Electrical lighting in open-plan offices

A laboratory study and simulations on lighting preferences and energy use

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Master thesis in Energy-efficient and Environmental Buildings

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Lund University

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Abstract

The need for energy use reduction raises the question of electrical lighting use especially in the non-residential sector. Office spaces are particularly sensitive in this area, as lighting is quite essential, and connected to satisfaction, mood and performance. Literature suggests a wide variety of preferred conditions, although most of the studies refer to older ways of working.

This thesis explored the lighting conditions' preferences through a laboratory study, by exploring the switch-on probability of task light when working in low illuminance levels. On a second level the results of the laboratory study were used to feed simulations on illuminance levels, uniformity and energy use in a hypothetical open-plan office.

Through this project, it was revealed that a reduction on illuminance levels is possible and with daylight implementation can lead to remarkable savings in energy. Finally, lighting preferences, are crucial to be investigated further.

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Table of content

Glossary

E – Illuminance [lx]

U_o – Illuminance uniformity is expressed as the ratio of minimum illuminance to average illuminance on a surface

Abbreviations

LED – Light Emitting Diode
TMY – Typical Meteorological Year
DA – Daylight Autonomy
LD – Lighting Dependency
IES – Illuminating Engineering Society

“Office in a Small City”, Edward Hopper, 1953

1 Introduction

According to European Commission, lighting accounts for 14% of all the electricity consumption in the European Union (Commission, 2015). In 2014, the energy use for lighting in the non-residential sector in the European Union (EU28) was 13.52 Mtoe (million tonnes of oil equivalent) , which accounts for 157.2376 TWh (Commission). In view of these numbers, many regulations aiming to lower energy use for lighting have been issued at both national and international level.

However, lighting energy reduction should not come at the expense of lighting quality. Lighting is one of the aspects that affects space appraisal and work engagement when it comes to workspaces (Spreckelmeyer, 1993, Veitch et al., 2005) and as such is a quite sensitive aspect to be explored both in terms of acceptance and adequacy but also in compliance to energy use reduction.

1.1 Research and guidelines

The office space may have different designs and sizes, cellular, small private offices, small shared office, or large offices. For the latter, although having been designed already from early 1900s, the German novelty of Bürolandschaft - which stands for landscaped office - became quite popular design during the 70s in both US and Europe. The concept of landscaped office spread quite broadly as it was space and cost effective. Although landscaped offices have some disadvantages, such as noise and lack of privacy (Sundstrom, 1986), they represent today a relevant portion of the built office space. In addition, in such spaces, artificial lighting is also one of the main sources of dissatisfaction of workers when it comes to conditions' acceptance (Danielsson and Bodin, 2009). Because of their commonness and lighting constituting one of the main sources of dissatisfaction, landscaped offices were chosen as the focus for this study.

In regards to electric lighting, the European standard EN12464-1:2011 defines the design criteria of electric lighting for work spaces (Standarization, 2011). For the case of office spaces, the standard proposes a number of different requirements. Among those, two are the focus of this study:

- A minimum maintained horizontal illuminance (E_m) on the task area, accounting for the 'amount' of light necessary for adequate for visibility;
- A minimum uniformity (U_o), which should avoid high contrast in the space.
-

Table 1.1 shows the different requirements for different activities in office spaces.

Table 1.1: Lighting requirements in office spaces according to different activities (EN12464-1:2011).

Activity	Em / lx	Uo
Writing, typing, reading, data processing	500	0.6
Filing, copying etc.	300	0.4
Technical drawing	750	0.7
CAD working stations	500	0.6
Conference and meeting rooms	500	0.6
Reception desks	300	0.6
Archives	200	0.4

Across the literature, illuminance levels and uniformity are widely explored when it comes to office spaces.

For the case of the maintained horizontal illuminance on the task space, a study demonstrated the unacceptability of very low (<200 lx) and very high illuminances (>1200 lx) (Slater and Boyce, 1990), and suggested that a range of horizontal illuminance 200 lx < Em <500 lx would be still acceptable. Similarly, in another study, subjects were asked to perform computer-based tasks, and the desktop illuminance levels were measured. 60% of the participants chose lighting below 500lx, 17% a dark environment combined with task lighting, while a 7.5% chose a totally dark environment (Veitch and Newsham, 2000). This suggests that preferred lighting conditions vary greatly among individuals.

A great variation in preferences was also concluded from a study through structured interviews, of employees of three different buildings (Escuyer and Fontoynont, 2001). In this study, participants working on computer-based tasks tended to prefer lower illuminance levels (100 lx-300 lx).

A reduction of illuminance compared to the recommended 500 lx is also suggested by other studies. A laboratory study by Akashi and Boyce (2006) in an office with low-rise partitions, demonstrated that a reduction to 360 lx is acceptable in long-term. In a newer study, the combination of 150 lx provided by general lighting, supported by additional task light, was considered comfortable (Xu et al., 2017).

In general, the E_m requirements for office work, derive mainly from past (1970-1980) research that was conducted mainly with laboratory studies, while the prevailed task was paper-based and horizontal. However, the task area, in most cases, is no longer the same as it was 30 years ago. The introduction of mainly computer-based activities introduced a self-illuminated vertical display as the surface to read and edit and changed the actual task area from the horizontal plane to a combination of both horizontal and vertical surfaces.

The preferred illuminance levels in task area when performing computer-based task were tested in a laboratory study (Chraibi et al., 2017). In this study, the preferred levels in the task area were explored in relation to the provided wall luminance and its uniformity. As it was resulted, lower illuminance levels in the task area were chosen when the wall was non-uniformly lit, with high luminance levels.

In conclusion, there are many indications in literature that illuminance levels can be reduced from 500 lx to 300 lx or even less, especially when computer-based tasks are considered.

When it comes to working places, lower illuminance levels for general lighting are already suggested from other regulations. The Danish State Building Research Initiative (Statens Byggeforskningsintitut), for example, considers 100-300 lx on the task area acceptable for PC work (Johnsen, 2009), and even lower levels when it comes to general lighting, while providing the 500 lx with a manually operated task lamp.

For the case of illuminance uniformity U_0, the underlying belief is that high uniformity is a necessary measurement to provide comfort. Indeed, McWhirter (1937) via Slater et. Al (1990) proposed a 0.7 of uniformity ratio as a reasonable criterion.
Slater and Boyce in 1990 (Slater and Boyce, 1990), when exploring uniformity in an open - plan office laboratory study, found through subjective ratings that the satisfaction of the occupants decreases when uniformity decreases. Although a general rule can apply for uniformity, the same study showed that this could have some drawbacks when there are local lighting units manually operated. In this case, those sudden changes can create higher sensitivity to non-uniformly lit spaces.
Annoyance with sudden changes in illuminance was also reported in a laboratory study by Escuyer and Fontoynont (2001), which was caused due to changes in occupancy and occupant control strategies. In 1993, in a laboratory study concerning adequacy of light and comfort on the task, argued that a need for greater uniformity values was risen in lower illuminance levels (Slater et al., 1993). The last two cited studies showed though, that task performance is not affected by changes in illuminance uniformity on the horizontal plane. Both studies were conducted with horizontal, paper-based tasks, which is not the main case when it comes to work spaces nowadays. There is a lot of research on the topic of illuminance uniformity with computer based tasks, but, in a recent study, occupants working with computer-based activities showed a higher preference for non-uniformly lit environments (Lim et al., 2017). This suggests that recommendations on uniformity may not hold true anymore, but additional research is needed.

The reduction of both provided horizontal illuminance and uniformity can create many opportunities for lighting design and energy savings, possibly with no expenses in comfort and users' satisfaction. For example, combining general/ambient lighting and individual task lighting is one of the most interesting in terms of energy savings. In such approaches, the general lighting guarantees a minimum horizontal illuminance on the space, for example 300 lux or less, while individual task lighting provides the adequate illuminance on the task area, which is 500 lux according to EN12464-1:2011. Shelko P.L. and Williams H.G. via Tabuchi et al. (1995) proposed the combination of ambient/task lighting in offices as a response in the oil crisis during the 70s. (Tabuchi et al., 1995)
According to Loe (2009), ambient/task lighting can also provide space flexibility, beside the aforementioned energy saving. In addition, general lighting may be provided by daylight during most of the working time, enhancing even more the energy saving. According to a literature review in 2011, the savings when using a daylight harvesting system can reach from 25% to 60%, depending on location, space design and shading strategies (Dubois and Blomsterberg, 2011).
For the aforementioned reasons, this study explores the use of combined general/task lighting in a hypothetical daylit landscaped office. Daylight is accounted for by using the validated daylight simulation engine of Radiance(Larson and Shakespeare, 1998), while, electric lighting is calculated according to individual preferences deducted from a laboratory study and integrated into Radiance.

