Assessment of Daylighting and Electric Lighting Performance in a Retrofitting Project

A Case Study in Sweden

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Master thesis in Energy-efficient and Environmental Buildings
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Lund University

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

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

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Abstract

Newly constructed building stocks have been decreasing in last decades; thus, renovation and retrofitting represent a large amount of opportunities to upgrade the building performance and energy efficiency of building assets in their life span, as well as to reduce greenhouse gas emissions. An overall assessment of a lighting retrofit project can support to judge the quality of a retrofit as good or bad and evaluate the application of a retrofit measure in practice, as well as provide quantitatively based cases for future implementations. In this thesis, a lighting assessment was conducted for a retrofitted project in an educational building situated at Lund University, Sweden. The aspects with regard to both daylighting and electric lighting performance were studied through field measurements and simulations. The main objective is to evaluate lighting performance of the case room, as well as to investigate the deviation between measured and simulated results according to data collected in daylighting assessment.

The results demonstrate that the case room in general provides a good visual comfort space under both daylight and electric lighting condition. A few building codes and voluntary environmental programmes were referred to for judgement of the lighting quality, such as Miljöbyggnad (the Swedish green building certificate) and SS-EN 12464: 2011. The room has a daylight factor of 2.44% from measurement versus 2.67% from simulation. Glare probability is measured/simulated and results from both methods output a small value. Moreover, a deviation study of measured/simulated results was conducted and the results show a good consistency in general.

Due to a low installed lighting density of 5.38 W/m^2 and short occupied hours, the annual lighting energy use is very low. The lighting system in the case room has an absence occupancy control system with a sensor delay time of 15 minutes. It can help reduce approximately 18% of the energy use if compared to the lighting system with a manual on/off switch control based on computational results. The study also investigated the impacts of design parameters on the energy use of different lighting control systems and the results were discussed.

Abbreviations

DF	Daylight Factor (%)
DGP	Daylight Glare Probability (%)
HDR image	High Dynamic Range image
LENI	Lighting Energy Numeric Indicator (kWh/m^2yr)

Definitions

Manual control system	Lighting system with manual on/off switch control at the door.
Absence control system	Lighting system which switches automatically off with a preset delay time when the occupant leaves the room but does not switch on automatically.
Presence control system	Lighting system which switches automatically on and off with a preset delay time as a function of room occupation.
Dimming control system	Lighting system with photo sensor dimming control.
Combo control system 1	Lighting system with combination of dimming and absence control.
Combo control system 2	Lighting system with combination of dimming and presence control.
Transmissivity	Ratio of total light that passes through the bulk of the glass, which takes account of multiple internal reflections in the glass.
Transmittance	Visual transmittance of glass, which is the measured ratio of visible light transmitted through glass window at normal incidence.

List of Equations

Eq. 1 Reflectance of material 27

Eq. 2 Relation between transmissivity and transmission of glass 28

Eq. 3 Equation of DGP 32

Eq. 4 Equation of DGP for low light 33

Eq. 5 Equation of LENI 34

List of Tables

Table 1 Optical properties of opaque surfaces..27

Table 2 Property of lighting system...30

Table 3 Glare level classified by DGP score. 33

Table 4 Criteria of assessing the luminance ratios...34

Table 5 Specified settings for each case of lighting control strategy in the simulations......44

Table 6 Range of relative difference* between simulated and measured DF values in each row. 51

Table 7 Luminance ratios..59

Table 8 Overall assessments of daylight quality based on measured and simulated lighting metrics..61

List of Figures

Figure 1 Location of Lund (left) and surroundings of Architecture building (right)............21

Figure 2 Building view from outside. 22

Figure 3 Plan layout of the case room and its adjacent space..23

Figure 4 Interior look of the case room, photographed image with a perspective view looking towards southwest...24

Figure 5 Interior look of the case room, modelled in Rhinoceros with a perspective view looking towards southwest...25

Figure 6 Layouts of the surroundings in the model. 25

Figure 7 Sky model, CIE overcast sky, Lund. 26

Figure 8 Sky model, CIE sunny sky with sun, Lund, 10am (left), 3pm (right), July 1st, Lund. 26

Figure 9 Layout of lighting system. The occupancy sensors are the circle symbol labelled with 'OC'. 29

Figure 10 Annual occupancy profile used for electric lighting simulation for the studied room. 31

Figure 11 Specified point used in the criteria to evaluate the daylight factor. 32

Figure 12 Layout of test points for illuminance measurement (Unit: m). 36

Figure 13 Fisheye photos of selected task positions, extreme task position (upper), typical task position (lower), Red dots represent the reference spot for luminance calibration........39

Figure 14 Measured DF distribution...47

Figure 15 Simulated daylight factor distribution. 48

Figure 16 Comparisons between simulated and measured DF values in odd number rows.50

Figure 17 Comparisons between simulated and measured DF values in even number rows. 51

Figure 18 HDR images showing potential glare sources and the DGP in the extreme position, 10am (left), 3pm (right). 52

Figure 19 HDR images showing potential glare sources and the DGPs in the typical position, 10am (left), 3pm (right). 53

Figure 20 Modelled scene showing potential glare sources and the DGP in the extreme position, 10am (left), 3pm (right). 54

Figure 21 Modelled scene showing potential glare sources and the DGP in the typical position, 10am (left), 3pm (right). 54

Figure 22 Annual DGP for the extreme task position (upper) and the typical task position (lower) 55

Figure 23 Luminance map at the extreme position from HDR image, 10am (left), 3pm (right). 56

Figure 24 Luminance map at the extreme position from simulated scene, 10am (left), 3pm (right). 57

Figure 25 Luminance map of the typical position from HDR image, 10am (left), 3pm (right). 57

Figure 26 Luminance map of the typical position from simulated scene, 10am (left), 3pm (right). 58

Figure 27 Luminance values at the extreme position. The real scene (upper), the simulated scene (lower) 59

Figure 28 Luminance values at the typical position. The real scene (upper), the simulated scene (lower) 59

Figure 29 Sun path diagram of the simulated sky model drawn on the model. 60

Figure 30 Simulated plan view showing illuminance distribution at the height of work plane of 0.7m. 63

Figure 31 Simulated plan view showing luminance distribution at the height of work plane of 0.7m. 64

Figure 32 Comparisons of different lighting control strategies on their annual lighting energy use. 65

Figure 33 Effects of sensor location on predicted lighting energy use. 66

Figure 34 Effects of the delay time of the sensors for occupancy control related lighting system. 67

1 Introduction

The human needs for lighting derive from fundamental physiological needs, including visual and circadian responses to light (Bellia, Pedace & Barbato, 2013). Because of the primary needs, lighting environment is one of the crucial concerns in architecture design. The lighting environment is maintained by daylight and electric light collaboratively. Daylight, if properly supplied, can positively affect human performance, mood, productivity, and consequently influence the welfare of human being (Li & Lam, 2001; Galasiu & Veitch, 2006). Due to these factors of importance, Daylight has its evident advantages in providing a pleasant and interesting interior lighting environment (Fontoynont, 2002). Additionally, daylight offers a good colour rendering in a way that better matches the human visual response if compared to electric lighting (Lim, Kandar, Ahmad, Ossen & Abdullah, 2012). However, the use of natural light requires elaborate design to serve various needs in building projects, which differ, for instance, from the building space and functionality to the interests of dwellers at different ages and occupations. The dwellers' interests in daylight utilization can subside when problems such as glare and overheat happen. The electric lighting adds in stability and reliability on indoor lighting environment when daylight provision is insufficient. Therefore, to achieve a good quality in a lighting design, it is inevitable to give equal attention on examining its daylighting performance and electric lighting performance.

Meanwhile, the human concern on lighting supply is not only an issue about visual performance, but also about how to optimize energy use in building industry. The paces of industrialization and urbanization accelerate at the cost of non-renewable energy resources, followed by a looming energy crisis and some environmental issues such as greenhouse gas emissions. The buildings share of global energy use has steadily increased and the figures were between 20% and 40% in developed countries (Pérez-Lombard, Ortiz & Pout, 2008). Among the energy end-users in buildings, lighting is responsible for a high proportion. For instance, lighting accounts for 25–30% of the total electricity use in non-residential buildings in Sweden (Dubois & Blomsterberg, 2011), 20-35% of total building electricity use in Hong Kong (Li D. H., Lam, Wong & Tsang, 2008) and 25–40% in the USA (Ihm, Nemrib & Krarti, 2009). Therefore, it has been a growing awareness to reduce the high amount share of building's lighting energy use. Building investors and inhabitants have become increasingly conscious of social impacts and carbon emissions of their building estates.

1.1 Background

In developed economies, there are about 2% of commercial buildings newly constructed each year, and a vast amount of opportunities to improve energy efficiency over the next decades will be in existing building stock (Johnson Controls, Inc., 2010). A same fact has been observed in the building construction sector in Sweden, where newly built projects account for a small amount (Dubois, Gentile, Amorim, Geisler-Moroder, Hoier, Jakobiak, Knoop, Matusiak, Osterhaus & Stoffer, 2015). The performance of existing buildings is constrained by factors such as old equipment, aging system, old operation practices and obsolete building codes complied at design stage. Among many building efficiency measures, retrofit of existing buildings represents an opportunity to upgrade the building performance and energy efficiency of building assets in their life span, as well as to reduce greenhouse gas emissions. In building lighting sector, retrofitting can attain a majority of lighting energy savings (Dubois, Gentile, Amorim, Geisler-Moroder, Hoier, Jakobiak, Knoop, Matusiak, Osterhaus & Stoffer, 2015). Hence, it is of great significance to study lighting retrofitted projects from their implementations in practice.

As aforementioned, the collaboration between daylighting and electric lighting can result in a win-win situation in lighting performance: a satisfying lighting environment and an efficient energy use. A good retrofit should take these two aspects into consideration at the same time. A good retrofit also “requires a fact-based, benchmarked, quantitatively oriented” (Lockwood, 2009) method to evaluate. In order to reflect the quality of a lighting retrofit project, it calls for a performable and normalized practice that allows lighting engineers to examine both lighting environment and lighting energy use holistically. This thesis documents a case study of a developed monitoring practice on an overall assessment of lighting performance.

1.2 Overall aims

Starting from a case study in Subtask D under the research project IEA-SHC Task 50, this thesis aims to holistically evaluate the lighting performance of a lighting retrofitted case project located in southern Sweden. More specifically, the daylight and electric light environment in this room, as well as the lighting energy use will be studied. In order to obtain an overall assessment, a sequence of daylighting and electric lighting metrics will be tested through field measurements and simulations. The analyses will be judged by comparing the measured or simulated results to the relevant benchmark values.

In the context of the main aim, this study has two further aspects to investigate. Firstly, the discrepancies between the measured and simulated results in regard to the assessment of daylight quality will be studied. Secondly, to explore the energy saving potential of the lighting installation in the case room, different lighting design parameters will be compared and their effects on the electric lighting energy use will be discussed.

1.3 Limitations

There are some limitations in the thesis stressed as follows.

Firstly, shading device is not considered in the lighting assessment, for which a higher glare may occur. Glare problem is a visual discomfort caused by luminous contrast and plays an important role in the judgement of daylighting performance. A well-functioning shading device can effectively reduce the risk of glare. Due to the shading device observed as fully open during the measurement periods, its effects are neglected in this study. Secondly, since there is no separate data logger installed for recording lighting energy use in the case room, the analysis of electric lighting is all based on simulations only, for which its conformance to field measurements is unknown. A few limitations have been made in regard to the simulation setup of the electric lighting system, which are explained further in the section Methodology.

1.4 Literature review

There have been a lot of research investigations regarding the assessment of lighting performance and lighting energy use.

Dubois et al. achieved an in-depth literature review about lighting and daylighting retrofit based on 160 research articles published between the year 1993 and 2013 (Dubois, Bisegna, Gentile, Knoop, Matusiak, Osterhaus & Tetri, 2014). According to the review, the present innovative lighting technologies in the market have been proved that they can achieve a high lighting energy saving in large amounts of real projects and research studies. The strategies covered in their review were commonly used in lighting retrofit projects nowadays, including replacement of lamps, ballasts and luminaires, reduction of maintained illuminance level, use of task-ambient lightings, and application of lighting control systems and daylight systems, etc. The authors summarized that the energy savings presented in these projects varied in a wide range, which mostly due to inherent building characteristics such as building location, geometry and function and initial energy use. They also stated that when several strategies were applied together, the total saving was not necessarily a simple linearly added-up of energy savings from individual retrofit measures (Dubois, Bisegna, Gentile, Knoop, Matusiak, Osterhaus and Tetri, 2014). Moreover, the authors pointed out that in spite of some proven energy savings, there were feedbacks indicated that unpleasant photometric effects were examined after retrofits, such as unsatisfied colour rendering, distracted flicker and poor light distribution (Dubois, Bisegna, Gentile, Knoop, Matusiak, Osterhaus and Tetri, 2014). In addition to that, some strategies were difficult to implement in practices and it was hard to estimate payback time at the early design stage, such as daylight-linked control system (Dubois, Bisegna, Gentile, Knoop, Matusiak, Osterhaus and Tetri, 2014). The authors in the end addressed the rareness of existing knowledge regarding monitored data in the study of lighting retrofit practices, and highlighted the demand in the future prospects on building up a better understanding for the spread and development of lighting retrofit.

In order to broaden the knowledge about research practices on existing lighting projects, further literature searches were conducted in related to lighting energy use and lighting performance. Some other researches, among which mostly were published recently, were reviewed and structured around three specific topics in next sections.

1.4.1 Studies on lighting/daylighting measurements

The first category is about the lighting assessment studies that based on instrumental measurements.

In America, Fernandes et al. (Fernandes, Lee, DiBartolomeo and McNeil, 2014) verified the actual lighting energy performance of the New York Times building, for which the lighting control system is promoted worldwide as a demonstration due to its successful lighting design. The study was a post-occupancy evaluation and the researchers studied three typical floors 6th, 11th and 20th in their open-plan office areas. The studied electric lighting was controlled by an automated dimming system that followed three control criteria: daylighting, setpoint tuning and occupancy. The total annual lighting savings were collected for a solstice-to-solstice period and were determined based on data estimation from the manufacturer. To verify the accuracy of these estimated data, they conducted independent on-field monitoring on the 20th floor and derived the correlation between the two datasets. The process of calibration showed that the measured data did not agree with the estimated data. The results revealed overall savings from dimming control were 12.6 kWh/m^2,yr for the three floors, which means a reduction of 20% relative to ASHRAE 90.1-2007 baseline, and savings from occupancy control were 17.6 kWh/m^2,yr for the same baseline. The authors pointed out that, even if the building located in a dense urban neighbourhood, there were no clear trends regarding saving variations identified by orientation within the same floor or similar spaces within different floors. They speculated this was due to the automatic shading system which adjusting various daylight availability within different floors. At the end of the study, the authors stressed the importance of obtaining on-site monitoring data when evaluating the field performance of energy-efficient lighting technologies.

The importance of field measurements was also emphasized in the study of Doulos et al. (Doulos, Tsangrassoulis & Topalis, 2008) on quantifying energy savings in daylight responsive systems with different dimming electronic ballasts. They presented that the measurements of ballast properties helped to provide more reliable results on energy saving calculation, and by comparison, using default values of the ballast property resulted in errors. In another study performed in America, Hebert et al. (Hebert, Kang & Thompsen, 2014) examined the lighting system at university laboratory during a ten-week summer period to test its energy savings and costs. The test lighting system had been newly renovated before the study by replacing all the luminaires with T8 fluorescent lamps and energy-saving ballasts. The energy savings of the system were determined based on energy use calculation from occupancy behaviour data, by comparing to the logged data before the renovation. According to the lesson obtained from the study, the strategies of de-lamping and use of occupancy sensor were recommended in retrofit projects of the type of laboratory building. The authors also demonstrated that, with careful consideration on recommended light level and installation budgets, lighting energy use can be reduced without sacrificing illumination levels. This field lighting study they conducted, as they noted, added value into documenting cost-effective methods to measure, record and manage laboratory lighting (Hebert, Kang & Thompsen, 2014).

1.4.2 Studies on Lighting/Daylighting simulation

The second category is about the application of simulation on daylighting and lighting studies and its validation. Researches have shown that setting up an accurate simulation model is critical to obtain reliable data, which can be affected by factors such as choice of sky model, material reflectance of the building and surrounding, the defined material type in simulation software, etc. (Mardaljevic, 1995; Ochoa, Aries, & Hensen, State of the art in lighting simulation for building science: a literature review, 2012). The deviation between simulation results and actual measurements, was considered as acceptable within the range of 20%, according to validation study performed by Reinhart and Andersen (2006) and was also mentioned by Galasiu and Atif (2002).

Recently, some researchers investigated daylight-induced energy saving potential in an educational building, which was equipped with a high frequency dimming lighting control system, located in Nottingham, UK (Yu, Su, & Chen, 2014). They performed the analysis of daylight availability by simulating daylight factor (DF) in four selected rooms using RELUX lighting simulation software. To check the validity of the simulated values, they conducted field measurements and the deviation was concluded as acceptable within a range of 20%. The difference showed that the simulated DF values from RELUX were generally higher than the measured values. This finding was conforming to what had been summarized in the literature review of Dubois et al. (Dubois, Bisegna, Gentile, Knoop, Matusiak, Osterhaus and Tetri, 2014): simulation generally overestimated the savings compared with results from field study; especially when the control system entailed advanced automated technology, such as daylight harvesting technology, the difference was larger. In Yu, Su and Chen's study, they also investigated the electric lighting energy saving that caused by daylight utilization via five different methods, computational calculation via Relux Energy using European standard (EN15193), manual calculation via daylight factor method with and without electric lighting consideration and manual calculation via simulated daylight coefficient method with and without electric lighting consideration.

1.4.3 Studies on assessment of daylight/electric lighting retrofit techniques

So many factors can cause a huge difference in the retrofitting evaluation of daylight performance and electric energy use, such as building geometric characteristics, obstruction effects from surroundings, room shape, window size and type, function of shading devices, lighting control strategies (Ochoa, Aries & Hensen, 2012), occupancy pattern and the function and density of the room (Fernandes, Lee, DiBartolomeo, & McNeil, 2014). Moreover, Cuttle (1999) addressed the difficulties of accurate daylight assessment if not taking indoor architecture and furniture into account.

In Hong Kong, Li et al. conducted field measurements of a daylight-linked dimming lighting control system at the atrium corridors in an institutional building (Li, Cheung, Chow, & Lee, 2014). The authors measured illuminance level in the corridor spaces after the retrofitting with all the lamps replaced as high energy efficacy T5 tubes. It turned out that the mean interior illuminance level was much higher than the recommended value which may cause excessive brightness and glare. In regard to energy use, the authors found out the lighting savings due to the installed high frequency dimming control system can range widely from 14% to 65% monthly in different zones in the atrium corridors. If compared to the review summarized by Dubois et al., the range of energy saving brought in by the use of a daylight-linked dimming control system was between 18% and 37% of total lighting energy use observed from various studies (Dubois, Bisegna, Gentile, Knoop, Matusiak, Osterhaus, &Tetri, 2014).

To generalize, the literature review reveals some limitations of current knowledge about the study on retrofitting assessment, which is summarized as follows.

