pipe that releases the light into the indoor space, was chosen to be clear glass with a light transmission factor of 92%. The direction of the light onto the working area was provided by a custom-made reflector, thus using the same approach as in the semi-empirical study recently done by the authors (Obradovic and Matusiak 2020). Here, the aim was to redirect the light to the working area (desk and wall in front of it) while maintaining the qualitative features of the daylight e.g., dynamics, variation, light patches and colour that is possible to deliver through the HLP.

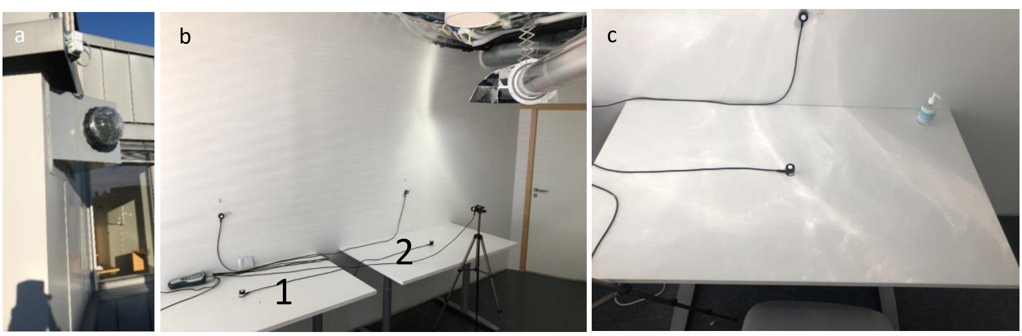

Fig. 3. Light pipe's dome mounted on the façade (a); light pipe's exit in the room, and two working areas in the room (b); daylight and light patches on desk 2 delivered from the HLP and via a custom-made reflector (c).

The design of the custom-made reflector underwent several stages. Due to the scope of this paper just a brief description is provided. When the HLP was installed (from winter 2019 to summer 2020), the light output pattern visible on the wall adjacent to the pipe's exit was observed to understand the expected light distribution at different times of the day and the year. It was first observed that the light flux exhibiting the tube is concentrated in a circular belt around the edges of the tube (Fig. 4a). The angle (cone distribution) of the outcoming light rays from the HLP was suitable to use a concave mirror as a custom-made reflector to obtain the supposed light coverage on the imaginary surface (desk 2 and part of the wall in front of it). The most useful form of the reflector would be a 3D, compound parabolic-formed reflector, as discussed by Chaves (2017), but in order to keep the number of reflector surfaces to a minimum, it was decided to divide the reflector into a net of 4 X 4 parts. The resulting multimirror consisting of 16 surfaces, make it possible to construct with simple workshop conditions while keeping the manufacturing error low (Fig. 4c). The reflector was designed using 3D Autocad software and handcrafted out of lightweight aluminium sheets and manually layered by 3M-mirror folium with a 99% light reflectivity.

Fig. 4. Circular belt formed by light output from the HLP with clear transparent diffuser on the adjacent wall (2 m-distance) in January at noon (a); view of the light pipe opening, with mirror surface (b); custom-made reflector; the suspension is enabled by a scissor mechanism that allows for an easy adjustment in place (c)

All reflected rays will, predicted upon the design, fall within an area between 1.2 m from the centre of the table and spread over the imaginary circular task surface which covers the table and the wall in front of it. However, the ad hoc measurement performed during the equinox, with darkened windows, to check the reflector performance, revealed that the daylight is spread also on the desk 1 (Fig. 5). This could have happened because of the white colour of the room surfaces and light interreflections on them. Between 200 and 300 lux is recorded by the three sensors connected to the desk 2 and up to 50 lux on the 2 sensors connected to the desk 1. The weather was clear and sunny and the vertical illuminance incident HLP was maximum between 60-80klux.

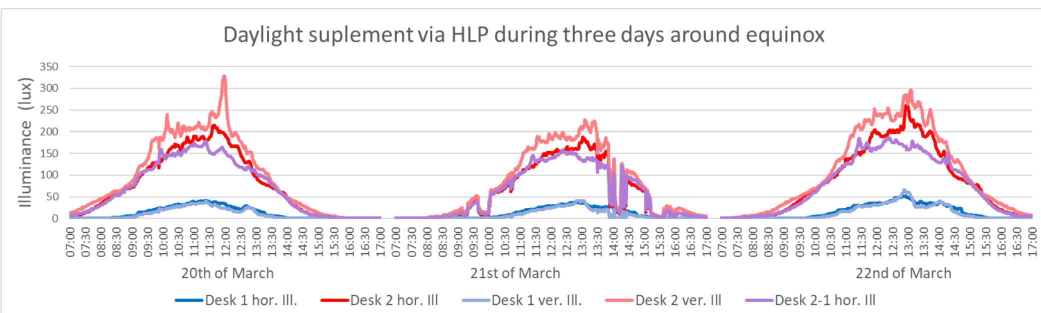

Fig. 5 Recorded values for the daylight illuminance provided just by HLP with the custom-designed reflector, during three days

around equinox. Desks 1 or 2 refer to the desk closest to the window and the desk far from the window, respectively. The illuminance is measured horizontally and vertically for both desks, and, the last point, horizontally, between the two desks.

2.1.5 Artificial lighting in the office

The artificial lighting in the test office was designed according to the Norwegian best practice to ensure fulfilment of lighting recommendation. Lighting solution consisted of two smaller, ceiling-mounted luminaires, manufactured by Glamox. The luminaires provided 2700 lm each, which enabled the required 500 lux of horizontal illuminance on both desks along with a uniformity of over 0.6, as specified in NS-EN 12464-1 (standard for illumination for indoor workplaces). The luminaires had a colour temperature of 4000 K and a colour rendering of Ra = 80.

The estimated LENI, using Dialux 4.13 software, was 10.37 kWh/m^{2}year. The calculation was based on a seven-day week and ten hours of occupancy, where just daylight dependency factors were employed. The operational hours of artificial lighting based on the availability of usable daylight were counted based on the threshold of solar altitude over 5° and accounting for the sun-shading on the windows as well (Appendix A). The daylight time usage was set to 2524 hours and non-daylight time usage was set to 1116 hours which in total results in 3640hours. Each luminaire was connected to a separate photosensor and programmed by a DLC. Luminaires should supplement with additional light when the daylight provided by the windows and light pipe does not reach 500 lux.

When lighting scheme consists of more than one luminaire there is an 'overlapping' illuminance effect. For example, one luminaire is able to provide 440 lux on the desk below it and up to 150 lx on the other desk (in the middle point of each desk). The effect is totally equal for both luminaires, as they are identical and have equally located in relation to the desks. As luminaires are controlled separately the energy use for each of them will be different, hence the provided illuminance solely from the artificial lighting must be estimated considering the overlapping effect. Fig. 6. shows the relation between the power (energy consumption) and illuminance on the desk under, as well as that supplemented to the other desk. The luminaire closest to the window is referred here to as 'L1', and the luminaire closest to the door is referred to as 'L2'.

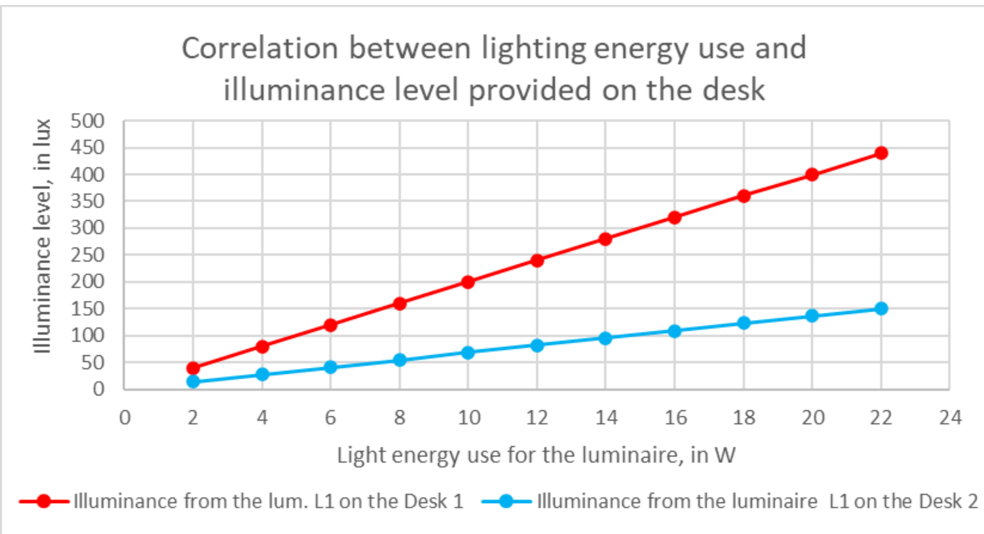

Fig. 6. Correlation between lighting energy use of each luminaire and the illuminance level on the desk under it or supplemented to the other desk. The effect is equal for both luminaires.