1.2 Problem motivation

During the lighting design process, space is considered as an empty shell ready to accommodate functions and people. This leads to a sterile perception of lighting quality and its impact on people, and it indicates that the distance between the lighting designer and the actual experience is big and changes over time.
The initial phase of such a procedure is dictated by several requirements from standards, in order to preserve a certain quality. However, the use of control strategies, the constant change in occupancy patterns and the individual interventions in the working environment tend to change the initial concept.
The questions risen and expected to be answered are the following:

1. Are standard requirements applicable to current needs?
2. How are lighting conditions affected by individual preferences?
3. What are the prospects concerning energy use reduction?

1.3 Goals and Objectives

The main goal of this study is to discuss some boundaries of existing standards, like maintained horizontal illuminance and illuminance uniformity, and whether they can be updated in order to save more energy for electric lighting, without compromising the lighting quality. To achieve this goal, this study:

· explores individual differences in preferred luminous environment when performing computer-based tasks, in particular with respect to the use of task lighting, and
· creates hypothetical lighting scenarios and compares these scenarios with criteria proposed by standards both in terms of lighting quality and energy use.

1.4 Limitations

This study comprises two parts: a laboratory study and a simulation study. The experimental methodology presents a number of limitations that may affect results and conclusions, namely:

- Laboratory study
  · The participation was voluntary and not awarded, therefore the tested population was limited in number (23 participants) and individual characteristics, e.g. age. This did not allow for a thorough statistical study.
  · Due to practical constraints, the individuals performed the test at different times of the day (morning, noon or afternoon), which could affect the preference in light setting.

- Simulation
  · The simulations are based on the Radiance engine, which uses backward ray-tracing. An actual luminaire as a system of an intense light source, and curved surfaces of high specularity would require a ray-tracing method with the opposite direction (Larson and Shakespeare, 1998)
  · Radiance, and its related software Daysim (2018) are specifically developed for daylight simulations and they were used to correctly account for daylight

penetration in the space, to accurately predict the need for electric lighting. However, Daysim uses a so-called "ideal lighting system" for electric lighting simulations, which does not take into consideration the light distribution of the actual luminaire; rather it simply adds "electrical lux" to the missing daylight illuminance. On the other hand, other simulation software specific for electric lighting, like Dialux or Relux, cannot perform advanced daylight simulations (e.g. climate-based simulations).

- The simulation input are partly fed-in from the laboratory study results, therefore the uncertainties of the laboratory study are also "passed" to the simulation.

2 Method

This study develops in two parts. The first part is a small laboratory study concerning individual preferences and switch-on probability of task lighting when performing computer-based tasks. The second part consists of simulations of different lighting design strategies in a typical open-plan office. The results of the first part were used in order to create the occupancy and electric lighting switch-on patterns used for the task light use in the simulations. The different strategies were tested in terms of energy savings.

2.1 Laboratory study

The laboratory study was carried out in Campus Helsingborg, which is located in the south-west part of Helsingborg, Skåne (56.07˚N, 12.69 ˚ E). A room with no access to daylight was chosen. This specific room was chosen, among other study rooms, for a couple of reasons: it was easily accessible to most of the participants, it is an internally located room and it was easy to block incoming daylight and potential light from the adjacent corridor. The room is a study room for four people that is located in the core of the building and it has a glazed partition facing a daylit corridor. This glazed partition was obscured with a black cloth to exclude any illumination from exterior sources.

2.1.1 Geometry of the room and light environment

The area of the room is 18.2 m^2. The room had the small side facing towards the corridor, with one light-coloured wood door and glazing, while the other small side had a whiteboard from side to side. The walls were white coloured and there were three light coloured wooden table and blue chairs. Photos of the room are presented in Figure 2.1.

The lighting system of the room included two Philips TPS642 2xTL5-49W lamps in a suspended luminaire of an 80/20 light distribution, to create ambient light through the ceiling reflection. The system was manually controlled and dimmable.
The lighting system was always on during the experiment and it was calibrated in order to provide 100 lux on average as general lighting level.
The task light used for the purposes of this laboratory study was a Luxo task light model Ninety. It was supplied with an integrated LED lamp with 7.4W of total power connected (Corporation, 2018).
Its flux was calibrated by means of a lux meter to provide 300 lux on the working space.
The task lighting was off in the beginning of the experiment and it could be manually switched on-off by the test subjects at any point in time during the experiment. Neither the position of the task lamp could be changed, nor could the directionality of its light beam be adjusted.

2.1.2 Participants

23 subjects, 11 male and 12 female aged between 21 and 36 years old, participated in the laboratory study. The laboratory study was conducted during two weeks in mid-February. The participation was voluntary, and there was no award to promote participation. The laboratory study was conducted during three main time slots, in the morning (9:00-11:00), during lunchtime (12:00-13:00) and after classes (13:00-16:30), mainly to encounter participants' scheduling needs. At the beginning, all participants were asked to state their sex, age and visual defects. In total eight people stated some type of visual defect, five males and three females.

2.1.3 Procedure

The procedure followed was the same for all participants. There was a check to the illuminance levels before each measurement. These were verified using a professional Hagner EC1 luxmeter (±3% accuracy).
Each participant was required to remain outside the room (in the adjacent corridor) for about 5 minutes prior to the experiment. After this short time, the participant entered the room and the author of this study provided instructions, submitted the preliminary questions concerning age, sex and possible visual defects, and started the test (see Appendix).
The duration of the experiment was 30 minutes.
During the 30 minutes of the experiment, the subject was asked to perform a computer-based task, which involved grammatical corrections of an English text document. The text editor had a white background with black fonts, providing a computer screen luminance of 219 cd/m² throughout the experiment.
The test started with general lighting on and task lighting off. The subject was free to switch on-off the task lighting, but was not allowed to regulate the general lighting. The switch on-off occurrences of the task lighting were logged by means of an Onset HOBO U12 stand-alone data logger located next to the screen ("sensor" in Figure 2.1) , which recorded variations in illuminance.
After 30 minutes, all participants had to stop grammatical corrections and answer orally to three closed questions concerning their lighting preferences. After the closed answer (yes/no), the subject could freely elaborate on his/her experiences and preferences regarding task lighting conditions.
Those questions were:
- Q1: Do you prefer to work in darkness?
- Q2: Do you ever use task lighting?
- Q3: Do you actively turn on/off lighting?

During this procedure, the temperature of the room was measured by a sensor installed in the room, and ranged between 22 °C and 24 °C, while the CO_2 levels never exceeded 800 ppm.

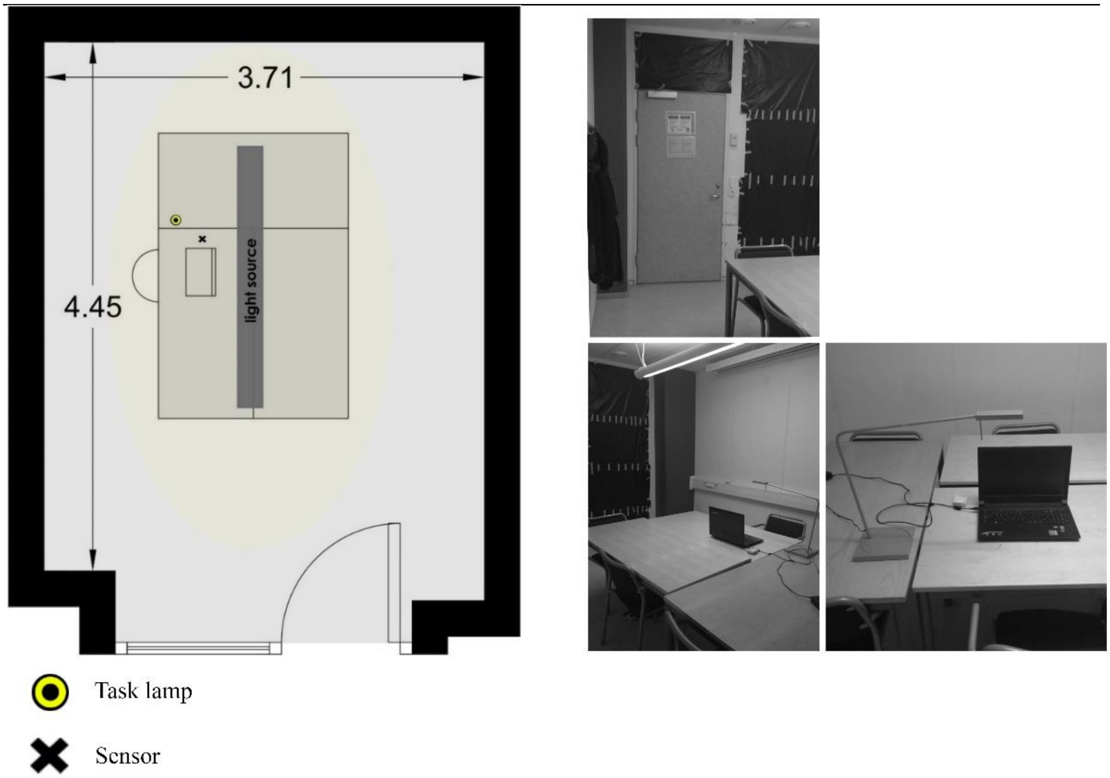


Figure 2.1: Plan and photos of the room.