- There is a rareness of existing knowledge regarding monitored data in the study of lighting retrofit practices, the demand should be highlighted in the prospects to build up a better understanding for the spread and development of lighting retrofit.
- Field measurement plays a very important role in a lighting performance assessment; the simulated results usually overestimate the saving effects especially when the lighting system is advanced control system.
- Many studies for the assessment of a lighting strategy either focus on a perspective of savings in energy use, or solely on photometric quality. Few of the studies included both aspects.
- From the aspect of evaluating a retrofit measure, the importance of a holistic assessment is critical to note.

Therefore, an overall assessment is able to package all the factors mentioned above and fill the gaps in these limitations, as well as to evaluate the retrofitting quality of a certain lighting strategy and maximize the impact of the lessons drawn from adopting new retrofitting techniques.

2 Methodology

As introduced in previous sections, in this thesis the assessment of lighting performance contains two parts, daylighting assessment and electric lighting assessment.

The daylight assessment was conducted through a set of lighting metrics investigations based on instrumental measurements and software simulations. These were carried out in a few stages: measurements preparation and implementation, results collection and assessment, simulation model set-up and validation, simulations and results assessment, and the last, comparisons between the measured result and the simulated result. In the part of electric light assessment, lighting performance in terms of lighting quality and energy use were investigated. The electric lighting energy use of this room, in the form of LENI (Lighting energy numeric indicator), were investigated by simulations. Besides, in order to investigate energy saving potential from electric lighting installation in this room, simulations were run under lighting control conditions with different design parameters and lighting control strategies.

Since the pre-retrofit condition of the studied project is unknown in this case, the lighting quality was evaluated by comparing the measured/simulated results to a set of relevant benchmark values which are described in detail in this Chapter.

2.1 Software

The computer programs and tools used during this study were listed and followed by a short description for each software.

- Rhinoceros.

Rhinoceros is a 3D modelling program and was used to set up the room model for simulation studies.

- DIVA for Rhino

DIVA for Rhino is an advanced lighting and energy modelling tool that can be added in the interface of *Rhinoceros*. It is the main tool utilized in the simulation part in this study. The calculation of lighting performance in the tool is based on two advanced lighting simulation software: *Radiance* and *Daysim*. *Radiance* is a validated lighting simulation tool and is used for the prediction of illumination, visual quality and appearance of spaces, as well as for the evaluation of new lighting installation technologies (Fritz & AMcneil, 2016). The method used in Radiance for calculation is a backward ray-tracing method, which means all the calculated 'view rays' follow a virtual path from a focus of an observation subject to an observed environment (Dubois, Impact of Shading Devices on Daylight Quality in Offices. Simulations with Radiance, 2001). The calculation requires input files which specify the geometry, materials, time and date, luminaires, and sky conditions in daylight calculations (Radiance: Sythetic imaging system, n.d.). During the simulation studies, some simulation settings were adjusted under *Radiance* and *Daysim* to fulfil customized goals in simulating the studied case, the details of which are explained in section 2.4 and 2.5.

- Evalglare

Evalglare is a *Radiance*-based tool to evaluate glare problem in day lit spaces. It was developed by Wienold and Christoffersen aiming for detection of glare sources and calculation of glare indices (Wienold and Christoffersen, 2006). The use of Evalglare was initiated after the developed technique of high dynamic range image (HDR), which can be created either from conventional digital images with a range of exposure settings taken by a digital camera or to be simulated in modelling software, both usages were implemented in this study. Evalglare is used in this study to calculate a glare index called daylight glare probability (DGP), as well as detect the glare sources in the room. By code-editing Evalglare commands under Command Prompt window, a given HDR image is analyzed and luminance values at each pixel of the image are calculated, and then based on the luminance information, a colour-coded image is recreated with identified glare sources.

- Photosphere Alpha

Photosphere Alpha is a photo editing tool. Images that are taken from a DSLR camera (digital single-lens reflex camera) with a wide range of exposures are input into the tool. Photosphere Alpha post-processes these images to generate HDR photos as well as calibrate them.

- *Microsoft Excel* was used to organize all the measured and simulated results and to generate graphs.

2.2 Case room

The studied room is one of the cases investigated in Subtask D: case studies under the work plan of IEA-SHC Task 50. This is a case study on an educational building: Architecture building in Lund University, located in Lund, Sweden. Lund lies in the south of Sweden, with latitude of 55°42’N and longitude of 13°12’E, seen in Figure 1. As presented in Figure 1, the Architecture building (No. 24) stands adjacent to the building of design center (No. 26), the Civil Engineering building (No. 1), the administrative building (No. 22F) and some open green lands. The Architecture building is a five-storey educational building providing a varieties of facilities to students and staff, which include numbers of working studios, seminar rooms, laboratories and staff office rooms and some communal dining rooms. The selected case room serves as a dining room for the staff located on the fourth floor of the Architecture building. Figure 2 provides the building view from outside. Detailed descriptions about room geometry and lighting systems follow in the section.

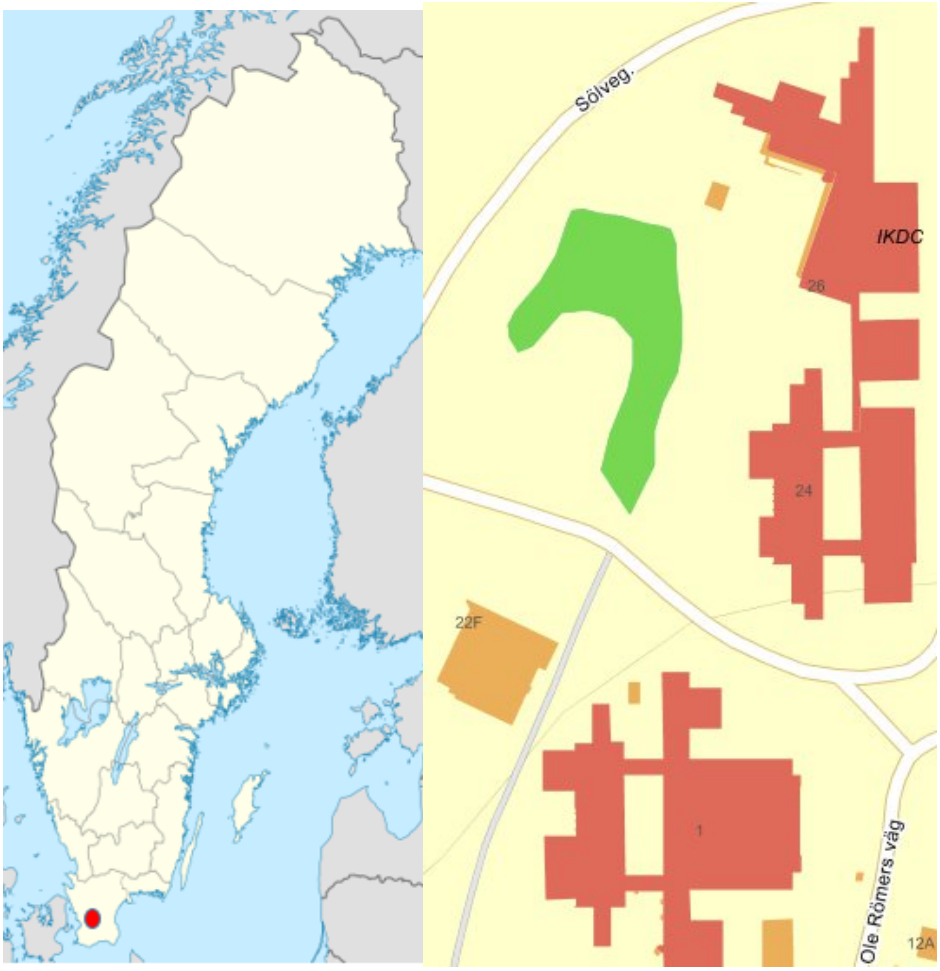


Figure 1 Location of Lund (left) and surroundings of Architecture building (right).

Figure 2 Building view from outside.

2.2.1 Room geometry

The room is measured as 5m in width and 12.7m in length, 2.85m at ceiling height. Four windows facing the west offer a direct view to the open lawn outside. Each window contains two parts: the size of upper glass is 1.33m wide by 1m high, and lower glass has the same width but 0.3m in height. The window sill is 1m high from the floor. The distance between each window is 3m. The room's east interior wall is adjacent to a corridor, where makes the access to some daylight. Some interior windows on the north lateral wall also provide some daylight accessibility from an adjacent office. Figure 3 shows the spatial relations between the room and its adjacent rooms and space.

The room is fully furnished and all the pieces of furniture, including dining table and chairs, cupboards in food preparation area, are considered in the assessment. In order to reproduce the room in simulation modelling, detailed dimensions of furniture and their locations were precisely measured.

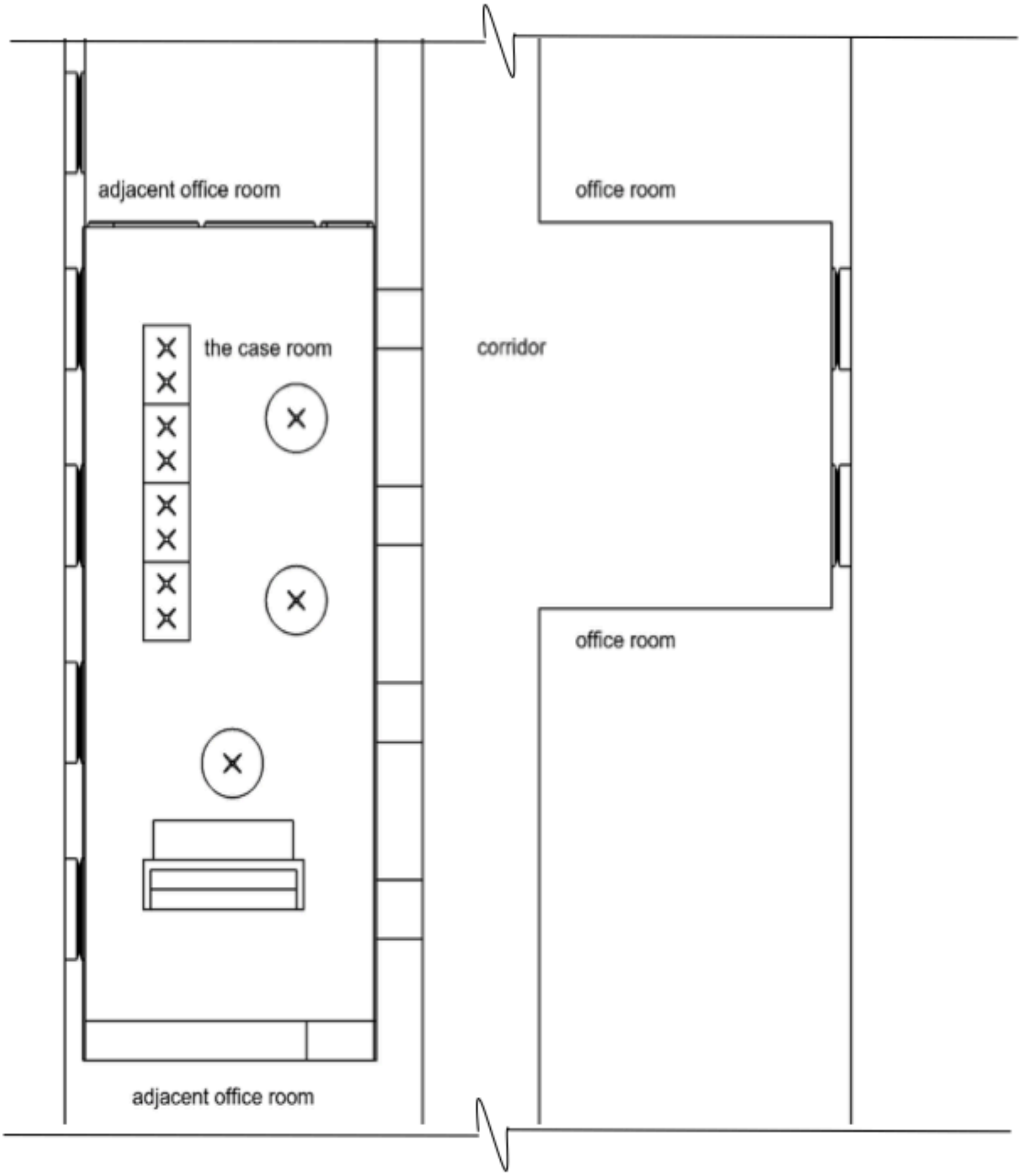


Figure 3 Plan layout of the case room and its adjacent space.

2.2.2 Room model

The case room and its surroundings were modelled in Rhinoceros to be precisely processed for further simulation in DIVA for Rhino. Figure 4 shows a room image with a perspective view looking towards southwest inside the room, while Figure 5 provides the modelled image with the same view. The dimensions of the room and the furniture follow the descriptions in section 2.2.1.

As noted in 2.2.1, daylight condition in this room is influenced by its neighbouring spaces. Thus, neighbouring rooms inside the building and surrounding building objects and plants outside the building were built up in the model as well. Figure 6 exhibits the modelled surroundings outside the building. The coordinate axis y is pointing towards north. In the picture, red block marks the location of the case room. Its surrounding buildings and trees are simplified as plane surfaces representing the main surfaces of these obstacles where light bounce from and towards that affecting lighting condition in the room. Besides the modelling of the surroundings, a ground plane must always be modelled for lighting simulation. In this case, a ground square dimensioned in 230m by 220m was created, guaranteeing the area wide enough for accurate simulation. External dimensions of the building, sites of its surroundings and the layout of roads were depicted based on a satellite picture captured on Google map.

Figure 4 Interior look of the case room, photographed image with a perspective view looking towards southwest.

Figure 5 Interior look of the case room, modelled in Rhinoceros with a perspective view looking towards southwest.

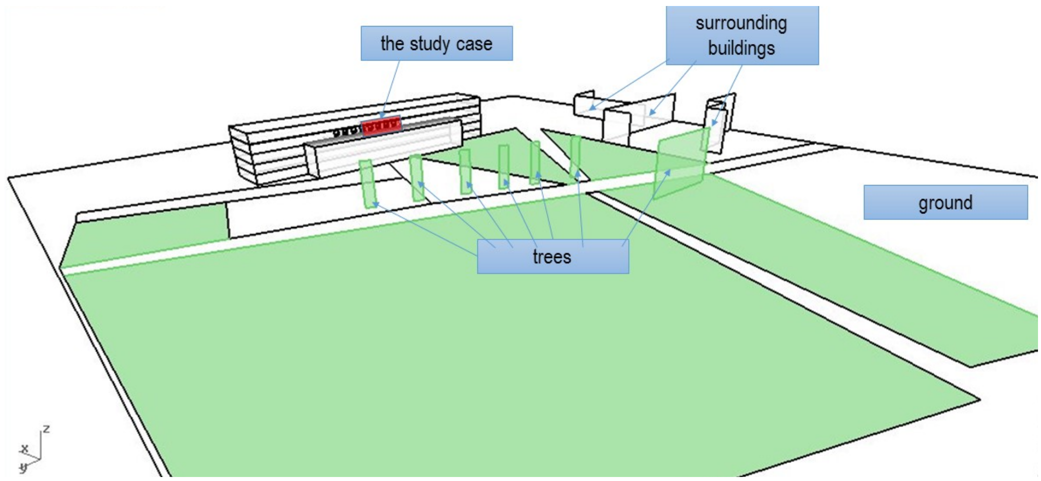


Figure 6 Layouts of the surroundings in the model.

2.2.3 Climate and sky models

The climate data and sky models run under the entire simulation are under Lund weather file. In order to assess daylight condition in the room, a few lighting metrics including daylight factor (DF) and illuminance and luminance values are calculated, the description of which are provided in section 2.3. To calculate these lighting metrics, some representative sky conditions were used. The sky model used for the calculation of DF is CIE overcast sky, seen in Figure 7. The sky models used for the calculation of illuminance/luminance values are CIE sunny sky with sun with a defined time in conformity with the measurements, shown in Figure 8. CIE (Commission Internationale de l'Éclairage, in English is international commission on illumination) overcast sky and sunny sky represent the two extreme sky conditions of a totally overcast sky and a perfectly sunny sky (Reinhart C. F., Tutorial on the Use of Daysim Simulations for Sustainable Design, 2010).

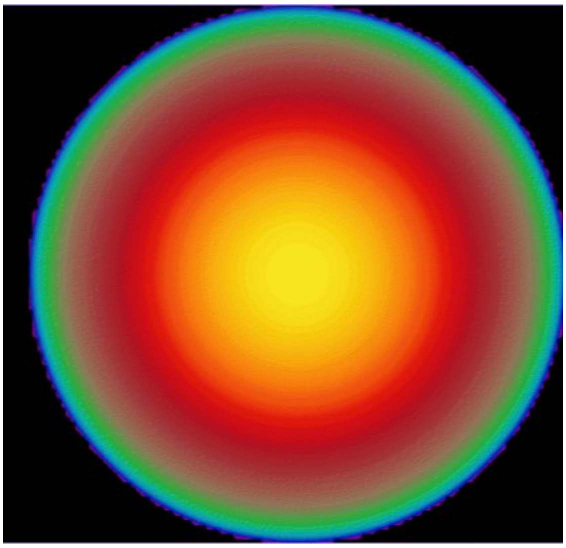


Figure 7 Sky model, CIE overcast sky, Lund.

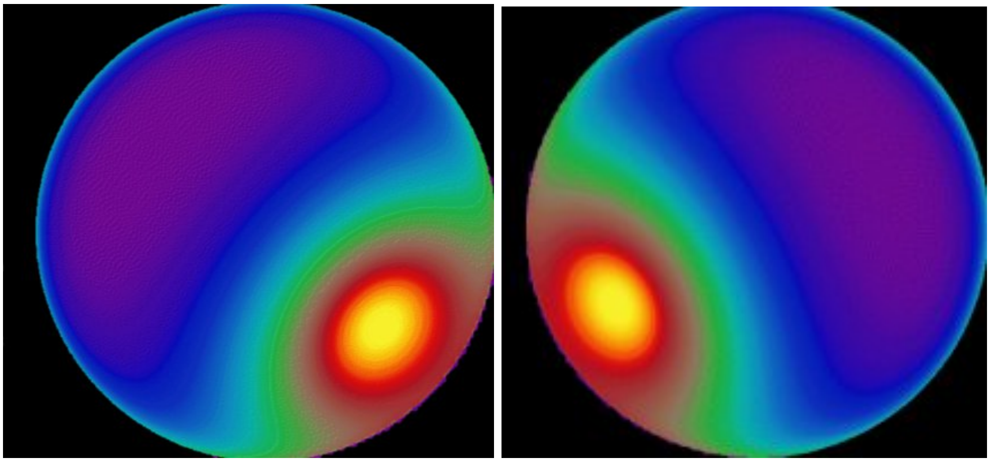


Figure 8 Sky model, CIE sunny sky with sun, Lund, 10am (left), 3pm (right), July 1st, Lund.

2.2.4 Optical property

Surface reflectance

The reflectance of the surfaces in the room were needed to define the materials for the simulation. The reflectance of opaque surfaces, like walls, ceilings, floor, roof and ground, were determined by measuring the luminance of these elements and comparing with the luminance of a reference surface with known reflectance. The luminance of the test elements and that of the reference surface were measured under a same lighting condition. The reflectance of the test surface was calculated as follows,

$$\rho_{test} = \rho_{ref} \cdot \frac{L_{test}}{L_{ref}} \qquad \textit{Eq. 1}$$

where ρ_{ref} is the reflectance of the reference surface, L_{test} is the luminance (cd/m^2) of the test surface and L_{ref} is the luminance (cd/m^2) of the reference surface.