2.1.6 Daylight and artificial lighting control system

The system was calibrated during the night (i.e., without daylight in the room), and the established controlling was with a 10-minute fade time from maximum to minimum flux, based on a measuring value of the last 1 minute, for each desk separately. This corresponds to the best practice in Norway, which is based on the experience with characteristic daylighting conditions. Applying this approach for DLC sudden peaks and drops in the light were avoided, as this would have otherwise disturbed the occupants. The qualitative part of the study discusses and proves this finding (Obradovic, Matusiak et al. 2021). The DLC components used in this study were 'off-the-shelf' products. This means that the results of this study are based on the use of products available on the market during the study period. Further, this acknowledges that the results could be different if this study (or a future similar one) had applied a different DLC strategy (i.e., choosing an alternative photosensor type or controlling algorithm).

The photosensors used for this DLC system, manufactured by Glamox, had a wide angle (120°, bicubic) and lacked any shield in order to obtain information on a wider field (where the daylight from the HLP was intended to be directed). The sensors were slightly tilted toward the wall (10°), as discussed in the introduction, so that the visual field could measure the vertical illuminance on the wall as well. The decision of photosensor position was made in order to detect differences in the illuminance values on both of the desks individually and to correlate these values with the supplementary illuminance the luminaires supposed to provide. The sensors were positioned near each other (Fig. 1) according to the most common practice with two working places, but this proximity was not closer than in the case of using a luminaire with an integrated sensor. In a case when both sensors are positioned too close to the window, they are assumed to not be affected by the excessive daylight on the working areas due to the sun-shading strategy applied. However, the authors did not predict that the light reflected on the slats—at a given tilt—would be redirected directly to the sensor.

2.2 Monitoring procedure and measuring equipment

The monitoring procedure included measuring the indoor illuminance, outdoor illuminance, and energy consumption of the artificial lighting every minute from 7am to 17pm, which was referred to as 'occupancy hours' in this study. Parametric measurements were logged continually on a PC. To ensure the study quality, standard calibrated measuring equipment was used.

Monitoring of the indoor illuminance was performed using 5 Ahlborn illuminance meters FL623VL and an Almemo logger to log the data on the PC. The illuminance meters were positioned to cover the horizontal illuminance on the first (desk 1) and second (desk 2) work areas (0.8 m height) as well as the vertical illuminance on the wall in front of both work areas (1.2 m height). The last illuminance meter was positioned on a tripod to record the vertical illuminance at the eye level of the user of desk 2. Those illuminance meters are referred to as Pim1 to Pim5, respectively (Fig. 1c). The CIE recommendation of using grid points is related to ad hoc point measurements, while using only one illuminance meter per desk is recommended for continuous measurements, as argued by Kruisselbrink, Dangol et al. (2018) and Gentile, Dubois et al. (2016). Illuminance meters in this study were placed at a location critical to or representing the typical illuminance of that zone. A placement of photosensor coinciding with the luminaire position is not recommended, but, in this project, the same place is the target for the output of the daylight via the HLP; therefore, the place was assumed as the most suitable position. Monitoring of the outdoor illuminance was performed via photosensors (Carlo Gavazzi lux sensors BSH-LUX-U) placed vertically along the same south-oriented vertical plane as the tube's entrance dome (Figs. 1b and 7a, marked as VI im), to measure vertical illuminance (VI) as well as via photosensors placed horizontally on the roof of the building (Figs. 1d and 7b, marked as GHI im) to measure global horizontal illuminance

(GHI). The measurement data was retrieved via a monitoring software UPW3 tool developed by Carlo Gavazzi. The lighting energy consumption was measured using separate power meters (10–20 A) for each luminaire. The scheme for artificial lighting solution and monitoring equipment for lighting energy use is presented in Fig. 8.

Fig. 7. Monitoring equipment: a) Monitoring of the VI incident to the HLP, VI im; b) monitoring of the GHI, GHI im; c) logging of energy consumption of each luminaire; d) logging of the indoor illuminance measurements from the five photosensors Pim1-5.

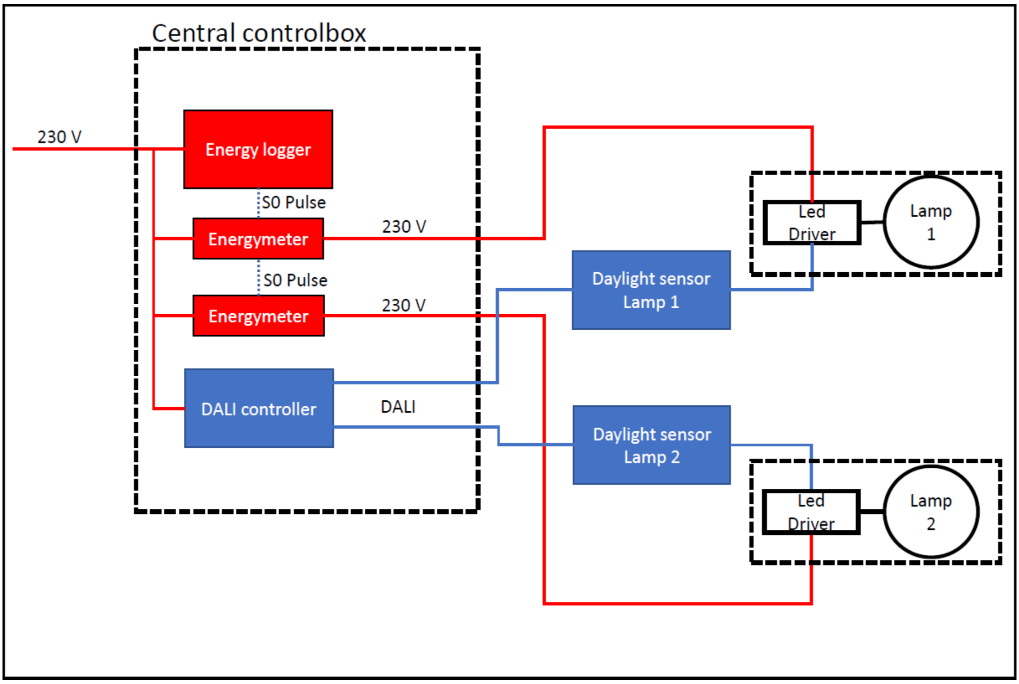

Fig. 8. Scheme for artificial lighting solution in the test office and monitoring equipment for lighting energy-use.

3. Monitoring results and analyses

Prior to analysis, it is necessary to note some facts the researchers became aware of just prior to start of the monitoring period. It has been noticed that the daylight conditions during the test and reference periods were not completely equivalent. Daylighting conditions are the only independent conditions (input data) that all other conditions (here, artificial lighting and energy consumption) depend on (output data). According to Satel-Light database statistical analyses (measured for the years 1996–2001), the global illuminance data for Oslo reveals that there are higher values for the spring period of each year compared to the autumn (Appendix B1). The difference in weather conditions (daylight illuminance values) will affect the lighting energy use during the test and ref monitoring period. The authors' perspective is that the validity of the results of this study is the important issue; they therefore chose the test period of the study to be during the worst conditions (lower daylight values), as this would represent the most reliable results.