2.1.4 Data processing

Light intensity data were logged through the sensor's software HOBOware v3.7.13. The location of the sensor is presented in Figure 2.1 All data were transferred and were processed through Microsoft Excel in order to link illuminance variation to switch on-off events.

Answers to the questions made after the main part of the laboratory study were recorded, and later transcribed.

During the transcription, the transcribed answers were clustered in three groups: clear negative answer, clear positive answer and ambiguous answer. In addition, there were two categories to separate the free answers: Lighting preferences-comfort and focus. The first category refers to four different sub-categories: Preference in lighting levels, preference in the lighting system, relation of preference to the task and dissatisfaction with the task lamp. The second one refers to two sub-categories: preference in daylight and relation to the time of the day and need for focus. Comments made before or after the questions, were also kept, as they were a valuable source of qualitative information.

2.2 Simulations

The second part of this project consists of simulations. The lighting conditions examined in the laboratory study were simulated in comparison to the conditions required by the standard, in order to discover the potential of energy use reduction. Moreover, the results of the laboratory study about switch on probability were used as a basic input. Three different lighting scenarios were examined in terms of lighting quality and energy use.

2.2.1 Software

The simulated office was modelled with a spatial resolution of 5 cm in the 3D modelling software Rhinoceros (Robert McNeel, 2018b). The lighting simulations were performed using Honeybee and Ladybug (Roudsari and Pak, 2013), which are two open source plugins for Grasshopper (Robert McNeel, 2018a). Honeybee connects to Daysim to perform annual Radiance simulations using daylight coefficients. Its accuracy has been validated by experimental studies (Mardaljevic, 1995, Reinhart and Walkenhorst, 2001).
Although several software can be used for lighting simulations when exploring different lighting systems, these were chosen because:

- they offer the possibility of running climate-based simulations
- different parameters can be tested more efficiently
- occupancy schedules and geometry are easily implemented.

2.2.2 Lighting scenarios

Three different lighting scenarios were tested. For all three, the average illuminance on the horizontal plane and the illuminance uniformity were calculated at 0.8 m above floor level, for the overall room area and the 40 workstations as seen in Figure 2.2. The maximum cell grid for performing the simulations was calculated according to the formula (1) provided by the EN12464-1:2011 (Standarization, 2011)

(1) $$p = 0.2 \times 5^{\log d} \quad \text{(m)}$$

Where:
p: the maximum cell size (m)
d: the longer dimension of the area (m)
Thus, the maximum grid cell to perform the simulation was calculated to 1,6 m and 0.32 m for the overall room area and the workstation respectively. For the latter the grid size was set to 0.25 m for modelling purposes.

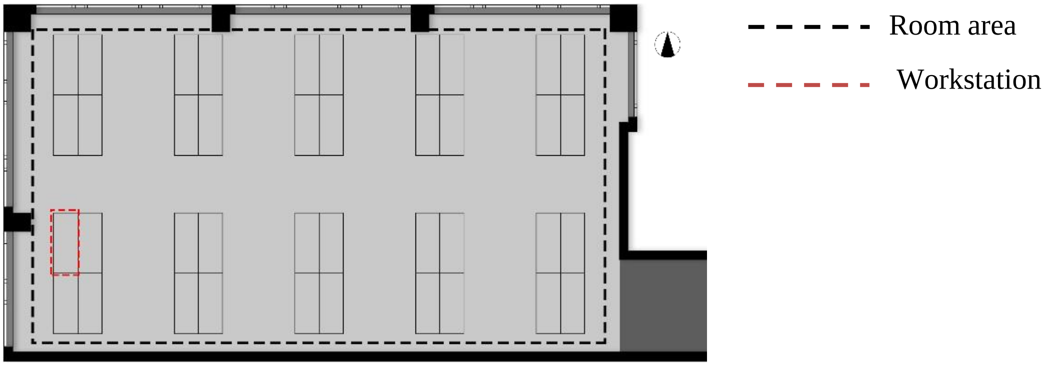


Figure 2.2: Plan of the office and location of the two different simulation grids

2.2.2.1 Scenario A

The lighting conditions in scenario A, were set according to the requirements of standard EN12464-1:2011. A maintained illuminance of 500 lx was provided in the horizontal plane, by a general lighting system. In this scenario, the system used was a grid of 36 luminaires with a lighting power density of 6.67 W/m^2. Table 2.1 presents the main specifications of the luminaire used. The simulations were performed using a sky model of zero luminance, to rule out daylight contributions. Figure 2.3 shows the location of the luminaires used.

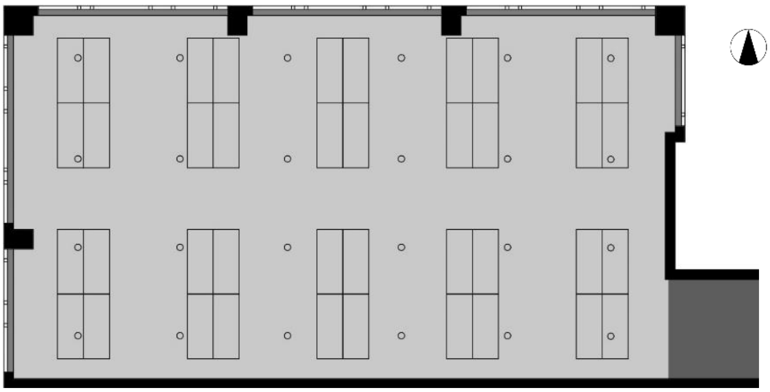


Figure 2.3: Plan of the office and location of the luminaires indicated with circular markers

Table 2.1: Luminaire used for the general lighting system in scenario A

Product Name	Number of lamps	Power of lamp / W	Total lamp flux / lm	Total power / W	CCT / K
TPS760 C 2xTL5-28W HFP AC-MLO FU SMS	2	25	5200	55	4000

2.2.2.2 Scenario B

For scenario B, the lighting conditions simulated were the ones used in the laboratory study. A general system was used to provide 100 lx in the horizontal plane while a task lamp, when on, could raise the illuminance to 300 lx. The lighting power density of the general lighting system and the 40 task lamps was 4.04 W/m^2 in total. In this scenario, the results of switch-on probability from the laboratory study were used as input. A pseudo-random number generator was used in Grasshopper to create three different cases for scenario B. In each case, a different placement of task lamps was tested. There were 40 total task lamps in the whole office, of which 59.1 % were switched on, as a result of the behaviour observed in the laboratory study. Consequently, the following cases were created: Scenario B-random1, Scenario B-random 2, Scenario B-random 3. Table 2.2 presents the specifications of the luminaires used for scenario B. Figure 2.4 indicates the location of the general lighting system with circular markers. Moreover, in Figure 2.5 the location of task lighting in the three random distributions is indicated by circular markers.

Table 2.2: Luminaire used for the general lighting system and the task lamp used in scenario B.

Product Name	**Number of lamps**	**Power of lamp / W**	**Total lamp flux / lm**	**Total power / W**	**CCT / K**
PAK234010 PAK-C01-104K-WA-CD (ambient)	1	13	700	13	6500
Birdie Bord 7W LED (task)	1	7	511	7	3000

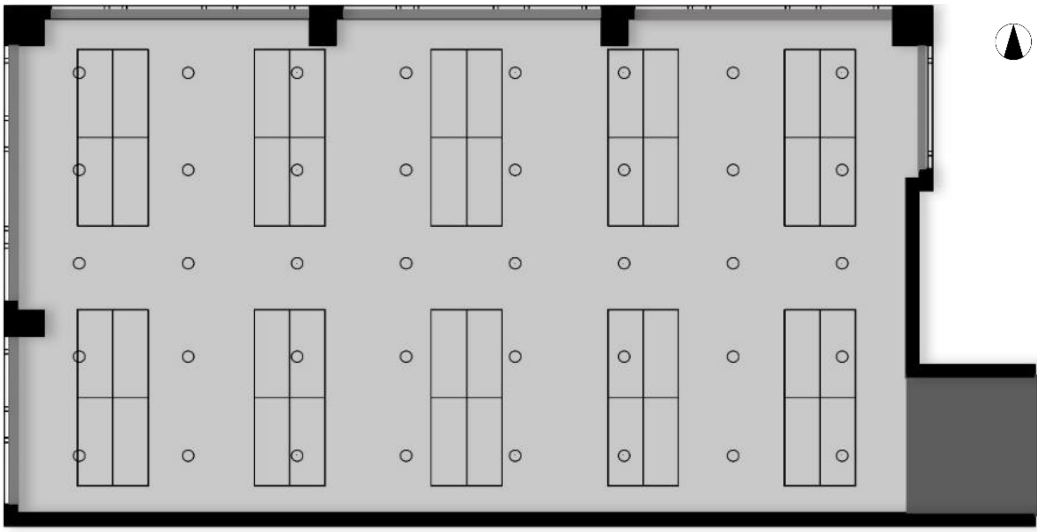


Figure 2.4: Plan of the office and location of the luminaires shown in circular markers.