Optical properties of opaque surfaces for the study room are summarized in Table 1.

Table 1 Optical properties of opaque surfaces

Object name	**Material**	**Reflectance**
Ceiling	Gypsum with small holes	0.9
Floor	linoleum	0.16
West wall	White painted cement with texture	0.90
North/East wall	White gypsum with small holes	0.85
South wall	White gypsum	0.96*
Ground, greenfield/Tree	plant	0.09
Ground, pavement	-	0.14
Facade	Brick	0.13
Asphalt roof	Asphalt	0.07**
Furniture	-	0.88
Window frame	-	0.98*

**Measured value was adopted even if it describes on Radiance material that reflectance over 90% is not realistic*

*** Value was obtained from web source* (group, n.d.)

Window: visible transmissivity

In daylight modelling, *Radiance* requires glazing parameters transmissivity for daylight simulation while the glazing manufacturer often provides data of transmittance for the window. Visible transmissivity is an optical property of a material which is intrinsic property depending on the type of the material itself. While visible transmittance of a glazing subject is the measured ratio between light transmitted through the glazing subject and the amount of incident light under certain test condition. The transmissivity of the window glass is derived from the transmittance of the glass according to Eq.2.

$$t_n = \frac{\sqrt{0.8402528435+0.0072522239 \cdot {T_n}^2}-0.9166530661}{0.0036261119 \cdot T_n} \qquad \textit{Eq. 2}$$

Where, t_n is the transmissivity of the window glass and T_n is the transmittance of the glass.

The transmission of the glass is 0.65 and the converted transmissivity is 0.7085.

2.2.5 Description of electric lighting system

Lighting system in the room consists of three types of luminaires, which are pendent, wall-mounted and ceiling recessed respectively. Figure 9 illustrates the layout of the luminaires in a plan view. The luminaires are grouped in three lighting control zones according to the design drawings provided by Akademiska Hus, each zone marked as areas in dash lines in Figure 9. Table 2 provides the properties of the luminaires in each zone with information of their mounted types, lighting power density and luminaire amounts.

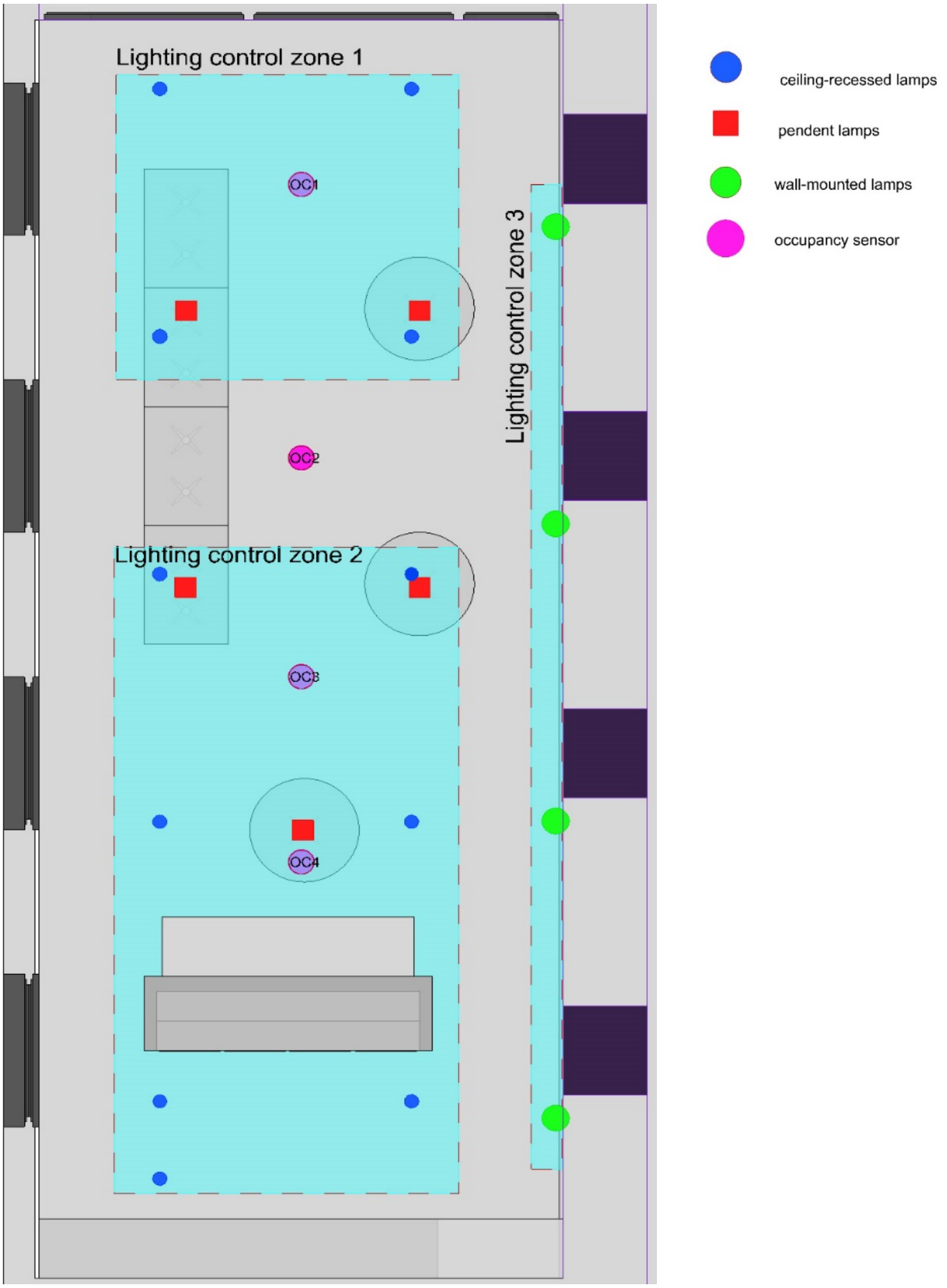


Figure 9 Layout of lighting system. The occupancy sensors are the circle symbol labelled with 'OC'.

Table 2 Property of lighting system.

	Luminaire mounted type		**Installed Lighting power** (W)		**Fixture Amounts**		**Lighting power density** (W/m^2)
Lighting control zone 1	Pendent	ceiling recessed	26	13	2	4	1.72
Lighting control zone 2	Pendent	ceiling recessed	26	13	3	7	2.80
Lighting control zone 3	Wall-mounted		13		4		0.86
Total installed lighting power							5.38

In regard to the lighting control strategy for the system, each lighting zone has its own on/off manual switch button beside the door and this manual control is combined with absence occupancy sensor control. The occupancy sensor sends a signal to turn off the lamps if there is no occupant detected within 15 minutes. These sensors are installed at air outlets and are automatically activated by the operation of ventilation system, so they do not consume standby power on the lighting energy part. Positions of the occupancy sensors are delineated in Figure 9, which are the circle symbols labelled with 'OC'.

2.2.6 Occupied hours

According to an initial site visit in the case room and the designed function of the studied room, occupied hours in a standard workday are decided at three separate hours, 10am, 12am and 3pm. A customized occupancy profile was generated in *Honeybee* in *Grasshopper* and was applied in all the simulated cases. The schedule profile has summer holiday between July 1st and August 22nd, and winter holiday between December 24th and January 3rd. The occupancy schedule for the modelled room, which is shown in Figure 10, has 777 occupied hours per year and it also takes daylight saving into account. The white patches in the picture indicate the occupied hours.

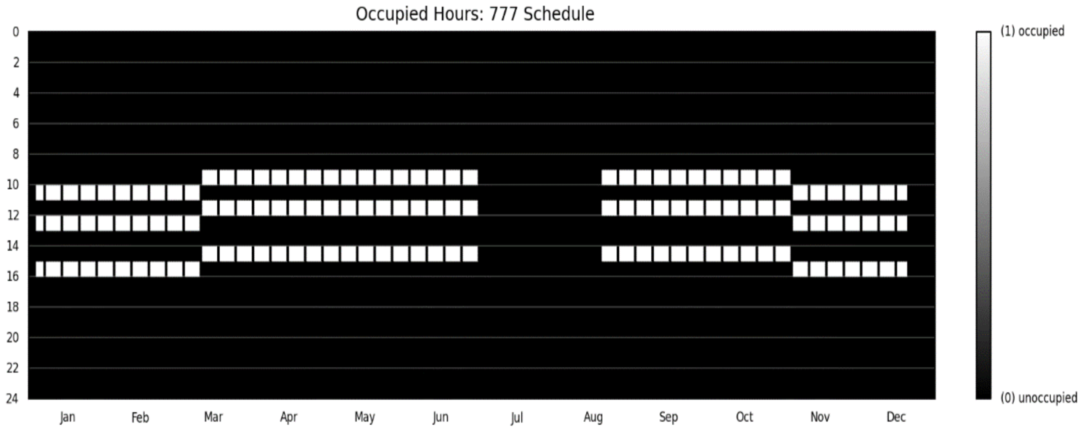


Figure 10 Annual occupancy profile used for electric lighting simulation for the studied room.

2.3 *Studied lighting metrics and their criteria*

There are many lighting metrics validated and widely applied to evaluate the photometric quality of a lighting design. Some main lighting metrics that affect lighting quality include luminance distribution, illuminance uniformity, glare, colour, flicker of lighting system and view from the studied room. Among them, the flicker condition cannot be measured therefore it is not quantitatively comparable and evaluated. Colour is measurable though this metric is not relevant in the study considering the room was white. Therefore, in this study, a few lighting metrics were selected for assessing the lighting performance, which include daylight factor, daylight glare probability, potential glare sources and luminance ratios in daylight assessment and lighting energy numeric indicator, maintained illuminance and illuminance uniformity in electric lighting assessment. Their definitions are explained in subset sections together with the evaluation criteria.

- DF (daylight factor)

The daylight factor is a common and practical parameter to quantify the daylight appearance of a room. It is defined as the ratio of the indoor illuminance at a point of interest to the simultaneous outdoor horizontal illuminance under an overcast sky. (Tregenza & Wilson, 2011) The daylight factor is used for interpreting indoor daylight levels and is widely used as a criterion embodied in building regulations. It enjoys considerable popularity as it is considered as an intuitive quantity which expresses the efficiency of a room by means of introducing light into the room (Dubois, 2001). The daylight factor metric provides an objective and quantifiable target to achieve for a building. And because the calculation of the daylight factor is based on a single sky condition, its credibility to judge the daylight situation in the building subject is intrinsically determined (Reinhart C. , 2010). However, it has some limitations when using the daylight factor to characterize daylight performance. The major weakness is that the daylight factor is independent of the orientation and geographical latitude of the building subject, since the CIE overcast sky is rotationally invariant and not influenced by the latitude where the building subject is (Reinhart C. , 2010).

The criteria for evaluating the daylight factor complies with the requirements in the Swedish regulations. In the European standard 'SS-EN 12464: 2011', it requires a minimum point DF value of 1% in the room. The same point is used in the Swedish green building certificate 'Miljöbyggnad', the daylight factor should have a lowest value of 1.2% at a specified point. The point is defined as at half of the depth of the room with a distance of one meter to the darkest side wall. An example demonstrated in Figure 11 explains the specified point according to the definition in the Swedish building code.

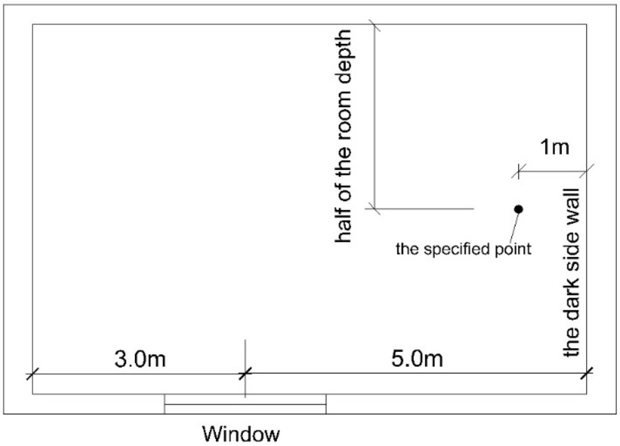


Figure 11 Specified point used in the criteria to evaluate the daylight factor.

- DGP (Daylight glare probability)

The image-based glare metric daylight glare probability (DGP) is one of the glare indices to predict user acceptance of the discomfort glare in day lit spaces, proposed by Wienold and Christoffersen (2006). Developed based on abundant experimental cases in their glare studies, DGP is a function of the vertical eye illuminance and the glare source luminance, its formula see in Eq.3 (Wienold and Christoffersen, 2006). The DGP score could be calculated based on captured or modelled HDR images in the tool *Evalglare*.

$$DGP = 5.87\times10^{-5}E_v + 9.18\times10^{-2}log\left(1 + \sum_i \frac{{L_{s,i}}^2\omega_{s,i}}{E_v^{1.87}P_I^2}\right) + 0.16 \qquad Eq.\ 3$$

where E_v is the vertical eye illuminance (lux); L_s is the luminance of source (cd/m^2); ω_s is the solid angle of source; P is the position index of source.

When the vertical eye illuminance E_v is smaller than 320 lux and the DGP is smaller than 0.2, the calculated DGP is out of the range of the experimental studies where DGP is based on. Therefore, a correction factor is used in calculations for 'low light' scenes in the tool

Evalglare, seen in Eq.4 (Wienold, http://infoscience.epfl.ch/record/208874/files/Wienold _glare_rad.pdf, 2014).

$$DGP_{\_lowlight} = DGP \frac{e^{0.024 \cdot E_v - 4}}{1 + e^{0.024 \cdot E_v - 4}} \qquad Eq.\ 4$$

The glare levels are classified according to the DGP score and the classification is defined in Table 3.

Table 3 Glare level classified by DGP score.

DGP	**< 0.35**	$0.35 \leq DGP < 0.4$	$0.4 \leq DGP < 0.45$	≥ 0.45
Glare level	imperceptible	perceptible	disturbing	intolerable

- Luminance ratio

The luminance distribution in the visual field of an observer must remain in reasonable ratios, especially for whom working in a static task for long periods of time. Athienitis and Tzempelikos (2002) mentioned that visual discomfort and fatigue could occur if very high contrast in between two adjacent surfaces.

The criteria for evaluating the ratio were referred to some provisions and research studies described in the following. In many lighting standards, a preferred luminance ratio is suggested, such as the European standard for lighting of indoor work places SS-EN-12464-1, and provisions from the British standard for building sevices CIBSE. A recommended luminance ratio of “1:3:5:10” for work places from Svensson (2010) requires:

- the ratio between the task area and the directly surrounding area should not exceed 3:1
- the ratio between the task area and the ‘exterior’ surrounding area should not exceed 5:1
- the ratio between the task area and the peripheral surrounding area should not exceed 10:1

It needs to mention that his recommendation is not used with the same rigor for any situation. It has been proved that humans are more likely to tolerate higher level of contrast in a daylit space (Osterhaus, 2002). The experiment, conducted by Sutter and Dumortier (2006), showed that in the conditions with windows in the field of view, a luminance ratio of 1:6:20, in the relation between the task surface to its immediate surrounding and to its remote surrounding, was tolerated by task-working observers. But a ratio of 1:40 between task area and any surrounding surface in the field of view is the maximum level that human can tolerate visually.

Considered the studied room is an adequately day-lit space and people do not work long periods of time in this space, the criteria of assessing the luminance ratios are summarized in Table 4.

Table 4 Criteria of assessing the luminance ratios.

Luminance ratio	**Surfaces**	**Interpretation**
< 1:6:20	Any surface: immediately surrounding: remotely surrounding	Ideal
< 1:20	Between any surface in field of view	Tolerable
> 1:40	Between any surface in field of view	Unacceptable

- Lighting Energy Numeric Indicator (LENI)

The lighting energy numeric indicator is an indicator of the total annual lighting energy required in the building. According to the definition in 'EN_15193-1: Energy requirements for lighting' (2006),

$$LENI = W/A \quad [kWh/(m^2 \cdot year)] \qquad \textit{Eq. 5}$$

Where, W is the total annual energy used for lighting [kWh/year], A is the total useful floor area [m^2].

Benchmark values to meet the desired lighting criteria are provided in European standard EN_15193:2006. For educational building, the benchmark default value is 27.0 $kWh/(m^2 \cdot year)$ if the studied building has automatic control lighting system. Additionally, in regard to buildings in North European, Dubois (2011) proposed a target energy intensity of about 10 $kWh/(m^2 \cdot year)$ realistically for low energy office buildings and new retrofit projects.

- Maintained illuminance

To judge the quality of electric lighting design in lighting environment, the criteria regarding target illuminance are complied. According to SS-EN 12464-1:2011, "Ljus och belysning – Belysning av arbetsplatser (Light and lighting – Lighting of work places)"

(2011), it is required that for canteens and pantries in general areas, the maintained illuminance shall not be less than 200lx.

- Illuminance uniformity

The illuminance uniformity is another critical index to assess the lighting quality from electric lighting installation. This index is defined as the ratio of illuminance values between the interest task area and its surrounding area. In SS-EN 12464-1:2011, it requires that in a task area that illuminated by electric lighting shall have the illuminance uniformity of not less than 0.40 in the immediate surrounding area, and not less than 0.1 on the background area (SS-EN 12464-1:2011 Ljus och belysning-Belysning av arbetsplatser, 2011). The first ratio is defined as the ratio of the illuminance value at the interest spot to that of its immediate surrounding area, and the second ratio is the ratio of the illuminance value at the interest spot to that of its background area.

2.4 Method: Daylight measurements

Recently, a monitoring protocol was under development in the context of IEA-SHC Task 50: Advanced Lighting Solutions for Retrofitting Buildings. The project IEA-SHC Task 50 focuses on evaluation of lighting performance in daylighting and lighting retrofit projects and seeks to promote daylighting and electric lighting retrofitting practices in non-residential building stocks. This monitoring protocol was designed to pursue a standard method that the overall lighting performance can be comprehensively assessed based on a sequence of field measurements (Dubois and Gentile, 2015). The aim is that through the guidance of this protocol, lighting engineers are able to judge the quality of lighting retrofit projects being a success or failure (Dubois and Gentile, 2015). The monitoring protocol was developed as a part of subtask D in this project, which contains case studies about lighting retrofit practices. This thesis started from applying this protocol on a case study in subtask D. The protocol includes four main aspects of a lighting retrofitting project, which are photometric assessment, energy use, retrofit costs, and users' assessment (Gentile, Dubois, Osterhaus, Stoffer & Cláudia, 2015). Each aspect has a five-phase procedure, which consists of initial visit surveys, pre-monitoring decisions, preparations, monitoring and analysis of results (Gentile, Dubois, Osterhaus, Stoffer & Cláudia, 2015). In this thesis, the first aspect in related to photometric assessment was conducted in the daylight quality assessment.

To collect the studied photometric data which referring to section 2.3, a sequence of instrumental measurements was instructed according to the monitoring protocol and was described in this section. The lighting metrics measured for daylight assessment contain the daylight factor, the glare potential and luminance ratio which demonstrated in subset sections.