In order to compare recorded values for the outdoor and indoor illuminances, pairs of days for test and reference period were chosen, fig 9. Days for each pair has compatible independent variables (equal solar altitude and daylight conditions profile (values off VI and GHI during the day)) which establishes the validity of the analyses.

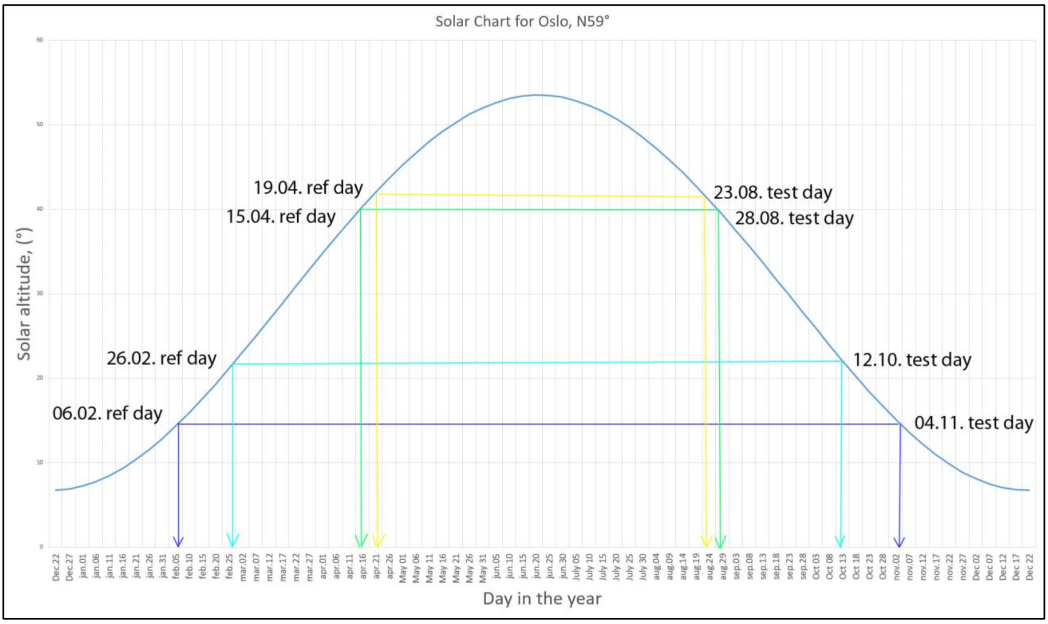

Fig. 9. Compatibility of the solar altitude for the test and reference pair days, which are used in the statistical analyses

As daylight supplement via HLP (and a custom-designed reflector), directed to the working area, is not uniform (caustic effect is visible in the Figure 2c) analysing a single point value could be unreliable. Recorded data from all 3 sensors connected to the desk 2 (on the desk, on the wall and on the observer's position) can be used to discuss the values of the daylight on the spread task area. In addition, the effect of the daylight via HLP, on the desk 1, is also present, as described in the section 2.1.4. Hence, the two illuminance meters connected to the desk 1 could be used in the discussion as well. Thus, the outdoor vertical illuminance (VI) was assumed to have a direct influence on desk 2 as the daylight via HLP is directed at it, and to a smaller extent on desk 1; while global horizontal illuminance (GHI) supplemented through the window, is assumed to have higher influence on desk 1, and lower on desk 2.

In order to analyse the supplement of HLP (with the reflector), illuminance values recorded on all five illuminance meters when artificial lighting was dimmed down to zero should be considered. During clear and sunny sky condition dimming of the artificial lighting totally to a zero-value occurred around the noon, even when the illuminance measured by the DLC sensors didn't reach the threshold value of 500lux. The authors discovered that the major reason for this was the daylight reflection on the semi-specular sun-shading slats (at a tilt angle 45°, for sunlight cut-off), resulting in a partial re-direction of the light to the DLC sensors. As such, the luminaires often received incorrect information regarding the supplementary illuminance they needed to provide, which resulted with lower illuminance values (which was recorded by the illuminance meters) then the threshold.

In figure 10, an example of the recorded values of the outdoor (Vi and GHI), and indoor (Desk 1 horizontal and vertical; and Desk 2 horizontal and vertical, and observer) illuminance for the test and reference pair days is presented for the time with luminaires dimmed down to zero (between 12 and 14:30 hours). Comparison of those two graphs affirm that during the time with close to equal outdoor daylight conditions recorded values on the three sensors on the desk 2 are much higher for the test day than for the reference day.

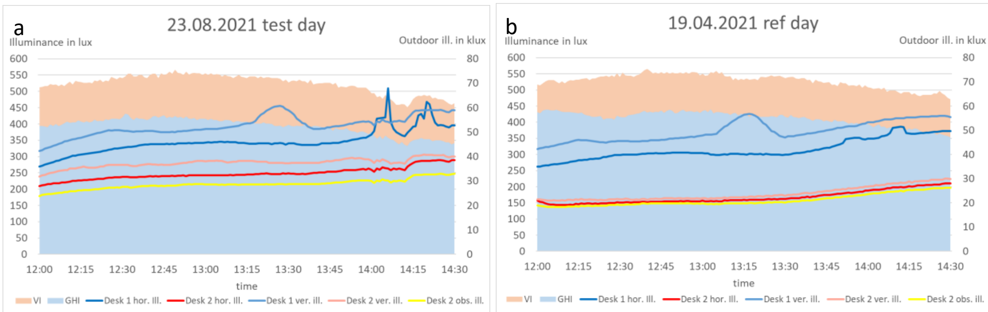

Fig. 10. Aggregative graphs of the illuminance values recorded for the test (a) and reference (b) pair days which were recorded between 12 and 14:30 hours. The light orange area present vertical illuminance incident pipe (VI), while light blue area present global horizontal illuminance (GHI); Bluish lines present illuminance recorded for the desk 1 and red, orange and yellow lines present illuminance values recorded for the desk 2.

The scatter plots in figure 11 illustrate the relation between illuminance values recorded on all sensors with the vertical illuminance incident on the pipe (VI). Comparison of those plots confirm again that for the same VI values the illuminances measured by all illuminance meters shows higher values on the test day than on the reference day.

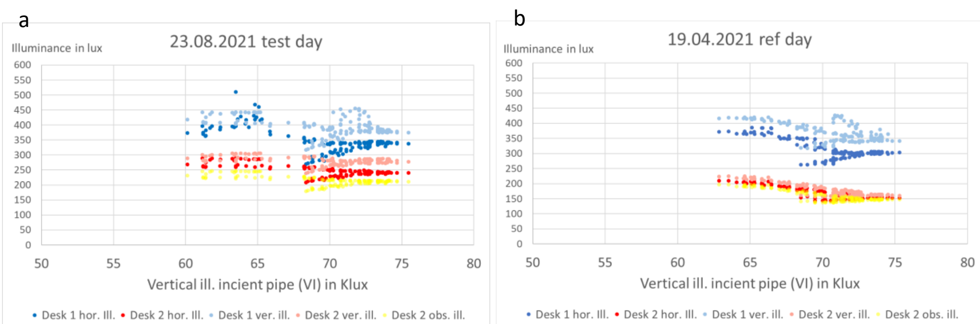

Fig. 11. Illuminance values for the test (a) and reference (b) pair days which were recorded between 12 and 14:30 hours. The scatters show the illuminance values recorded for all five illuminance meters referred to the vertical illuminance (VI); Bluish lines present illuminance recorded for the desk 1 and red, orange and yellow lines present illuminance values recorded for the desk 2.

3.1 Statistical analyses of photometry recordings

In order to test hypothesis in this study and to answer the research questions, the inferential statistical analyses need to be performed to check if the recorded values for the Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance are higher in case of test days compared with the reference days. Figure 9 presents the pair of days for TEST and REF period (chosen to cover the equal daylight profiles) used in the analyses. To performed statistical analyses just a period (each minute recorded values) when artificial lighting is dimmed to 0 is taken in comparison. This period is between 12am and 14:30 pm. In the following tables (1-8), for each pair of days (Fig. 9) independent sample t-tests (with following graphs) and a point biserial correlation (PBC) is shown. The IBM SPSS 27 software was used to performed statistical analyses. Bonferroni correction, usually used to account for error type 1, in large sample size analyses, was not used, simply because of the nature of values in population samples. Variables in the analyses are values of outdoor and indoor illuminances, which in the whole population can suddenly vary greatly, due to the sudden cloud passing and covering the sun, or due to the caustic nature of the illumination recorded on the indoor illuminance meters. Those situations were exactly something the analyses were supposed not to account for.

