Sensitivity analysis of important parameters affecting daylight

Assessment of a typical cellular office in Sweden

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Master thesis in Energy-efficient and Environmental Buildings

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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Keywords: daylight, office, dynamic metrics, static metrics, orientation, glazing transmittance, surface reflectance, window size, shape, position, number and niche, obstruction angle, sensitivity analysis

Thesis: EEBD - # / 2018

Abstract

The objective of this thesis was the impact evaluation of several parameters affecting daylight conditions in a typical cellular office in Lund, Sweden. The research approach that was followed consisted of three distinct steps; the literature review in order to specify the dependent and independent variables of the study, the simulation part to produce daylight performance data and the graphical analysis as interpretation of the data produced. The studied independent variables were: orientation, window shape, window size, window position, number of windows, glazing transmittance, window niche, reflectance of the surfaces and obstruction angle. To monitor their performance both dynamic and static indicators were used, generating both expected and unexpected results. Some parameters such as the obstruction angle and the window-to-wall ratio, WWR, showed significant influence on the results. On the other hand, the window niche proved not to have any quantitative impact on office daylighting for the studied room. Considering the number and the shape of windows, for WWRs up until 30 % the best performing cases corresponded to single and square windows. Finally, meaningful correlations between static metrics were found.

Acknowledgements

I am highly indebted to my supervisor Marie-Claude Dubois for her constant guidance and her expert advice, as well as providing an effective oversight on thesis procedure. I also wish to thank the co-supervisor Iason Bournas for his constructive feedback, authentic engagement and valuable support throughout this project.

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Nomenclature

DF	Daylight Factor (%)
U	Uniformity Ratio (-)
DA	Daylight Autonomy (%)
sDA	spatial Daylight Autonomy (%)
UDI	Useful Daylight Illuminance (%)
DGP	Daylight Glare Probability (-)

Abbreviations

BBR	Boverkets Byggregler
BREEAM	BRE (Building Research Establishment) Environmental Assessment method
CIE	Commission Internationale de l′ Éclairage
IESNA	Illuminating Engineering Society of North America
LEED	Leadership in Energy and Environmental Design
T_{vis}	Visual transmittance through glazing
WWR	Window-to-wall area ratio
ab	ambient bounces
ad	ambient divisions
as	ambient samples
ar	ambient resolution
aa	ambient accuracy
lw	limit weight
lr	limit reflection

1 Introduction

Several studies from the last decades have emphasized the significant benefits of daylighting for human health (Robbins, 1986, Tregenza and Wilson, 2011, Beute and de Kort, 2018). Daylight not only provides visual but also mental stimulation, which is significant for the regulation of the circadian rhythm. Daylight makes people feel better while its absence usually leads to illness, mood disorders, stress, and even seasonal affective disorder (SAD), which is a recognized form of depression.

On that account, it is argued that daylight must be present not only in private spaces but also in work environments. The majority of working hours take place during daytime and represent a significant portion of a person's daily life. Daylighting in working spaces is thus of high concern for humans.

Additionally, people who work in places exposed to daylight were observed to have better physical heath, as well as better mental health, well-being and higher productivity, compared to workers in windowless environments (Boubekri et al., 2014). The World Health Organization (WHO, 2018) indicated that mental health is a fundamental component of overall health that could be affected by stressful work conditions among other factors and that should be further promoted in the future.

From an economic point of view, it has been demonstrated that daylight integration strategies in commercial and institutional buildings could lead to energy savings of the order of one third of the total energy needs in buildings (Ander, 2016). This rather high potential energy saving includes both the direct reduction in electric lighting and cooling reduction.

1.1 Goal definition

The ultimate goal of this thesis is to provide information that could be used to develop a set of guidelines for architects concerning daylight conditions of working spaces aimed at the early design stage. The study explores important parameters of initial design that affect the daylight conditions of a generic normal rectangular office room. It assesses the impact of design parameters on daylighting indoors, as expressed by known daylight metrics.

1.2 Background

As highlighted previously, daylight admission in a building is of high importance and especially in places where it is scarce or less abundant due to overcast sky conditions or high latitude. In Scandinavian countries like Sweden, there are regulations and recommendations in the building code for daylight admission when constructing and/or renovating buildings. Furthermore, environmental certification systems like Miljöbyggnad, BREEAM, LEED grant extra credits when demonstration of sufficient daylight levels is provided.

More specifically in the building profession, there is currently a high interest regarding the optimum geometric characteristics of spaces to promote good daylighting. The indicators that quantify this daylight admission are also of concern as part of ongoing scientific research internationally.

1.3 Scope and limitations

This thesis is limited to daylight assessment of a cellular side-lit office space. The energy performance of different cases is not assessed. Nevertheless, some comments concerning the energy impact are made in a qualitative way based on basic principles of energy-efficient design.

Following, a more realistic approach would require frame thickness calculation for each case scenario according to window size and shape but, for simplicity purposes, the frame thickness was considered constant throughout the study.

In locations dominated by overcast sky conditions, skylights are known to provide excellent performance but the possibility of a cell office to be daylit through skylights is quite low, so this option was not considered in the present study.

Finally, no shading devices were tested and no visual comfort in terms of viewpoint evaluation (luminance calculation) was assessed. All simulations were carried out for illuminance levels.

1.4 Research methods

The methods that were used in this study are listed below:

- Literature review to situate the thesis topic in the broader academic field and identify variables of interest for the simulations.
- Simulations to produce daylight performance data.
- Graphical analysis to assess performance and parameter correlations.

Firstly, the literature review was considered essential in order to specify the important parameters that should be included in the study, including their options or numerical range. Secondly, the simulations are at the heart of this thesis, where an extensive parametric study was performed with variable geometry and optical properties. Finally, the graphical analysis is provided with the aim to discover meaningful trends and correlations in the resulting dataset.

2 Literature review

The following literature review is divided into two parts: The first part reviews research background regarding independent variables affecting daylight levels in side-lit offices. The variables included orientation, glass transmittance, window position, window shape, window size, number of windows, surface reflectances, window niche, and obstruction angle. The second part describes the dependent variables chosen for this study. These are the daylight performance metrics used to quantify daylight availability.

2.1 Review of independent variables

These variables were the ones that were studied in the parametric simulations, as described further down, in the "Methodology" section. The effect of each parameter is described here shortly, according to previous research.

2.1.1 Orientation

Orientation is the arrangement or directionality of a façade or other element with regard to the azimuth angle. The optimum orientation is thus related to the building use, the geographical area and the climate.

Orientation studies have mostly been associated with shading strategies. It has been widely argued that placing windows on north and south orientations is the most efficient in terms of daylight control. The former due to constant ambient light provision, while the latter is the most desirable orientation due to light abundance and easy shade control. The northern exposure is then the one to be optimized and southern exposure to be maximized, if daylight is the main objective. It has been demonstrated that façade tilts up to 30° towards east or west have small daylight performance deviations (Enermodal Engineering, 2002).

Daylight from east and west orientations is difficult to control. For a satisfactory shading system the exact element angle that blocks direct solar radiation, the effective solar altitude, should be examined: "*The effective solar altitude against the window must be calculated and not just the solar altitude*", as Bülow-Hübe indicated (Bülow-Hübe, 2007). It was venetian blinds that were assessed in that study and thus it was possible to define more than one position of the system in order to correspond to the varying sun positions during day and season. The study conducted with measurements in a laboratory of Energy and Building Design of LTH located in Lund followed by simulations using Radiance and ParaSol and was oriented towards indoor climate improvement and energy need reduction in office buildings. It was shown that towards east for all studied periods, the effective solar altitude reached 90° which meant a time with fully closed slats so that for preventing the direct sun-light, the diffuse daylight and view also had to be blocked. West oriented windows can be claimed to have the same outcomes but reversed during the day. In a recent climate-based daylight study of a residential living room occupied between 18:00 and 22:00, it was shown that a west orientation could achieve a higher daylight autonomy (Bournas and Haav, 2016). For an occupancy schedule centered at 12:00, the differences between east and west orientations are lower, as both east and west provide half-day sunlight exposure during the day. Consequently, the occupancy of a space can determine the suitable orientation for a specific use.

In terms of energy use, east and west orientations differ and especially the west is the one to be avoided because of the accumulated heat gains through the day that yield cooling system operation to assure thermal comfort. This is especially true in buildings with high internal gains. Atzeri et al. (2013) analyzed the impact of shading systems on the energy need as well as visual and thermal comfort in an open-space office in Rome, Italy, for different window properties (Atzeri et al., 2013). The energy need was simulated using EnergyPlus 7.1 software. The outcome was that east-facing windows and the combination of east and west-facing windows had the highest cooling need, regardless of window size, glazing properties or the shading device used.

2.1.2 Glass transmittance [%]

Visible light transmittance is the fraction of transmitted light through the glazing parts and consists of an important aspect of windows. The higher this value, the more daylight can penetrate in the interior area.

The range of this value can be from 90 % which corresponds to single-pane clear glass to 5 % for a highly reflective glass. Most windows, especially in cold climates, are double or triple pane assemblies covered with coatings and have gasses such as argon or krypton between panes to allow the transmission of visible wavelengths while avoiding near infrared heat gains. More panes, mean smaller visual transmittance (Bülow-Hübe, 2001). A few years before, Wegener (1997), as a Glass Technologies Division member, had already witnessed that coated glazing was extensively produced, since before 90s. At that period, he foresaw that a time would come when every piece of glass for commercial buildings and the majority of those destined for residential use would contain some form of coating (Wegener, 1997). Coating, similar to the number of panes, generally reduces light transmission.

Robinson and Selkowitz prepared an updated guide that referred primarily to office-like occupancy buildings towards an integrated approach to economic design of new commercial buildings or existing building refurbishments (O'Conner et al., 1997). In this guide, it was recommended to use visual transmittance of 30 %, 50 % and 70 % for large, medium and small windows, respectively, while encouraging the selection of spectrally selective glazing for glare control. These values, as they identified, only consisted of starting point information. For each individual case, visual tasks, glare sensitivity, window size and other parameters should also be considered.

2.1.3 Window position

Window position is the vertical and horizontal placement of the glazing part on the exterior wall of the room.

The window position affects the room illumination and daylight distribution tremendously. It has been shown that high window positions assure deeper daylight penetration into the room (Reinhart, 2014). By placing a window in the lower part of the façade, less daylight can penetrate deeper, while energy losses due to lighting increase. M. J. Bokel (2007) documented this in an office-room study while analyzing the impact of sunlight and daylight penetration on the annual energy demand as a function of window position and other window characteristics. In his study, the reference office room was located in northern Netherlands and the method followed was simulations via Daysim.

Moreover, placing the window in the lower part of the façade means that if no part of it is above the workstation height, the reflected daylight would be completely prevented from reaching the task area as the desk would act like an obstruction.

A centered position, located at the eye level, is also valuable as it yields the view-out and thus a connection with the surroundings, the time of the day and the weather conditions. A study Vartiainen et al. (2000) analyzed the impact of window position as well as other window properties of a multifunctional solar façade on daylight availability at four latitudes. The analysis was performed considering a typical office room in Helsinki, used to verify the daylight model. Following that, the rest of the methodology lied on simulations made by DeLight simulation tool. In that analysis, it was demonstrated that the vertical position of a window (window placement along the y axis) had substantial impact on daylight availability, greater than the choice of horizontal position (window placement along x axis). Optimum vertical position was shown to depend on orientation. The study concluded that the parameter of window position on the vertical axis is more important than the window shape. In terms of the horizontal position, the center of the façade was the optimum.

2.1.4 Window shape

The particular physical form of the window is a parameter that mainly affects the distribution of daylight into the room. The window shape for a simple room geometry located in Helsinki, Finland and Trapani, Sicily, and for all orientations was studied by Vartiainen et al. (2000). That study, using the daylight simulation tool DeLight, concluded on horizontal windows for higher daylight availability while occasionally the difference from the square shaped was almost negligible. The research showed that in Helsinki, the optimal length-to-width ratio for a 15 % WWR window was 2,5 for northern while 1,5 for the other orientations. Finally, it was pointed out that as the window area was increased, the difference between the various shapes was weakened.

15 years later, Acosta et al. (2015) explored, among other fenestration properties, the impact of window shape by altering the length-to-width ratio of the window under overcast sky conditions so that location or climate determination did not intervene in the results (Acosta et al., 2015). The building or room use was not defined either. In this study, it was stated that square windows have slightly better daylight performance than horizontal ones, while the vertical windows were the worst in terms of daylight performance. Eventually, the horizontal windows presented higher energy savings for electrical lighting.

2.1.5 Window-to-wall ratio (WWR [%])

Window-to-wall ratio, WWR, is defined as the window area in relation to the total façade area, expressed in percentage, and is the indicator of the relative window size. A window can be characterized for its size mainly in relation to the corresponding façade, as humans tend to perceive space in a relative way.

In terms of energy need, the WWR should be restricted in area and designers must aim to the lowest values that still provide adequate room illumination to promote energy efficient buildings and reach passive house standards. Flodberg et al. (2012) underlined the necessity for reasonable WWR as the cooling demand increases dramatically with window size (Flodberg et al., 2012). A year later, Dubois and Flodberg (2013) conducted a research on the impact of Glazing-to-Wall ratio, among other parameters, on the daylight utilization for office spaces located in the perimeter of office buildings at high latitudes. The research was carried out using DAYSIM 3.1b and the optimal WWR was found to be 20 % - 40 % depending on façade orientation (Dubois and Flodberg, 2013).

In the same time period, Goia et al. (2013) demonstrated that the optimal WWR for low energy office buildings, regardless of orientation, lies within the range of 35 % - 40 % considering the energy need in terms of heating cooling and lighting (Goia et al., 2013). The investigation was carried out under temperate maritime climate conditions and it was based on simulations using EnergyPlus software. This study also stated that for the specific climate, the actual WWR plays no role when window location and shading are configured using advanced technology (i.e. taking advantage of glazing properties, low emissivity coatings and integrated external solar shading system).

More recently, a survey conducted on employee's preferences on window size in an individual office proved that large windows of WWR about 40 % was the preferred size for users and that satisfaction decreases with smaller window sizes (Guidolin, 2014). The experiment took place in a daylight laboratory located on the roof of Fraunhofer Institute for Solar Energy Systems in Germany, Fraunhofer ISE. A rotating mechanism made it possible to assess different orientations and the evaluation conducted on the data process of a questionnaire filled by 25 subjects.

However, post-modern architecture has promoted highly or even fully glazed buildings. This trend not only yields higher energy use, but it also creates visual problems to pedestrians and adjacent buildings and leads to increased cooling demand and dissatisfaction from users (Motuzienė, 2017).

2.1.6 Number of windows

The number of windows plays an important role in daylight distribution. The same WWR divided among more openings can increase the uniformity of illumination. At the same time, though, a close placement of windows in the same façade could create lighting contrast issues between the windows and the intermediate wall parts.