2.4.1 Daylight factor

Measurement set-up

The measurement of daylight factor (DF) is actually a procedure of measurements of indoor and outdoor illuminances. In order to measure the indoor illuminances, the points of interests were identified and a grid of 48 points was plotted at the work plane of 0.70m high from the floor in the room. Figure 12 shows the layouts of these test points. The test points were distributed in eight equal rows with a distance of 1.5m between each other along the long side of the room. Within each row there were six points which were located with a smaller spacing when looking closer to the windows. This arrangement is considered that the daylight performance generally changes more notably at the area by the window. The distances between the test points are marked in Figure 12 and the measured rows are named in sequence from X1 to X8.

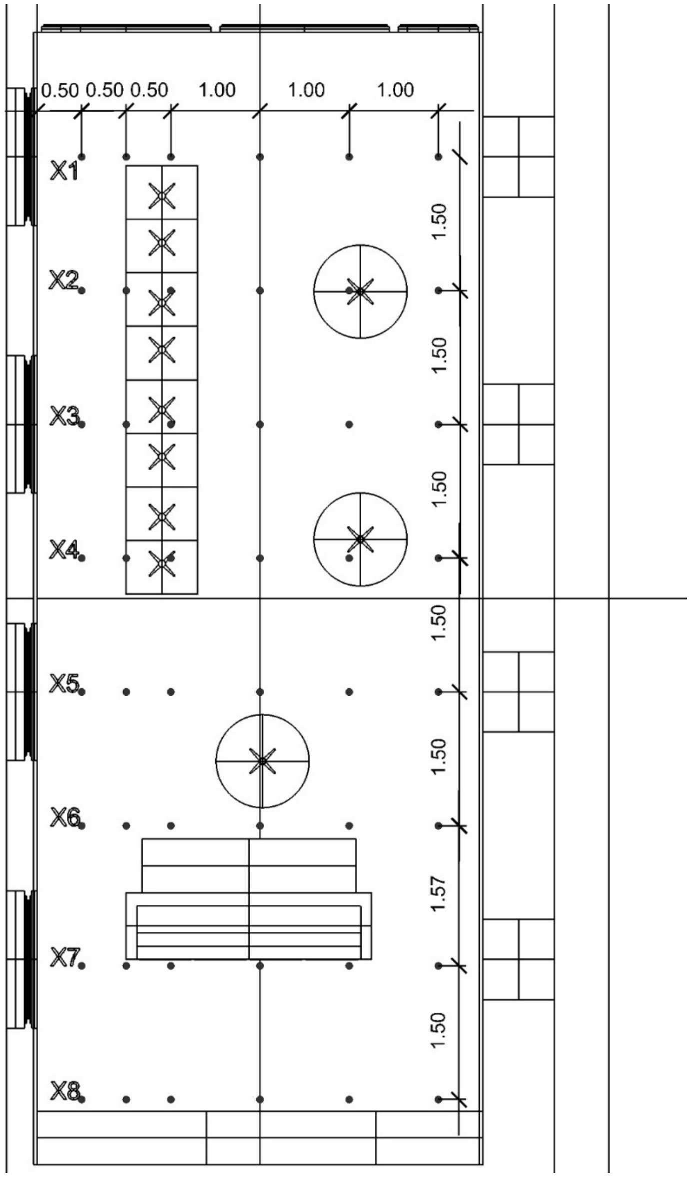


Figure 12 Layout of test points for illuminance measurement (Unit: m).

Measuring instruments

Four handheld lux meters were used:

- for measuring indoor horizontal illuminances

Two Hagner lux meters EC1-0X. One was fixed stably on a tripod to ensure a measuring height of 0.7m for testing points not located on the work plane. Another lux meter was placed on the table for testing points locating just on the work plane.

- for measuring outdoor horizontal illuminances

One Hagner lux meter E4x for measuring global diffuse illuminance, and one Hagner 'Screen Master' for measuring global illuminance. The value of outdoor horizontal illuminance is estimated as the measured global illuminance deducted by global diffuse illuminance.

Measuring procedure

This measurement was conducted under an overcast sky condition, in this case on October 16th, and was operated by two people to ensure that the indoor and outdoor illuminance were recorded simultaneously. After the measurement, indoor illuminance values at the 48 test points and the correspondent outdoor illuminance values were collected in Excel spreadsheet, and the DF score were calculated and plotted.

Besides, to evaluate the daylight quality in the room, the point beside the 'dark' side wall was specified according to '*Miljöbyggnad'*, as mentioned in section 2.3. In this studied case, since the room has a symmetrical shape, the fourth point in row X1 and X8 which were 2.5m away from the window wall were defined as the specified points.

2.4.2 Glare analysis

In this section discomfort glare was evaluated by studies of (1) the glare index DGP and (2) glare sources in the room. Both of them were obtained based on HDR images. This section introduces the procedures of the HDR images generation and glare problems investigation using Evalglare.

2.4.2.1 Generate the HDR images

To investigate the glare problem in the room, two typical task positions were selected. This selection was decided after a pre-analysis of the daylight condition in the studied room. One task position is a sitting spot representing lighting condition with very big potential of glare problem, named as *extreme position* in this paper; another one being a place where a person could perceive a typical and average light situation in the room, named as *typical position*. The selected positions are shown in Figure 13. After the selection, these positions were photographed for glare analysis.

The HDR image, namely high dynamic range image, contains a complete information of luminance in the image. In this measurement, it is generated from a series of photos taken by a digital camera Nikon D5300. A standard 180° fisheye lens from Sigma with specification of 4.5mm F2.8 was used for capturing fisheye photos. These photos were captured in a wide range of shutter speeds, from fully under-exposure to over-exposure, to ensure that the HDR images provide a complete luminance map. In this study, 19 photos were captured for each position. They were afterwards imported into the software called 'Photosphere' to create the HDR images. The capture was performed on July 1st, 2015 with a clear sunny sky condition, and at two times of the day which were at 10 and 15 o'clock. During the procedure, the camera was mounted stably on a tripod at eye level of a sitting observer.

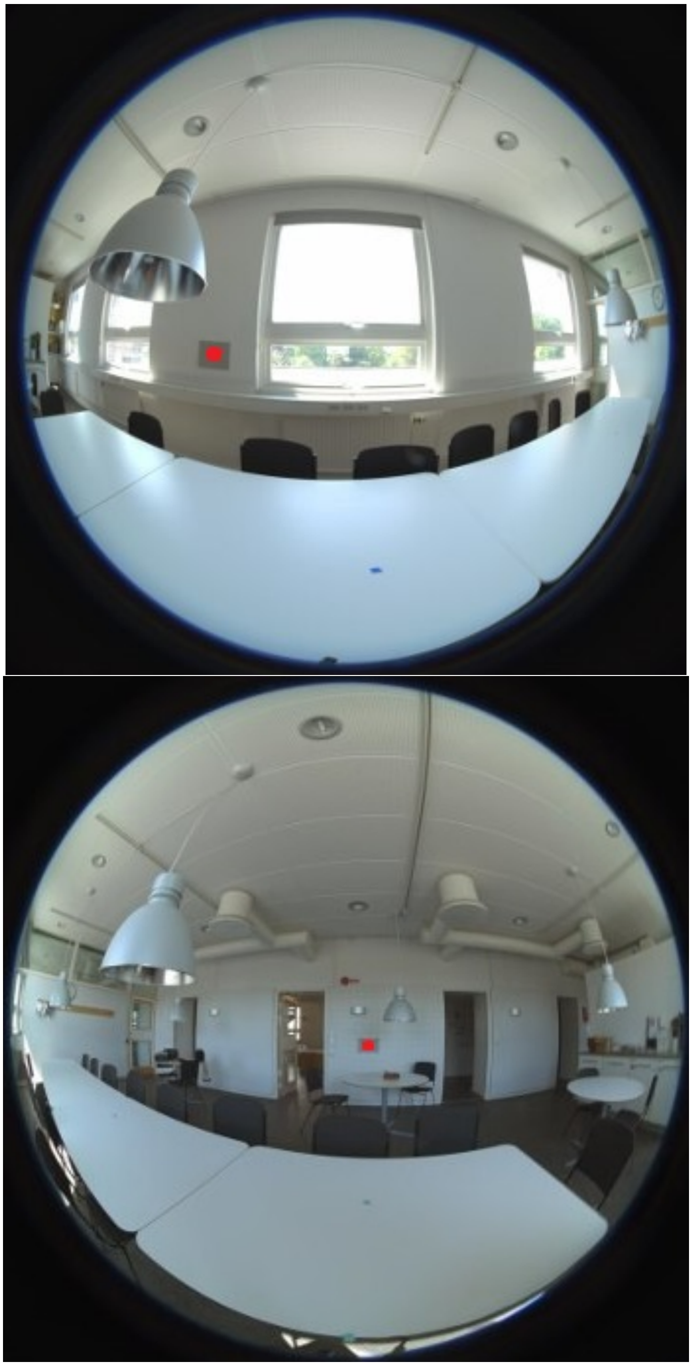


Figure 13 Fisheye photos of selected task positions, extreme task position (upper), typical task position (lower), Red dots represent the reference spot for luminance calibration.

It is important that the HDR images were calibrated to ensure that the luminance values were consistent with reality. To achieve this, a spot in each actual scene was picked and its luminance value was recorded as reference for the calibration. The reference spot lay on an evenly illuminated grey surface fixed in the scene (2015). This was considered for the accuracy of calibration. During the calibration process, the reference spot was manually pinpointed on each HDR image and its luminance value was adjusted to the recorded luminance value. By using the grey surface, the luminance uniformity near the reference spot was maintained thus the error because of pinpointing was reduced. In Figure 13 the reference spots are marked as red dots in each task position. For measuring the luminance values of the reference spots, the handheld luminance meter Hagner Model S4 was used and luminance values were recorded simultaneously while the photos were taken.

2.4.2.2 Investigate glare problems in Evalglare

Once the HDR images of the two task positions were generated, they were ready to be investigated in Evalglare.

The program Evalglare was operated in DOS by running a set of commands. In this study, the commands were written and executed to calculate DGP score and verify potential glare sources in the room for each task position. It is necessary to note that the glare sources are determined by a given threshold defined in the commands. In this case of glare study, they were detected when their luminance values were 5 times larger than the average luminance values of the whole image. After running the program, for each task position, DGP score was calculated and images were generated with highlighted glare sources. An example follows, showing the commands to assess the glare problems of the extreme task position at 10 o'clock.

```
> pfilt -x /4 -y /4 -e 0.5 extremenoon.hdr > extremenoon_small.hdr

> evalglare extremenoon_small.hdr > extremenoon.dat

> evalglare –b 5 -c testex_noon_cal.pic extremenoon_small.hdr

> ra_gif testex_noon_cal.pic > test_ex_noon_cal.gif
```

In the commands, '*pfilt*' resized the HDR image to make it readable in Evalglare, by dividing x and y pixels by the same factor 4, *'-e'* was defined to adjust the exposure so the generated *.gif* file has a proper level of brightness to show the results. The DGP score was given in a *dat* file and glare sources were shown in a *gif* file.

2.4.3 Luminance distribution

To investigate the luminance distribution in the room, the luminance ratios were studied from reading luminance values on false colour images. The false colour images, were obtained from HDR photos, with the support of the tool wxfalsecolor.exe. In this tool, luminance values were manually pinpointed and read, and their ratios were assessed according to the criteria mentioned in Table 4.

2.5 Method: Daylight Simulation

The lighting metrics was also investigated through simulations with *DIVA for Rhino*. The simulated results were afterwards compared to the measured ones to check the discrepancies between the two methods.

This part was divided into a few steps. First of all, set up simulation setting properly, which is prerequisite to the accuracy of simulations. Secondly, simulated the same lighting metrics which were investigated during measurements, including the DF, the DGP and the potential glare sources on the task positions and finally the luminance distribution of the task positions.

2.5.1 Simulation settings

As already noted in section 2.1, the software *DIVA for Rhino* runs lighting simulations with the support of *Radiance* and *Daysim*. In order to ensure high accuracy levels in the results, some adjustments were made on simulation settings based on rendering options in *Radiance*. *Radiance* uses backward ray-tracing rendering techniques where the lighting sources were determined through tracing rays in direct and indirect calculations.

In *Radiance*, different rendering options are defined to control the accuracy during the calculation of the sample rays, and rendering options consists of direct options, indirect specular options and indirect ambient options (Larson & Shakespeare, 1998). To achieve a relatively high accuracy, several test simulations were run on the room model to choose the optimum rendering options. The optimum rendering options means that they would yield a relatively high level of accuracy within a reasonable rendering time.

With regard to the optimum rendering options, Dubois concluded some suggestions in her report about simulations with Radiance (Dubois, Impact of Shading Devices on Daylight Quality in Offices. Simulations with Radiance, 2001): the indirect ambient rendering options have great effects on the results, and the influence from adjusting direct rendering options is more apparently to see under a sunny sky model than an overcast sky model. Moreover, the specular options can also affect a lot if objects with strong specularity exist in the scene.

For the studied case, both sunny and overcast sky models were used in the calculations, so a higher level of ambient and direct rendering options were adjusted. Since there were no objects with strong specularity, the indirect specular option was kept at a medium accuracy level. Finally, the rendering options were adjusted as follows,

-ps 4 -pt 0.10 -pj 0.9 -dj 0.5 -ds 0.25 -dt 0.25 -dc 0.5 -dr 1 -dp 256 -st 0.5 -ab 6 -aa 0.15 -ar 512 -ad 2048 -as 1024 -lr 6 -lw 0.01.

After the simulation settings were decided, the room model described in 3.1.2 was simulated in *DIVA for Rhino*. The following lighting metrics were studied.

2.5.2 Daylight factor

For the simulation of the daylight factor, the analysis nodes were created in eight rows at the table height of 0.7m, which followed the same as the measured rows shown in Figure 5. Within each row there were 26 nodes with a distance of 0.18m, which is denser than the measured nodes. After the simulation, the results of DF were sorted in Excel.

2.5.3 Glare analysis and luminance ratio

In the glare assessment, the study process was divided into two steps. Firstly, false colour images of the two selected task views were rendered in *DIVA*. The false colour image, just like the HDR image, provides luminance values in the scene. The false colour images of the two tasks were set up with virtual view cameras in the room model in *Rhinoceros*. In order to simulate the correct position of the sun, the time in simulation were set up at 9 and 14 o'clock on July 1st, which are one hour earlier than the measured time, since *Radiance* uses the solar time, which is specified without daylight saving time. After that, the glare problem in each rendered image was analysed by calculating the DGP scores and potential glare sources, with the support of *Evalglare* which is embedded in *DIVA*.

To obtain the luminance ratios in each task view, the rendered false colour images were imported into the tool 'wxfalsecolor.exe' and luminance values were read by simply clicking on the images.

2.6 Method: Electric lighting study

The study on electric lighting system in the room consists of two parts. First, the electric lighting performance were assessed in terms of luminous environment and total annual energy use. Secondly, to investigate the saving potential from different lighting control strategies and design parameters, some parametric studies were conducted based on a series of simulations.

2.6.1 Assessment of electric lighting system

The assessment of electric lighting system is divided into two parts: the visualization of luminous environment and the estimation of the total annual lighting energy use.

2.6.1.1 Luminous environment

To investigate the luminous environment under electric lighting condition, the room model was visualized in the tool DIVA to obtain images with illuminance and luminance distribution.

Before running the visualization, firstly the lighting sources of the luminaires were imported into the model. These lighting sources, which are called IES files, carry photometric information giving angular spread of the luminous intensity of a certain fixture. The IES files were looked up on the manufacture webpage for the luminaires which were described previously, and were listed in Appendix A. To import IES files into DIVA, there is a limitation that DIVA does not recognize luminaire from the IES file when its geometry is defined as ‘ring’. This were solved by editing the IES file before loaded, by converting the geometry type from ‘ring’ to ‘point’ without changing luminous distribution.

Secondly, in DIVA, it only visualizes scenes with luminance values. In order to simulate the scene displayed with illuminance values, scripts under the command ‘*rpict*’ were edited. These scripts were in a batch file generated for image renderings, which is operated under *Radiance*. To represent illuminance value at every pixel of the image opposed to luminance value, ‘- i’ was added in the command ‘*rpict*’. In the end, images presenting illuminance and luminance values were generated respectively.

2.6.1.2 LENI calculation

Since there is no separate metering for the electric lighting use of the studied room, the total annual lighting energy use was estimated by simulations. The numeric indicator LENI, as described in the section 2.3, was used to assess the annual lighting energy use.

The electric lighting simulations were run in *DIVA* with the support of *Daysim*. It is necessary to explain that *DAYSIM* assumes an 'ideal lighting system' for electric lighting in the calculation. This means that the lighting system is assumed to deliver its target illuminance when fully switched on. So instead of modelling the actual luminous condition offered by the lighting system, the tool simulates the daylight in the space and calculates the demand lighting energy needed to achieve a defined target illuminance. For this simple method, the parameters required to describe the lighting system are the installed lighting power and the target illuminance. In this case the installed lighting powers were set up for each lighting zone as described in Table 2. The target illuminance, as specified in section 2.3, was set as 200lx.

The lighting control settings, as described in section 2.2.5, are manual switch combined with absence occupancy sensor control. The absence sensors send signal to turn off the lights if no occupancy is detected in 15 minutes. The sensor setting in the simulation is different from the reality regarding to the height setting of the occupancy sensors. In reality, each sensor in the room is installed at a height of 2.9m and detects a cone-shaped space below its installed height with interest targets at the height of the work plane, therefore four sensor nodes were defined within one target “cone” corresponded to each sensor at the height of the work plane of 0.70m from the floor.

2.6.2 Parametric studies

The parametric studies were carried out with a purpose to investigate the saving potential of the lighting system by applying different lighting control strategies in the studied room. Besides this, it is known that some design parameters can affect a lot on lighting energy use. Due to the interest on this regard, this section also investigates the effects of variable design parameters through a series of simulations.

The control strategies compared in the simulations include: manual on/off switch control, absence occupancy control, and presence occupancy control, photo sensor dimming control as well as the combination of dimming and presence or absence occupancy control. The case with absence occupancy control is the actual control strategy applied in the lighting system in the studied room, while the other cases were studied for comparison. Settings for each control strategy are specified in detail in Table 5.

Table 5 Specified settings for each case of lighting control strategy in the simulations.

Common settings	1. Target illuminance: 200lx 2. The lighting powers were set according to the descriptions in *Table 2*
Manual on/off switch control at the door (manual control)	
Absence occupancy control (absence control)	sensors with a delay time of 15 mins
Presence occupancy control (presence control)	
Photo sensor dimming control (dimming control)	Ballast loss factor*: 3%
The combination of dimming and absence occupancy control (combo control 1)	Ballast loss factor: 3% sensors with a delay time of 15 mins
The combination of dimming and presence occupancy control (combo control 2)	Ballast loss factor: 3% sensors with a delay time of 15 mins

* The ballast loss factor means the percentage of peak energy used by the dimming system when fully dimmed down.

After the comparison study of different control strategies, the impacts of some design parameters were studied, including the target illuminance, the sensor positions and the delay time of the occupancy sensor control. The results were simulated in *DIVA* and analysed in *Excel*.