Figure 2.5: Plan of the office and location of the task lamps, in the generated random positions

2.2.2.3 Scenario C

Scenario C is identical to scenario B, with the addition of daylight. The need for electric lighting was calculated roughly as the percentage of the year that adequate illuminance levels could not be provided by daylight alone. Annual daylight availability can be quantified with the use of the Daylight Autonomy (DA) metric. Daylight autonomy indicates the percentage of occupancy time for which the illuminance at given points does not meet a specific threshold (lx). To quantify the electric lighting use, one can use the Lighting Dependency (LD) metric which is a derivative of DA (Bournas and Haav, 2016, Iversen et al., 2012). Lighting Dependency is practically the percentage of time when there is no Daylight Autonomy. It is expressed as LD = 100 - DA and thus expresses the hours when electrical lighting has to operate in order to maintain adequate illuminance levels.
The energy assumption for this scenario was calculated, using formula (2)

$$(2)\quad E = \left(\frac{LD_{500}}{100} * n * LPD\right)/1000 \qquad (\text{kWh/m}^2\text{year})$$

Where:
E: the annual energy use,
LD_{500}: the lighting dependency expressed as 100-DA_{500}, “$_{500}$” indicating a 500 lx threshold
LPD: the lighting power density as estimated in scenario B
n: the working hours per year, here calculated as 1820 hours

To achieve that, several assumptions were made. The hypothetical office as a part of a highly glazed office building was decided to have a manual shading system. Concerning the operation of the shading system, it was assumed that the person sitting in the position presented in Figure 2.6 is the one responsible for lowering the shading as this position is exposed to the largest glazing surface both in terms of visual but also thermal comfort. Another assumption was the illuminance threshold for lowering the shading. It was decided to be 2500 lx on the point of measurement. This threshold was decided according to two factors: Useful Daylight Illuminance and visual comfort considerations. For Useful Daylight Illuminance the upper level for UDI achieved is 2000 lx (Nabil and Mardaljevic, 2006) and was recently revised to 3000 lx (Mardaljevic et al.). Moreover the probability of visual discomfort when it comes to horizontal illuminance rises significantly above 2500 lx (Lindelöf and Morel, 2008).
The shading device used was a roller shade, whose visual properties are presented further down.

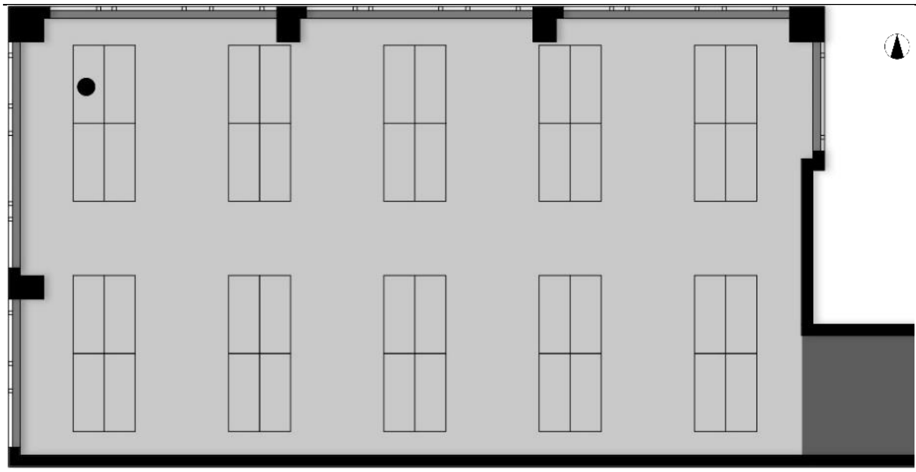


Figure 2.6: Location of the shading "controller"

Figure 2.7 presents the DA_{500} distribution over the total office space floor area. The average DA_{500} was calculated 52 %.

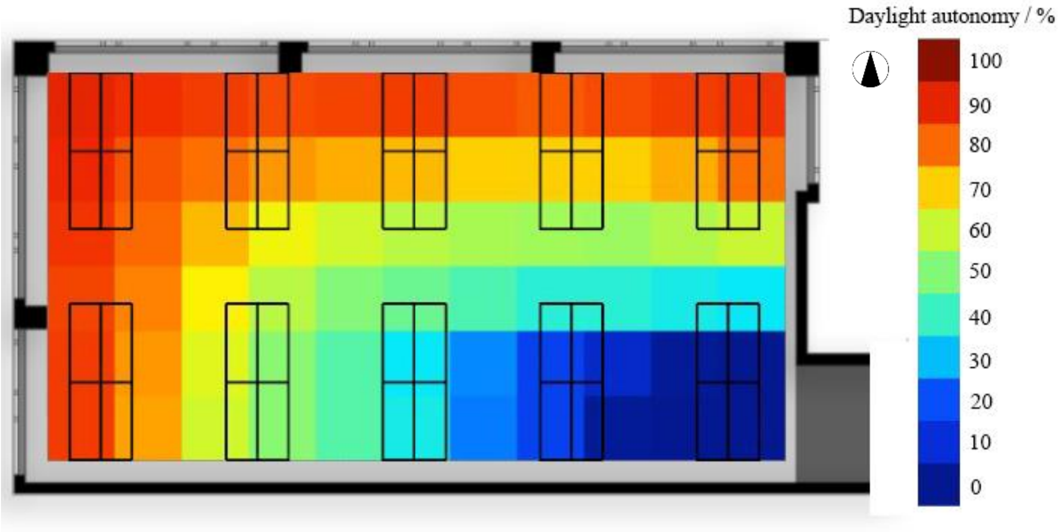


Figure 2.7: Synthetic visualisation of Daylight Autonomy in space.

2.2.3 Scene geometry and location

The hypothetical office is "located" in Denmark by use of climatic data based on a typical meteorological year (TMY) for Copenhagen (US-DOE, 2018). The office is on the third floor, and no external obstructions are considered. Figure 2.8 shows a plan of the office and Figure 2.9 shows images of the office spaces as they were created in DAYSIM.
The longest façade is due north. Tables 2.3, 2.4, 2.5 show the material properties used for the simulation.

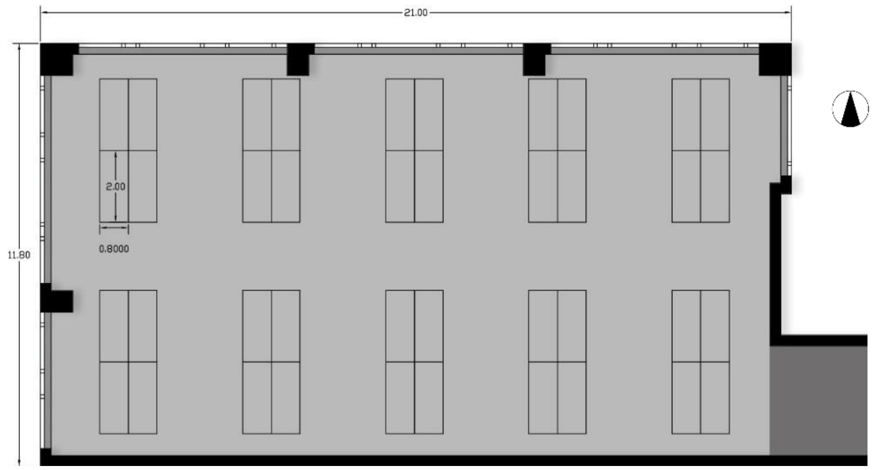


Figure 2.8: Plan of the office

Figure 2.9 :Images of the office space, created in DAYSIM

Table 2.3: Properties of opaque materials used in the simulation.