In the survey of Fraunhofer ISE described above (see WWR sub-section), the number of windows was one of the studied parameters (Guidolin, 2014). This study indicated that for a high WWR, the satisfaction of subjects seemed to increase when the number of windows was increased to two and three windows, while for medium and small WWR it was preferable when there was only one window. In the same paper, the origin of these preferences was questioned and it was argued that also the placement of the divided windows in horizontal arrangement could have affected the results similarly.

Two years later, Bournas and Haav (2016), in a multi-objective study of façade arrangement in residential spaces, demonstrated that for a studied living room of a west apartment located in Malmö, when daylight and energy needs were concerned, the optimal solutions were found using two to three windows (Bournas and Haav, 2016). This study did not assume equal WWRs when increasing the window number. According to their results, increasing the amount of windows was only beneficial until a certain number (in their case three windows). More windows induced less daylight gains compared to the consequent heating losses. The simulation software used were: Radiance, Daysim and EnergyPlus.

2.1.7 Surface reflectances

Reflectance of a material is the ability to reflect the luminous energy incident on its surface and is expressed as the ratio between the luminous reflected energy to the initial radiant energy. Thus the maximum reflectance value is one when there are no losses due to absorbed or transmitted light.

Depending on the spread of the incident light after it is reflected it will have specular, diffuse or, as most commonly, a combination of these two types of reflection. A perfectly specular surface is when the angles of incident and reflected beam to the surface are equal and opposite, and the light has the same intensity, as in a mirror. A perfectly diffuse, Lambertian surface reflects light towards all directions evenly, regardless of the angle of incidence, with no specular reflection. This is the typical reflection of plastered wall (TSLL and NPL, 2001). The reflectance properties of a surface are determined by the structure and colour of the material. White reflects the same proportion at all wavelengths while if coloured, the surface has a reflectance profile that varies according to wavelength.

When it comes to buildings, white is the colour that is typically proposed for interior surfaces. The interior surfaces' reflectance have impact on daylight performance as reflective surfaces can help daylight propagate deeper in a room. Additionally, the standard 'selection' of the surfaces should be matte or eggshell, meaning diffuse, for better distribution and glare problems avoidance.

Hagenlocher (2009) identified that areas surrounded with high reflective surfaces tend to have more light uniformity between the window and the interior space which leads to a better visual comfort. In this study, three experiments were conducted with colour games and room models on people's perception of space colour and reflectivity. The research concluded that people and designers overestimate colours and get confused over their light reflectivity and that colourfulness does not necessarily correspond to dark colours. Another conclusion was that a common room could appear very colourful if one wall was coloured even though it hardly changed the average reflectivity of the room (Hagenlocher, 2009). Moreover, as pointed out in National Physical Laboratory's, NRL's, Lighting Guide the designer should consider, apart from generic surfaces reflectance, the effect of possible accumulated dust or dirt that could decrease the reflectance of a surface and users should be encouraged to a regular surface maintenance (TSLL and NPL, 2001).

A more recent study on surface reflectances was carried out by Mohelnikova and Hirs (2016), who investigated the impact of reflectances on daylight performance in residential buildings. The study was conducted with simulations via Velux Daylight Visualizer software and the selected building was located in Prague. The first part of that study concerning ground reflectance proved that it is of high importance for the indoor illuminance. The second part of the study examined the impact of internal surfaces reflectance, which were proved very important parameter as the daylit area in the room increased significantly. However, it was noted that the effect of internal surfaces reflectance on daylight illuminance/ reflected light contributing to indoor illuminance was greatly dependent on the window size and the sky conditions (Mohelnikova and Hirs, 2016).

The European Standard defines ranges of: 70 % - 90 % for ceiling, 50 % - 80 % for walls and 20 % - 40 % for the floor (SS-EN12464-1, 2011). Worth mentioning is that Neufert design guide recommends reflectances of 70 %, 60 % and 20 % for ceiling, walls and floor respectively (Neufert, 2000). Regarding surrounding surfaces, a study indicated that an average reflectance of existing façades is 44 % (Leder et al., 2007). The study was conducted with measurements in Florianópolis city, Brazil. While referring to this study, Reinhart defined this value (44 %) as typical diffuse reflectance façade corresponding to a brick wall with moderate WWR, and called attention not only to ground but also to surrounding façades reflectances when simulating (Reinhart, 2011). On the other hand, the Illuminating Engineering Society, IES, recommends to assume 30 % reflectance for surrounding vertical surfaces if the reflectances are unknown (IES_LM-83-12, 2012).

2.1.8 Window niche

The window niche is the peripheral lining around the window. Earlier research has shown that splayed wall edges around the window can reduce the probability of glare and create a more comfortable light transition for the human eye (Enermodal Engineering, 2002, Lechner, 2015). In the past, several thick constructions like castles and churches had splayed walls to ensure better daylight conditions, but during the 20th century, wall constructions have generally been reduced due to light-frame constructions. Nevertheless, this reduced wall thickness is currently changing towards thicker wall as passive and net-zero buildings require thick insulation layers.

Szczepanska-Rosiak and Heim (2015) studied the impact of wall thickness, among other variables, on daylight conditions in offices with climate-based metrics. The studied building was located in a temperate climate and simulated using Daysim software. The examined thicknesses were 25 cm and 50 cm and the conclusion was that the effect of wall thickness is noticeable depending on the different window arrangements (Szczepańska-Rosiak and Heim, 2015).

The effect of window niche has not yet been investigated thoroughly and is identified as a subject which needs further research.

2.1.9 Obstruction angle

The obstruction angle is defined in the Swedish standard (SS 91 42 01). It is the angle between the horizontal line from the center of the window to the opposite building, and the line between the center of the window and the highest building point. Thus, the smaller the obstruction angle, the more daylight penetration into a room.

The surroundings substantially affect the daylight conditions of a room. Obstacles can be vegetation and surrounding buildings. Their distance from the window and their reflectivity affects daylighting onto the façade. An analysis on the effect of urban context on solar and daylight availability proposed the proportion of visible sky as a parameter that could be associated to urban regulation for ensuring daylight availability instead of distances that were not always clear (Leder et al., 2006). The study was conducted in a city in Brazil and carried out with simulations run in Apolux software in 2006. For that place 30 % of visible sky proved to correspond to poor illuminance levels and less than two sunshine hours in winter.

The next year, another study investigated the effect of shading on energy and daylight, for a generic office building in urban context. The study was conducted for Hong Kong using EnergyPlus (Li and Wong, 2007). The authors highlighted that as one of the most important financial centers globally, there are numerous commercial skyscrapers in several business districts, most of them between twenty and forty floors, which lead many buildings to suffer from the shading effect from such surrounding developments. The study showed that the surrounding obstructions have a remarkable effect on the annual electricity need and more specifically: when the whole building was concerned, the electricity savings had an exponential relation with the angle between the façade of the reference building with the highest obstruction point. When that angle was at about 90° or more, the energy saving was almost negligible. What was interesting was that for an individual floor, the correlation between the obstruction angle and the electricity savings was logarithmic growth indicating the 30° as the critical angle for daylight availability. After that point, energy savings reduced but after 70° they became almost stable i.e. independent of obstruction angle.
Finally, it should be pointed out that this parameter applies not only to architects but also to urban planners as a valuable tool in an early stage of spatial configurations and building typologies having impact not merely on daylight availability but also on urban ventilation, thermal comfort, building form relationship, urban climate and acoustic environment (Zhang et al., 2012). In real case studies, without uniformity in surrounding heights, assessment considering the 'obstruction factor' approach is considered more suitable. When calculating the losses from shading, this approach takes into consideration the percentage of the view obstruction of the whole window from a typical task position instead of a single point (Reinhart and LoVerso, 2010, Robinson and Selkowitz, 2013).

2.2 Review of dependent variables

Daylight simulation results are usually calculated values of either illuminance (grid-based studies) or luminance (image-based studies). Post-processing these values leads to the definition of different performance metrics, which are used to evaluate the daylight performance of a given space. Following are the metrics that were investigated.

2.2.1 Diffuse illuminance metrics

Initially, diffuse illuminance metrics were assessed as they were widely used in most standards and regulations. What was their advantage (easy to assess) and at the same time their disadvantage (incomplete) was that these measures were assessed under Commission Internationale de l′ Éclairage, CIE, overcast sky which implied that they were insensitive to orientation, climate and location. Due to these limitations, they are most usually referred to as static metrics. Sweden has a high percentage of overcast sky while the clear sky is scarce. Figure 1 illustrates the high annual percentage of overcast days in Lund based on 30-year retrieved data (Meteoblue, 2018).

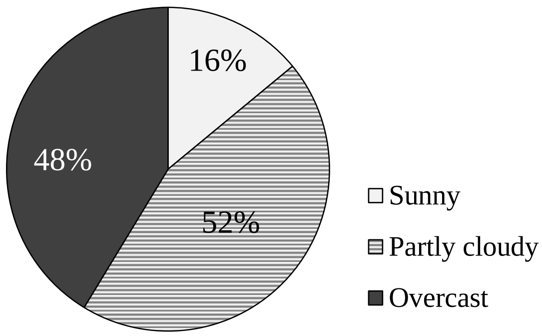

Figure 1. Annual percentage of overcast, partly cloudy and sunny days in Lund, Sweden.

Average Daylight Factor, DF_{avg}: It is the ratio of the daylight illuminance on a given surface to the simultaneous illuminance under an unobstructed CIE Standard Overcast Sky. As a ratio it is expressed in percentage and usually considered a better indicator than a single point measurement (Tregenza and Wilson, 2011). It represents the sum of (diffuse) direct sky, external and internal illuminance reflections.

The daylight factor is the dominant evaluation metric for more than 60 years now because of its inherent simplicity rather than its realism (Nabil and Mardaljevic, 2005). Reinhart et al. (2006) pointed out that practically, the advantage of DF is the intuitive predictions and easy to communicate within a design team. Following in the same document, the disadvantages of not including occupancy schedule, climate and orientation and no provision of “warning flag” for possible glare problems were emphasized (Reinhart et al., 2006). It could be summarized as: *“...the daylight factor method serves as a worst-case scenario of the annual daylight availability, since direct sunlight is discarded”* according to Reinhart and Herkel (2000).

Tregenza and Wilson (2011) indicated that the range between 2 % and 5 % provides good daylight conditions, while lower values correspond to gloomy spaces and higher values create visual and thermal discomfort. Note that a room with DF_{avg} of 2 % could involve underlit areas and a space with DF_{avg} of 5 % glare issues so the value itself does not always correspond to high daylight quality.

BREEAM certification system uses DF_{avg} as daylight indicator. Depending on the building function, the latitude and the certification level pursued, DF_{avg} should be equal or higher than different thresholds ranging from 1,3 % to 3,2 % (BREEAM, 2016). For Sweden, the threshold lies in the range of 1,6 % to 3,2 %, depending on the aforementioned parameters (BREEAM-SE, 2017). For instance, the threshold for an office in southern Sweden corresponds to 2,1 % DF.

Daylight Factor point, DF_p: It is the ratio of the daylight illuminance at a specific point inside a room to the simultaneous global illuminance under an unobstructed CIE Standard Overcast Sky, expressed as a percentage.

In Swedish building regulations, BBR, the DF_p is measured at a point located one meter from the darkest wall (perpendicularly), halfway along the room's depth and at the working plane level (0,80 m above floor) (Boverket, 2016). The value required by the BBR is DF_p > 1%. The certification system Miljöbyggnad attributes daylight credits when DF_p is higher than 1,0 % - 1,2 % - 1,5 % (according to certification level bronze - silver - gold) (Miljöbyggnad, 2017). In BREEAM this metric is an alternative and should be higher than thresholds ranging from 0,48 % to 2,24 % (depending on site latitude, existence of glazed roof, number of building floors and the pursued credits) (BREEAM-SE, 2017).

DF_p could not be characterized as representative of the space as it provides no information on illuminance distribution but for a single point. This metric has been used for historical reasons rather than logic since it is easier to calculate DF on a grid with the software available today.

Median Daylight Factor, DF_{median}: The median value of the daylight factor of all points defined by a grid of points. Together with DF_{avg}, it could possibly provide a level of understanding of the illuminance distribution in the room. As the definition indicates, half of the points lay below a given DF_{median} and half would lay higher. It is considered a more stable and descriptive metric than DF_p. According to Christoffersen and Mardaljevic (2017), for side-lit spaces DF_{median} always corresponds to lower values than the DF_{avg} and is more accurate than the DF_{avg}. They showed results for two rooms of the same glazing area, one side-lit and one illuminated from two aspects; the first case had a higher DF_{avg} while the second case, which provided better DF spatial distribution, had a higher DF_{median} (Mardaljevic and Christoffersen, 2017).

Uniformity ratio, U: The ratio of the minimum to the average illuminance of all points of a defined grid. It is a unit-less metric that ranges from zero to one. This metric refers more to light quality rather than light quantity and is usually used as an electrical lighting indicator as well.

For a side-lit room, uniformity decreases when the room depth increases. The deepest area would become more underlit and thus the illuminance values would have a wide range. In BREEAM uniformity is recommended to be minimum 0,3 (BREEAM, 2016, BREEAM-SE, 2017) but very high levels of uniformity could lead to monotonous spaces. In Swedish standard for lighting in work places, uniformity is recommenced to be minimum 0,4 (SS-EN12464-1, 2011). Dubois and Angeraini recommended a uniformity of 0,4 for spaces occupied more than occasionally and 0,6 for transitory spaces like circulation areas (Dubois and Angeraini, 2017).

2.2.2 Climate-based metrics

These indicators are referred to as dynamic metrics. They consider the actual sun path for a given location, making them aware of site latitude, orientation and time. The methodological comparison between static and dynamic metrics is currently a subject of ongoing scientific research internationally and part of a lively debate. Below are the selected dynamic metrics along with their specifications.

Daylight autonomy, DA: Reinhart and Walkenhorst (2001) defined DA as the time interval throughout the year when the daylight illuminance is above a specified threshold. DA could act likewise as an electrical demand indicator as it expresses the time that electrical lighting can be avoided (Reinhart and Walkenhorst, 2001). The DA is the first and most widely used climate based daylight metric that took into account not merely the climate and orientation but also the occupancy since a schedule needs to be defined.
The basis for a dynamic simulation concept was set in 1983 when Tregenza and Waters introduced the daylight coefficients by dividing the sky dome into 145 circular patches (Tregenza and M. Waters, 1983). A decade later, in 1993, the Perez sky model, providing patterns gathered from real data for all sky conditions, was also established (Perez et al., 1993). The first step to DA approach was made in 2000 when Reinhart and Herkel proposed a new/improved sky division for the daylight coefficients where the whole celestial hemisphere was included and three ground coefficients were also proposed (Reinhart and Herkel, 2000). It was validated one year later and DAYSIM, which is the first climate based simulation tool based on daylight coefficients and Perez sky models, was established by Reinhart and Walkenhorst (2001).