3 Results

The results presented in this chapter contain four main parts:

- Daylight assessments
- The discrepancy study on the methods of measurement and simulation for the assessment of daylight performance
- Electric light assessment
- Parametric studies of various design parameters in electric lighting system

3.1 Daylighting assessment and discrepancy studies

The daylight quality in the case room was investigated through studies of a few lighting metrics obtained from measurements and simulations. The following sections present the assessments of daylight quality based on those results and the comparisons. The studied lighting metrics, as briefly explained in methodology part, include the daylight factor, the glare problem and the luminance distribution.

3.1.1 Daylight factor

3.1.1.1 Measured results

The indoor illuminance values at 48 test points, and the simultaneous outdoor global illuminance and the outdoor global diffuse illuminance values were measured. The test points are presented in earlier section in Figure 12. The data of 48 groups were collected in Excel and were used to calculate the daylight factor (DF).

The measured DF results are displayed in Figure 14. In this figure, the legends from X1 to X8 represent the test rows. The odd rows X1, X3, X5 and X7 were aligned with the centre lines of the windows, and the even rows X2, X4, X6 and X8 were located across the centre lines of the walls.

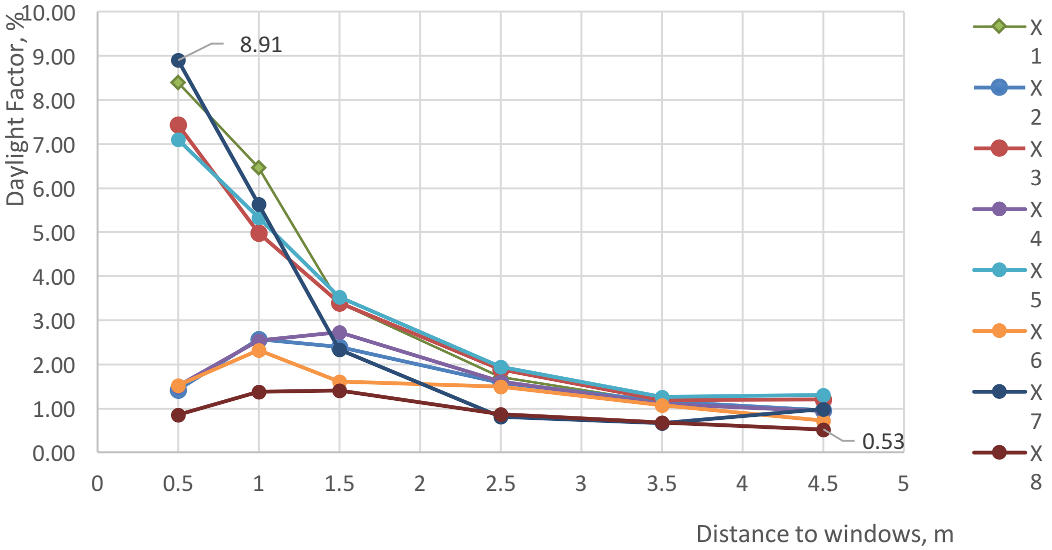


Figure 14 Measured DF distribution.

As can be seen in Figure 14, the DF values drop as the distances to windows increasing. It shows different distribution patterns for the rows in odd number and even number. This is normal considering the locations of the rows. The odd number rows (X1, X3, X5 and X7) have a larger DF range, dropping from 8.91% to 1.95% within the distance of 3.5m to the windows. Since the even number rows (X2, X4, X6 and X8) were across the wall, they have lower DF values ranging between 2.74% and 0.88% within the distance of 2.5m to the windows. However, the impact of the locations of the rows does not seem to affect the DF values a lot when the distance continues increasing. When the distance to the window is more than 3.5m, the DF values are mostly stable and below 1.5%.

The mean DF value of all the tested points is 2.44%. The specified dark points in this room are the fourth point in row X1 and X8. They have values of 1.95% and 0.88% respectively. The specified point in row X8 does not meet the requirement in 'SS-EN 12464: 2011', which requires DF at the specified dark point above 1%, also does not meet '*Miljöbyggnad'*, in which requiring a lowest DF value of 1.2%.

3.1.1.2 Simulated results

The daylight factor values of the same test points were also simulated in *DIVA.* As mentioned before, the test nodes in simulation were distributed denser in each row compared to the measured nodes. Figure 15 presents the simulated DF distribution.

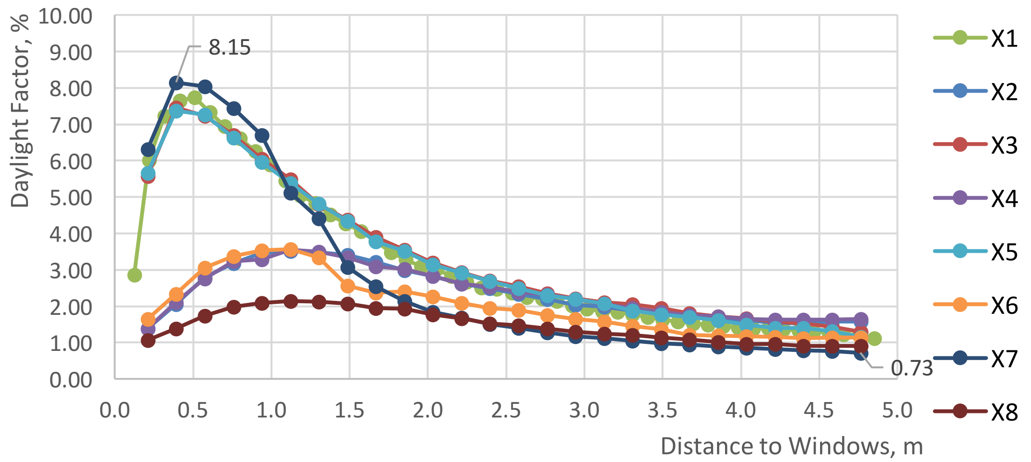


Figure 15 Simulated daylight factor distribution.

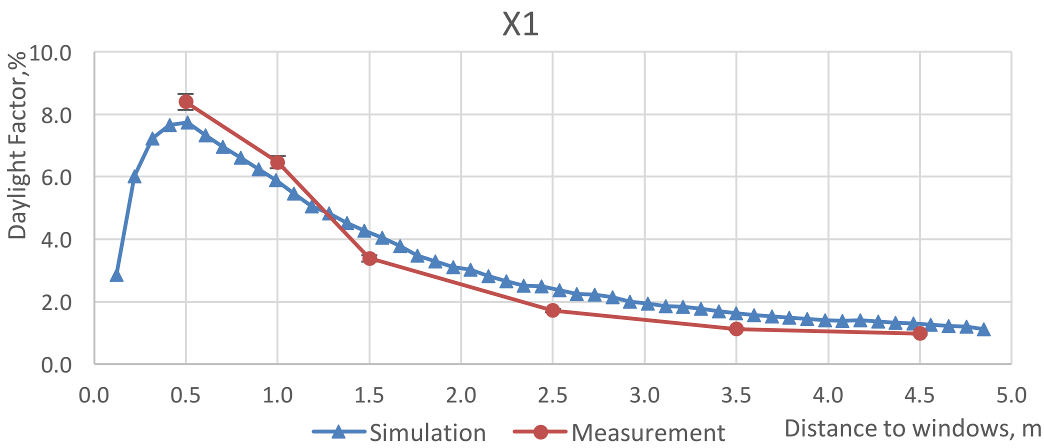
Similar to the measured results, Figure 15 also displays two different distribution patterns for odd number rows and even ones. Among the odd number rows, DF values range approximately from 8.15% to 2.50% within the distance of 2.5m to the windows. The even number rows, alike the measured results, have lower DF values and the range is between 3.53% and 1.47% within the distance of 2.5m to the windows. Furthermore, the impact of the locations of the rows on the DF values looks similar when compared with that of Figure 14. It does not seem to affect a lot when the distance continues increasing. When the distance to the windows is more than 3.5m, the DF values stay nearly stable and below 2%.

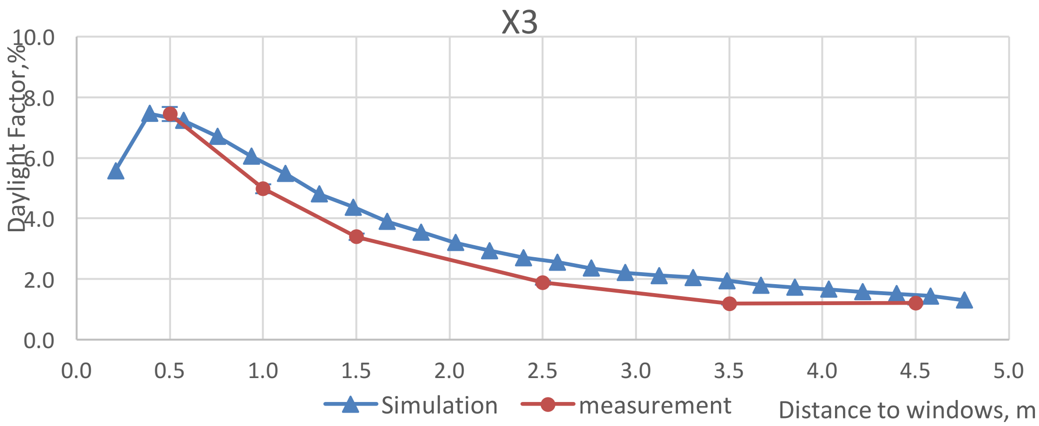
It is clearly to see that the curves X6 and X8 are different from the other even number rows, and row X7 different from the other odd number rows. This difference can also be observed in Figure 14. This is probably affected by having tall furniture obstructed in that area. For this regard, the simulated results reflect very well in the accordance with the measured results.

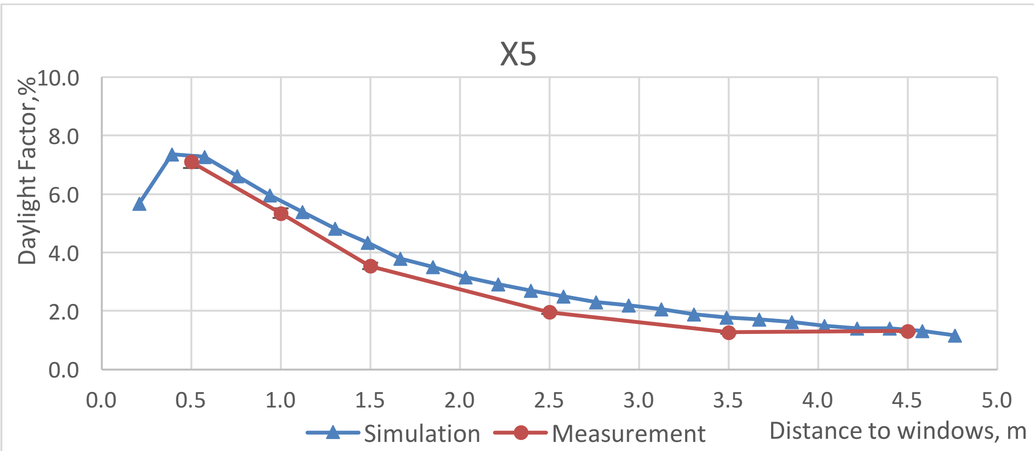
The mean DF value is 2.67%. The specified dark points have values of 1.9% and 1.47% and both meet the requirement in 'SS-EN 12464: 2011' and '*Miljöbyggnad*'.

3.1.1.3 Comparison between the measured and simulated results

To have a close look at the discrepancy between the simulated and measured DF values, the comparisons in each test row were plotted in Figure 16 and Figure 17. Figure 16 presents the DF values in odd number rows, and Figure 17 presents these in even number rows. The instrument error from measurement is 3%, which is plotted but not clear to see in the graphs since it is a small error.


X1
Daylight Factor,%
10.0
8.0
6.0
4.0
2.0
0.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
Simulation
Measurement
Distance to windows, m


X3
Daylight Factor,%
10.0
8.0
6.0
4.0
2.0
0.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
Simulation
measurement
Distance to windows, m


X5
Daylight Factor,%
10.0
8.0
6.0
4.0
2.0
0.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
Simulation
Measurement
Distance to windows, m

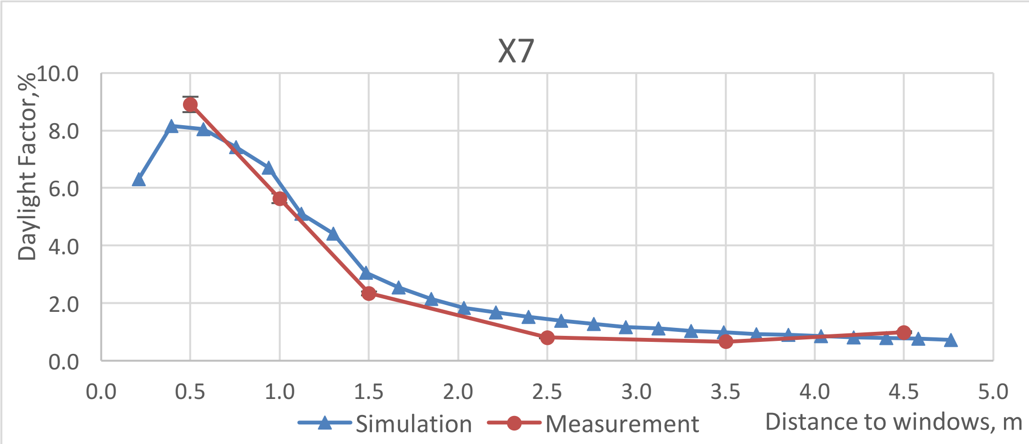
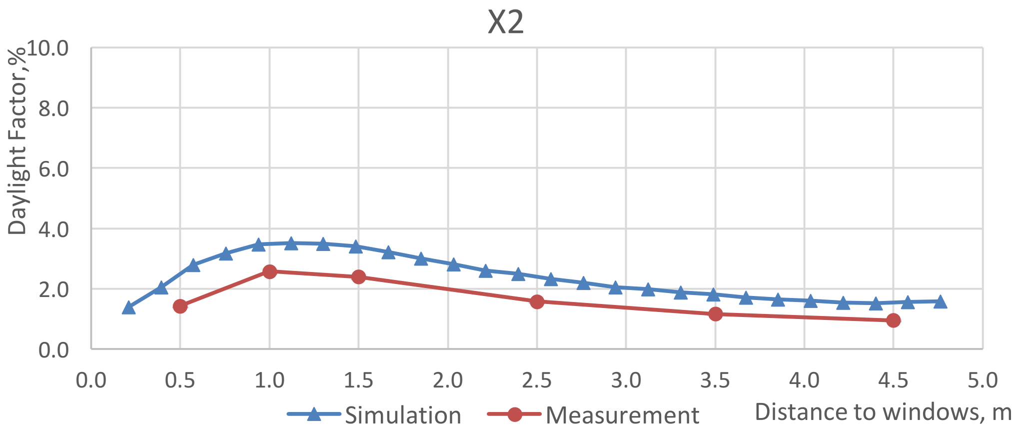
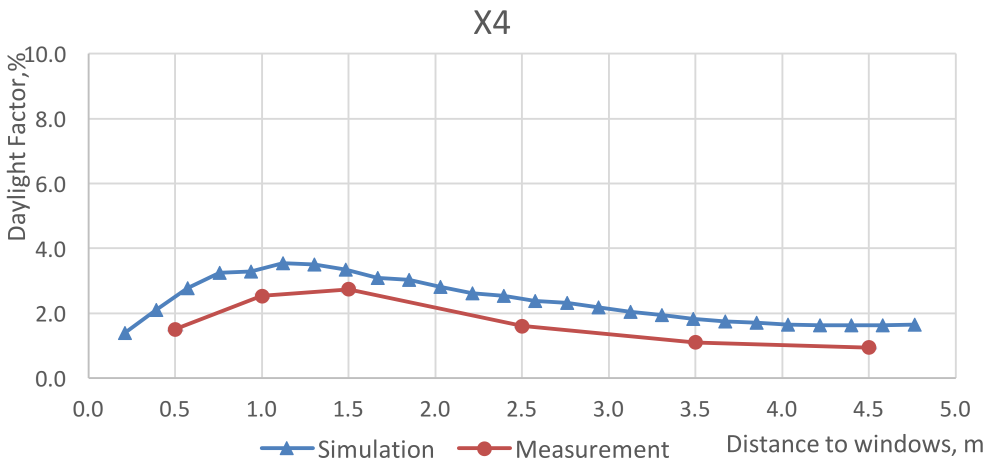
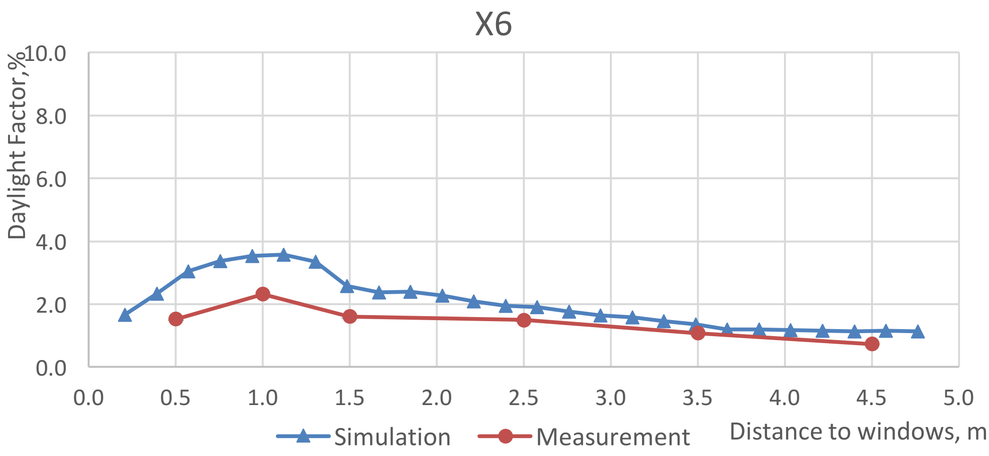


Figure 16 Comparisons between simulated and measured DF values in odd number rows.







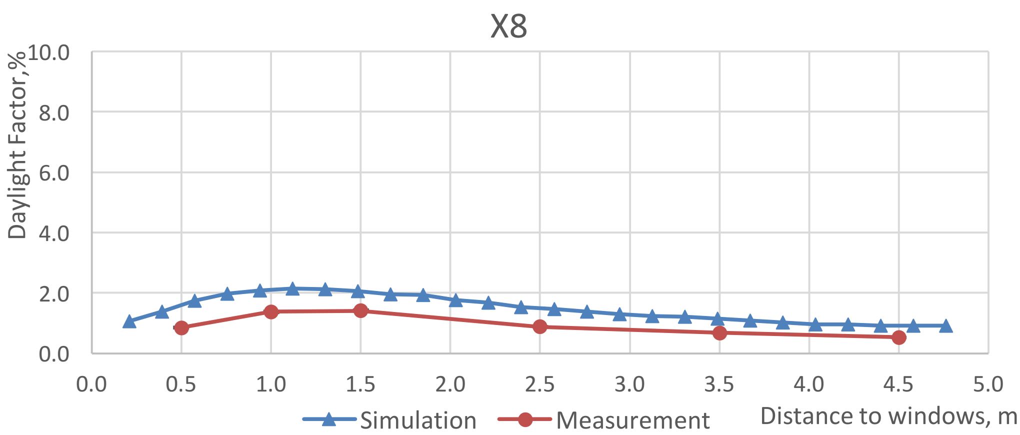


Figure 17 Comparisons between simulated and measured DF values in even number rows.