Opaque surfaces(Lab, 2015)	RReflectance	GReflactance	Breflactance	Roughness	Specularity
Tables	0.541	0.541	0.541	-	-
Window frame	0.49	0.34	0.13	0.016	0
Walls	0.9	0.87	0.76	0.005	0
Floor	0.31	0.31	0.31	0	0.005
Ceiling	0.86	0.85	0.8	0	0.005

Table 2.4: Properties of glazing used in the simulation.

	Rtransmittance	Gtransmittance	Btransmittance	Refractive index
Glazing	0.7	0.7	0.7	-

Table 2.5: Properties of transmissive materials used in the simulation.

	RDiffuse reflectance	GDiffuse reflectance	Bdiffuse reflectance	Specular reflection	Diffuse Transmission	Specular Transmission
Roller shade (Dubois, 2001)	0.313	0.313	0.313	0	0.02	0.039

2.2.4 Occupancy, lighting control systems

An occupancy schedule was created for the purposes of the study. The analysis period is one year, and the working hours are 9:00-17:00 with an hour of absence between 12:00 and 13:00. This makes a total of 1820 working hours. Concerning energy use, the three different scenarios had different settings:

- For scenario A, the general lighting was always on during occupancy hours
- For scenario B, the general lighting system was always on during occupancy hours and the task lamps were on according to the pseudo-random generated schedules based on the laboratory study results
- For scenario C, the general lighting system and the task lighting was considered always on during occupancy hours

3 Results

The results of the two main parts of this project are presented in the following sub-sections. Firstly, are presented the results of the laboratory study and secondly the simulation results.

3.1 Laboratory study

Concerning the laboratory study, the results are presented in three different sections: preliminary assessments, switch-on patterns of task lighting and interview responses.

3.1.1 Preliminary assessments

One participant did not strictly follow the experimental procedure, so that case was excluded. In total, data from 22 participants were analysed. The final sample consisted of 11 males and 11 female subjects, aged between 21-36 years old. More information on the statistical sample are reported in Table 3.1.

Table 3.1: Identity of the statistical sample

			Participants
Participants			22
	of which	Male	11
		Female	11
	of which	Morning slot	5
		Noon slot	4
		Afternoon slot	13
Visual defects		Visual defects	8

A preliminary statistical analysis showed that the switch-on probability of task light while working on computer-based tasks did not show any significant variation between age, gender, visual defect or time of the day in which the experiment was performed. However, the lack of significance was most probably linked to the small statistical sample. For the same reason, no further statistical analysis was performed. Simple frequency distributions were rather reported.

3.1.2 Switch-on patterns of task lighting

Table 3.2 shows the switch-on probability, according to gender. 13 people turned on the task light at least once during the experiment, and nine did not use it at all.

Table 3.2: Switch-on probability of task lighting among the participant, with gender distribution

Switch-on of task light	Male	Female	Total	Percentage / %
Yes (at least once)	5	8	13	59.1
No	6	3	9	40.9
Total	11	11	22	100

From a total of 13 participants that turned on the task light, eight participants decided to keep it on until the end of the test. Among those who decided to turn it off again, four did so immediately, as it was perceived as disturbing. Table 3.3 shows the switch-on patterns found during the laboratory study. Figures 3.1.a, 3.1.b and 3.1.c show examples of the three different switch-on patterns shown in Table 3.3, as recorded for the participants during the laboratory study. In this graph we can see time -variation, while the switch-on probability is presented as 0 (off)-1 (on)

Table 3.3: Distribution of subjects concerning their preference in the time the task light was on

switch-on pattern	on until the end	on but off before the end	instant on-off
People	8	1	4
Percentage in total / %	36.4	4.5	18.2
Percentage in people that switched on / %	61.5	7.7	30.8

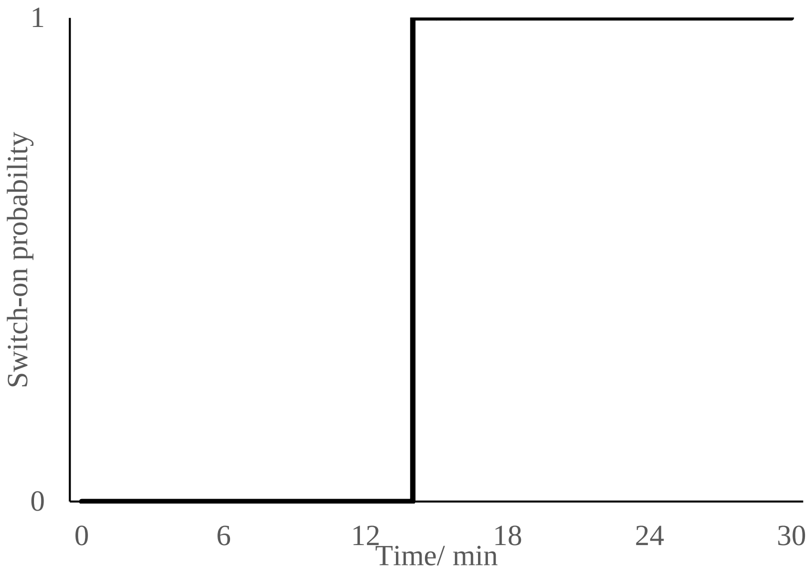


Figure 3.1.a: Switch-on pattern: on until the end

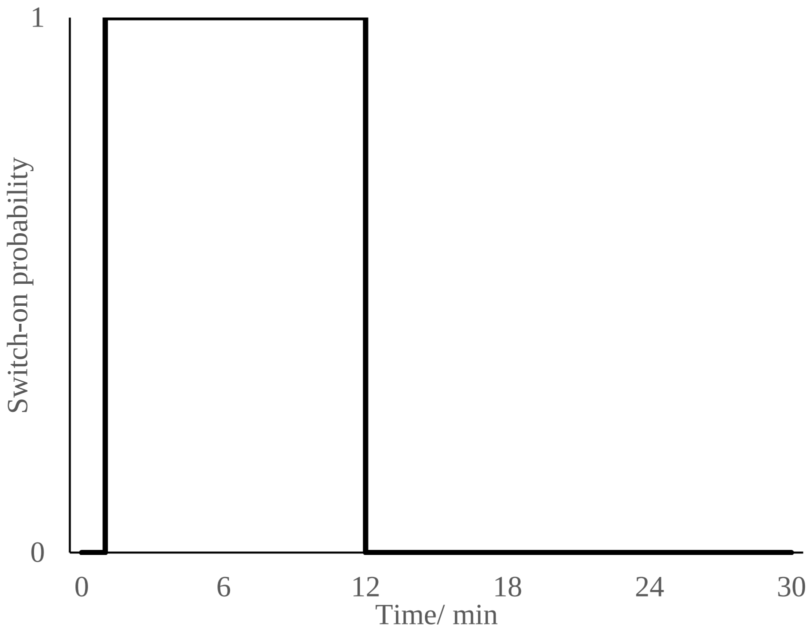


Figure 3.1.b: Switch-on pattern: on but off before the end

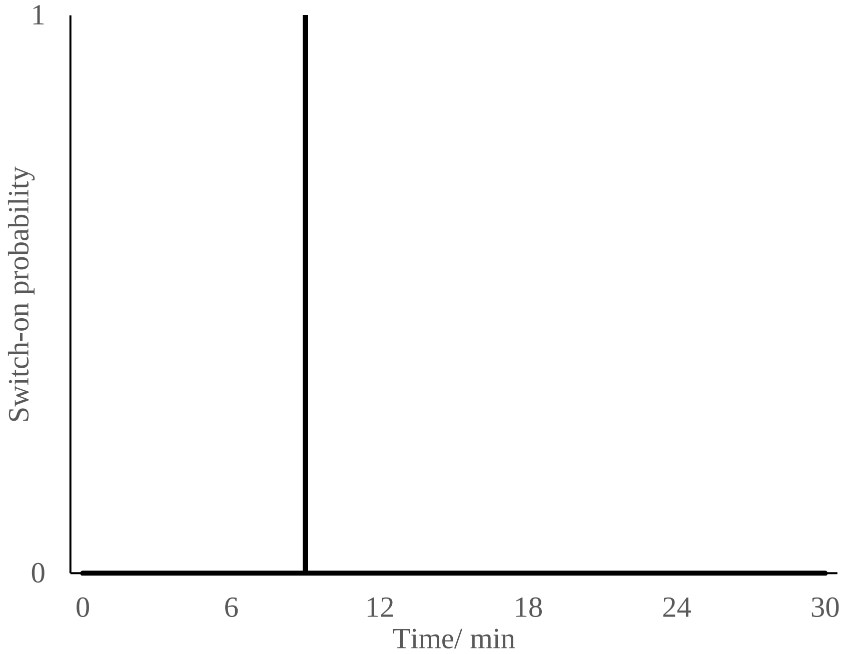


Figure 3.1.c: Switch-on pattern: instant on-off

According to the data taken from the sensor, 4 people switched on the light, during the first 6 minutes which counts for the 20% of the time of the procedure.