Independent t-test is used to compare Mean values of the independent variables (VI and GHI) with the Mean values of the dependent variables (Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance) and to draw a picture about the effect of the HLP presence during the test days. Difference presented in the figures following tables show relative difference between Mean values of test and reference days (Test-Ref)/Ref), thus showing the improvement (in %) for the test comparing to the Ref.

In the point biserial correlation analyses, all dependent variables (Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance) are used in corelation with binary nominal explanatory variable (Test= 1 and ref =0) to get the value of correlation coefficient. The result of biserial correlation is a coefficient R which is used to build a relation between the variables. The relation (R^2) is presented in the graphs following tables (for solely Desk 2 horizontal and vertical illuminance).

Table 1. Independent sample *t*-test analyses compare Mean values for the independent and dependent variables for the test day 04.11.2020 and the ref day 06.02.2021

	Test day 04.11.2020			Ref day 06.02.2021					
	M	SD	SE	M	SD	SE	t	df	p
VI (Klx)	44.92	11.37	.73	44.28	7.92	.51	-.71*	428.55	.474
GHI (Klx)	5.09	1.132	.07	4.95	1.07	.07	-1.37	480	.170
Desk1 hor. Ill.	572.38	168.89	10.88	453.23	141.87	9.14	-8.38*	466.12	**<.001**
Desk2 hor. Ill.	331.72	83.46	5.37	240.18	59.33	3.82	-13.87*	433.23	**<.001**
Desk1 ver. Ill.	489.65	116.22	7.48	429.53	116.02	7.47	-5.68	480	**<.001**
Desk2 ver. Ill.	415.16	145.84	9.39	236.11	59.17	3.81	-17.66*	316.94	**<.001**
Desk2 obs. Ill.	351.26	121.79	7.84	255.96	102.11	6.58	-9.309	480	**<.001**

*Levene's Test violated

First pair of days is the test day 04.11.2020, and the reference day 06.02.2021. Table 1 presents independent sample *t*-test analyses. Mean values of VI and GHI for test and reference days are nearly equal (44,92 klux and 44,28 klux for the VI, and 5,09 klux and 4,95 klux for the GHI, for test and ref day respectively), but the recorded indoor illuminance values for the test and ref day show statistically significant difference (p = <.01) for all parameters. Figure 12. present comparison of Mean values resulting from the independent *t*-test analyses. The improvement of Mean values for Desk 2 hor. Ill and Desk 2 observer ill is slightly under 40%, while the improvement of Mean value for Desk 2 ver. Ill is over 70% in case of test day.

In Table 2, Point bi-serial correlation test for all independent (VI and GHI) and dependent variables (Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance) show correlation strength regarding increase of the nominal parameter (0 for ref and 1 for test). Statistically significant correlation (p<.01) is shown for all dependent variables, meaning that the values of them were higher for the test day (nominal parameter 1). The PBC coefficient is higher for the Desk 2 hor. Ill. (.535) and Desk 2 ver. Ill. (.628), which is also illustrated in figure 13. with PBC coefficient (R^2).

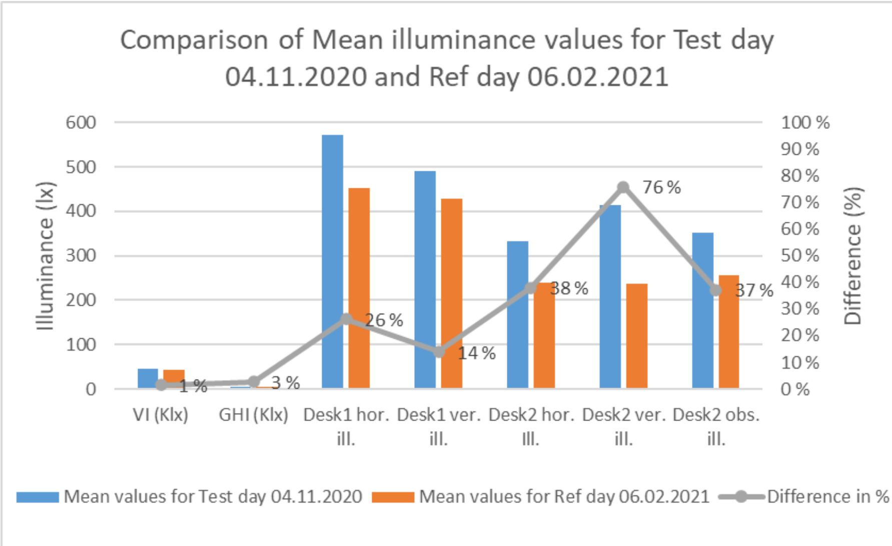

Fig. 12. Comparison of Mean Illuminance values for the test and reference pair days which were recorded between 12 and 14:30 hours. VI and GHI are shown in Klx.

Table 2. Point bi-serial correlation test for the test day 04.11.2020 and ref day 06.02.2021, and, Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance

Point biserial correlation between ref day 06.02.2021 (0) and test day 04.11.2020 (1)							
	VI	GHI	Desk1hor	Desk2hor	Desk1ver	Desk2ver	Desk2obs
Pearson Corr.	.033	.063	**.357****	**.535****	**.251****	**.628****	**.391****
Sig. (2-tailed)	.474	.170	<.001	<.001	<.001	<.001	<.001

Significance levels: * p<.05; ** p<.01. The analyses are based on n: 482.

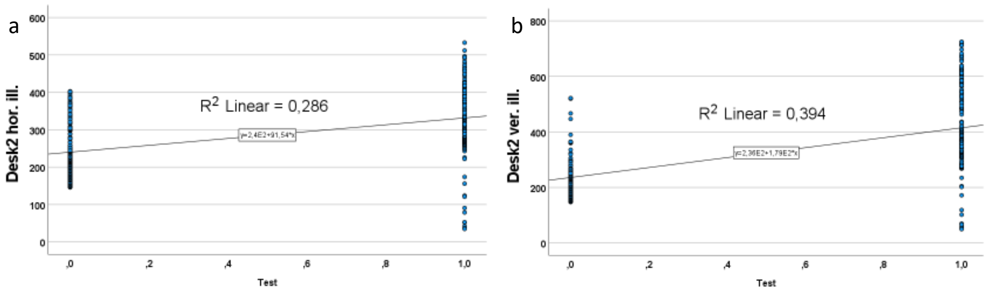

Fig. 13. Point-biserial correlation coefficient show a relation between the values of desk 2 hor. Ill. (a), and Desk 2 ver. Ill. (b) for pair of days, ref (0) and test (1).

Second pair of days is the test day 12.10.2020, and the reference day 26.02.2021. Table 3 presents independent sample *t*-test analyses. Mean values of VI for test and reference days are 65,33 klux and 71,02 klux, respectively. Mean values of GHI for test and reference days are 16,19 klux and 11,73 klux, respectively. Thus, this pair of days has slightly lower VI and higher GHI values for test day compared with reference day. Recorded indoor illuminance values for the test and ref day show statistically significant difference (p = <.01) for all parameters. Fig. 14. presents comparison of Mean values resulting from the independent *t*-test analyses, where the improvement of Mean values for Desk 2 hor. Ill and Desk 2 ver. Ill. is over 100%, while the improvement of Mean value for Desk 2 obs. Ill is 70% in case of test day.