Generally speaking, the simulated DF results are well consistent with the measured ones. The data within the distance of 0.4m to windows were not collected during measurements, while the simulated results present a fuller DF distribution. In Figure 16 and Figure 17, they clearly show that the simulated results are mostly larger than the measured ones in each row. To quantitatively show the differences, the relative difference between simulated and measured DF values were calculated and summarized in Table 6.

Table 6 Range of relative difference between simulated and measured DF values in each row.*

Row No.	X1	X2	X3	X4	X5	X6	X7	X8
Relative difference (%)	-8~31	26~49	-3~26	18~45	1~29	21~50	-11~33	32~51

* The relative difference $= \frac{simulated\ DF\ value - measured\ DF\ value}{simulated\ DF\ value} \times 100\%$

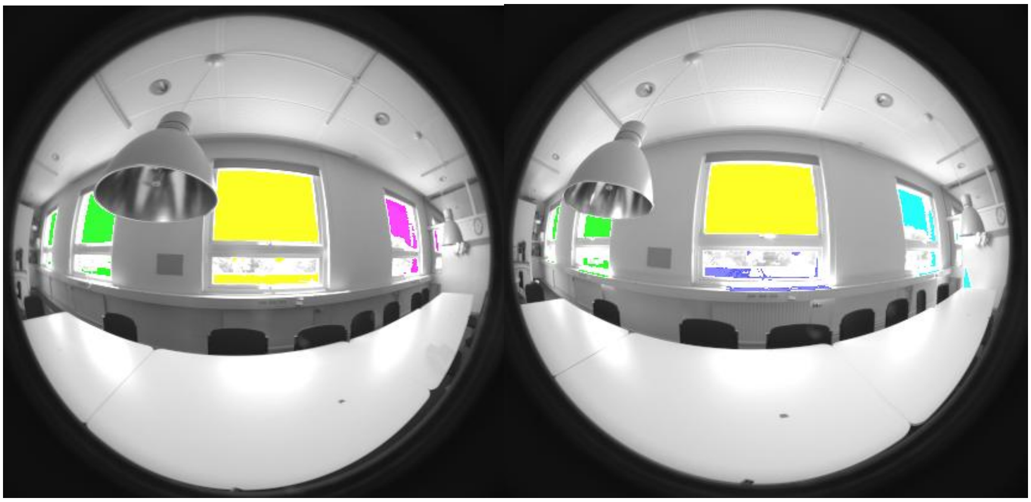
It is observed in Table 6 that the relative differences in the even rows are bigger than those in the odd rows, which means that in the rows that align with the centre of windows, where there are more direct light rays, the simulated results are closer to the measured ones, and the disparity is bigger for the rows that align with the centre of the walls, where there are more diffused light rays. This disparity is to be expected since when most of the calculated 'virtual rays' are diffused, it gets harder to calculate in daylight simulation because it requires higher ambient bounce factor in the simulation settings which is costly in simulation time.

3.1.2 Glare analysis

The glare problem was assessed based on images with illuminance values. As introduced in section 2.4.2, two task positions were selected, representing typical daylight conditions in the room. One position was named as *extreme position*, another one as *typical position.* The DGP scores and potential glare sources in the scenes were presented and assessed in this section.

3.1.2.1 Measured results

The generated HDR images are displayed in Figure 18 and Figure 19, showing potential glare positions and the DGP scores.

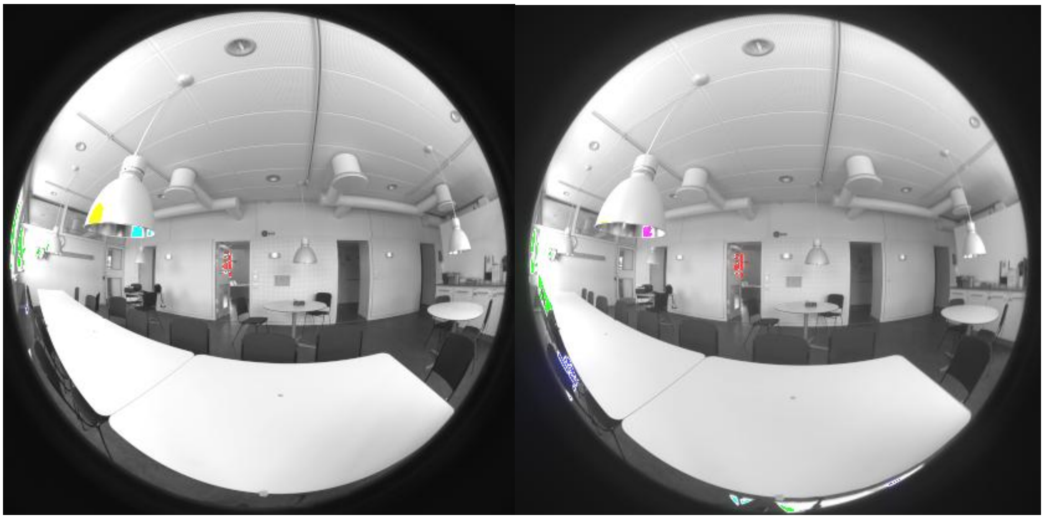


DGP 25% DGP 26%

Figure 18 HDR images showing potential glare sources and the DGP in the extreme position, 10am (left), 3pm (right).

Figure 18 provides the results at the extreme position for the test times at 10am and 3pm. It can be seen that at both times, the glare areas were detected from the west-facing windows. The DGP scores at the two times are very close, 25% and 26%. Even though the glare problems can be seen from almost all the window areas, the DGP scores are under 35%, which are interpreted as imperceptible glare.

Photos captured at the same time, Figure 19 provides the results for the typical position. The pictures show that only small glare patches can be observed. They are found in areas close to the windows and from the windows in the corridor. The DGP scores of 15.9% and 17.2% are interpreted as imperceptible glare. It is expressed from both task positions that the potential glare problem is slightly stronger in the afternoon than in the late morning.

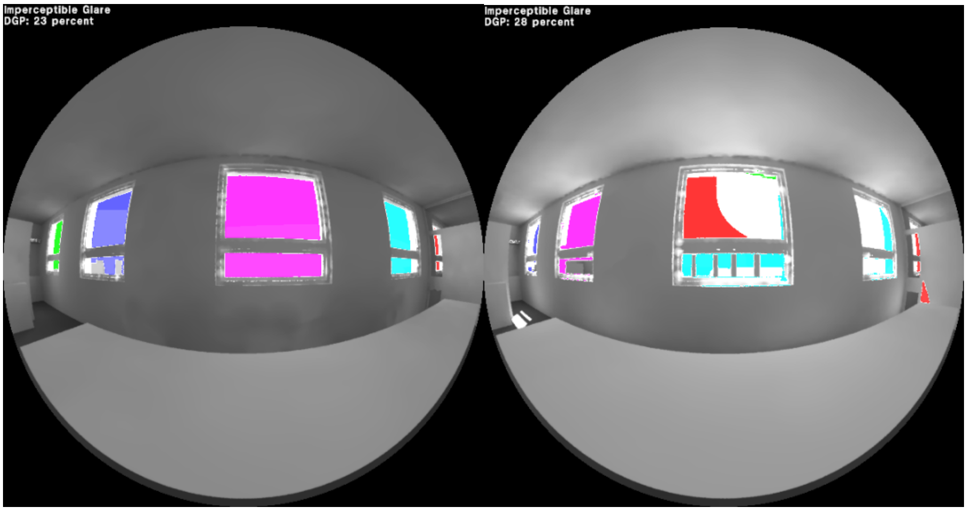


DGP 15.9% DGP 17.2%

Figure 19 HDR images showing potential glare sources and the DGPs in the typical position, 10am (left), 3pm (right).

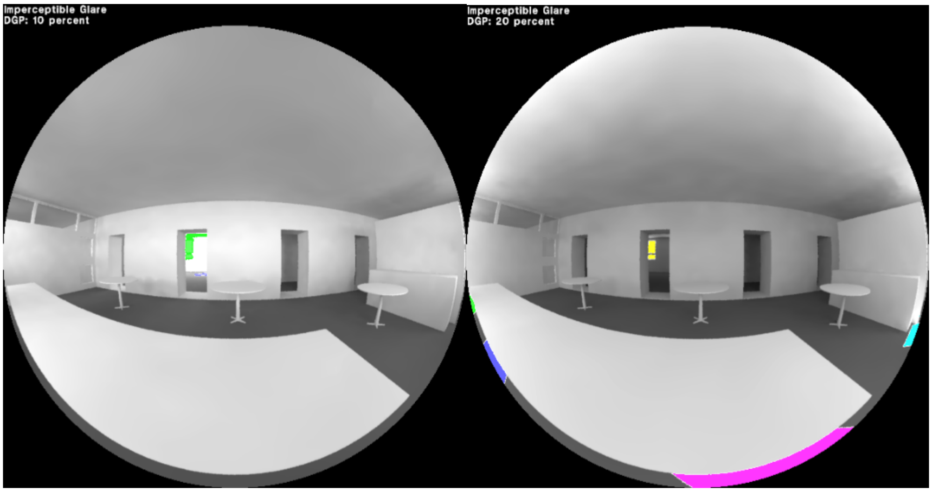
3.1.2.2 Simulated results

For the same task positions, glare studies were conducted via simulation as well. Figure 20 and Figure 21 show the simulated images.



DGP 23.0% DGP 27.9%

Figure 20 Modelled scene showing potential glare sources and the DGP in the extreme position, 10am (left), 3pm (right).



DGP 9.62% DGP 19.6%

Figure 21 Modelled scene showing potential glare sources and the DGP in the typical position, 10am (left), 3pm (right).

As displayed in Figure 20, the windows are still the dominating glare sources in the extreme position, with a DGP score of 23% and 27.9% respectively at each simulated time. For the typical position in Figure 21, the DGP scores are 9.62% and 19.6% respectively. Some narrow patches close to the window areas and from the windows in the corridor are the primary glare sources. The glare level for this task position is classified as imperceptible glare.

Besides the DGP score at the test times of 10am and 3pm, the annual DGP scores for each task position were also simulated. Figure 22 displays how they distribute in the course of the year. The DGPs showing in red marks represent the occurrence of intolerable glare.

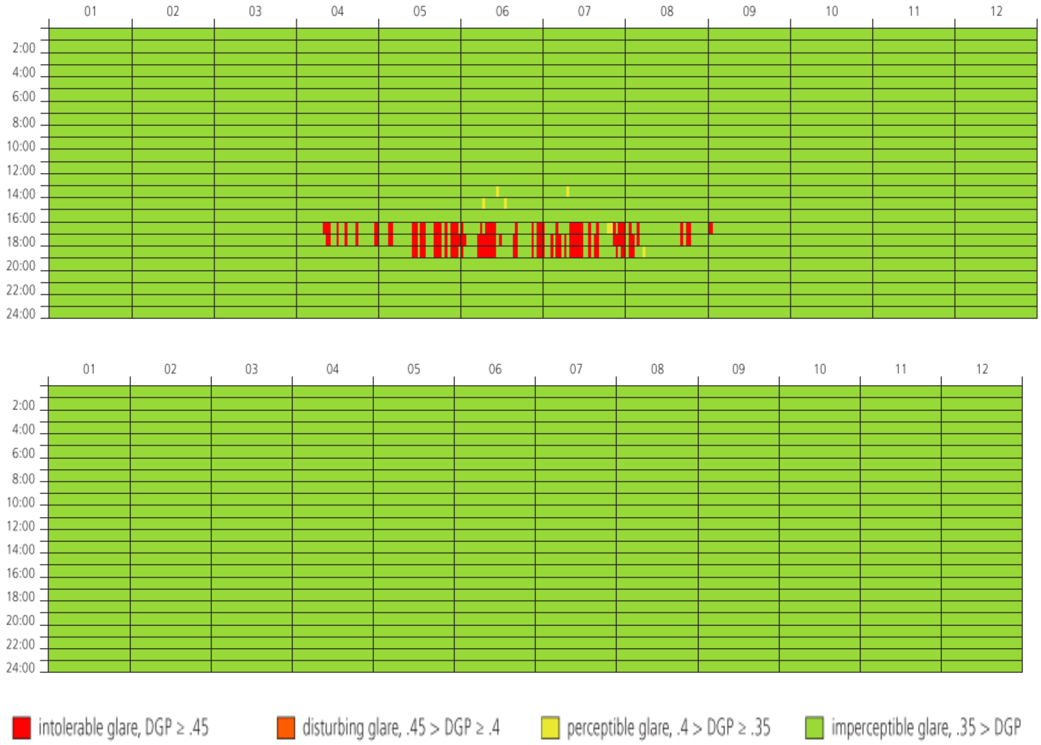


Figure 22 Annual DGP for the extreme task position (upper) and the typical task position (lower)

It can be seen that at the extreme task position, the occurrence of intolerable glare is quite high from April until August between 4pm and 7pm, and in the second graph, it shows the annual glare is imperceptible at the typical position. The annual DGP graphs present the perspective of annual glare problems, which are fuller than the previous glare results which tested at specific times of 10am and 3pm.

3.1.2.3 Comparison between the measured and simulated results

The simulated results achieved a satisfied accuracy on reflecting the glare problems in the reality scenes. By comparison, they clearly present identical areas with potential glare problems at the same time in the same task position. They both indicate that the obtained DGP scores are higher at 3pm than at 10am.

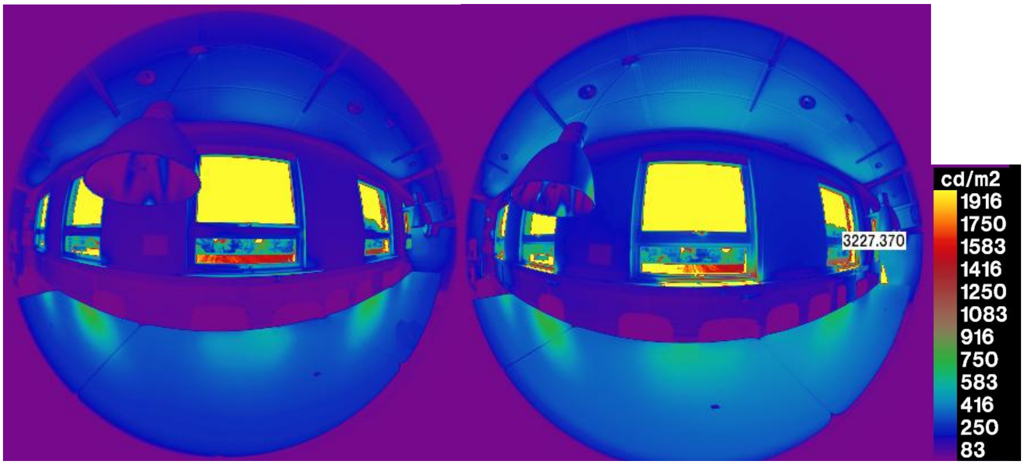
It is interesting to observe two differences between the simulated and the measured values. First, no matter in which task position, the simulated DGPs are lower than the measured ones in the morning but higher in the afternoon. Secondly, the simulated results are mostly very close to the measured ones, except for the value at typical position in the morning, which is 9.62% compared to 15.9%. The possible reasons are discussed in chapter 5.

3.1.3 Luminance distribution

This chapter presents the results of luminance maps and luminance ratios.

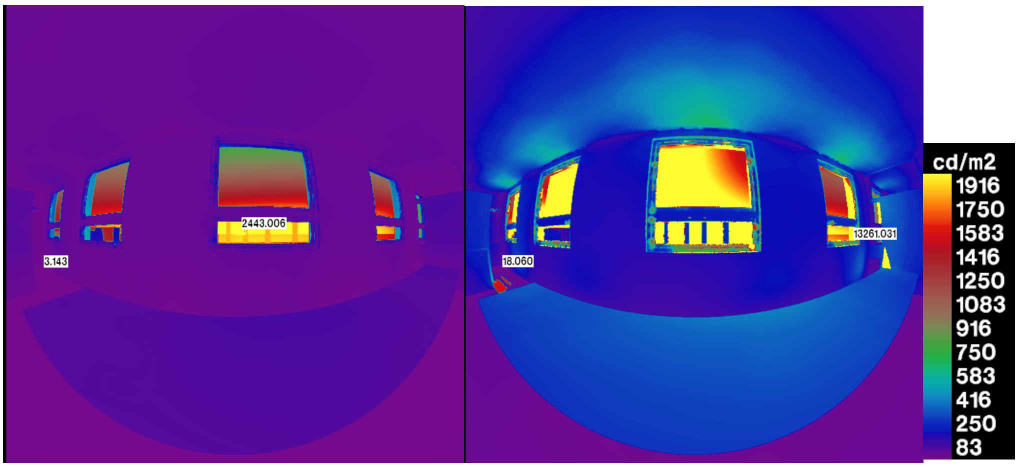
3.1.3.1 Luminance map

Figure 23 and Figure 24 display luminance maps in false colour of the real scene and the simulated scene at the extreme position.



(a) *(b)*

Figure 23 Luminance map at the extreme position from HDR image, 10am (left), 3pm (right).

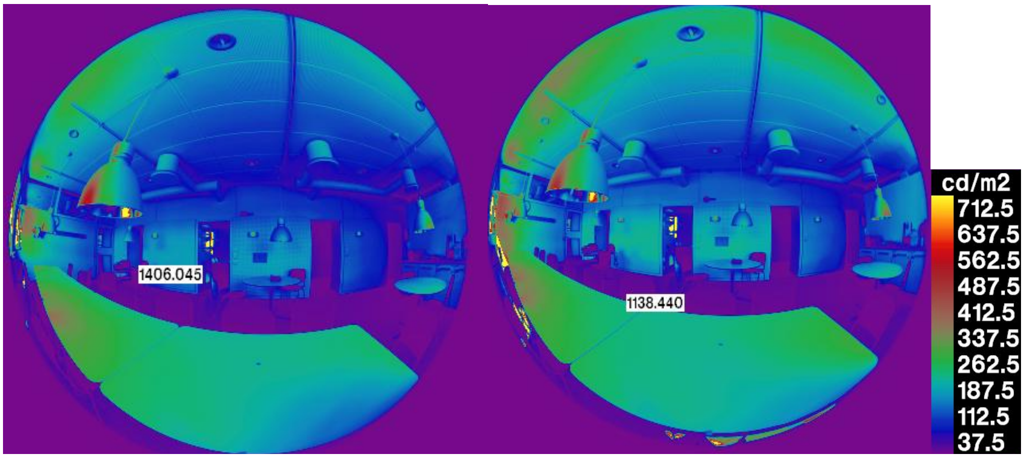


(a) *(b)*

Figure 24 Luminance map at the extreme position from simulated scene, 10am (left), 3pm (right).