3.1.3 Interviews

The first step was to categorize answers in order to have a first clear image of the participants' behaviour when it comes to electrical lighting. Table 3.4 presents the categories of answers to every question.

Table 3.4: Categorization of answers to every question.

	Yes	No	ambiguous	Total
Q1 Do you prefer to work in darkness?	2	16	4	22
Q2 Do you ever use task lighting?	14	5	3	22
Q3 Do you actively turn	8	9	5	22

on/off lighting?

There were 16 comments on the lighting levels provided, and how comfort is considered when working. The relation between the task and the chosen lighting levels was commented by 4 out of 22 participants, and 4 out of 22 participants commented on the relation between light and their focus and mood while working. Table 3.5 presents the answers according to their theme.

Table 3.5: Answers according to their theme categorization.

Participant Nr.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Total
Lighting preferences-comfort	preference in light levels		■	■		■	■								■			■	■					7
	preference in system										■					■								2
	relation to the task			■			■						■								■			4
	dissatisfaction with the task lamp							■							■							■		3
Focus-mood	preference for daylight														■				■					2
	time of the day-focus			■			■																	2

The free answers provided many valuable comments from most participants. Most comments were made concerning the preferences in lighting levels while working. Those comments were made while answering different questions and not only the first one, which clearly asks on lighting levels. Participant n.2 said:

“I’m not used to work in darkness, but it really depends. For me, this is ok because I still can see everything.”

Similarly, participant n.3 said

“Yeah, it’s not that I need that much light, it’s usually the laptop brightness”.

A preference in brighter conditions, than the provided 100 lx was stated by participant n. 14,

” I’m used to the conditions back home, so I prefer that (that it’s bright, n.a.) yeah”,

relating the preference to her/his country of origin.
On the contrary, participant n. 5 mentioned a general preference for

“A little bit darker”,

environment. While participant n.6 said

“Depends on the light of the computer, right now this light is too much for me, in the same situation I would put down the light from the computer”

commenting in the relation of the lighting provided from the system to the luminance of the computer’s screen.
Concerning the lighting system used participant n.10 stated:

“Sometimes I prefer to have the surrounding dark but then I have a spotlight towards the workstation”

while participant n.15 showed a preference in a generally lit room,

“No, I prefer when all the room is light (bright, n.a.)*”.*

The use of task light was highlighted by two participants (n. 12 and 20), as both mentioned that task lighting is used when reading or performing a paper-based task.
During the study, as mentioned, the participants were not allowed to move the task lamp. Participant n.14 stated:

“Under these conditions I would require but I turned on this lamp for some seconds, but it was too bright, so I wouldn’t use this.”,

on the same side participant n.21 said:

“I tried but I didn’t use it, I just turned on the lighting and I didn’t like it much”.

Concerning the general use of task lighting participant n.7 mentioned:

“I try to avoid, but I do have task lighting”.

Participants n.3 and n.6 stated a connection between the time of the day, the mood and their preference. More thoroughly, participant n.3 stated:

“Yeah, I have it home, not every time, it depends; if I’m very sleepy then I use it”,

while participant n.6 said:

“Depends on the moment, for example when it’s very late in the night and I’m still on my computer, I will put down the light and put down the computer, but if it’s like, I still need to be active like before 9 o clock, I will have all the lights up”.

Many valuable comments were also made after the end of the experiment, as participants felt more free to discuss further. The position of the lamp, as it was not allowed to be changed was commented by two participants. Participant n.9 said that the task light was annoying, while he stated that he uses task light to illuminate the wall behind the computer screen. Participant n. 11 declared a preference in the position of the task lamp behind the computer screen too.
Moreover, participants n.12 and n.17 both found it difficult to follow the grammar correction task and had to zoom in the text document. Participant n.12, in particular, said that she/he started the test with some headache, which worsened after the participation. When she/he left the room, she/he said:

“Oh, finally some daylight!”

Finally, participant n.7 mentioned a difficulty to focus, which she/he attributed to the lack of view from the room, as it was fully blocked.

3.2 Simulations

The results for the simulations part of this project are presented in two sub-chapters. In the first subchapter, scenario A and scenario B are examined in terms of compliance to lighting requirements, as those were explained in section 1. Horizontal illuminance and Uniformity are presented on the overall room area and the workstation as they were presented previously. The two cases can be seen in Figure 2.2. On the second subchapter the results of the energy of the different scenarios are presented.

3.2.1 Horizontal illuminance and uniformity

This section presents the results for the horizontal illuminance and the Uniformity ratio for scenarios A and B.
Figure 3.2 presents the findings for scenario A, where 500 lx are provided by a general system, as measured both in the room area but also in the 40 individual workstations .

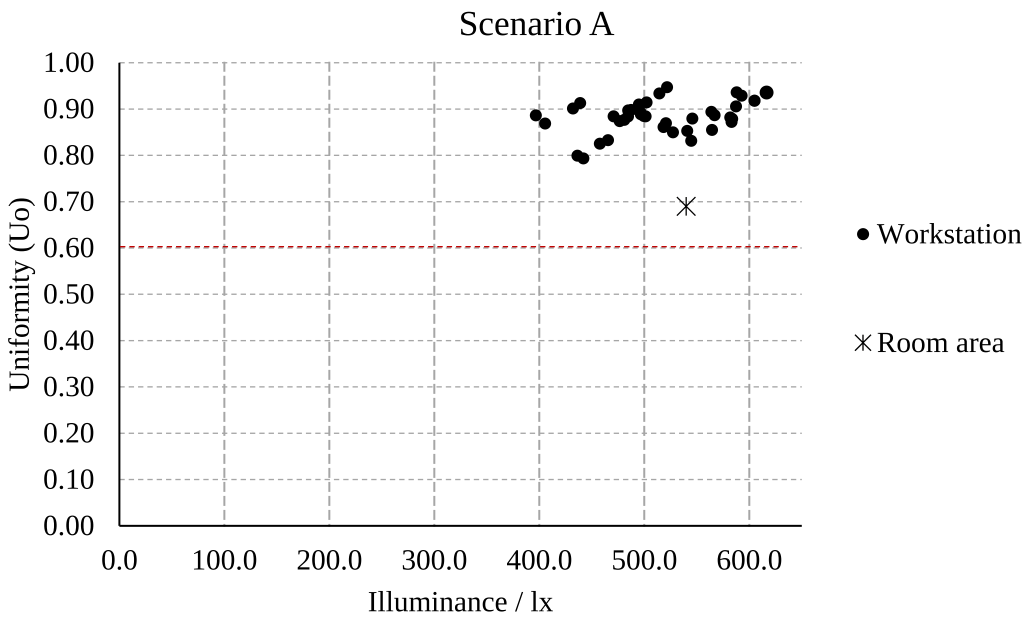


Figure 3.2: Scenario A: horizontal illuminance and Uniformity ratio.

In Figure 3.3 are presented the results from scenario B. In this scenario 100 lx are provided in the horizontal plane by a general system.