Table 3. Independent sample *t*-test analyses compare Mean values for the independent and dependent variables for the test day 12.10.2020 and ref day 26.02.2021

	Test day 12.10.2020			Ref day 26.02.2021					
	M	SD	SE	M	SD	SE	t	df	p
VI (Klx)	65.33	4.89	.31	71.02	9.520	.708	7.34*	251.16	**<.001**
GHI (Klx)	16.19	2.23	.14	11.73	2.774	.206	-17.70*	338.34	**<.001**
Desk1 hor. Ill.	603.14	178.41	11.49	446.49	86.297	6.414	-11.90*	365.52	**<.001**
Desk2 hor. Ill.	462.32	84.46	5.44	225.13	93.334	6.937	-26.90*	365.74	**<.001**
Desk1 ver. Ill.	599.05	152.84	9.84	462.35	120.876	8.985	-10.26*	418.86	**<.001**
Desk2 ver. Ill.	472.99	132.94	8.56	232.94	68.433	5.087	-24.10*	376.70	**<.001**
Desk2 obs. Ill.	367.58	77.68	5.00	215.89	33.664	2.502	-27.11*	346.17	**<.001**

*Levene's Test violated

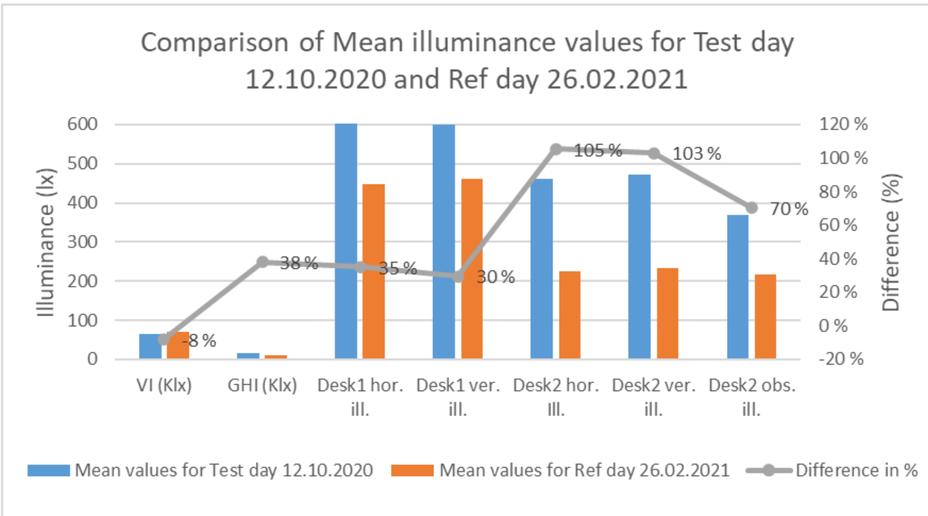

Fig. 14. Comparison of Mean Illuminance values for the test and reference pair days which were recorded between 12 and 14:30 hours. VI and GHI are shown in Klx.

In Table 4, point bi-serial correlation test for all independent (VI and GHI) and dependent variables (Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance) show correlation strength based on the increase of the nominal parameter (0 for ref and 1 for test). Statistically significant correlation (p<.01) is shown for all dependent variables, meaning that the values were higher for test day (nominal parameter 1). The PBC coefficient is higher for the Desk 2 hor. Ill. (.800), Desk 2 ver. Ill. (.734), and Desk 2 obs. Ill (.768), which is also illustrated in figure 15. with PBC coefficient (R^2).

Table 4. Point bi-serial correlation test for the test day 12.10.2020 and the ref day 26.02.2021, and, Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance

Point biserial correlation between ref day 26.02.2021 (0) and test day 12.10.2020 (1)							
	VI	GHI	Desk1hor	Desk2hor	Desk1ver	Desk2ver	Desk2obs
Pearson Corr.	**-.363****	**.665****	**.469****	**.800****	**.436****	**.734****	**.768****
Sig. (2-tailed)	<.001	<.001	<.001	<.001	<.001	<.001	<.001

Significance levels: * p<.05; ** p<.01. The analyses are based on n: 422.

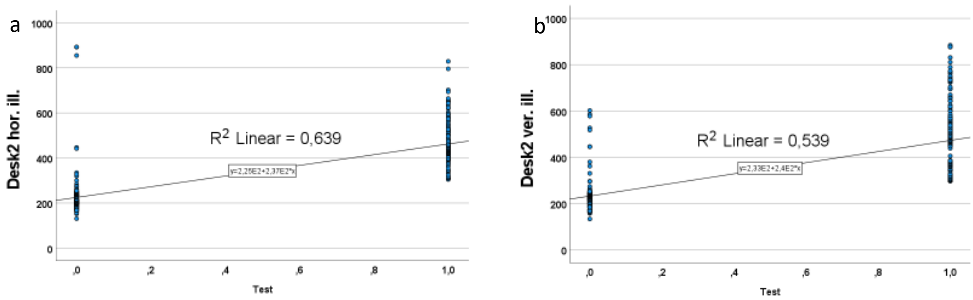

Fig. 15. Point-biserial correlation coefficient show a relation between the values of desk 2 hor. Ill. (a), and Desk 2 ver. Ill. (b) for pair of days, ref (0) and test (1).

Third pair of days is the test day 28.08.2020, and the reference day 15.04.2021. Table 5 presents independent sample *t*-test analyses. Mean values of VI for test and reference days are 71,40 klux and 66,63 klux, respectively. Mean values of GHI for test and reference days are 48,01 klux and 50,63 klux, respectively. Thus, this pair of days has slightly higher VI and lower GHI values for test day compared with reference day. Recorded indoor illuminance values for the test and ref day show statistically significant difference (p = <.01) for all three parameters regarding Desk 2. Figure 16. presents comparison of Mean values resulting from the independent *t*-test analyses, where the improvement of Mean values for Desk 2 vert. Ill. is over 40%, while the improvement of Mean values for Desk 2 hor. Ill. and for Desk 2 obs. Ill is over 30% and over 20%, respectively, for the test day.

Table 5. Independent sample *t*-test analyses compare Mean values for the independent and dependent variables for the test day 28.08.2020 and ref day 15.04.2021

	Test day 28.08.2020			Ref day 15.04.2021					
	M	SD	SE	M	SD	SE	t	df	p
VI (Klx)	71.40	16.03	1.10	66.63	8.20	.61	-3.78*	322.79	**<.001**
GHI (Klx)	48.01	8.89	.61	50.63	5.74	.42	3.51*	363.57	**<.001**
Desk1 hor. Ill.	333.23	86.36	5.94	338.85	100.69	7.48	.59	390	.552
Desk2 hor. Ill.	242.70	54.54	3.75	183.00	29.46	2.19	-13.74*	332.30	**<.001**
Desk1 ver. Ill.	377.94	88.73	6.10	385.99	60.29	4.48	1.06*	371.37	.289
Desk2 ver. Ill.	275.17	62.23	4.28	190.95	29.67	2.20	-17.48*	310.63	**<.001**
Desk2 obs. Ill.	208.91	48.29	3.32	169.87	26.79	1.99	-10.07*	337.08	**<.001**

*Levene's Test violated

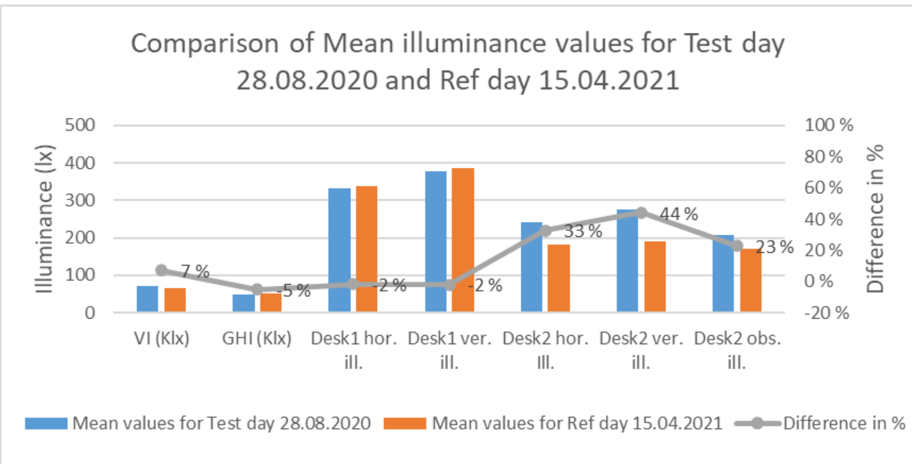

Fig. 16. Comparison of Mean Illuminance values for the test and reference pair days, recorded between 12 and 14:30 hours. VI and GHI are shown in Klx.