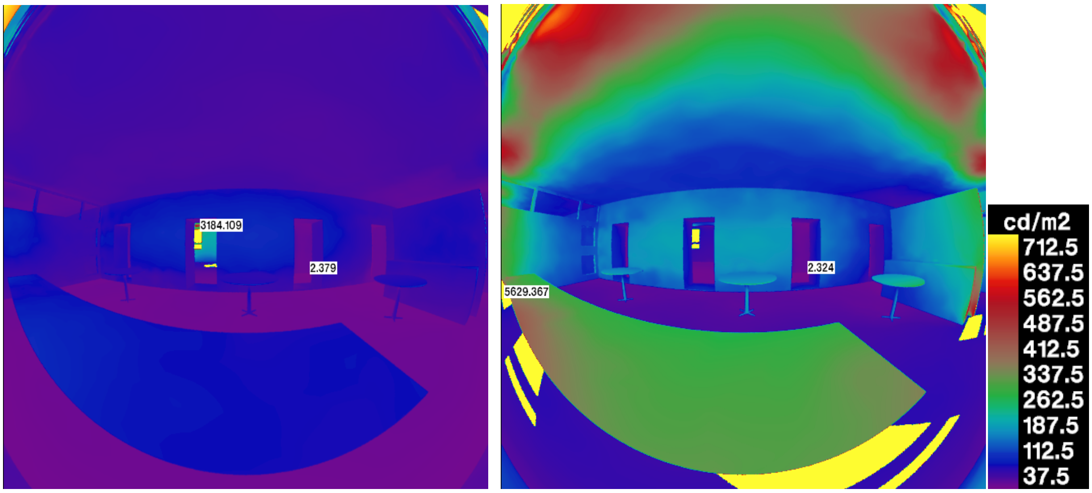
By comparison, the simulated scene is overall darker than the real one at 10am. Even so, the highest luminance value in each scene is similar, which is 2962 cd/m^2 in the real scene and 2443 cd/m^2 in the simulated scene. At 3pm in the afternoon, the luminance pattern in Figure 23(b) and Figure 24(b) are in very good accordance. As can be seen in the two images, the patterns of the luminance transitions in the simulated scene coincide well to the real scene; between the wall and the windows, between the wall and the table, and between the table and the ground. However, the highest value differs a lot in each scene, which is 3227 cd/m^2 and 13261 cd/m^2 respectively.

Figure 25 and Figure 26 display luminance maps in false colour of the real scene and the simulated scene at the typical position.



(a) *(b)*

Figure 25 Luminance map of the typical position from HDR image, 10am (left), 3pm (right).



(a) *(b)*

Figure 26 Luminance map of the typical position from simulated scene, 10am (left), 3pm (right).

The same finding observed at the extreme position applies to the typical position. At 10am, the simulated scene in Figure 26 (a) has a darker view than it in the real scene in Figure 25 (a). The luminance patterns are obviously different, and it is clear to see that the luminance values stratify in different levels in the real scene but not in the simulated scene. When it comes to the images at 3pm, the luminance patterns in Figure 25 (b) and Figure 26 (b) show a very good coincidence. In the two images, the range of the luminance values are at the same level at certain location in the room. Nevertheless, the highest value in the simulated scene is much larger than that it in the real scene, which is 5629 cd/m^2 versus 1138 cd/m^2.

3.1.3.2 Luminance ratio

To study the visual contrast in the scenes quantitatively, the luminance ratio was reviewed. Since the previous glare analysis indicates a higher glare potential in the afternoon than in the morning, this section focuses on luminance ratios in the task positions at 3pm.

Figure 27 displays the luminance distribution map of the extreme position obtained from the real scene and the simulated image. The luminance ratios were calculated between the task area, its immediate surroundings and its remote surroundings, which are marked as A, B and C in the image. Figure 28 presents the values at the typical position.

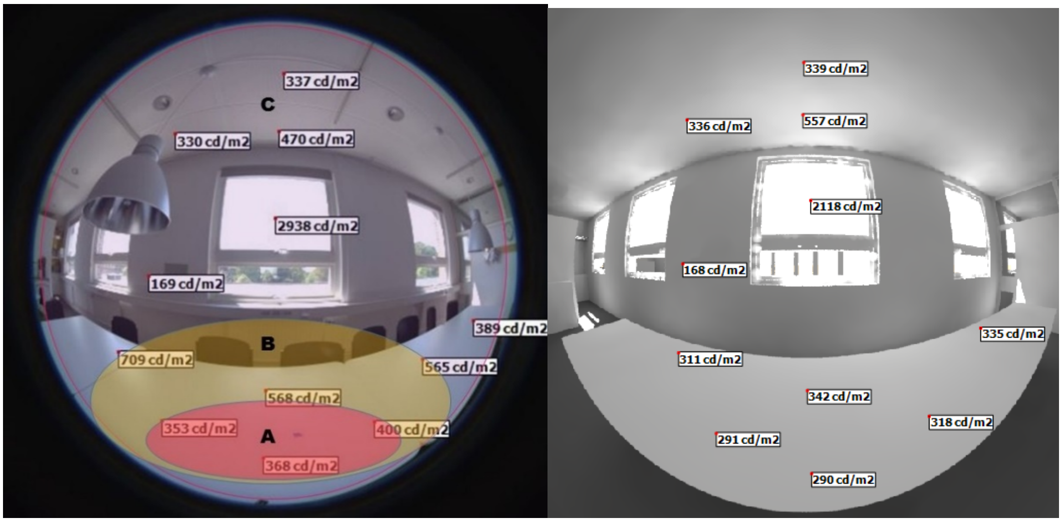


Figure 27 Luminance values at the extreme position. The real scene (left), the simulated scene (right)

Figure 28 Luminance values at the typical position. The real scene (left), the simulated scene (right)

When comparing the luminance values marked in Figure 27 and Figure 28, they clearly prove that the simulated results achieved a satisfied accuracy in reflecting the real scene. Table 7 presents luminance ratios and assessments according to the criteria given in Table 4.

Table 7 Luminance ratios.

The task position	Luminance ratios A:B:C	Assessed level

	The real scene	The simulated scene	
Extreme position	1:1.9:9	1:1:7.3	Ideal
Typical position	12:1:101	15:1:107	Unacceptable

In Table 7, the luminance ratio in the typical position is criticized as ‘unacceptable’. However, it is necessary to mention that the areas with high visual contrast are very small and come from the windows in the corridor. This needs to be considered in the assessment since the ‘unacceptable’ visual contrast could probably be assuaged with this concern. If neglecting the influence from the small area, the ratio at typical position is 12:1:8.4, which is considered as ‘ideal’.

It is observed that both the simulated DGPs and simulated luminance values are lower than the relevant measured values in the morning but higher in the afternoon. In order to understand this observation about their relations, the sun path diagram was modelled and shown in Figure 29. It can be seen from the picture that in simulation the modelled direct light rays are blocked by the building at 10am while penetrating inward the building at 3pm, which means diffused and reflected light rays were higher accounted at 10am than 3pm. Whereas in reality, the path of light rays is not as same as that. More details are discussed in Chapter 4.

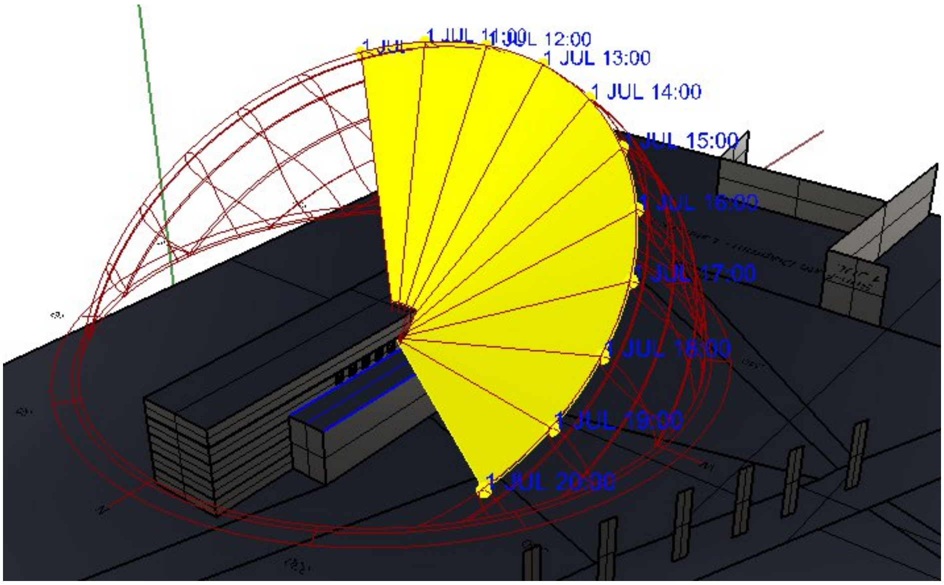


Figure 29 Sun path diagram of the simulated sky model drawn on the model.

3.1.4 Summary

The daylight quality in the studied room was assessed through investigations on some lighting metrics, which are summarized in Table 8. The overall assessments based on all the studied lighting metrics demonstrate that a good daylight quality could be expected in the studied room.

Table 8 Overall assessments of daylight quality based on measured and simulated lighting metrics.

Studied lighting metrics	The measured results	The simulated results
The daylight factor	Average DF is 2.44%. • The specified point DFs are 1.95% and 0.88% respectively, the second point DF does not meet the requirements in *SS-EN 12464: 2011* and '*Miljöbyggnad'*.	Average DF is 2.67%. • The specified point DFs of 1.9% and 1.47% both meet the requirement in *SS-EN 12464: 2011* and '*Miljöbyggnad'*.
Glare analysis	Extreme position	
	DGP: 25% (at 10am) 26% (at 3pm) Classified as imperceptible glare	DGP: 23% (at 10am) 27.9% (at 3pm) Classified as imperceptible glare
	The potential glare sources are detected from all the window areas	The same potential glare sources are detected from all the window areas
	Typical position	
	DGP: 15.9% (at 10am) 17.2% (at 3pm) Classified as imperceptible glare	DGP: 9.62% (at 10am) 19.6% (at 3pm) Classified as imperceptible glare
	Some small glare patches are observed from the windows	Same as the measured results, small glare patches are detected from the windows

Luminance ratios	Extreme position	
	1:1.9:9 Evaluated as ideal.	1:1:7.3 Evaluated as ideal.
	Typical position	
	12:1:101 Evaluated as ideal, but need to be noted that very small areas with high visual contrast could be expected in the typical task.	15:1:107 Evaluated as ideal, but need to be noted that very small areas with high visual contrast could be expected in the typical task.

The comparisons of results based on the two methods are clearly clarified in Table 8. In all the studied lighting metrics, the simulated results achieved a satisfied consistency with the measured results from both visual and quantitative concern. Some discrepancies are summarized as follows. Possible reasons for the differences are discussed in Chapter 4.

- With regard to the discrepancy between the simulated and measured results, the former are well consistent with the latter. Generally, the simulated DF values are slightly larger than the measured ones, and the discrepancy is smaller for the rows aligning with the windows.
- The difference of the average DF value is only 8.6%, which is in line with results from previous validation studies mentioned in the literature review. However, the difference could be in a range between -11% and 51% at specific points.
- When comparing the results of glare problems, the simulated results showed a satisfied consistency with the measured ones. The detected glare sources are identical. The highest DGP score occurred in the extreme task position at 3pm, which is 26% from the measurement and 27.9% from the simulation.
- In the comparison of results of luminance distribution, the simulated luminance maps achieved a satisfactory accuracy compared with the measured ones, both visually and quantitatively. It is interesting to observe that the simulated scenes are darker than the real scene at 10am, but the highest luminance value in the simulated scenes is larger than that in the actual scenes at 3pm.

3.2 Electric lighting assessment

In order to analyse the electric lighting environment, the luminous conditions were simulated. This section presents simulated plan views of the room showing illuminance and luminance distributions. The results display that overall it indicates a good electric lighting environment according to simulated images.

3.2.1 Lighting environment

The plan view in Figure 30 displays the illuminance distribution at the work plane of 0.70m high from the floor at the condition when all the luminaires performing at their fullest lighting power. The illuminance values marked in red squares illustrate the average illuminance value at each specified surface.

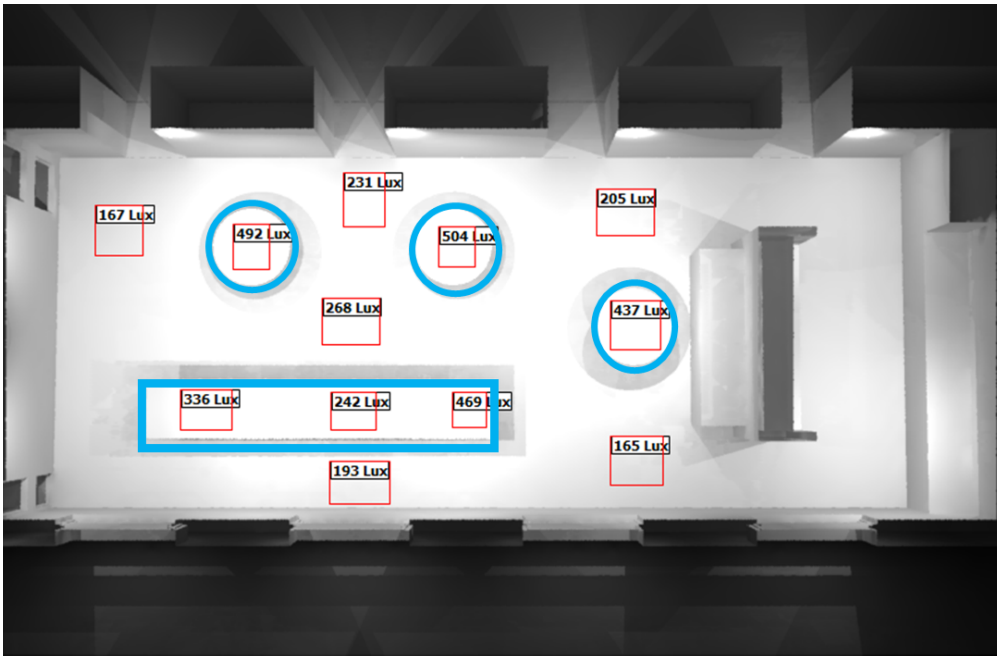


Figure 30 Simulated plan view showing illuminance distribution at the height of work plane of 0.7m.

It can be seen that the illuminance values at the table areas (marked in thick frames) are over 200lux, which conform to the requirements clarified in SS-EN 12464-1:2011. A fraction of areas at the room corner have values less than 200lx. The illuminance uniformity is calculated as less than 0.4 at where between the table areas and the background area, which also fulfilled the requirement.

Figure 31 presents the luminance distribution in false colour at the same cutaway view. The luminance ratio between the task areas and surrounding areas is calculated as 1:5:14, which is 'ideal' according to the criteria for luminance ratio in section 2.3.

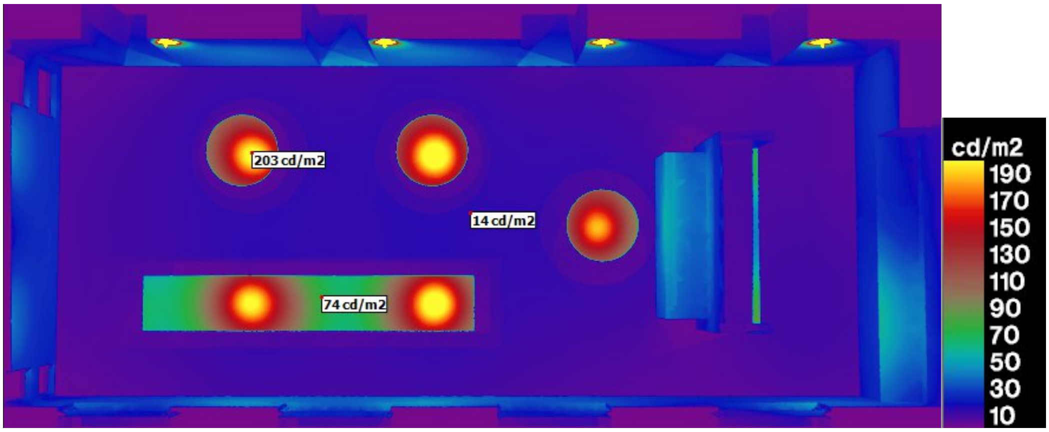


Figure 31 Simulated plan view showing luminance distribution at the height of work plane of 0.7m.

3.2.2 LENI calculation

The annual energy use of the lighting system was estimated using the tool *DIVA*. Equipped with absence control in its lighting system, the room is estimated to have a total annual lighting energy demand of 50.6 kWh, which means the LENI indicator is 0.8 $kWh/(m^2 \cdot year)$. It is very low but still reasonable in this case, considering the rather low installed lighting power of 325W, a low target illuminance of 200lux and a short period of occupied hours which has only three hours on working days. This result is far below the benchmark default value of 27 $kWh/(m^2 \cdot year)$ required in 'EN_15193-1', as specified in the section 2.3.

3.2.3 Parametric studies

This section presents the results on, firstly, the energy saving potential due to applying different control strategies on the lighting system, and secondly, the impacts of some design parameters on the lighting energy use.

3.2.3.1 Lighting control strategies

Different lighting control strategies, as described in Table 5, were simulated on the given lighting system and their total annual lighting energy uses were plotted in Figure 32.

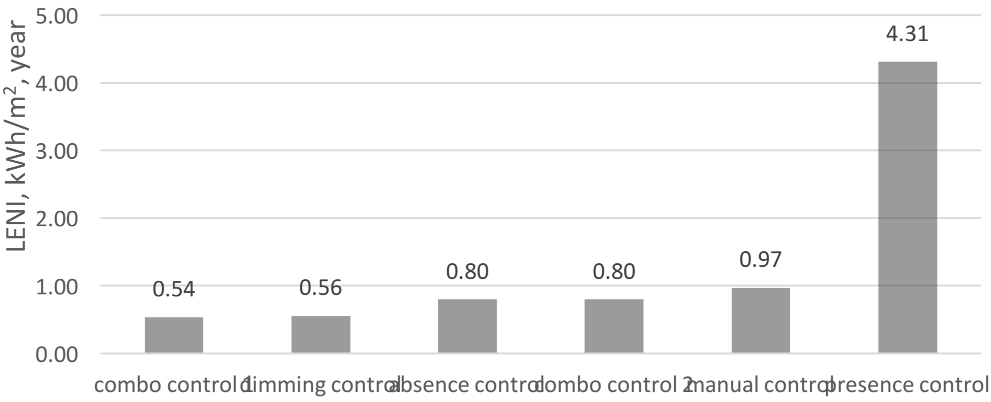


Figure 32 Comparisons of different lighting control strategies on their annual lighting energy use.

Combo control 1 represents the control strategy of dimming control combined with absence control, and combo control 2 represents the control strategy of dimming control combined with presence occupancy control. As can be seen in the graph, combo control 1 and dimming control have a potential to cut off more energy use than the currently applied control option, the absence control. They respectively cut down energy use of 32.6% and 30% compared to the absence control. The control options are sorted in sequence according to their saving potential: combo control 1, dimming control, absence control, combo control 2, followed by manual control and presence control. This finding based on simulated data is conforming to the measured results of lighting control systems in the same building in Gentile's recent research (Gentile, Laike, & Dubois, 2016). Even with a less complicated control strategy, the saving potential from dimming control is almost the same as that of combo control 1. The absence control, if compared to the manual control option, can save energy use of 17.8%. The combo control 2 appears to consume the same as the absence control option. The presence control option is undoubtedly the worst scenario on the energy use, requiring four times the energy use than the manual control option.