The European Standards set the illuminance threshold to 500 lux for writing and reading tasks for offices while 300 lux for computer practice rooms for educational spaces (SS-EN12464-1, 2011). However, the office tasks tend to be more and more computer based but there is not such category in that standard that combines these tasks and activity. Two decades ago, a survey conducted on more than one and a half thousand office employees in Denmark proved that more than 55 % of their time was computer-based work, with consistency exceeding the nine out of ten subjects (Christoffersen et al., 1999). Nowadays, this percentage would be far increased due to technology development.

IESNA committee set the task illuminance threshold for work spaces at 300 lux based on recommendations and standards but marked that in some cases another threshold might be appropriate (IES_LM-83-12, 2012). Reinhart (2014) marked that usually the threshold for offices and classrooms corresponds to 300 lux when the main illuminance source is daylight and 500 lux for electrical light, due to better luminous efficacy and colour rendering of the former light source.

Spatial Daylight Autonomy, sDA: Spatial daylight autonomy (sDA) is the percentage of an analysis area with a daylight illuminance above a specified threshold for a defined occupancy schedule per year (IES_LM-83-12, 2012). In the same standard of 2012, it was also described as the annual sufficiency description of ambient illuminance by daylight in interior spaces. A level recommendation on sDA was the ‘preferred’ and the ‘nominally accepted’ which corresponded to values that meet or exceed 75 % and 55 % respectively. The threshold of 300 lux, and the analysis period from 8.00 to 18.00 was recommended together with this metric declaration. The metric is therefore expressed as $sDA_{300/50\%}$, meaning that 300 lux must be provided by daylight alone 50% of the occupancy time, for 55 % of the space (‘nominally accepted’) or 75 % of the space (‘preferred’).

Useful Daylight illuminance, UDI: Mardaljevic and Nabil (2005) introduced the metric useful daylight illuminance (UDI) to narrow the DA down to a range that does not include neither low nor high illuminance values that are visually unbeneficial. The range between 100 lux and 2000 lux was defined as useful. The useful range together with the lower and the higher bin can also provide a comprehensible illustration of daylight availability zoning in space. Unlike the DA, the UDI metric can include daylight illuminances that do not meet a specified threshold but still contribute to lower electrical lighting use. A year later, a study based on past research on occupant behavior and preferences proposed four categories for UDI (Nabil and Mardaljevic, 2006) as presented in Table 1.

Table 1. The four initial UDI categories, proposed by Nabil and Mardaljevic in 2006.

Daylight illuminance	Comment	Useful range
100 lux < x	Insufficient	-
100 lux < x < 500 lux	Effective	√
500 lux < x < 2000 lux	Desirable or Tolerable	√
x > 2000 lux	Causing visual and/or thermal discomfort	-

In a later publication, Mardajevic et al. (2012) proposed a shift in the intermediate thresholds from 300 lux to 100 lux and from 2.000 to 3.000. The former shift was based on usual tolerance of people in lower illuminance levels when it comes for daylight and not for electrical light sources. The latter shift was based on surveys implemented in office buildings (Mardaljevic et al., 2012). Table 2 shows the four updated UDI categories.

Table 2. The four updated UDI categories, proposed by Mardaljevic et al. in 2012.

Daylight illuminance	Comment	Useful range
100 lux < x	Insufficient	-
100 lux < x < 300 lux	Effective	√
300 lux < x < 3000 lux	Desirable or Tolerable	√
x > 3000 lux	Causing visual and/or thermal discomfort	-

Daylight Glare Probability, DGP: DGP was first devised in 2006. It is the probability, expressed in percentage, that occupants of an office space would experience discomfort glare due to daylight (Wienold and Christoffersen, 2006). This metric takes into consideration: the vertical eye illuminance E_v (lux), the source luminance L_s (cd/m^2), the angle of the source ω_s and the index position P (the impact of the angular displacement of the glare source from the field of view. Equation (1) provides the corresponding formula.

$$DGP = 5.87 \cdot 10^{-5} \cdot E_v + 9.18 \cdot 10^{-2} \cdot \log\left(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1.87} \cdot P_i^2}\right) + 0.16 \qquad (1)$$

where:
E_v: Vercical illuminance at eye level (lux);
$L_{s,i}$: Luminance of the glare source (cd/m^2);
$\omega_{s,i}$: Angular size of the glare source (perceived at the eye position, sr);
P_i: Guth's position index for the glare source.
The minimal DGP which may be obtained with this formula is 0,16 (16 % probability of glare) but DGP values below 20 % should be interpreted as situations where glare is not important.

Glare can occur because of high view brightness, high visual contrast in the view field or poor glare-sources positioning. Before DGP, which combines source luminance and view field illuminance, most glare indicators were luminance based. In 2009, Wienold also proposed a simplified DGP called 'DGPs', based only on illuminance levels, E_v (lux). This metric could be applied only when there was no direct light penetrating in the view field of the observer i.e. neither direct sun beam nor specular reflection of it, (Wienold, 2009). The formula for DGPs is provided in Equation (2).

$$DGPs = 6.22 \cdot 10^{-5} \cdot E_v + 0.184 \qquad (2)$$

where:
E_v: Vercical illuminance at eye level (lux)

Finally, Table 3, shows the interpretation that was suggested and is currently used for defining DGP according to Wienold (2009).

Table 3. The interpretation table for DGP.

DGP limit (95 % of office time)	average DGP limit (5 % band)	Daylight glare comfort class	Glare rating
≤ 0.35	0.38	A (best)	Imperceptible
≤ 0.40	0.42	B (good)	Perceptible
≤ 0.45	0.53	C (reasonable)	Disturbing
> 0.60	-	-	Intolerable

2.3 Summary

The literature review provides background information on daylight design and evaluation principles. It was used to connect research findings with the materials and methods implemented in this thesis. It also provides useful knowledge to the reader, regarding current daylight regulations and guidelines, the previously investigated parameters and the ongoing debate on the suitability between static and dynamic daylight metrics.
The following conclusions summarize the information deducted from the studied research articles:

- The vast majority of the studied papers focused on offices.
- About three out of four articles conducted research on cold climates.

- The parameter that was mostly researched was the WWR followed by orientation which was included in almost half of the publications, as presented in Figure 2. On the contrary, quantified research results considering niche geometry was not found in any publication. There was one publication that investigated the impact of wall thickness but without considering different inclinations on the window niche.
- Among the studied publications, 85 % included dynamic metrics while 40 % included static metrics. This is attributed to the publishing dates that range mainly from 2000 onwards, when climate based analysis techniques became more available, as stated previously.
- More specifically on metrics, the most commonly used were the illuminance (E) and Daylight Autonomy DA which were used in nearly half of studies. As shown in Figure 3, the DF_{avg} was used in about 35 % of the studies, making it the most widely used static metric.

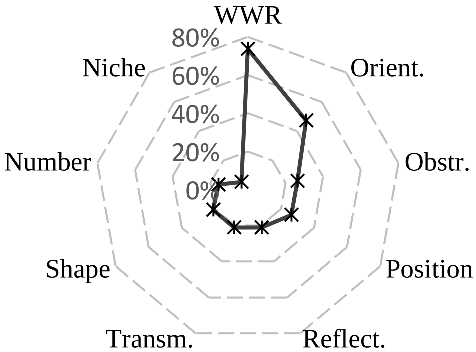

Figure 2. Representation of the percentage of literature that included research on the different independent variables.

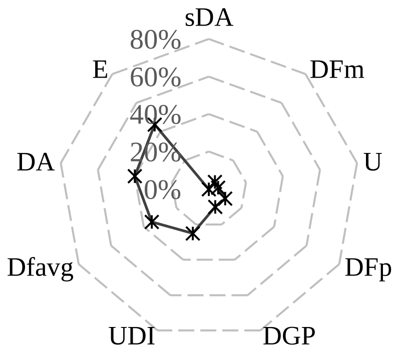

Figure 3. Representation of the percentage of literature that included research on the different dependent variables.

- Concerning the method that was followed 22 papers included simulations, 10 measurements and only 6 subjective evaluations like questionnaires.
- Half of the studies that used simulation method were conducted using Radiance and/or Daysim, one fourth using another daylight assessment software while the rest were about the energy savings or other simulation aspects.
- Half of the scientific articles were published after 2007, and most of them in the decade between 2006 and 2016, as Figure 4 shows.

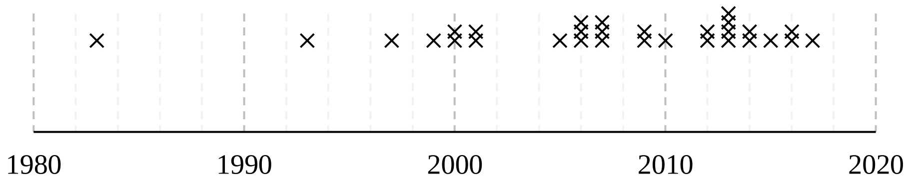

Figure 4. The allocation of literature based on the year of publication.

Finally, Table 4 summarizes the main scientific articles that were used for this review.

Table 4. Comments on main scientific articles that were used for the literature review of this thesis. Information on studied parameters, metrics and climates of the studied articles are also included.

no	Authors	Year	Parameters: Orient.	Trans	Reflect.	Obstr.	WWR	Position	Shape	Numb.	Niche	Metrics: DFp	DFm	DFavg	U	E	DA	sDA	UDI	DGP	Office spaces
1	Tregenza & Waters	1983														●					-
2	Perez et al.	1993								●											-
3	Christoffersen et al.	1999	●			●	●							●		●					●
4	Reinhart &Herkel	2000												●		●					●
5	Vartiainen et al.	2000	●				●	●	●								●				●
6	Bülow-Hübe	2001	●	●			●														●
7	Reinhart &Walkenhorst	2001														●					●
8	Nabil &Mardaljevic	2005														●			●		-
9	Leder et al.	2006				●										●					-
10	Reinhart et al.	2006												●			●		●		●
11	Wienold &Christoffersen	2006																		●	●
12	Bokel	2007					●	●													●

13	Bülow-Hübe	2007														●					●
14	Li &Wong	2007				●															●
15	Hagenlocher	2009			●																-
16	Wienold	2009																		●	●
17	Reinhart &LoVerso	2010		●		●	●						●	●							●
18	Flodberg et al.	2012	●				●														●
19	Ji Zhang et al.	2012				●															-
20	Atzeri et al.	2013	●	●			●			●											●
21	Dubois &Flodberg	2013	●	●	●		●										●				●
22	Goia et al.	2013	●				●										●		●		●
23	Acost et al.	2014			●		●	●	●			●									-
24	Magistrale	2014					●			●						●	●				●
25	Szczepanska-Rosiak & Heim	2015					●	●	●		●			●			●		●		●
26	Bournas &Haav	2016	●				●	●	●	●		●		●	●		●		●		
27	Mohelnikova &Hirs	2016			●		●									●	●				
28	Motuzienė	2017	●																		●

no	Measurm.	Simulation Program	Comments	Location	Cold climate
1		-	Daylight coefficient introduction	-	-
2		-	Perez sky distribution	-	-
3	●	-	Field survey, subjective visual&thermal	Danemark	√
4		Radiance	Daysim "basis"	Freiburg (Germany)	√
5	●	DeLight	Latitudes, office reference, also electricity	Sicily, Paris, Helsinki, Sodankyla	√
6	●	ENORM, Derob-LTH	Heating, cooling, lighting savings	Sweden	√
7	●	Daysim	-	Freiburg (Germany)	√
8		-	UDI "establishment"	-	-
9		(Apolux)	Daylight avail. in urban environment, sky factor, façade	Brazil	x
10		Radiance	Investigation of façade alternatives	Arcata (California), Boulder (Colorando)	√
11	●	EvalGlare	Plus subjective (questionnaire)	Freiburg (Germany), Copenhagen (Dnmk)	√
12		Daysim	Lighting, Heating&Cooling Energy-Daylight availability	Netherlands	√
13	●	Radiance, ParaSol	Shading, Electricity use, Luminance, glare comments	Lund (Sweden)	√
14		EnergyPlus	Shading effects due to obstruction, lighting need	Hong Kong	x

15	●	-	Subjective evaluation	-	-
16	●	Daysim	Plus subjective (questionnaire), laboratory in Freidburg	Brussels (Belgium)	x
17		Radiance		-	-
18		IDA ICE	Energy savings, heating cooling lighting	Stockholm (Sweden)	√
19		(Houdini)	Urban block typology and Sky exposure factor	Amsterdam, Barcelona, Paris	√
20		EnergyPlus 7.1	Shading systems, Heating and Cooling	Rome (Italy)	x
21		Daysim	Plus venetian blinds, Dimming	High latitudes: (Malmö, Stockholm)	√
22		EnergyPlus	EnergyPlus for energy & daylight	Temperate oceanic climate	√
23		Daylight Visualizer 2.6	Daylight factors	-	-
24		EnergyPlus & Trnsys, Radiance 2phase method & classic	Questionnaire, Three phase method validation, Energy demand	Germany	√
25		Daysim	Heat gains-daylight utilization, Visual comfort indexes	Central Europe	√
26		Radiance, Daysim, HB, LB EnergyPlus,	Daylight & Energy	Malmö (Sweden)	√
27		Velux Daylight Visualizer	-	Prague (Spain)	x
28	●	-	Meaurements and subjective evaluation	Lithuania	√

3 Methodology

The following section describes the selected geometrical scene, the modelling approach and the simulation considerations. A brief description of the performance indicators is given in the end. For detailed descriptions of these indicators, the reader can refer to the literature review section.

3.1 The generic office room

The study object is a typical side-lit office room located in Lund, Sweden (latitude 55°N and longitude 13°E). The literature review provided the necessary documentation for the selection of the room characteristics, which are described below.

3.1.1 Geometry

The office room was modelled with an intermediate position i.e. it was situated on the 3rd floor of an ordinary office building. This building was determined after Poirazis (2008) to be 66 m long, 15,4 m wide and 21 m high. In his study, a project team consisting of architects and engineers from Swedish market and LTH researchers designed this reference building and therefore it is considered as a typical Swedish office building (Poirazis, 2008).

The surrounding building façades were placed at 14 m distance according to urban transport characteristics of streets, according to a study on street types (i.e. arterial, suburban street and urban street) in Swedish cities (Aronsson et al., 2006). The urban street type in each city case consisted of two lanes and two ways that were not divided. The total street width was set to 14 m as an exemplary width for a local street between building blocks in southern Skåne and more specifically in Västra Hamnen in Malmö (Larsvall et al., 2010). Therefore, a two lane street of 6 m was modelled for this research and the surrounding buildings were placed at 14 m in order to include sidewalk pavements and planting as shown in Figure 5. The height of the surrounding buildings was iterated in order to explore the impact of urban context.