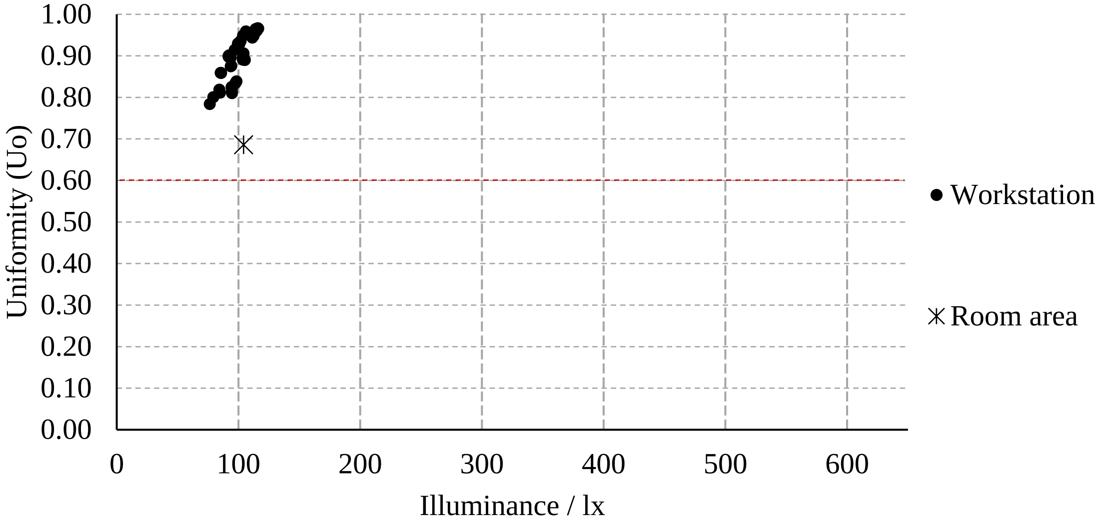
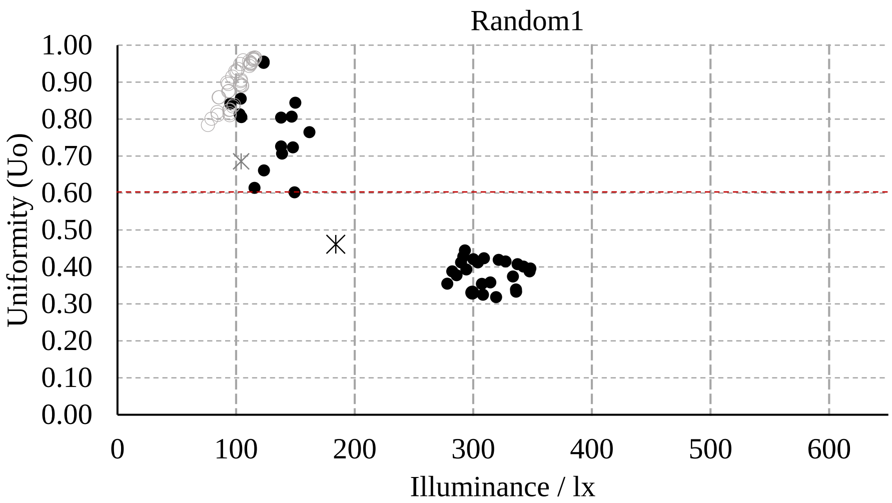
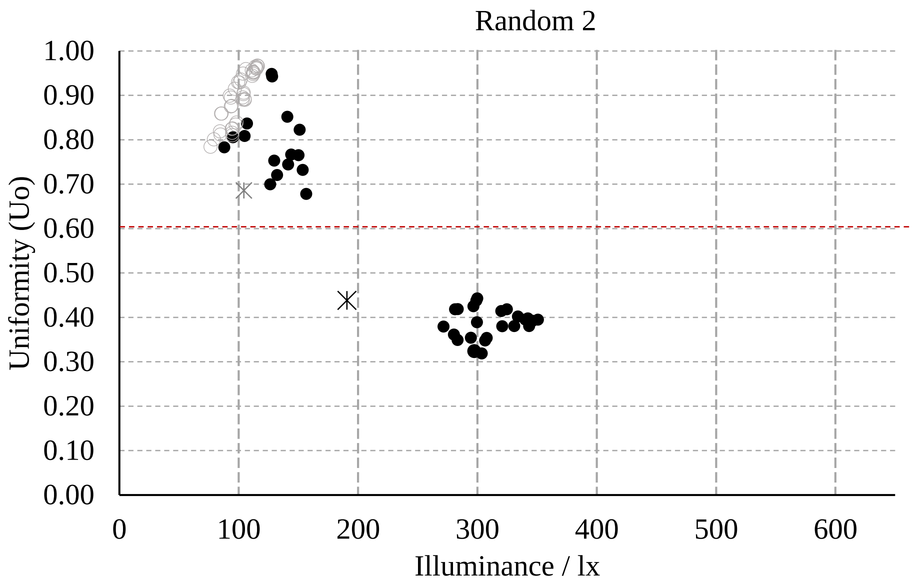


Figure 3.3: Scenario B: horizontal illuminance and Uniformity ratio

In the following Figure 3.4 the three different cases of scenario B are presented. As mentioned, in these cases three different random placements of task lamps were evaluated. The three graphs present both the workstation and the room area results. Every graph presents the results with the task light and without.





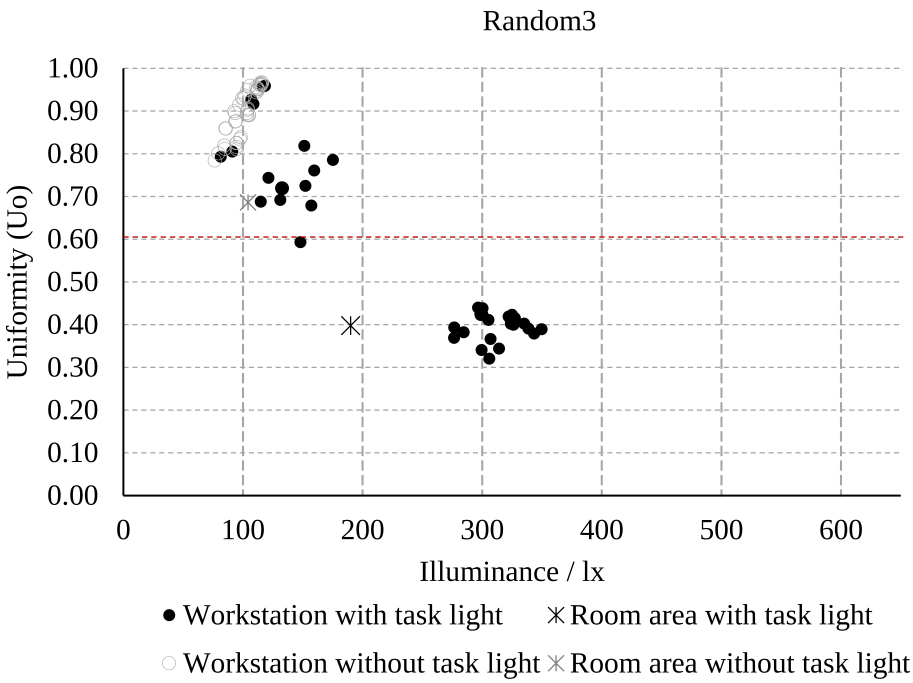


Figure 3.4: Scenario B: horizontal illuminance and Uniformity ratio in the three random cases.

As seen from the graphs the operation of task lighting lowers the uniformity in the workstations but also the uniformity of the whole room area. In cases random 1 and random 3, the graph shows that the task light operation affects also workstations that do not have a task light.

Scenario C is not considered in this part of the results, as its objective was not to explore variations in horizontal illuminance or Uniformity.

3.2.2 Energy use

The three different scenarios are presented in Figure 3.5 in terms of annual energy use per area unit. Energy use for scenario A is 16.06 kWh/m^2 annually, while for scenario B was 6.74 kWh/m^2 annually, which accounts for a reduction of 59 % from scenario A. In scenario C, it is reduced even more to 3.53 kWh/m^2 annually. Daylight implementation leads to a reduction of 48 % to scenario B.

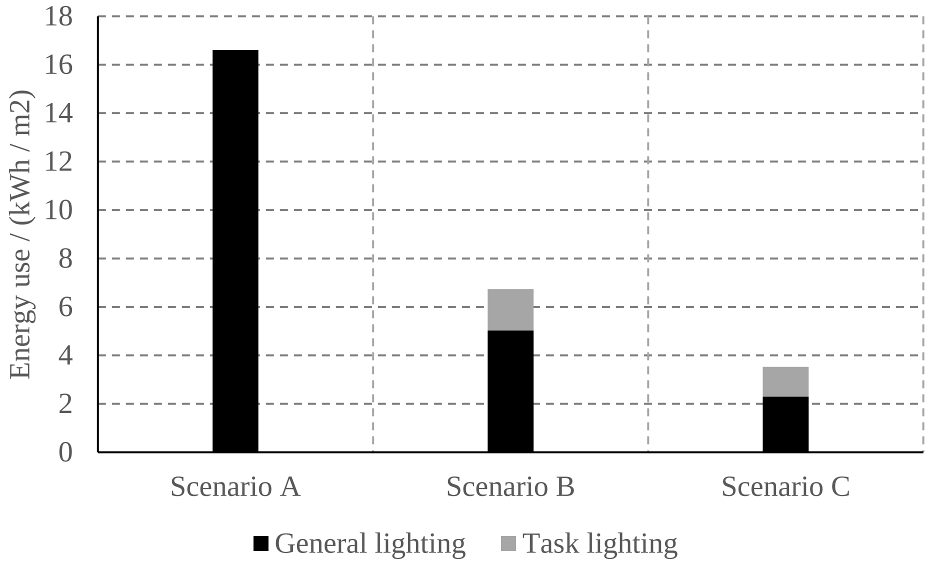


Figure 3.5: Energy use as calculated for the three different scenarios.

4 Discussion

During this project, both the experience of the laboratory study and the simulation part revealed the real challenges of electrical lighting, its quality and the potential energy use reduction in open-plan offices.