3.2.3.2 Design parameters of the lighting system

Some design parameters were studied through simulations to check their impacts on lighting energy use. They include the target illuminance, the sensor locations as well as the delay time of the occupancy sensors. The results were presented as follows.

3.2.3.2.1 The sensor position

Different sensor locations were tested on manual control, absence control and dimming control lighting system. All the sensors were defined at the height of work plane of 0.70m. The distances to windows vary from 0.5m to 3.5m. The curves in Figure 33 illustrate how the indicator LENI changes with the changing locations of sensors.

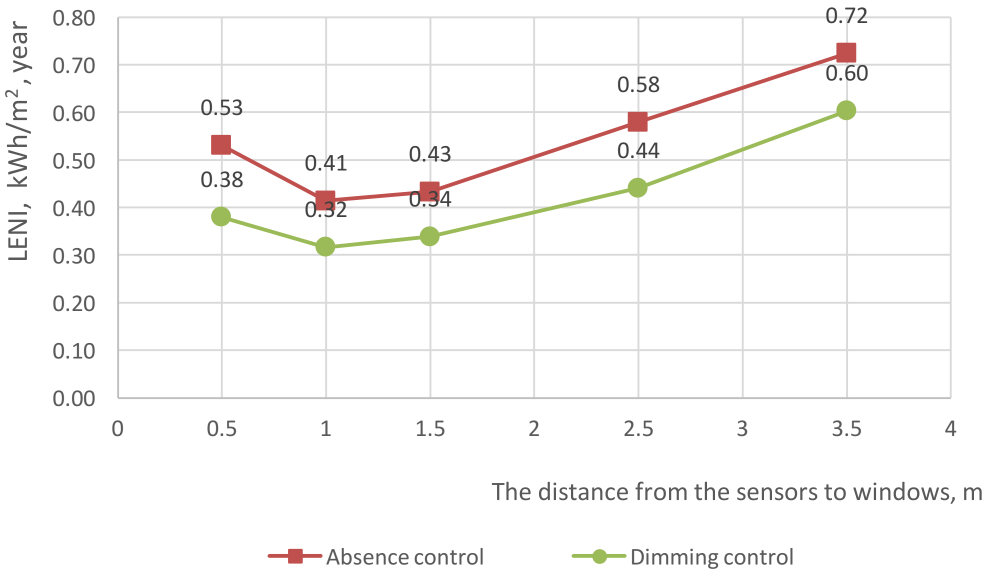


Figure 33 Effects of sensor location on predicted lighting energy use.

A clear influence can be seen: less energy is demanded when sensors set closer to the windows, where daylight illuminance values are higher. The exception at 0.5m is because this location lies very close to the wall and the daylight was obstructed locally. In the graph, the three curves roughly parallel to each other, which implies that the impacts of the sensor location on the energy use of system under each control case are similar. Statistically speaking, the maximum LENI difference is 55% in the manual control option, 57% in the absence control option and 53% in the dimming control one. This large difference in a row indicates that layout of a control sensor is a crucial factor in the design of a cost-effective lighting system and it may affect the output energy use a lot. It is critical to estimate a control sensor reasonably according the room layout at the design stage.

3.2.3.2.2 The delay time of the occupancy sensor

The absence occupancy control, which is the current control strategy for the lighting system in the studied room, has its sensor delay time of 15 minutes. The impacts of the delay time on energy saving potential are tested in this part. A delay time of 5 minutes, 10 minutes, 15 minutes and 30 minutes were simulated successively. The control strategy combo control 1, which is absence control combined with dimming control, was also tested to compare the impacts.

Figure 34 presents the energy saving potential of each control system under different delay time of occupancy sensors. All the energy savings were calculated through comparing to the same lighting system with a simple manual switch on/off control. The curve with triangle marks illustrates how energy savings of the absence control system are influenced by variable delay times, while the curve with cross marks illustrating the influence on the combo control system.

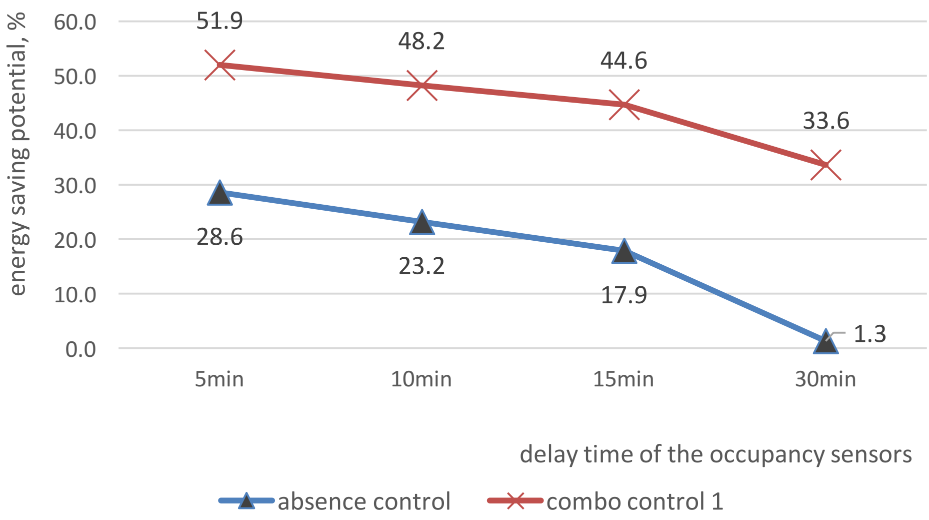


Figure 34 Effects of the delay time of the sensors for occupancy control related lighting system.

The figure shows that the absence control alone can potentially save up to approximately 29% with a delay time of 5mins. When the delay time is 30mins, the predicted lighting energy use is almost the same as that of the lighting system under manual control. For the combo control case, the saving potential is between 33.6% and 51.9% with varied delay times. If comparing the slopes, it looks like that the curve of absence control almost has the same slope as that of combo control strategy. This may indicate that the use of a dimming control does not affect much on the saving effect of an absence control due to the change of delay time, which proves what was discovered in the literature review that the effects of two different control strategies are not a simple linear combination.

4 Discussion

4.1 Lighting assessment

Some judgements made during the assessments were discussed below.

In the daylight assessment, all the lighting metrics were assessed under the condition that the room was fully furnished. Due to the obstruction of the furniture in the room, some effects on daylight accessibility appear in the results. For example, the DF values mostly distributed along the depth of the room in two patterns, depending on the test rows in line with the centre of the windows or the centre of the walls. Exception occurs in row X8 that was obstructed by a high shelf. In this row, DFs are generally smaller than in the other even number rows, which is affecting a specified point (P2) in row X8 not meeting the requirement of minimum 1.2% in '*Miljöbyggnad'*. At the same time, another specified point (P1) in row X1 fulfilled the requirement. Considering the obstruction effect at special spots, both of the DFs at P1 and P2 were judged as qualified.

The glare analysis was made based on images of two selected task positions and these images were captured/simulated at two test times: 10am and 3pm. From the limited images, the glare problem was appraised as imperceptible glare, which is classified when the DGP score is below 0.35. However, if looking at the annual glare results obtained in simulations, a high occurrence of intolerable glare was observed at the extreme task position from April until August between 4pm and 7pm. In this case, the simulated annual glare results do not alter the glare judgements, because the intolerable glare occurred outside the occupied hours, which are at three separate hours: 10am, 12am and 3pm. Even though the annual glare result does not affect the decision of glare analysis in this study, it demonstrates the importance of a proper selection of test times during a glare analysis. In addition, since glare is primarily the result of a relative location between a few lighting sources and an observed object, the detection of glare problem is highly dependent on the position of the selected spots. It is possible that the limitation of an inappropriate selection might yield erroneous glare assessment. A proper selection requires the expertise of lighting experts and a set of initial studies of the lighting conditions in the room before conducting glare measurement. Besides the importance of proper selection of typical task positions and test times, the application of simulation also proved its supplementary support on glare analysis based on measurements.

In the electric lighting assessment, all the results were obtained in simulations. Due to some inevitable reasons, it can be expected that the simulated results might not be close to the actual scenario. For example, during the simulation of the luminous environment, the IES files for the luminaires stand for the luminaire at its best working condition. But in reality, due to dirt and life depreciation of the luminaires, the actual illuminance and luminance distribution can be expected weaker than in the reality. Another inevitable reason is that, in the annual electric lighting energy use simulations, the software mimics the occupancy behaviour in a standard one-user office. This behaviour pattern might not accurately align with the occupancy activities in this studied case, which is a multi-users dining room. It can be predicted that the actual annual energy use is larger than the simulated result. Considering these reasons, the simulated results can only be used as reference for the electric lighting assessment. But during the parametric studies, since all the cases had a same basis of occupancy behaviour pattern, their comparisons might well reflect the energy saving potential.

For the electric lighting system in the room, the estimated LENI is 0.8 $kWh/(m^2 \cdot year)$, which is far below the benchmark value of 27.0 $kWh/(m^2 \cdot year)$ required in 'EN_15193-1' for a dining area. It is very low but still reasonable due to a rather low installed lighting power density of 5.38W/m^2, a low target illuminance of 200lux and a short setting period of occupied hours which are only three hours each working day (seen in Figure 10).

4.2 Discrepancy between measurements and simulations

According to the comparisons between the measured and simulated results of the three lighting metrics in daylight assessments, the simulated results are generally very well consistent with the measured ones. Some discrepancies, however, can be observed and are discussed below.

When looking at the comparisons on DF results, the average difference of DF value is only 8.6%, and the simulated results mostly are slightly larger than the measured ones in each test row. These findings agree with the previous discrepancy researches mentioned in the literature review that the discrepancy is normally within 20%. However, at specific points, the relative difference can be at a range between -11% and 51%. The reasons for the differences can be some of the followings: the modelled sky condition differing from the real one, the error in measuring the reflectance of interior surfaces, the instrument error and so on. Moreover, it is also found that the relative differences are relevant to the locations of the test rows. The difference is larger in the even rows than in the odd rows, which means that when the test points are in line with the windows, the simulated results have better accuracy. It is normal to get this result because of the traced light rays in simulation, which can yield an accurate result with fewer bounce times in the spaces that are directly open to the windows compared to the spaces that are behind the walls. Fewer bounce time means less accumulative effect from errors of interior surface reflectance. The accuracy is expected to increase by setting a higher ambient bounce number, but it is costly in simulation time.

The simulated results do not always overestimate the real photometric performance. It turns out to be true in DF values, especially at the window nearby area in this study but not in the glare study. In the glare analysis, the simulated DGPs are lower in the morning but higher in the afternoon compared to measured results. Apparently, the relation of disparity between the simulated and the measured DGP scores change at different test times. Similar disparities were also found in luminance distribution: in the morning at 10am, the simulated luminance values look overall darker than the actual scenes; in the afternoon, the simulated scenes look very close to the actual scenes but the highest luminance value in the simulated scenes is much larger than in the actual scenes. The sun path diagram in Figure 29 may explain the change in their relations. The modelled direct light rays are blocked by the building at 10am while they penetrate inward the building at 3pm, which means diffused and reflected light rays were accounted more at 10am than 3pm. This effect is probably caused by that the direct sunlight is weaker in the afternoon and stronger in the morning when compared to the simulated sky model. Moreover, it is deducted that if adjusting the number of ambient bounce, the discrepancy may be smaller.

5 Conclusions

In this study, the lighting quality of a retrofitted room located at Lund University was assessed, providing as an exemplary case for educational building under the work plan of IEA-SHC Task 50. The lighting assessment was conducted through investigations on a series of lighting metrics. A few building regulations and voluntary programmes were referred to during the evaluation.

According to the overall assessment, the lighting environment was good under both daylight and electric light condition. In the daylight part, three lighting metrics were studied: the daylight factor for daylight accessibility study, the DGP scores for the glare analysis and luminance distribution as another metric to check the visual comfort. In general, the room provides a visual comfort space under daylit condition with sufficient daylight accessibility and low glare potential. As demonstrated in the thesis, all the lighting metrics fulfilled the requirements for the relevant criteria. The mean DF value is 2.44% from measurements versus 2.67% obtained from simulation. The glare level in the room is classified as imperceptible. It is very low especially noting that shading devices are not considered during the study. The window areas are detected as the main glare source. The third lighting metrics, the luminance ratios, indicate that the visual condition can be considered as 'ideal'.

When it comes to the electric lighting part, the assessments were based on simulated luminous environment and energy use. The illuminance values at the task areas are above 200lux, which meet the standard required for general canteens and pantries in SS-EN 12464-1:2011. The lighting energy use indicator LENI was estimated as 0.8 $kWh/(m^2 \cdot year)$, far below the benchmark value of 27 $kWh/(m^2 \cdot year)$. This low annual energy use may be due to an originally low installed lighting density of 5.38W/m^2. Even though in this study, the electric lighting assessment was referred to the simulated results solely, it is recommended to collect on site real-time measurements if the condition allows in practice. The simulated results of the comparisons of lighting control system in this room are conforming to the measured results in the study of Gentile et al. which was conducted in individual offices at the same building (Gentile, Laike, & Dubois, 2016).

Comparisons between the measured and simulated results through daylight analysis demonstrated that the simulated results can reach a satisfactory accuracy and the assessment results based on each method were consistent. Some discrepancies were identified as follows,

- The deviation between simulated/measured Daylight Factor values were smaller in the test space lit with direct light rays than it with indirect light rays.
- The simulated values were generally higher than the measured values which is consistent with the findings from the literature review.
- The disparities in glare results and luminance distribution showed that the accuracy of simulated results is higher in the afternoon when direct sunlight is penetrating into the room.

The lighting energy use in this room is very low due to its low installed lighting density and shortly occupied hours annually. Comparisons between six different control strategies manifested that the current control option could cut down approximately 18% of energy use if compared to a manual on/off control option with switch buttons installed at the door side. Besides, there are two control methods potentially performing better than the current strategy in the regard of energy saving, which are the dimming control option and a combination control option between the absence control and dimming control. They both can save energy use up to approximately 30% compared to the current option. Among them, the dimming control option is apparently a better choice due to its simpler control technique and a similar energy saving target. This finding verified the finding in Literature Review that a more complicated control strategy does not necessarily save more energy.

In addition, this study also investigated the impacts of two design parameters: (a) the delay time of the occupancy sensors and (b) the sensor location on lighting energy use of different control strategies. The results indicated that (a) has an increasing effect on energy saving when it is adjusted to longer time, and the effects were observed as linear for different control strategies. Meanwhile, the impacts of (b) were observed similar for both an absence controlled system and a dimming controlled system.

For achieving a comprehensive retrofit evaluation, the economic-technologic aspect should also be analysed to provide a quantitative feedback about payback times. Due to a limited time and a lack of practical knowledge about the studied project, a retrofit cost cannot be calculated in this thesis.

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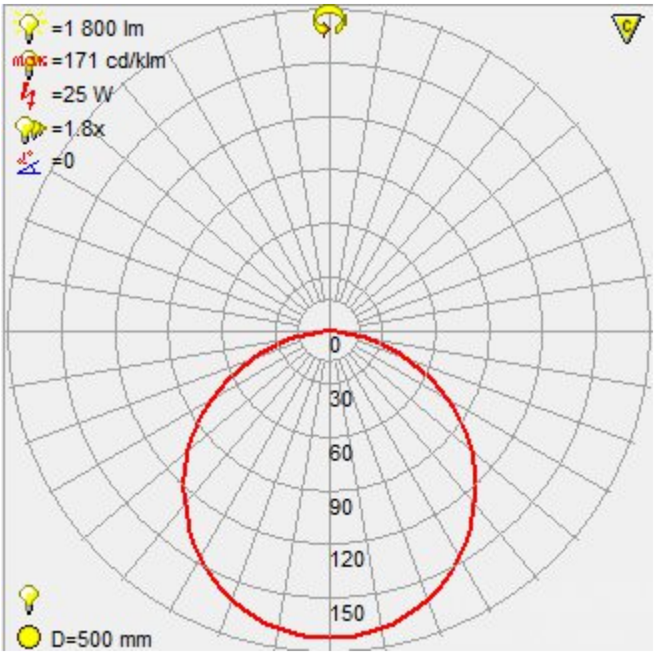
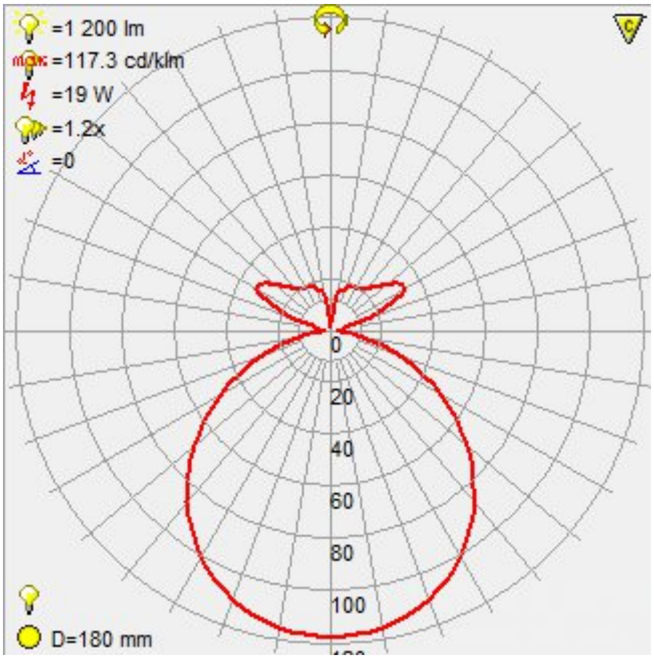
7 Appendix

The IES files of the luminaire types applied in the electric lighting systems are demonstrated in the following, which contain three types of luminaires: a pendent luminaire, a wall-mounted luminaire and a ceiling recessed luminaire.

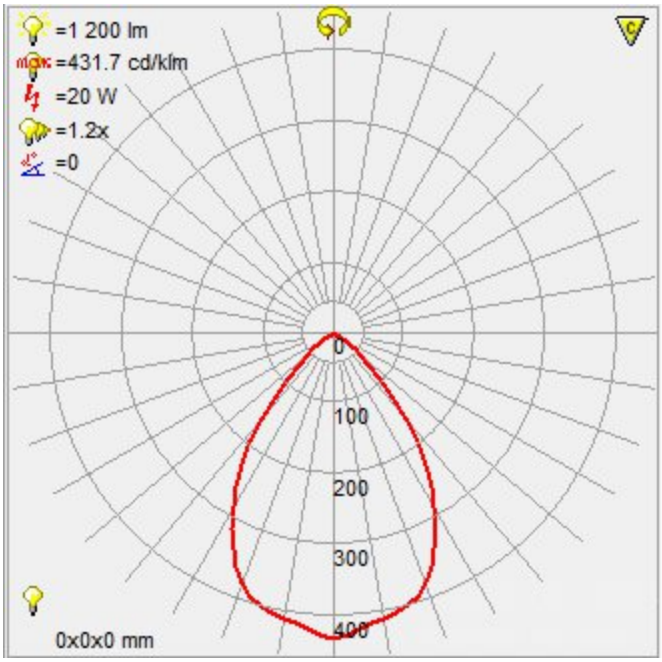
1 The pendent luminaire



2 The wall-mounted luminaire



3 The ceiling recessed luminaire



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