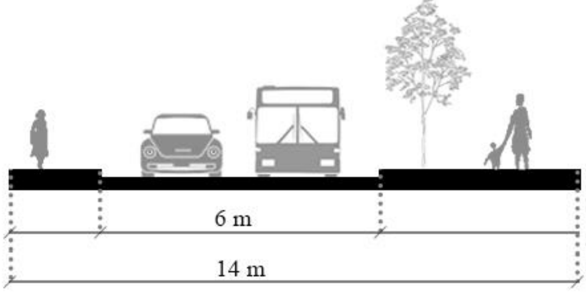

Figure 5. Illustration of an exemplary local street width.

The room geometry was set to: 3,62 m x 4,61m x 3,00 m as shown in Figure 6. Wienold (2009) used the width of 3,62, depth of 4,61 and 2,85 m height for a study on glare evaluation in offices as an exemplary model of test rooms in Fraunhofer ISE, in Freiburg. For this thesis, the width and depth were set according to Wienold and the height was set at 3,00 m in order to investigate cases that have windows placed higher on the façade. Along these lines, for this study only one front workplace was used in simulations regardless of the fact that this type of office has normally two workplaces.

The external wall thickness was set to 410 mm, after proof was found that 408 mm was considered the typical Swedish wall for office building of 1980s (Burton, 2013). Furthermore, when defining the reference office building, Poirazis (2008) used wall thicknesses of about 300 mm and 500 mm for exterior walls. Thus, the selected value of this master study stands for an average wall thickness in regards to the research of office buildings conducted by Poirazis (2008).
The window frame was considered to have a typical thickness of 80 mm.

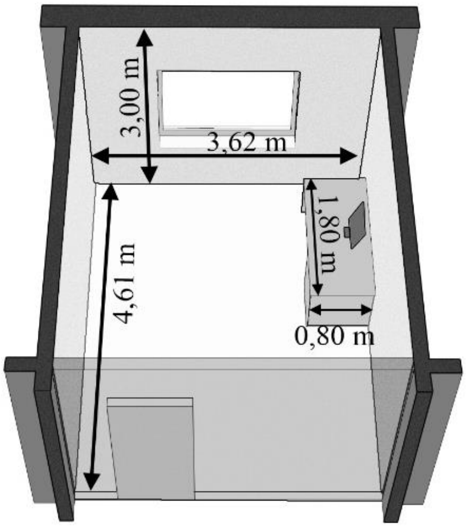

Figure 6. The room geometry.

3.1.2 Optical properties

All surfaces of the office were considered to be purely diffuse and simulated as ‘grey’ i.e. colourless since this study does not focus on colour perception. The reflectance values of the main surfaces varied from dark to bright, as described further down in section 3.4. The reflectance of the frame was set to 70 % and for the surrounding buildings to 30 % according to IES LM-83-12. Finally, the surfaces of the workstation and door were set to 50 % and 40 % reflectance respectively to correspond to an average light brown wooden material.

3.2 Modelling and simulation software

The geometry was modelled in Rhinoceros 5.0, which is a software for commercial 3D computer-generated images and computer-aided design (Rhinoceros, 2017). Following, the model was linked to the Grasshopper environment in which the parametric study was performed (Grasshopper, 2018). Grasshopper is a visual programming editor integrated into the Rhino 3D modelling tools.

Considering the daylight simulation part, Radiance was used as illumination engine with a broad range of modelling and simulation capabilities (Larson and Shakespeare, 2004). In addition, the climate-based daylight modelling (CBDM) tool Daysim was used to generate hourly schedules for occupancy and dynamic metrics (Daysim, 2018). Finally, two Grasshopper plugins were also used in the process: Honeybee and Ladybug. The former connects the Grasshopper environment with Radiance and Daysim and the latter is used for importing the weather data file (Sadeghipour Rousdari and Pak, 2013).

3.3 Simulation inputs

The horizontal illuminance was calculated for a normal grid of 0,30 m · 0,30 m spacing, after an offset of 0,50 m from the lateral walls, resulting in 117 measurement points. A second grid of 0,30 m · 0,30 m spacing was also assessed for the workstation resulting in 14 points, see Figure 7. The points for both grids were placed at 0,80 m height according to the specifications of Miljöbyggnad certification system version 3.0 (Miljöbyggnad, 2017). Furthermore, the illuminance levels at eye level i.e. at 1,2 m, was assessed hourly during occupancy schedule for the visual comfort study.

For the dynamic metrics the weather file of Lund was used.

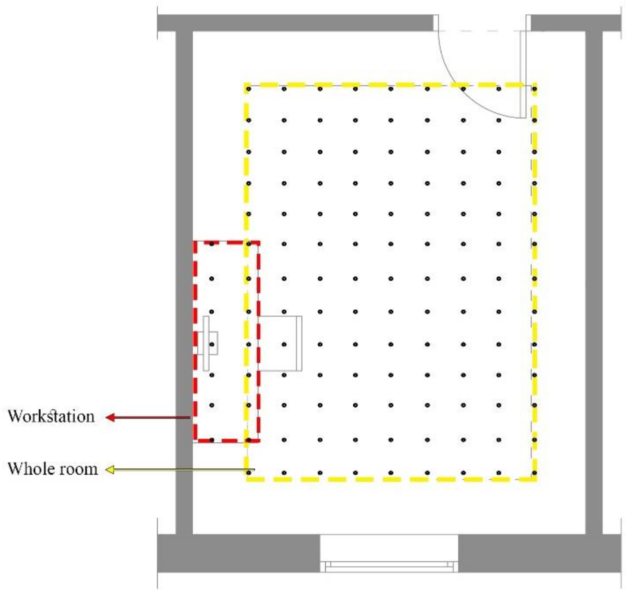

Figure 7. Illustration of the points that consist of the room (big rectangular) and workstation grid (small rectangular).

The Radiance parameters define the simulation quality while also affecting the simulation time. Preliminary simulations determined the parameters in order to provide high accuracy in manageable time, since numerous cases were to be assessed. The Radiance parameters that were chosen are presented in Table 5.

Table 5. The key Radiance simulation parameters used for this study.

Parameter	Description	Value
ab	Ambient bounces	6
ad	Ambient division	2000
as	Ambient samples	1000
ar	Ambient resolution	288
aa	Ambient accuracy	0,1
lw	Limit weight	0,001
lr	Limit reflection	8

3.4 Independent variables

The independent variables studied were determined based on the literature review.

- Orientation: For this study only three orientations were assessed: north, south and west. As explained in Section 2.1, east and west orientations have the same impact on daylight availability for an occupancy schedule centered at 12:00. Some differences may arise only for dynamic simulations, as weather patterns may change from morning to afternoon.

- Glass transmittance: It was considered realistic to explore two steps of visual transmittance, T_{vis}, of 0,50 and 0,69. The values were selected to represent typical high and low T_{vis} of available windows today, according to manufacturer data (National Glass, 2018, Eastman, 2018).

- Window position: Concerning the ‘vertical’ position on the façade, two options were investigated: one centered position, and a high position, see Figure 8. For the ‘horizontal’ placement which was considered of substance in order to evaluate the light distribution, three positions were assessed: left, middle and right.

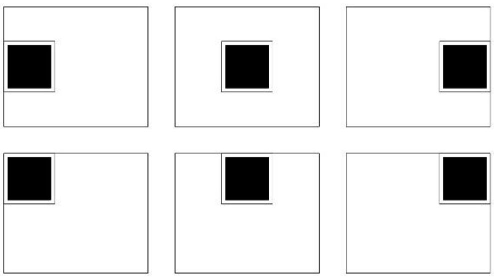

Figure 8. Window positions. Upper row: center-left, center-middle, center-right Lower row: high-left, high-middle, high-right, accordingly.

It should be noted that the exact positions along the axis depend on the number of windows. For cases with two or three windows, the position along the x axis is shown further down.

- Window shape: Three window shapes were investigated: square, horizontal and vertical for equal WWRs. Shape was defined by the length-to-height ratio, which was set to 1:1, 2:1 and 1:2 for square, horizontal and vertical, respectively as in Figure 9.

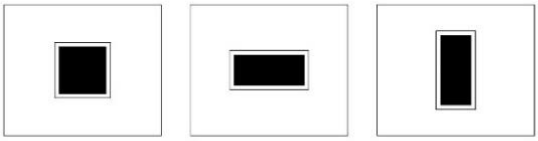

Figure 9. Window shapes. From left to right: square, horizontal and vertical.

- WWR: The WWR was varied in the range between 15% and 60% in increments of 15 % i.e. 15 %, 30 %, 45 %, and 60%. As the size increased, the possibility of larger windows diminished. For example, for a 60 % WWR, only one square window was possible. Consequently, a different amount of cases was studied for different WWRs.

- Number of windows: Three design cases were studied, one-window, two-window and three-window cases. Same as previously, large WWRs decreased the applicability of more than one windows due to façade area limitation.

  For squared and horizontal windows the division was made by keeping the same window sill and upper window height and splitting the window in two parts so that the new width would be half of the corresponding single window. Instead of moving the two parts from left to right, it was considered of more importance to iterate the distance between windows at: $\frac{a}{2}$, a and $2 \cdot a$ where “a” was the new window width of each part as Figure 10 shows. For three-window cases only the distance of $\frac{a}{2}$ was applicable due to façade area limitations.

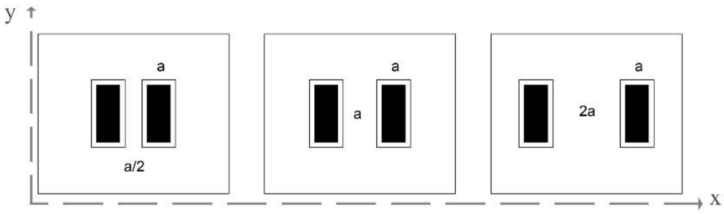

Figure 10. The possible steps for two-window cases.

  For vertical windows, the approach was the same but reversed concerning the x – y axis of the façade plane. The vertical sides of the window were the same and it was divided vertically into two new windows having once again half the height of the corresponding single window. For this vertical case only one iteration was applicable due to the façade height limit. This one iteration corresponded to a case where the distance between the two windows was half of the new window height as

Figure 11 illustrates. Same as before, for three-window cases only the distance of $\frac{a}{2}$ was applicable due to façade area limitations.

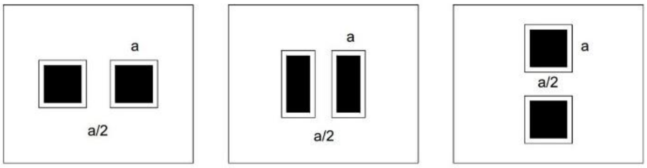

Figure 11. The window division for two-window cases when the corresponding one-window case had horizontal, square and vertical shape, from left to right accordingly. The vertical corresponds to the only possible iteration.

The middle point of the two windows acted in every case as a reference point.

- Surface reflectances: Based on the literature review, three scenarios of reflectance values were assessed: dark, medium and bright, as seen in Table 6.

Table 6. The selected surface reflectances for each scenario.

	Ceiling	Wall	Floor
Dark	70 %	60 %	20 %
Medium	80 %	70 %	30 %
Bright	90 %	80 %	40 %

- Window niche: The window niche was iterated between sharp, splayed at 30°, 45° and 60°, as shown in Figure 12. In order to capture its impact, the window was splayed in both vertical and horizontal directions. A different niche angle would result in a different coverage of façade area, as shown in Figure 12. This affected the possible positions for different niche angles. The dashed lines in the bottom sketches of Figure 12 show the boundaries within which the different cases were positioned. The 60° cases had the least position iterations, due to the façade area limitation.

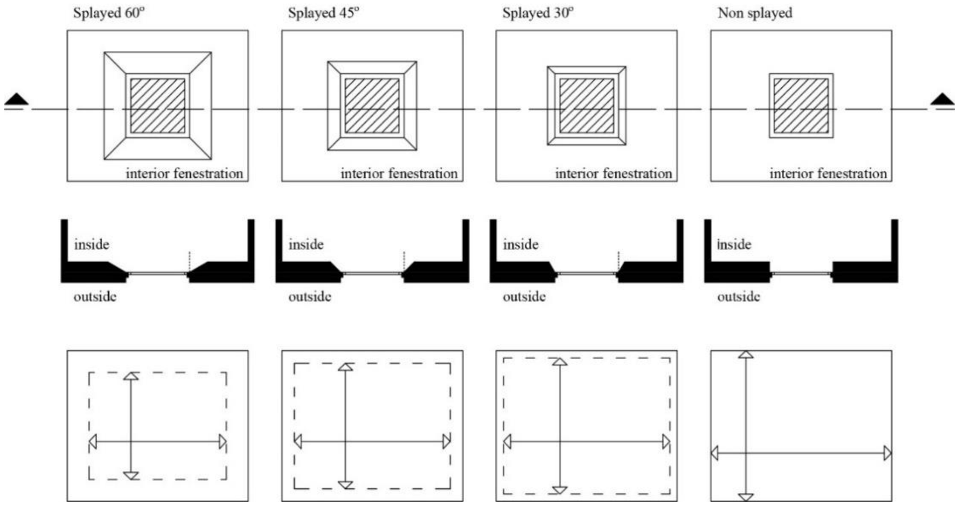

Figure 12. Above: example of fenestration as seen from inside. Middle: plan of window niche. Low: the range of possible window positioning for each case.

- Obstruction angle: The obstruction angle was iterated between 0°, 30° and 60° by designing an opposite building as shown in Figure 13. The height of the opposite building was relevant to the predetermined road width, in order to provide these obstruction angles.

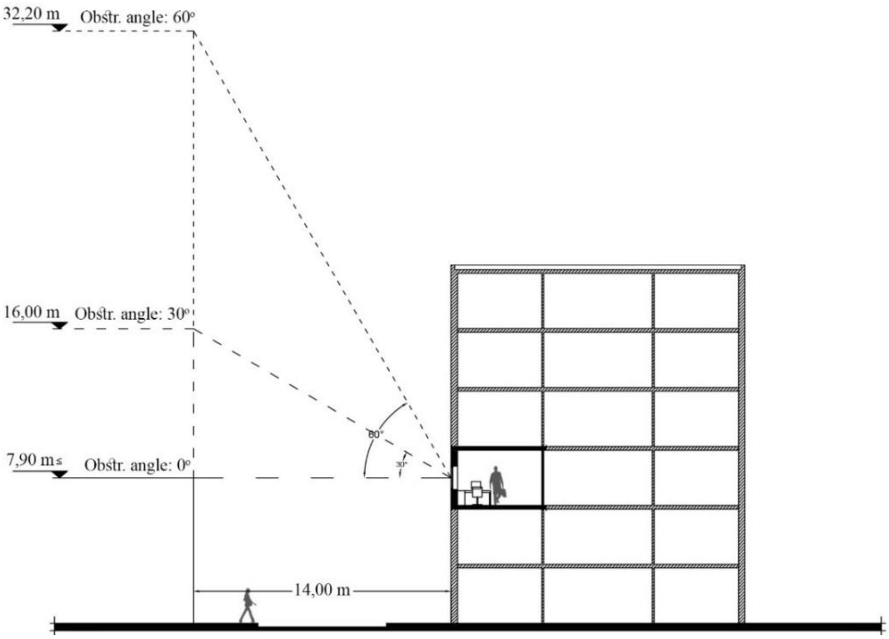

Figure 13. Illustration of the studied obstruction angles.