In Table 6, point bi-serial correlation test for all independent (VI and GHI) and dependent variables (Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance) show correlation strength based on the increase of the nominal parameter (0 for ref and 1 for test). Statistically significant correlation (p<.01) is shown for all dependent variables regarding desk 2, meaning that the values were higher for test day (nominal parameter 1). The PBC coefficients show positive correlation for the Desk 2 hor. Ill. (.555), Desk 2 ver. Ill. (.645), and Desk 2 obs. Ill (.440), which is also illustrated in figure 17. with PBC coefficient (R^2).

Table 6. Point bi-serial correlation test for the test day 15.04.2020 and ref day 28.08.2021, and, Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance

Point biserial correlation between ref day 15.04.2021 (0) and test day 28.08.2020 (1)							
	VI	GHI	Desk1hor	Desk2hor	Desk1ver	Desk2ver	Desk2obs
Pearson Corr.	**.180****	**-.170****	-.030	**.555****	-.052	**.645****	**.440****
Sig. (2-tailed)	<.001	<.001	.552	<.001	.303	<.001	<.001

Significance levels: * p<.05; ** p<.01. The analyses are based on n: 392.

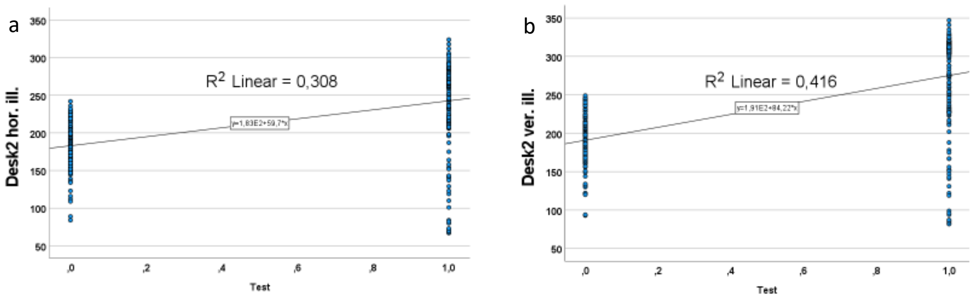

Fig. 17. Point-biserial correlation coefficient show a relation between the values of desk 2 hor. Ill. (a), and Desk 2 ver. Ill. (b) for pair of days, ref (0) and test (1).

The last analysed pair of days is the test day 23.08.2020, and the reference day 19.04.2021. Table 7 presents independent sample *t*-test analyses for this pair. Mean values of VI for test and reference days are 69,83 klux and 70,43 klux, respectively. Mean values of GHI for test and reference days are 52,38 klux and 54,59 klux, respectively. This pair of days has nearly equal VI, while GHI values for test day are slightly lower compared with reference day. Recorded indoor illuminance values for the test and ref day show statistically significant difference (p = <.01) for all parameters. Figure 18. presents comparison of Mean values resulting from the independent *t*-test analyses, where the improvement of Mean values for Desk 2 vert. Ill. is nearly 60%, while the improvement of Mean values for Desk 2 hor. Ill. and for Desk 2 obs. Ill is slightly under 50% and over 30%, respectively, for the test day.

Table 7. Independent sample *t*-test analyses compare Mean values for the independent and dependent variables for the test day 23.08.2020 and ref day 19.04.2021

	Test day 23.08.2020			Ref day 19.04.2021					
	M	SD	SE	M	SD	SE	t	df	p
VI (Klx)	69.83	3.79	.30	70.43	2.92	.23	1.54*	282	.125
GHI (Klx)	52.38	3.36	.27	54.96	2.90	.23	7.16	300	**<.001**
Desk1 hor. Ill.	346.13	37.24	3.03	315.17	31.66	2.57	-7.78	300	**<.001**
Desk2 hor. Ill.	247.83	18.09	1.47	167.06	19.65	1.60	-37.15*	297.97	**<.001**
Desk1 ver. Ill.	394.36	30.62	2.49	371.82	31.19	2.53	-6.34	300	**<.001**
Desk2 ver. Ill.	280.91	13.06	1.06	178.21	20.98	1.70	-51.06*	251.07	**<.001**
Desk2 obs. Ill.	215.09	14.74	1.20	157.86	17.95	1.46	-30.26*	289.07	**<.001**

*Levene's Test violated

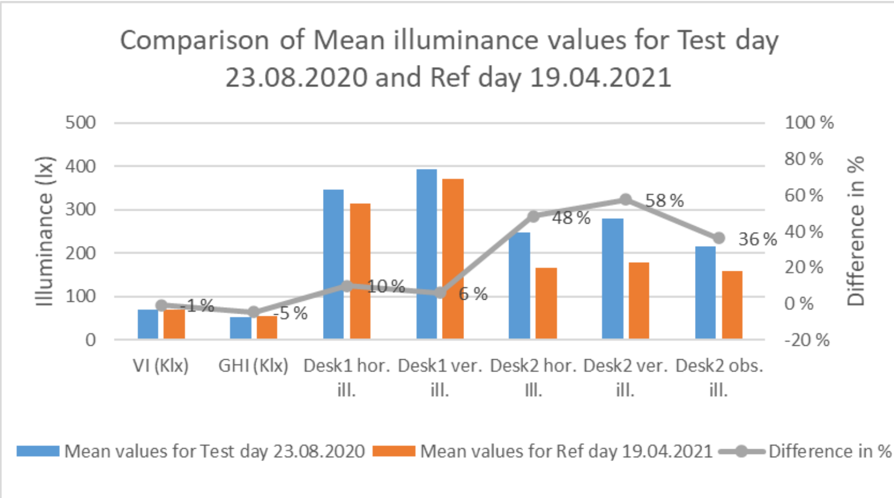

Fig. 18. Comparison of Mean Illuminance values for the test and reference pair days, recorded between 12 and 14:30 hours. VI and GHI are shown in Klx.

In Table 8, point bi-serial correlation test for all independent (VI and GHI) and dependent variables (Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance), for the test day 19.04.2020 and the ref day 23.08.2021, show correlation strength regarding increasement of the nominal parameter (0 for ref and 1 for test). Statistically significant correlation (p<.01) is shown for all dependent variables, meaning that the values were higher for test day (nominal parameter 1). The PBC coefficients show high positive correlation for the Desk 2 hor. Ill. (.906), Desk 2 ver. Ill. (.947), and Desk 2 obs. Ill (.868), which is also illustrated in figure 19. with PBC coefficient (R^2).

Table 8. Point bi-serial correlation test for the test day 19.04.2020 and ref day 23.08.2021, and, Desk 1 horizontal and vertical illuminance, and Desk 2 horizontal, vertical and observer illuminance

Point biserial correlation between ref day 19.04.2021 (0) and test day 23.08.2020 (1)							
	VI	GHI	Desk1hor	Desk2hor	Desk1ver	Desk2ver	Desk2obs
Pearson Corr.	-.088	**-.382****	**.410****	**.906****	**.344****	**.947****	**.868****
Sig. (2-tailed)	.125	<.001	<.001	<.001	<.001	<.001	<.001

Significance levels: * p<.05; ** p<.01. The analyses are based on n: 302.