4.1 Laboratory study

The main purpose of the laboratory study was to explore the switch-on probability of a task lamp, while working in low ambient illuminance levels, and use it as an input for the simulations part. Moreover, illuminance reduction and acceptance while working was essential for the second part of the project. The decision to run an laboratory study was more demanding than what was expected. However, the results part, both the recording of probability and the interviews were very rewarding in terms of information.
There were comments regarding the position of the task lamp. Two of the participants commented that they preferred the position of the lamp not towards the task but behind it. Satisfaction with the position of the task lamp, is also met in literature. Xu et.al (2017) mention that human behavior is important to achieve visual comfort and one way is being able to change the position of the lamp. This is also linked to the satisfaction for the user having control when it comes to workstation attached lighting (Rubinstein and Enscoe, 2010, Escuyer and Fontoynont, 2001).
Preference both for general levels but also for the lighting system, was linked to the actual task performed by some participants. Change in workspace is not only met in the big scale design, but also in the equipment used, furnishing and technology. The luminous display provides enough illuminance according to some participants as it is implied that the horizontal task area is the keyboard. This is linked to the actual motivation behind this project, as newer ways of office design are starting to develop further.
A quite high percentage of people (30.4%) instantly switched on and off the task light, while there were comments about the inadequacy of the specific lamp. Three participants mentioned that they were disturbed instantly after they turned on the task lamp, while another participant mentioned that he always tries to avoid task lighting, even in other occasions. This is an indicator, of a poorly designed luminaire but also of the fact that the position and the angle could not be modified. The importance of luminaire and furnishing design is mentioned as important also in literature (Newsham and Sander, 2003).
During the individual interviews, there were many important comments by the participants, as they were presented in previous chapter. Although many participants mentioned that the lighting levels were adequate, there were comments on difficulty to focus on the task, while one of them mentioned the need for an opening not in terms of daylight but in terms of view to the outside. This need is also found in literature, where the existence of windows raise the satisfaction more than daylight access. (Veitch et al., 2005)
As previously mentioned in the methodology part, the instructions were oral and the same for all participants. One participant mentioned that it would be better if the instructions were written as they could be easily forgotten, while 9 out of 22 participants answered that they do not turn on/off lighting actively. Moreover, the setting of the laboratory study, as it was accessible to other students, led to other quite interesting findings. Three students that used the room after the end of the experimental sessions, did not change the lighting conditions (100 lx), and continued working under them, as they were not notified about it. It is noticeable that the way, and if instructions are given can affect user’s behaviour.

Finally, four people switched on the light during the first six minutes of the study, as mentioned in the results part. This finding shows that this kind of behaviour is not related to tiredness or need for better visual environment, but it is connected also to habit and preference.

4.2 Simulations

Using the results of the laboratory study as an input, was the real challenge in this project. The laboratory study however, was about cellular office conditions and not open-plan as they were simulated in the second part. This was the main reason that only horizontal illuminance and uniformity ratio were examined. Vertical or cylindrical values would not be representative as the space examined in the two parts had big differences.
The results concerning lighting simulations showed a degradation of uniformity with task light operation. As Figures 3.4 present, switching on the task lamp can lower the uniformity on the workstation by almost 50% while for the room area uniformity ratio is reduced, and eventually falls below the requirement levels. Moreover, in random 1 and 3 cases, it was shown that some of the workstations that did not have an operating task lamp, were affected by the operating task lamps, as their uniformity ratio showed. This shows a certain limitation of Uniformity as a metric when it comes to large open spaces, different lighting preferences and occupancy patterns.
As referred in literature, differences in illuminance in the laboratory of view can be very annoying (Escuyer and Fontoynont, 2001), however it was hard to represent this, due to software limitations that were explained earlier.
Concerning energy use, as it was expected, lowering the illuminance levels and combining it with task lamps resulted in a decrease in annual energy use. Daylight utilisation showed an even bigger reduction in energy use, although it was a rough estimation in this study. In scenario B, there was however the potential to have an even lower energy use. The objective of this scenario was to find a general lighting system to provide the horizontal level with 100 lx, which was difficult to be achieved. This is mainly because, luminaires that have a lower luminous flux, are mainly designed for different uses. Most of these luminaires' design is not suitable for office as it does not have, in most of the cases, a wide photometric distribution. This led to choosing a bigger number of luminaires and as a result a bigger lighting power density.
Due to the way Radiance, simulates electrical lighting by using IES files, the problem mentioned before could be bypassed by using the candela multiplier in order to create the preferable luminous environment. By using that, the power of the system would be proportionally lowered. However, this was not used as there are many things that affect energy use, and it was important to explore a realistic scenario and its limitations.
Daylight utilization is found to have a big impact in energy use reduction. The benefits are obvious in energy terms. However, even though the highly glazed facades, as a trend in non-residential architecture, reinforce this potential, shading design is more than crucial. In this project, there was a very rough estimation of shading control which however is not far from existing systems. A bigger impact in energy would be achieved with a potential daylight harvesting system combined with a more advanced shading control, always with respect to visual and thermal comfort.

5 Conclusions

The aim of this study was to explore individual lighting preferences through a laboratory study and examine the different lighting scenarios on a hypothetical open-plan office. Several conclusions were made from both the parts of this project.

- Reduction of illuminance levels in office buildings, is a goal that is both necessary and realistic. This in combination with a control strategy and daylight implementation can lower the energy use for lighting dramatically.
- Towards this strategy, software that can combine both climate-based daylight simulations and complex electrical lighting installations, is necessary to be developed.
- Uniformity cannot be representative, when it comes to big spaces with complex occupancy patterns and different lighting patterns.
- Preferred lighting conditions have to be explored further in order to lead to a general illuminance reduction.

Summary

Electrical lighting accounts for 14% of the total electrical energy use in the European Union. The need for energy use reduction has led to the development of complex control systems, and of the ambient-task strategy. Moreover, lighting design is dictated by requirements in order to maintain quality according to a specific task.

Literature suggests differences in preferred illuminance levels especially when it comes to computer-based tasks and more complex spaces, than the typical cellular office. Lighting design though is not stable to the designed conditions. Individual preferences change the lighting environment constantly.

The aim of this project was to explore the boundaries of existing requirements, both in terms of preference but also in terms of energy use. The project consists of two parts. The first part was a laboratory study concerning switch-on probability of a task lamp while working on a computer-based task while on the second part three different lighting scenarios were simulated in a hypothetical open-plan office. The first scenario consisted of a general system providing 500 lx. In the second scenario, the laboratory study conditions were recreated while the switch-on probability was fed as an input in order to examine illuminance levels and uniformity in three random located cases, finally, at the third scenario daylight was taken into account to explore energy use impact.

The laboratory study was held in a room in Campus Helsingborg, where 22 individuals were asked to perform a computer-based task for 30 minutes in low illuminance levels (100 lx). The result of this study showed that almost 60% of the participants chose to switch on the task lamp. This laboratory study contained also an interview part. After the end of each dandy all participants were asked three identical questions. The answers to the questions showed a relation with the switch-on probability logged, while more comments were written down as valuable. Lighting preferences was revealed as the subject participants were more eager to talk about.

The results of the simulations' part showed that switching on the task lamp in an open plan office affects the workstations that do not choose to switch it on, while the overall room area uniformity fails to stay above the required level. Concerning energy use reduction, the reduction of illuminance levels showed a 59 % reduction in energy use, which did not prove however to be proportional to the illuminance levels reductions. The scenario with the daylight consideration, showed an energy use reduction on 48 %.

Although there were many limitations, mainly in the laboratory study, the results showed that uniformity as a metric of quality is prone to human behaviour and is hard to be maintained in a complex lighting environment. Finally, illuminance levels reduction and utilization of daylight can lead to important energy use reduction.

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Appendix

Below is presented the procedure as followed, for the laboratory study.

Subject wait 5 minutes in the corridor.
Subject enter the room.
The general lighting is on and the task lighting is off.
The subject is requested to sit at the desk.

"Hello, please sit down there.
First of all, let me just inform you that the participation in this experiment is anonymous and voluntary. You can drop the experiment at any time and without need of explaining.
The duration of your participation is 30min, and some questions after that.
I just want to ask you some preliminary questions:
Do you have any visual defect? If so, please can you tell me which
And please can you state your sex and your age."

On a next step the subject receives information on the task provided.

"On the laptop in front of you there is a word file where you are supposed to read the text and check it for misspells and provide a correction.
During your task you are allowed to change lighting conditions only by using the desk lamp next to you, by turning it on but do not change its place.
The duration as I said is 30 minutes. I will interrupt you, when it is time.
Thank you"

The subject ends the experiment and keep sitting. The experimenter enters the room.
Here, some questions on lighting preferences follow.

- Do you usually prefer to work in darkness?
- Do you ever use task lighting?
- Do you usually actively turn on-off lighting?

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