All independent parameters, when iterated for all possible combinations, led to a total of 11.124 different alternatives. It should be noted that each parameter was only iterated in two to four discrete steps (depending on parameter) in order to reduce simulation time (11.124 was already a substantial number of cases).

3.5 Dependent variables

The daylight performance indicators studied were determined based on the literature review. Table 7 presents the monitored dependent variables, which are further discussed thereafter. The light grey dots refer to static metrics while the black dots refer to dynamic metrics.

Table 7. The daylight metrics for each parameter.

	DF_{avg}	DF_{point}	DF_{median}	U	DA_{300}	$sDA_{300-50\%}$	$UDI_{100-3000}$	DGPs
1. Orientation	-	-	-	-	●	●	●	●
2. Transmittance	○	○	○	○	●	●	●	●
3. Position	○	○	○	○	●	●	●	●
4. Shape	○	○	○	○	●	●	●	●
5. Size	○	○	○	○	●	●	●	●
6. Number	○	○	○	○	●	●	●	●
7. Reflectances	○	○	○	○	●	●	●	●
8. Niche	○	○	○	○	●	●	●	●

9. Obstruction	○	○	○	○	●	●	●	●

○ static indicator ● climate-based indicator

Static metrics: In consistence with the literature review, DF_{avg}, DF_{point}, DF_{median} and U were assessed.

Dynamic metrics: Following are the specifications for each dynamic daylight performance metric.

- DA: The required illuminance level was set to 300 lux for this study and the schedule was set from 8:00 to 17:00 with a lunch break between 12:00 and 13:00 (eight hours daily). The same threshold was set for the workstation area and the total office.

- sDA: In this study, the spatial daylight autonomy sDA was selected to describe the percentage of floor area that received at least 300 lux for at least 50 % of the occupied hours per year ($sDA_{300\text{-}50\%}$, in accordance with the standard recommendation) for the same occupancy schedule as in DA.

- UDI: According to Mardaljevic et al. (2012), the range between 100 lux and 3000 lux was considered as useful. Details were previously described in section 2.2.2.

- DGPs: According to Wienold (2009), the simplified DGP should only be used when no direct light is visible to the occupant. The position was therefore selected specifically, in order for DGPs to be applicable. This was achieved by a few preliminary fisheye renderings, from the view perspective of the occupant. Figure 14 shows the assumed occupant position, where direct view of the sun is eliminated for all possible fenestration designs.

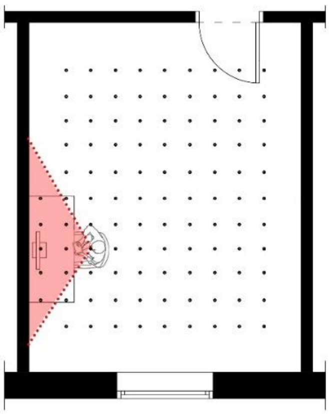

Figure 14: The visual field of the occupant

4 Results

The presentation of the results begins with metric correlations, to justify why only specific metrics were used in the sections that follow. These correlations were observed during data processing. Subsequently, the impact of each independent variable on the daylight conditions of the study room is presented in separate subsections. Distinction is made in each subsection between dynamic and static metrics. Finally, combined results are presented to extrapolate meaningful conclusions. Overall, benchmark compliance facilitated the presentation and comprehension of the research findings.

4.1 Metric correlations

Figure 15 shows the correlation between DF_{median} and DF_{point} for all studied cases. The 11.124 cases were correlated with a linear regression fit (R^2 = 0,995). The correlation was high and significant (N = 11.124). The linear regression had a 1,0343 slope, meaning that the calculation of one metric can lead to the deduction of the other metric.

Due to this correlation the rest of the study does not include DF_{point} performance as it is represented well by DF_{median} values.

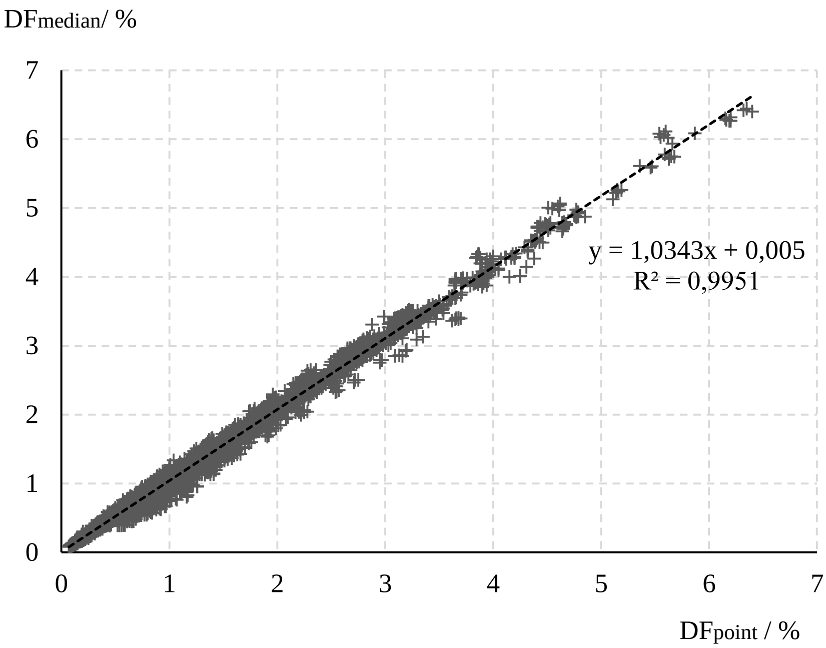

Figure 15. DF_{median} and DF_{point} correlation.

Figure 16 presents the correlation between DF_{median} and DF_{avg} for the entirety of assessed cases (N = 11.124). This correlation was not as strong as the previous one. It was high though (R^2 = 0,954). On average, DF_{median} was lower than DF_{avg}, by a factor of 0,78 as the slope of the regression line indicates. The correlation was not considered strong enough to exclude either metrics from the results presentation, so both DF_{median} and DF_{avg} are presented in the sections that follow.

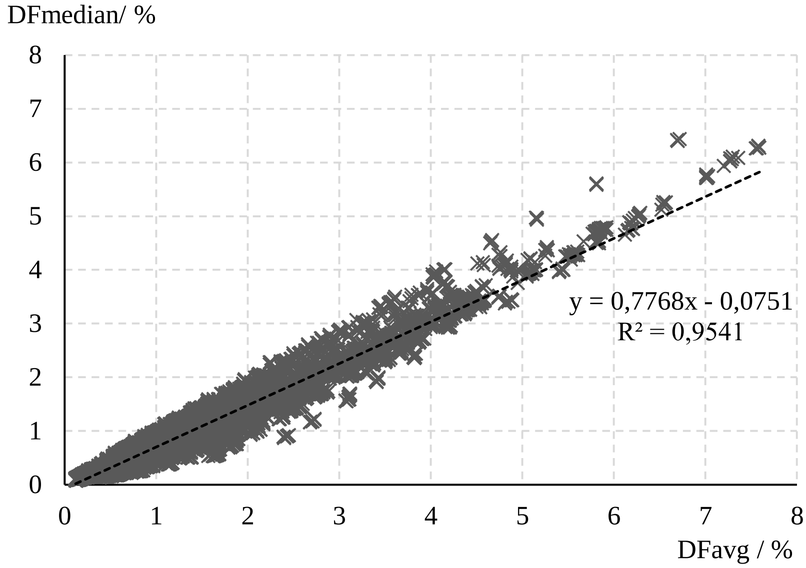

Figure 16. DF_{median} and DF_{avg} correlation.

4.2 Effect of independent variables

4.2.1 Orientation

The ranges of $sDA_{300/50\%}$ results for the assessed orientations are shown as boxplot diagrams in Figure 17. The figure includes all parameter iterations i.e. all glazing transmittances, window sizes, window shapes and so on. The 'x' markers indicate the average $sDA_{300/50\%}$ value. It can be seen that the south orientation had the best performance, as 50 % of the cases lied above $sDA_{300/50\%}$ = 22 % (upper quartiles). West oriented cases reached little higher $sDA_{300/50\%}$ values than the north oriented ones. This can be attributed to the occupancy schedule that favors west (8:00 – 12:00 and 13:00 – 17:00). For all orientations, at least 25 % of the cases had zero $sDA_{300/50\%}$ (lower quartile values are all zero).

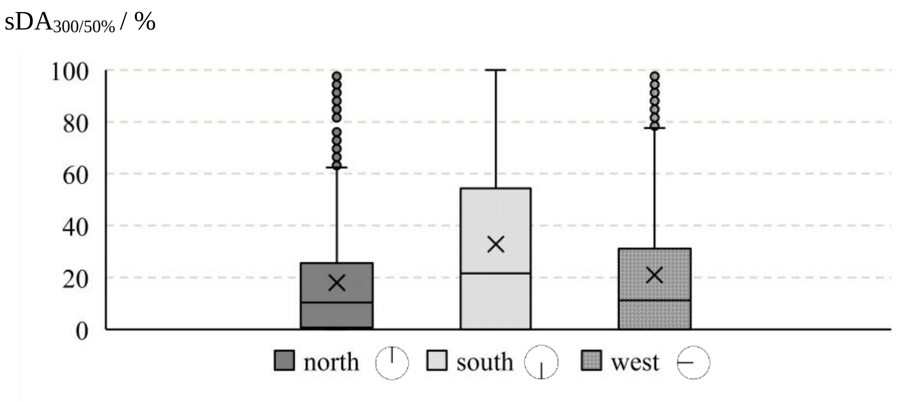

Figure 17. Boxplots of $sDA_{300/50\%}$ for assessed orientations.

Figure 18 shows the percentage of assessed cases for each orientation when one of the following was true:

a. the workstation had DA_{300} for at least half of the occupancy time,
b. the overall office room had DA_{300} for at least half of the occupancy time and
c. the $sDA_{300/50\%}$ of the overall room area was at least 55 %.

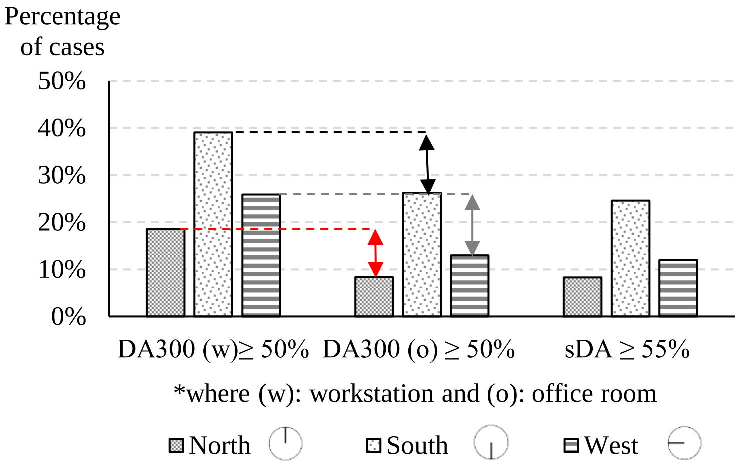

Figure18. Impact of orientation on dynamic daylight metrics.

For south oriented offices it was considerably easier to succeed or exceed these reference points, as for all these metrics the south orientation had at least the double amount of complying cases compared to north or west orientations. For all orientations, the DA_{300} of the workstation grid was higher than the DA_{300} of the overall office room area. The relative difference between the workstation and the overall room area was lower for south.

Figure 19 demonstrates the relative percentage of cases that do not experience disturbing glare for each orientation. These corespond the A (best) or B (good) DGPs comfort classes. The north orientation had no case with disturbing glare i.e. all cases fulfilled the ‘A’ class criterion DGPs ≤0 ,40 for 95% of office time and the average DGPs ≤ 0,42 for the rest 5% of occupancy time. For south and west offices, 10 % of the cases had disturbing glare rating.

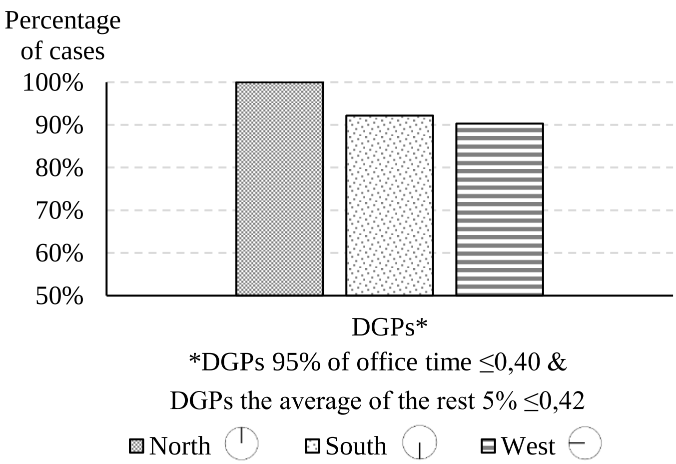

Figure19. Impact of orientation on simplified glare probability.

However, the Figure 18 is refered to the potential autonomy metrics and Figure 19 to the worst scenario. In reality, the south orientation would have a shading device decreasing the DA. The same would be applied for the west orientation but for less time of the occupancy schedule compeared to the south. Along these lines, the difference between the DGPs could be even smaller.

4.2.2 Glass transmittance

The presented results include all parameter iterations i.e. all orientations, window sizes, obstruction angles etc.

Dynamic metrics

The effect of glass transmittance on DA_{300} is presented in Figure 20. When the glazing changed from 0,50 to 0,69 T_{vis}, the complying cases with DA_{300} of the workstation shifted from 22 % to 34 %. The complying cases with DA_{300} of the office grid increased from about 10 % to about 20 %. The change for the $sDA_{300/50\%}$ was similar.