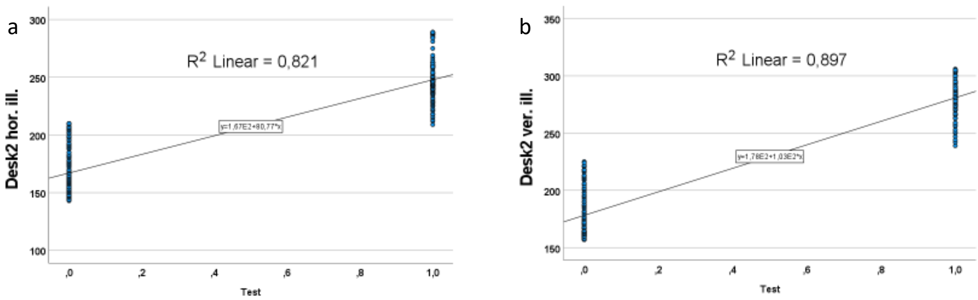

Fig. 19. Point-biserial correlation coefficient show a relation between the values of desk 2 hor. Ill. (a), and Desk 2 ver. Ill. (b) for pair of days, ref (0) and test (1).

Finally, we can answer the research question from the introduction: Does daylighting provision via the HLP lead to an increased level of daylight on the second working area in the office? The recorded data and analyses of pair days demonstrates that, under equal daylighting conditions (here, the sun's altitude and GHI and VI daily value profiles) the situation with the HLP provides higher illuminance levels on the second task area compared to the situation without the HLP (solely window daylighting). The improvement is from 30% to over 100%.

3.2 Lighting energy use and saving potential

The energy-saving potential is an estimate of how much energy can be saved if the original or basic solution is altered with another one. The term energy efficiency is also in use, referring to a practice of using less energy to provide the same amount of useful output from a service or a device. We could talk about the energy efficiency of an alternative luminaire for example, but since this study is about the reduction in energy consumption of a complex solution (a multidevice solution consisting of artificial lighting, windows, HLP) the energy-saving potential suits better. The analyses of energy-saving potential in this study rely on the relative difference between the energy used in the reference period and energy used in the test period and is expressed in percentage. The energy-saving potential shows that part of the energy that is used in the base case (REF) and could potentially be saved if an alternative solution was applied.

Monitoring data regarding the energy consumption of both luminaires individually was collected and analysed. The luminaire dimming was found to be linear, as shown in Fig. 6.

The overlapping of the illuminance, as described in section 2.1.5, triggered an unexpected issue, namely the luminaire dominance, that the authors can explain just with reasoning on function of the bus controlling system (DALI), which is not a perfectly coordinated component. It seems that the system sends signals to each luminaire not at exactly same moment but with seconds of delay. This has been shown to be of great importance to the performance of this lighting solution. Additionally, the signal is sent first to a random luminaire (i.e., not always the same one). Further, the luminaire turned on first does not only provide lighting onto the desk below but also to the other desk, as argued over (Fig. 6), which then immediately gives information to the photosensor of the 'delayed' luminaire about the specific level of illuminance on the desk, giving it the opportunity to provide just the necessary supplementary illuminance to reach the required 500 lux. The result of this is that the first luminaire takes on the role of the dominant illuminance-provider throughout the rest of the day and, consequently, has a much higher energy consumption. This is a consistent and significant occurrence on days with an overcast sky; however, this trend is present under other sky conditions as well.

An analysis of the number of incidents of the dominant luminaire (recorded data) at the beginning of the working day (i.e., 7am) is in Fig. 20. During the test period, which is in total 182 days, L1 is dominant 47 days, while L2 is dominant 121 days; the remaining days in the test period both luminaires started at the same point of time. This shows that the L2 was dominant (exhibiting the dominant illuminance) 2.57 (121/47) times more often than L1. In the reference period (182 days as well), L1 is dominant 66 days, while L2 is dominant 79 days. This results in 1.22 times of L2 as the dominant luminaire comparing to L1. The monthly frequency values show no correlation with either the winter or summer period, with the daylight effect from the window potentially being a main reason for this. The assemblage of months is equal for the test and reference period when it comes to the daylighting values at the starting time (for the occupancy period starting at 7am) when the luminaires have started. The only conclusion the authors have to offer is that the initial signal was randomly sent and was not affected by the input illuminance values, which the DLC photosensor could have received, of the dominant luminaire.

As a result, the authors conclude that the collected data on the lighting energy use for L1 and L2 in both the test and reference periods was strongly affected by this occurrence of dominant luminaire. Therefore, it was not possible to confidently conclude on the magnitude of the effect this occurrence had on the total energy consumption results, hence the collected monitoring data on lighting energy consumption were unreliable and authors choose therefore not to report it.

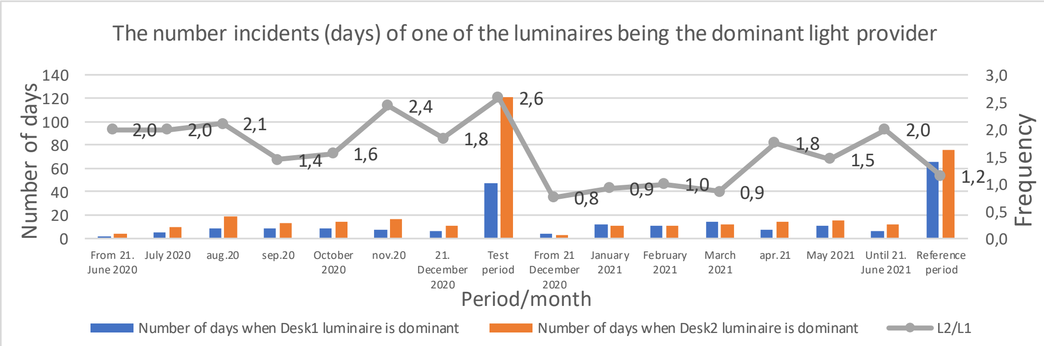

Fig. 20. The number of incidents (days) of one of the luminaires being the dominant light provider for each month in the TEST period and REF period. A frequency of 1 means that the number of incidents is the same for both luminaires.

Authors are not able to answer the research question about the lighting energy saving potential for a single luminaire. However, the authors can report total light energy consumption. The calculated LENI for this test office, was 10.37 kWh/m^{2}year, as mentioned in section 2.1.5, but the value of LENI based on the recorded light energy use for test period of the study was 5.79 kWh/m^{2}year, which can be argued as a direct effect of the daylighting via the HLP. The energy-saving potential could be then expressed as a relative difference between calculated and realistic situation, being ((10.37-5.79)/10.37) 44%. Arguing this we must provide some important notes. The recommended light level (constant and stable target value of minimum 500lx) has not been always achieved in situations when DLC system was affected by daylight reflected from sun-shading, as discussed above. Such situations occurred during the days with clear and sunny weather, which is for the location of this study historically recorded to be about 30% of the daylight time. However, the monitored data and analyses of a pair days suggests that in such situations the illuminance values on the desks were around 400 lux (varying between 300 and 500 lux). Hence, the periods with artificial lighting under the recommended level might have also contributed to lower energy use.

4. Discussions

First, it is important to note that the collected data shows a large variation. Examining the monitored data, it can be noted that, with similar daylight profiles (i.e., solar altitude, VI and GHI values), the luminaires behaved quite similarly regardless of the illuminance values recorded on the surfaces where the DLC sensors were supposed to look. This indicates that the DLC sensors were triggered by the daylight being reflected from the slats. Further, there was only one illuminance meter positioned on each desk recording the illuminance at a point, but there could have been higher illuminance values around this point that the illuminance meter had missed but which the DLC sensors have caught. The lighting patches were of a random nature, as shown in figure 3c.

The potential of the HLP to bring about higher daylighting levels has been shown through the analyses in section 3, but there is one more fact to add. Specifically, in our full-scale office, there were glare-free situations, and daylighting via the window was consistently enabled. Such optimal situations cannot be taken for granted in all buildings—even in the newly constructed. On the contrary, it is widely expected that there will be need for sun-shading regulation whenever there is a clear sky and sunlight, and, depending on the sun-shading system, this often will result in total rejection of the daylight via the window. In such situations, the percentage of the daylight supplemented via the HLP, as discussed in chapter 3.1, becomes even more important.

The results from the semi-empirical study, using scale model of a HLP showed that there was a potential for improving daylight autonomy (DA) for a HLP of the same aspect ratio (16) and in the same location (Oslo) if laser cut panes (LCPs) were used as a light collector (Obradovic and Matusiak 2020, Obradovic and Matusiak 2021). Values of daylight autonomy of up to 300lux (DA_{300}), which has been directly demonstrated in this full-scale test, can be improved by up to 16%, if a certain LCP configuration described in the study is used. This represents a suggestion to future work.