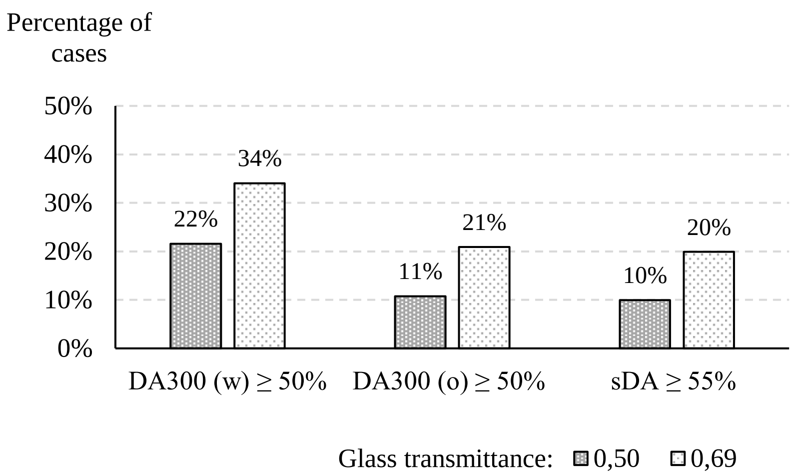

Figure 20. Impact of glass transmittance on dynamic daylight metrics. The "(w)" stands for workstation, and the "(o)" for the whole office room.

Static metrics

The percentage of cases that reached the benchmarks of $DF_{avg} \geq 2,1$ %, $DF_{median} \geq 1\%$ and $U \geq 0,4$ for each T_{vis} are shown in Figure 21. The figure includes all assessed cases. For the first two metrics, the glass transmittance alteration led to about 40 % more complying cases while for uniformity U, raising the glass transmittance led to a 4 % decrease. Considering this, a higher transmittance increased illumination at the expense of uniformity, since this is a side-lit room, but only to a small extent.

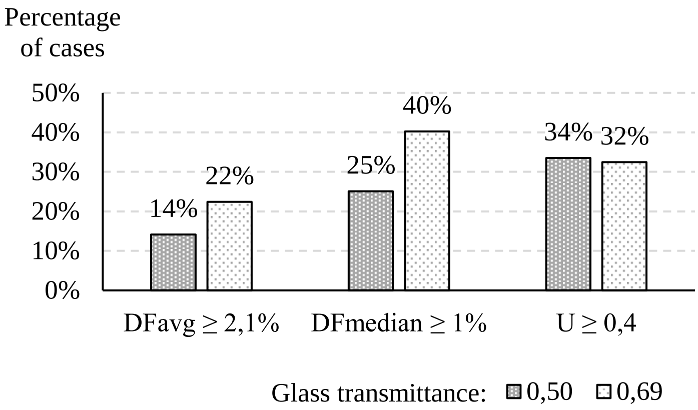

Figure 21. Impact of glass transmittance on dynamic daylight metrics.

4.2.3 Window position

The presented results concerning the window position do not include 45 % and 60 % WWR in order to have comparable results, as fewer cases could be studied for large window areas. For this subsection, the sample for the centered positions i.e. center-left, center-middle and center right was almost 1300 and for high positions i.e. high-left, high-middle and high-right was around 1000 cases per category. The following figures consist of relative results per category.

Dynamic metrics

Figure 22 shows the amount of cases that achieved $sDA_{300/50\%} \geq 55$ %, for different window positions. Higher positions (the three right-most bars) performed considerably better. Moving windows higher (from Center to High) had the highest potential for Middle positions (difference between Center-Middle and High-Middle equals 21 % - 12 % = 9 % more cases). Middle positions also performed considerably better, whether windows were located High or Center along the y axis (second and fifth bar). When comparing Right and Left positions, it is shown that Left was slightly better. The difference can be attributed to the position of the workstation that blocks some light bounces.

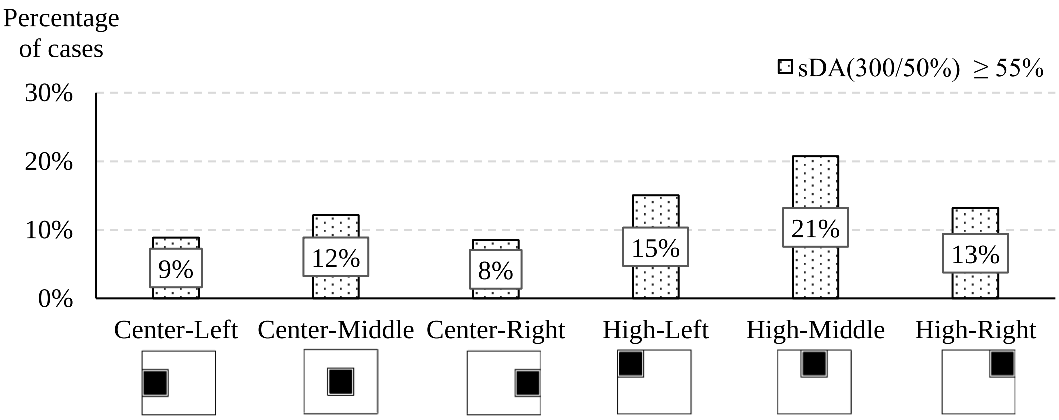

Figure 22. Cases complying with $sDA_{300/50\%} \geq 55$ % for different window positions. Cases of 45 % and 60 % WWR are excluded.

Figure 23 shows the amount of cases that achieved $UDI_{100-3000}$ for at least half of the occupancy time, when different positions are used. Again, High positions were considerably better (three right-most bars) than Center positions (three left-most bars).Middle positions (second and fifth bar) were also better compared to Right and Left positions for each vertical placement (55 % for Center-Middle and 68 % for High-Middle). Unlike in the previous figure, the potential of increasing $UDI_{100-3000}$ when moving the windows higher (from Center to High) was indifferent to horizontal position. The gains for the Left and Right positions (from 48 % to 61 % = 13 % more cases) were the same for Middle positions (from 55 % to 68 % = 13 % more cases).

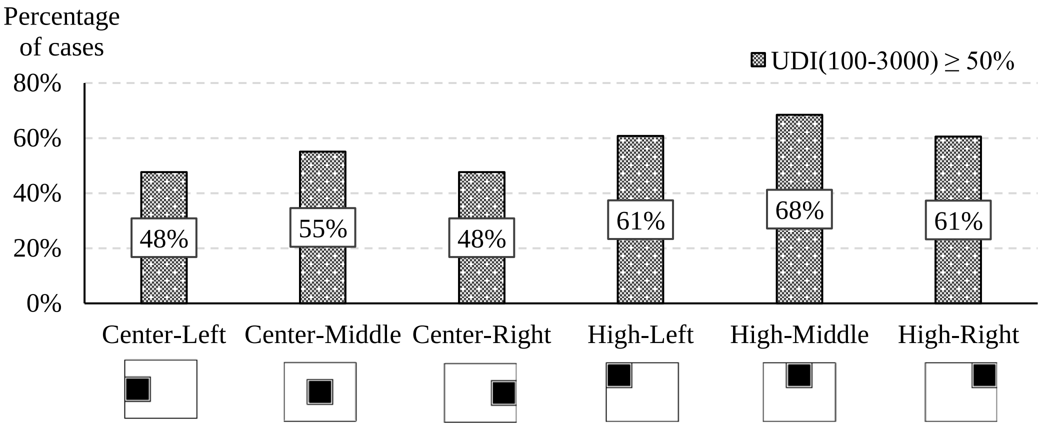

Figure 23. Cases complying with $UDI_{100-3000} \geq 50$ % for different window positions. Cases of 45 % and 60 % WWR are excluded.

Static metrics

Figure 24 shows the percentage of cases that fulfilled the benchmark of $DF_{avg} \geq 2{,}1$ % for each position. The results show the same pattern with the results obtained with dynamic metrics. High and Middle positions achieved the benchmark more usually.

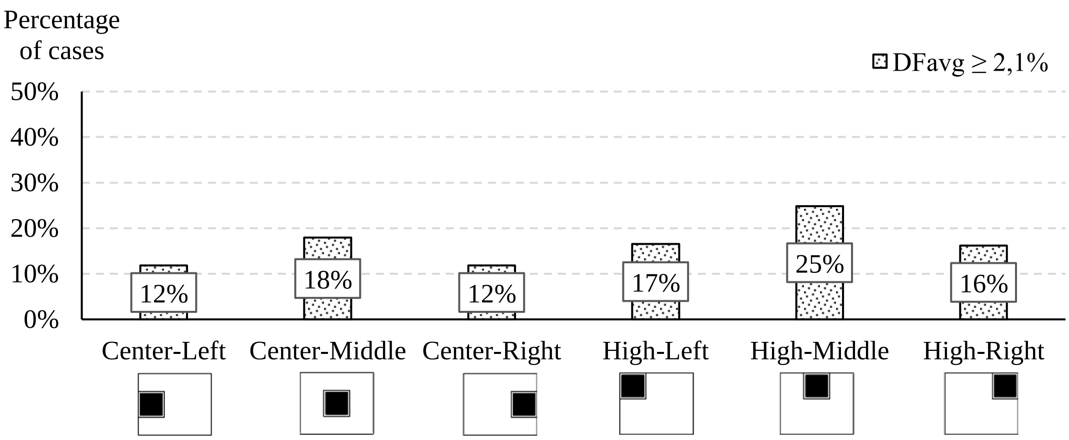

Figure 24. Cases complying with $DF_{avg} \geq 2{,}1$ % for different window positions. Cases of 45 % and 60 % WWR are excluded.

Figure 25 shows the percentage of cases that had a uniformity of at least 0,4 for each position. Same as previously, High positions performed better (three right-most bars) than Center positions (three left-most bars). However, the horizontal position that outperformed the rest is the Right position, instead of the Middle. Offices with Centered-Left windows were the worst performing in terms of uniformity. This is attributed to the fact that when the window was closer to the workplace (Left), dark areas were created due to the workstation surface.

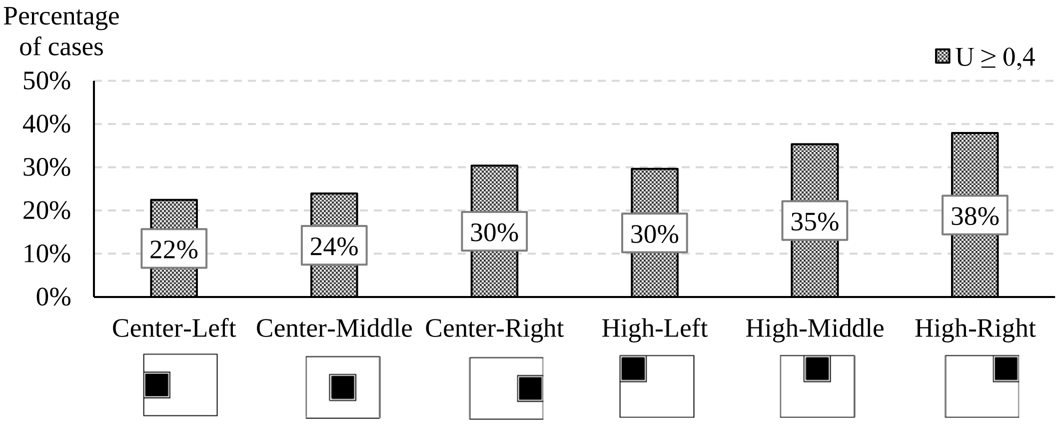

Figure 25. Cases complying with $DF_{avg} \geq 2{,}1$ % for different window positions. Cases of 45 % and 60 % WWR are excluded.

4.2.4 Window shape

The presented results, concerning the window shape, are one-window-cases and do not include 45 % and 60 % WWR nor high window positions in order for results to be comparable. For this subsection, the individual samples of square, horizontal and vertical windows were just above one thousand cases for each.

Dynamic metrics

The relative amount of offices that reached a 55 % $sDA_{300\text{-}50\%}$ and 50 % $UDI_{100\text{-}3000}$ are shown in Figure 26 and Figure 27 respectively. For both metrics, the cases that complied more often were those with squared windows. Vertical window shape were the worst for the $sDA_{300\text{-}50\%}$ benchmark while for the UDI, vertical and horizontal shapes had the same performance.

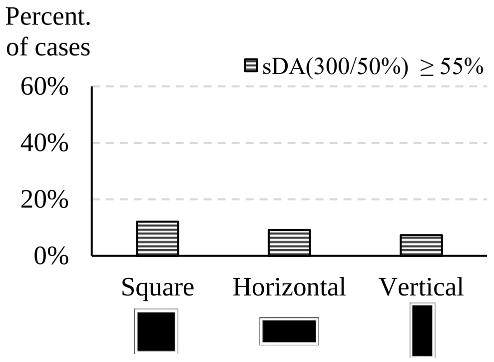

Figure 26. Cases complying with $sDA_{300/50\%}$ ≥ 55 % for different window shapes. Cases having 45 % and 60 % WWR and high placed windows are not included.

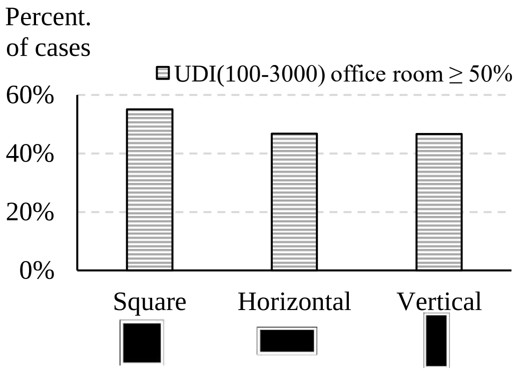

Figure 27. Cases complying with $UDI_{100\text{-}3000}$ ≥ 50 % for different window shapes. Cases having 45 % and 60 % WWR and high placed windows are not included.

Static metrics

Figure 28 depicts the numerical range of DF_{avg} for each window shape case. The lines inside the boxes represent the median and the ‘x’ mark the average DF value. The reader is reminded that this diagram only includes cases of WWR = 15 % or WWR = 30 %. Higher DF_{avg} can be achieved when the window is square, followed by horizontal shape. The vertical window performed slightly less than the two other window shapes.

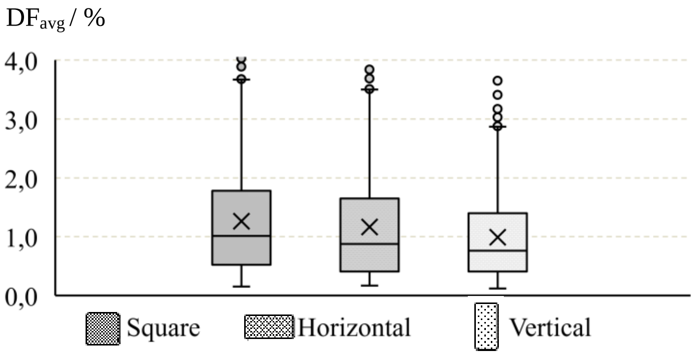

Figure 28. Boxplots of DF_{avg} for different window shapes. Cases having 45 % and 60 % WWR are not included.

For a deeper understanding of the previous figures in this section, Figure 29 illustrates the DF distribution as a coloured mesh with contour lines for all grid points calculated. The illustrated case was a one-window case of 30 % WWR. The window in all steps was centered at both x and y axis of the façade. The T_{vis} was 0,69, the surface reflectances were medium and the obstruction angle was 30°. The walls around the window were not splayed (0° niche). The only difference was the window shape.

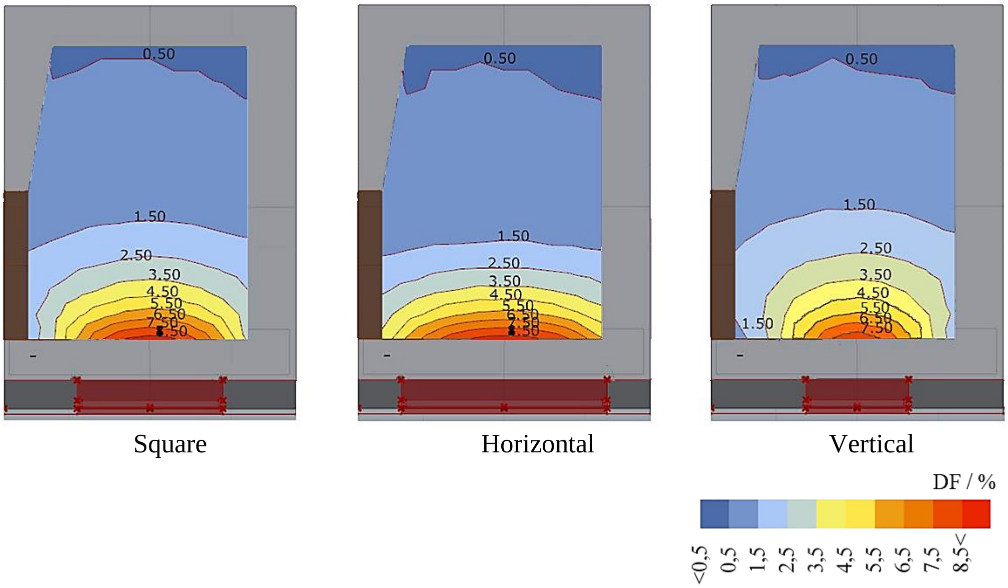

Figure 29. Illustration of DF distribution with contour lines for different window shapes. All shape options have: one window, centered in the exterior wall, 30 % WWR, T_{vis} of 0,69, medium surface reflectances, obstruction angle of 30°and not splayed walls.

As it is shown, the Horizontal shape provided higher illuminance levels closer to the window, but lower levels at the back of the room. The Vertical provided deeper daylight penetration than the Horizontal (see contour line for 1,5 %), as the head height was located higher, but with moderately lower illuminance levels closer to the façade wall. Finally, the daylight performance of the Square shape was a combination of the Horizontal and the Vertical, achieving deeper daylight penetration than the Horizontal and higher illuminance levels than the Vertical closer to the façade. Therefore, the square shaped windows performed better statistically.

4.2.5 Window size (WWR)

Dynamic metrics

Figure 30 shows the percentage of cases that reached (or failed) $DA_{300} \geq 50$ % benchmark. The first four bars regard the workstation grid and the other four the office room grid. The absolute number of cases corresponding to each WWR is indicated on the right ($n_{15\%}$, $n_{30\%}$, etc.). The figure includes all assessed cases. For both grids, increasing the WWR induced higher compliance rates. The largest increase occurred for a change from 15 % WWR to 30 % (quadruple increase of compliance or more). As the WWR increased further, the compliance rate was increased at a slower pace. For the workstation grid, higher percentage of complying cases was observed and more convergence as the WWR became greater.

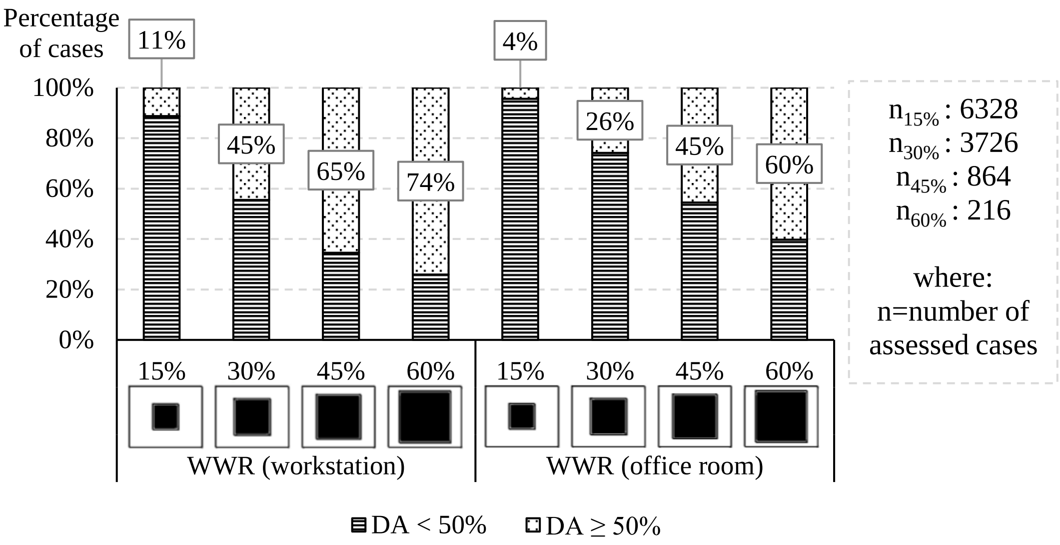

Figure 30. Cases complying with sDA ≥ 55 % for different window shapes. All assessed cases are included.

Static metrics

Figure 31 shows the impact of the WWR on DF_{avg} for a representative sample of cases i.e. including iterations of all parameters. The larger window sizes resulted in higher DF_{avg} as anticipated. They also took more advantage of decreased obstruction angles. As the WWR became smaller, the obstruction angle became irrelevant. Unobstructed cases (obstruction angle = 0°) could achieve an increase of 5 units DF_{avg} (from 1,96 % to 7,36 %).

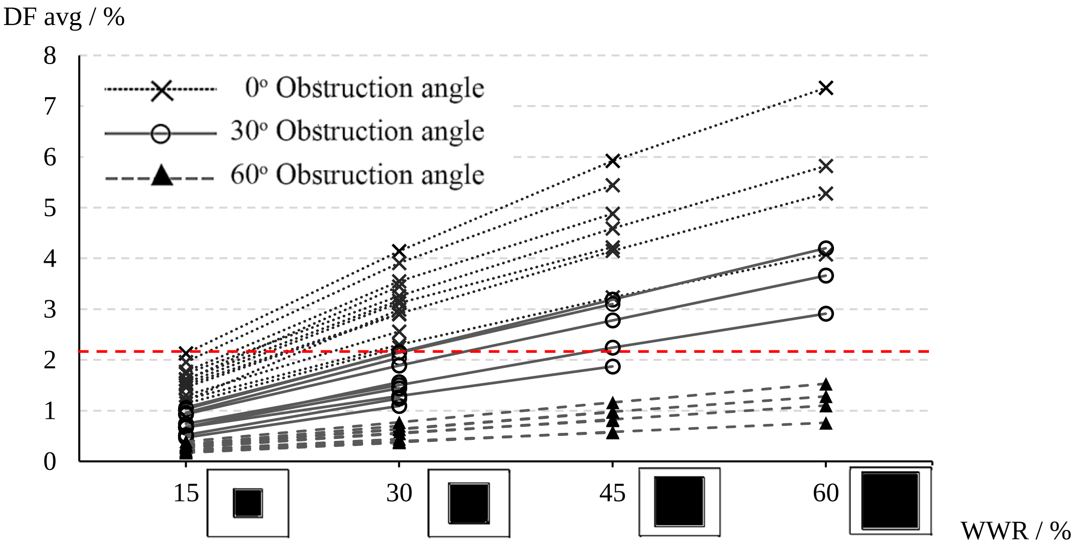

Figure 31. The DF_{avg} for different WWRs in relation with obstruction angle. The lines show the same cases with only window size alteration.

4.2.6 Number of windows

4.2.6.1 Effect of window quantity (for the same WWR)

For this subsection, only cases positioned in the Middle of the façade (Centered or High) were taken into consideration, to avoid the effects due to one-window cases outnumbering the other categories. Additionally, only 15 % WWR were selected since the three-window-cases were not applicable with larger window areas. It is also pointed out that the glass-to-frame ratio was different for different numbers of windows. A constant frame thickness was initially set as a modelling simplification. This means that a window of a given WWR (i.e. 30 %), would have less frame material than two windows of a 30 % WWR.

Dynamic metrics

Figure 32 shows the $UDI_{100\text{-}3000}$ results for different number of windows. The figure includes cases that have exactly the same WWR distributed in one, two and three windows. The $UDI_{100\text{-}3000}$ results indicate that for a given WWR (15% in Figure 32), the least-window cases performed better. The cases with three windows had the lowest compliance rate, both for the workstation and the office room grids. The decrease of compliance was more obvious when shifting from one to two-window cases. The workstation was consistently better than the overall office room area.

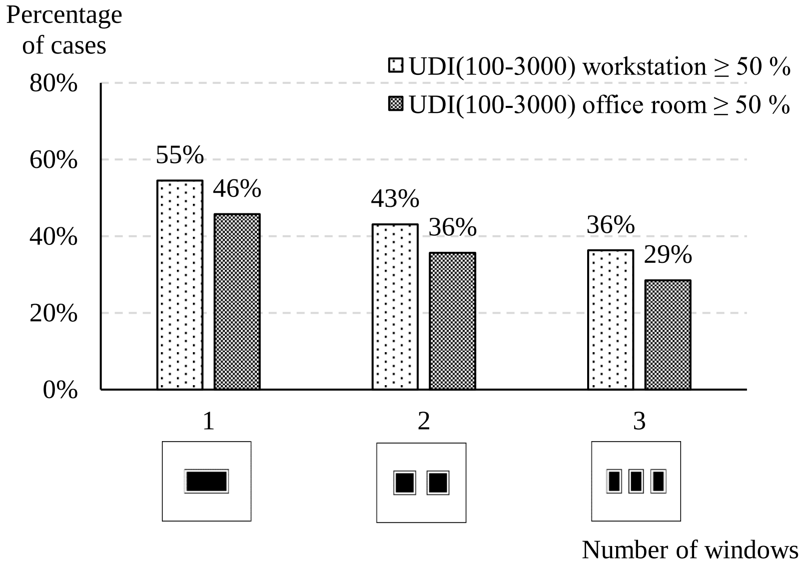

Figure 32. Cases complying with $UDI_{100\text{-}3000} \geq 50$ % on the workstation and on the whole office room for different number of windows, while having the same WWR. Cases with middle position of window/s and of 15 % WWR are included.

Static metrics

Increasing the number of windows from one to three, while keeping the WWR constant, decreased compliance in Daylight Factors, as seen in Figure 33. 27 % of the cases that had one window reached 1 % DF_{median} while for the two windows, the percentage was 17 % and for three windows only 11%. The same cases were studied for compliance with 2,1 % DF_{avg}.

It was found that only a small fraction of one-window cases could fulfill this criterion (4 % of one window cases). The two and three-windows cases of the same WWR had no complying case. This is attributed to the small WWR (15 % WWR) shown here.

The reversed trend was observed in illuminance uniformity as Figure 34 presents. As the number of windows increased, for the same WWR, the uniformity increased moderately, showing that when the DF grid values were darker the distribution was more uniform.

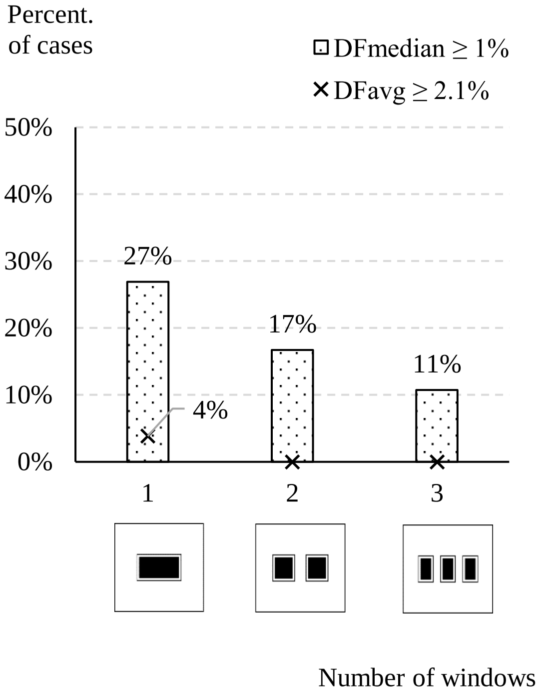

Figure 33. Cases complying with $DF_{median} \geq 1$ % and $DF_{avg} \geq 2,1$ % for different number of windows having same WWR. Cases with middle position of window/s and of 15 % WWR are included.

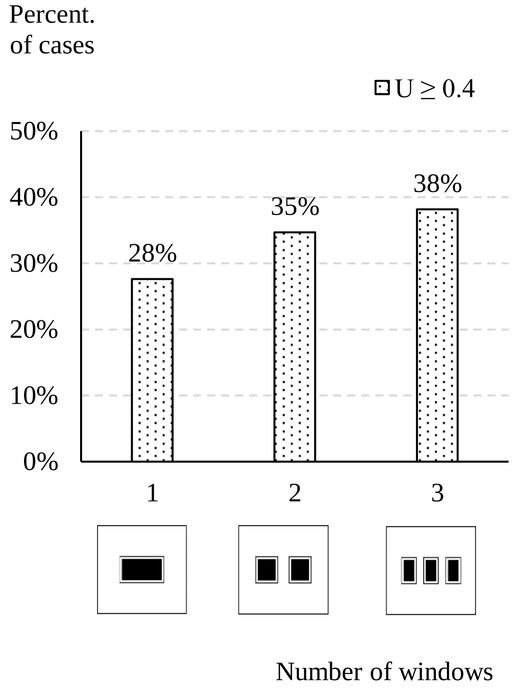

Figure 34. Cases complying with $U \geq 0,4$ for different number of windows having same WWR. Cases with middle position of window/s and of 15 % WWR are included.

Figure 35 illustrates the DF distribution for one, two and three windows of the same overall WWR. The WWR was 15 % and the windows placed centered on the façade. The T_{vis} was 0,69, the surface reflectances were medium and the obstruction angle was 30°. The walls around the window were not splayed (0° niche). As the number of windows increased the illuminance levels decreased. Therefore, the one window case performed better. In spite of this, the more uniform, though dark, was the case with three windows, as mentioned before.