5. Conclusion

The authors indicate the potential of a HLP installed on the south façade of unobstructed building at a latitude 60° in increasing the indoor illuminance levels on the horizontal and vertical surfaces positioned at a distance of nearly four meters from the façade. The recorded data and analyses of pair days demonstrates that, under equal daylighting conditions (here, the sun's altitude and GHI and VI daily value profiles) the presence of the HLP results with higher illuminance levels on the task areas compared to the situation without the HLP. An increase in illuminance level on the working area in the rear part of the office of approximately 200 to 300 lux was recorded during clear and sunny days at equinox. The increased daylight level on the working area near window of approx. 50 lux was also recorded. At the desk 2 (located close to the door) 40% to over 100% higher daylight level can be expected as compared to the case of solely window-daylighting and no electric light.

As a consequence of the daylighting via the HLP, the lighting energy-consumption (LENI) was improved by 44% compared to the estimated value without HLP. The authors view this information as of a great importance for, e.g., on-site energy generation using PV and for ZEB design concepts. Such information is also useful for system capacity decisions, as it can help directly reduce amount of material, costs, and the build-in carbon amount. In the case of ZEN design concepts, it could also provide insight regarding the PV system and the amount of generated energy that will not be needed at site and that could instead be promised to the grid.

The full-scale monitoring revealed some core issues related to unreliable lighting energy forecasting and unmet lighting quality conditions set as recommended illuminance levels on the task surfaces. The authors conclude that the complex relationship between the daylight, sun-shading device, and information-sharing protocols within the DLC system comprise a factor involved in integration failure.

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Contributions: B. Obradovic conceived and wrote the study (B.O. designed the full-scale test room and customized equipment, prepared monitoring procedure, performed monitoring and data collection, analysed data, developed illustrations and tables, and wrote the article); B. S. Matusiak helped with the definition of the study, topic, and methodology, contributed by performing quality assurance and proofreading of the paper.

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Energy Evaluation According to Following Standard: EN 15193

Results

Total Energy Lighting: 133.62 kWh/a
LENI: 10.37 kWh/(a · m²)

Total Energy Visual Task: 128.50 kWh/a
Total Energy Parasitic (Total): 5.12 kWh/a
Total Energy Parasitic (Standby): 5.12 kWh/a
Total Energy Parasitic (Loading the Emergency Lighting): 0.00 kWh/a
Total Area: 12.89 m²

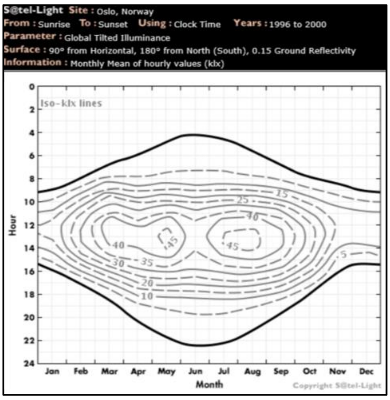
Monthly Results

Month	Lighting [kWh]	Lighting [kWh/m²]	Visual Task [kWh]	Visual Task [kWh/m²]	Parasitic [kWh]	Parasitic [kWh/m²]
Jan	13.22	1.03	12.79	0.99	0.43	0.03
Feb	12.33	0.96	11.90	0.92	0.43	0.03
Mar	11.03	0.86	10.60	0.82	0.43	0.03
Apr	9.95	0.77	9.52	0.74	0.43	0.03
May	9.50	0.74	9.07	0.70	0.43	0.03
Jun	9.21	0.71	8.78	0.68	0.43	0.03
Jul	9.34	0.72	8.91	0.69	0.43	0.03
Aug	9.69	0.75	9.26	0.72	0.43	0.03
Sep	10.87	0.84	10.44	0.81	0.43	0.03
Oct	12.06	0.94	11.63	0.90	0.43	0.03
Nov	13.06	1.01	12.63	0.98	0.43	0.03
Dec	13.46	1.04	13.03	1.01	0.43	0.03

Fig. A1 Calculation of the LENI value for the test office, performed in Dialux 4.13 software

Parameter	Value
Total installed lighting power [W]	44
Parasitic power of controls with lamps off [W]	1
Parasitic power of controls with lamps off [W] (Calculated Value)	0
Emergency lighting charging power [W]	0
Daylight Time Usage [h]	2524
Non-Daylight Time Usage [h]	1116
Emergency lighting charge time [h]	0
Constant illuminance factor	1.00
Constant Illuminance Controllable	/
Light loss factor	1.00
Occupancy dependency factor	1.00
Absence Factor	0.00
Occupancy control factor	1.00
Daylight Source	Window
Daylight dependency factor	0.71
Daylight control factor	0.75
Control of artificial lighting system	Automatic / Daylight Dependent
Daylight Supply Factor	0.38
Maintenance Value of the Illuminance [lx]	500
Maintenance Value of the Illuminance [lx] (Calculated Value)	300
Classification of daylight penetration	Low (4%>DRb>=2%)
Classification of daylight penetration (Calculated Value)	Middle (6%>DRb>=4%)
Middle daylight factor for windows (building shell opening)	5.9
Effective light transmission factor	0.49
Latitude [°]	59.90

Fig. A2 Parameters used in the calculation of the LENI value for the test office, performed in Dialux 4.13 software



	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
4-5	0.0	0.0	0.0	0.0	0.1	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.1
5-6	0.0	0.0	0.0	0.1	1.3	1.9	1.6	0.2	0.0	0.0	0.0	0.0	0.4
6-7	0.0	0.0	0.4	0.9	3.2	3.6	3.5	1.6	0.1	0.0	0.0	0.0	1.1
7-8	0.0	0.2	4.4	2.8	5.3	5.6	5.6	3.8	1.9	0.2	0.0	0.0	2.5
8-9	0.1	3.6	14.1	8.5	11.7	9.7	10.5	9.8	8.0	3.1	1.4	0.0	6.7
9-10	2.6	12.4	25.8	17.7	23.0	18.7	21.7	20.5	18.0	10.1	5.4	1.6	14.8
10-11	8.4	21.5	34.7	27.7	34.5	28.3	33.0	32.4	28.8	17.7	10.0	7.9	23.8
11-12	14.9	27.8	42.6	34.3	42.6	34.6	41.1	42.0	36.2	23.8	13.6	13.4	30.6
12-13	16.4	30.3	44.5	40.3	46.4	36.7	44.8	46.1	41.1	29.1	14.4	15.0	33.8
13-14	14.3	29.9	41.0	41.0	47.4	35.8	45.5	46.8	41.9	28.0	10.7	10.7	32.8
14-15	8.4	24.8	36.0	38.1	43.3	34.2	40.9	44.8	38.1	25.5	5.8	3.7	28.7
15-16	2.6	15.0	25.8	32.2	36.5	30.5	34.8	37.3	32.1	20.2	1.5	0.1	22.4
16-17	0.1	4.4	15.0	24.0	27.4	24.7	27.9	28.2	23.2	10.5	0.0	0.0	15.5
17-18	0.0	0.2	5.1	15.2	16.8	16.2	18.6	18.1	13.1	3.4	0.0	0.0	8.9
18-19	0.0	0.0	0.8	6.6	7.6	8.5	9.3	8.1	4.4	0.2	0.0	0.0	3.8
19-20	0.0	0.0	0.1	2.1	4.4	5.6	5.5	3.4	0.7	0.0	0.0	0.0	1.8
20-21	0.0	0.0	0.0	0.4	2.2	3.3	3.1	1.2	0.0	0.0	0.0	0.0	0.9
21-22	0.0	0.0	0.0	0.0	0.5	1.4	1.2	0.1	0.0	0.0	0.0	0.0	0.3
22-23	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0

Fig. B1 Global vertical illuminance on the south surface, monthly mean of hourly values. Source: Satel-Light http://www.satel-light.com/pub/Obradovic06052019093340/soutdoor.htm (accessed 20 July 2021)

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