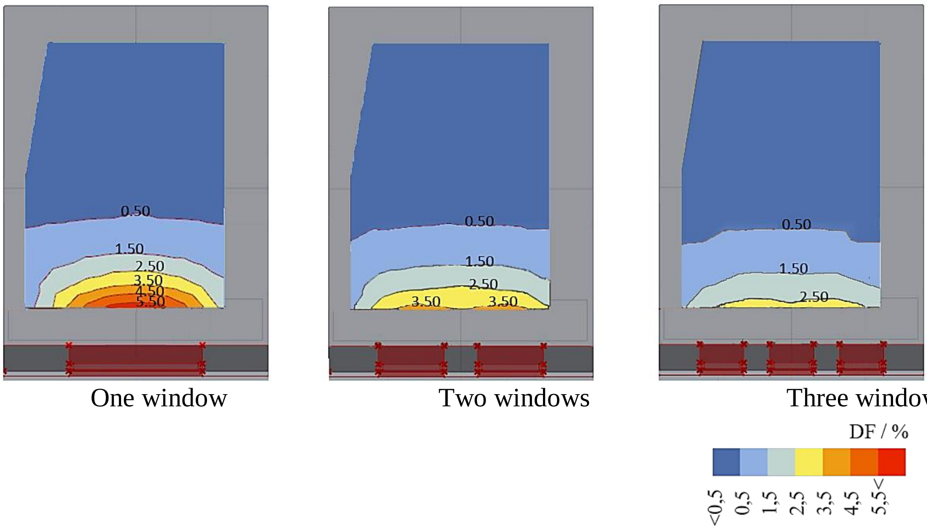

Figure 35. Illustration of DF distribution with contour lines for different number of windows. All steps have: 15 % WWR, T_{vis} of 0,69, medium surface reflectances, obstruction angle of 30°and not splayed walls.

4.2.6.2 Effect of distance between two windows

When two windows were deployed, they were distributed in different ways on the façade. This subsection presents the performance of the different alternatives, all of which have a WWR between 15 % and 30 %. The samples vary in population, so only relative results per category are presented. The 'a' stands for the window width and the x axis indicates the distance between the two windows.

Dynamic metrics

Figure 36 shows the percentage of cases that achieved $UDI_{100\text{-}3000} \geq 50$ % for different distances between two windows, placed at Center or High, 15 % and 30 % WWR. There are no significant differences detected by the UDI metric. The cases that were slightly worse were the ones with the windows positioned far from each other. The latter did not affect the results when windows were placed High and WWR was 30 %.

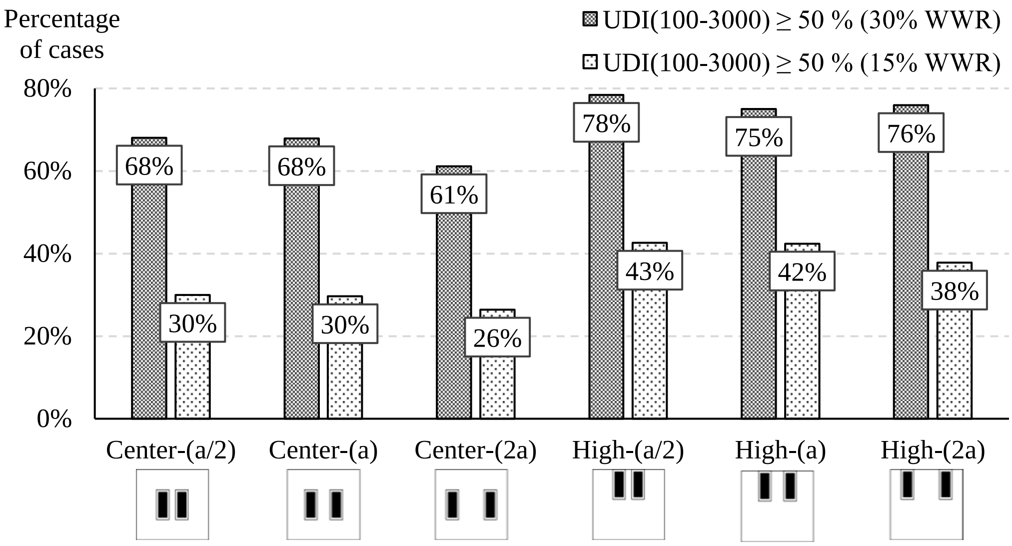

Figure 36. Cases complying with $UDI_{100\text{-}3000} \geq 50$ % for different distances between two windows, centered or high placed. The "a" stands for the window width and defines the distance area between the windows. Only 15 % and 30 % WWR cases are included.

Static metrics

Figure 37 shows the percentage of cases that fulfil $DF_{median} \geq 1$ % for different distances between two windows, for Centered or High positions. The results show the same trends observed with the UDI metric. The lowest scores were found for an increased distance between the windows. When the windows were placed High (six right-most bars), the impact of their intermediate distance was less significant.

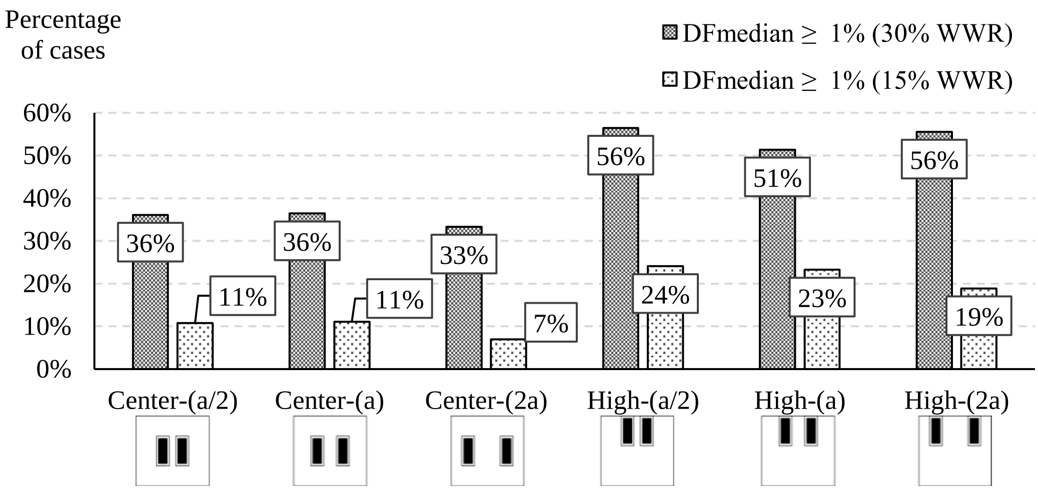

Figure 37. Cases complying with $DF_{median} \geq 1$ % for different distances between two windows, centered or high placed. The "a" stands for the window width and defines the distance area between the windows. Only 15 % and 30 % WWR cases are included.

The uniformity U results are presented in Figure 38. The most uniform cases were Centered, with 30 % WWR and had a longer distance between windows. For Centered windows with 30 % the uniformity increased as the distance between the windows increased. Apart from this, no other consistent pattern can be observed.

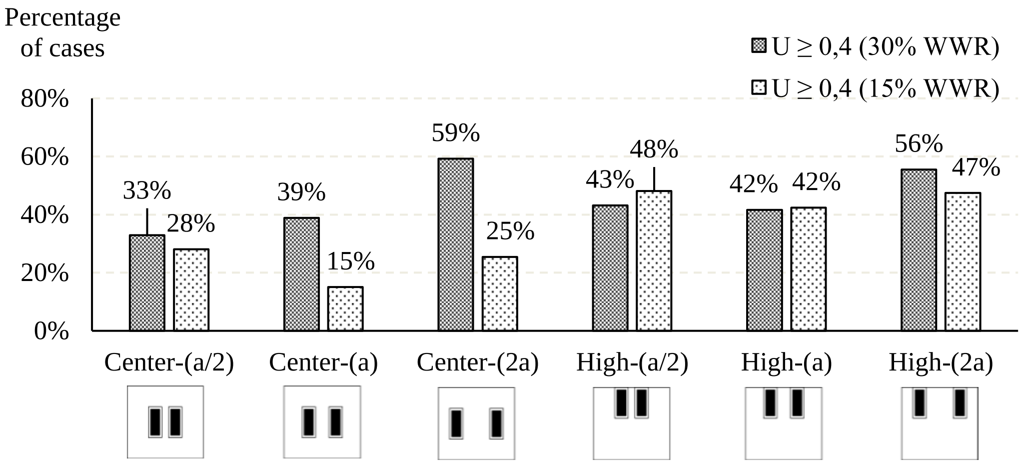

Figure 38. Cases complying with $U \geq 0,4$ for different distances between two windows, centered or high placed. The "a" stands for the window width and defines the distance area between the windows. Only 15 % and 30 % WWR cases are included.

4.2.6.3 Effect of vertical / horizontal placement of two windows

Figure 39 shows the relative amount of cases that fulfil the criteria for DF_{median} and DA_{300} (see x axis). The sample consisted of two window cases of 15 % WWR from which: 108 were vertically placed and 108 horizontally placed. Horizontal window arrangement performed moderately better than the vertical placement in dynamic and static metrics. However, the static indicator of uniformity showed opposite results. More than half of the cases that had two windows with vertical placement had higher uniformity than 0,4 which was almost five times more than the percentage of cases with horizontal arrangement of windows.

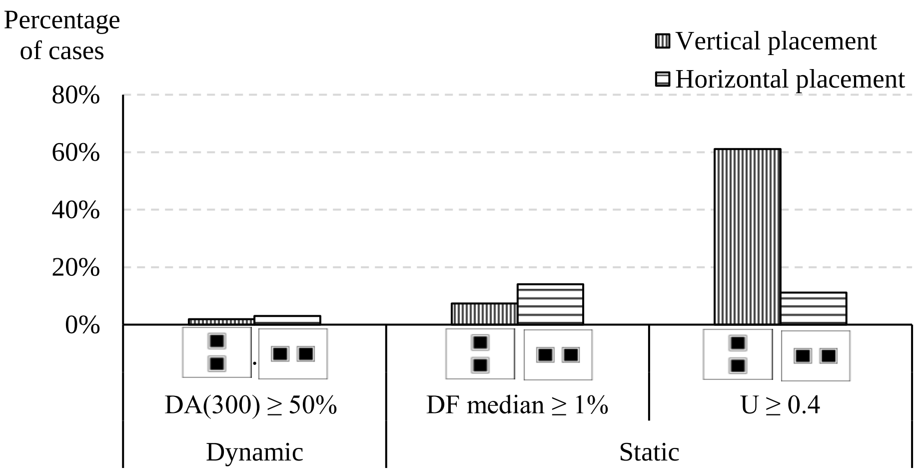

Figure 39. Cases complying with $DA300 \geq 50$ %, $DF_{median} \geq 1$ % and $U \geq 0,4$ for vertical and horizontal placement. The cases included are 15 % WWR.

4.2.7 Surface reflectances

The presented results include all parameter iterations i.e. all orientations, window sizes, obstruction angles etc.

Dynamic metrics

Figure 40 demonstrates how many cases for each reflectance scenario reached or exceeded 50 % DA_{300}. The bright surface reflectance scenario had more cases performed better, followed by medium and last was the dark scenario. Significantly more cases fulfilled the criterion when the workstation grid was taken into consideration. However, the increase was steeper when the whole office grid was accounted. This shows that the reflectance increase was more beneficial at the back of the room. Shifting from the dark to the bright surface scenario, the complying cases doubled, increasing from 10 % to 22 %.

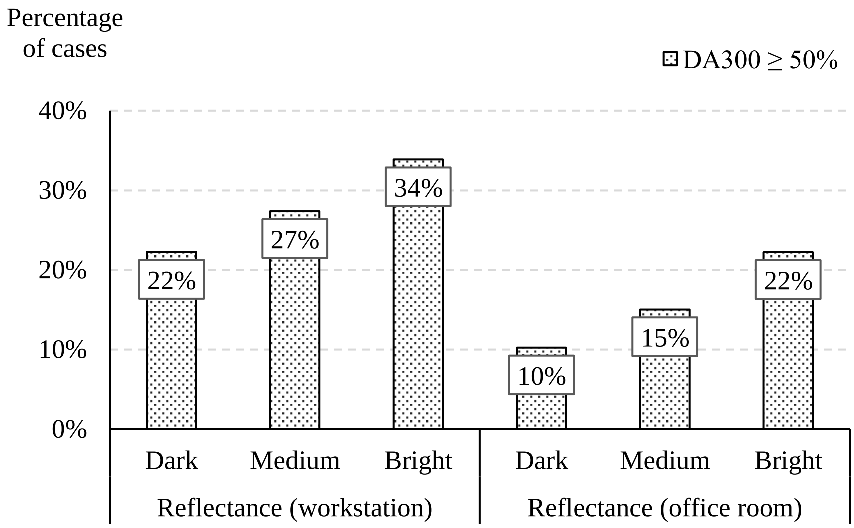

Figure 40. Cases complying with $DA_{300} \geq 50$ % for different reflectance scenarios. All cases are included. The results of the workstation grid are shown in the left part and of the office room grid in the right part.

Static metrics

The impact of surface reflectances on the uniformity is presented in Figure 41. Uniformity increased as the surface reflectances increased. There is no significant difference between the range of uniformity achieved for different combinations of obstruction angle and reflectance.

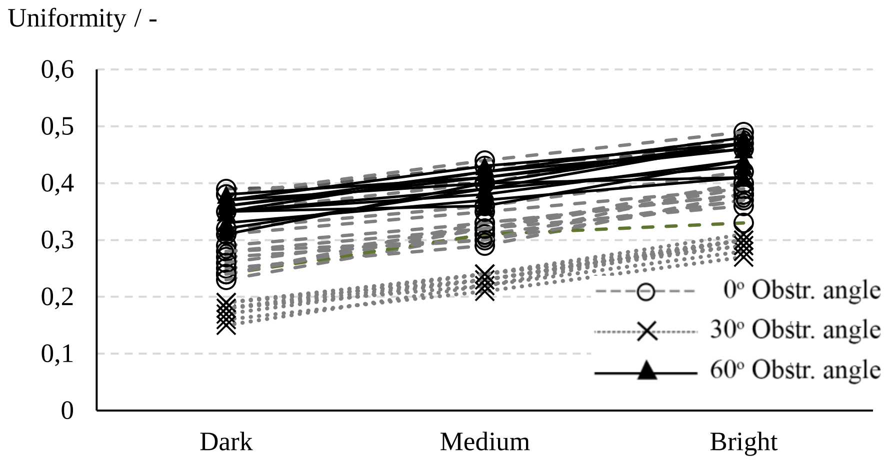

Figure 41. The uniformity levels for different reflectance scenarios in relation with obstruction angle. The lines show the same cases with only surface reflectance alteration.

The percentage of cases achieving the U ≥ 0,4 benchmark are shown in Figure 42. The increase of complying cases was linear, as the surfaces reflectance shifted from Dark to Medium to Bright. Considering the DA_{300} result (Figure 40) and this one, it can be seen that surface reflectance was the sole independent parameter that increased illuminance levels (Figure 40) and uniformity simultaneously.

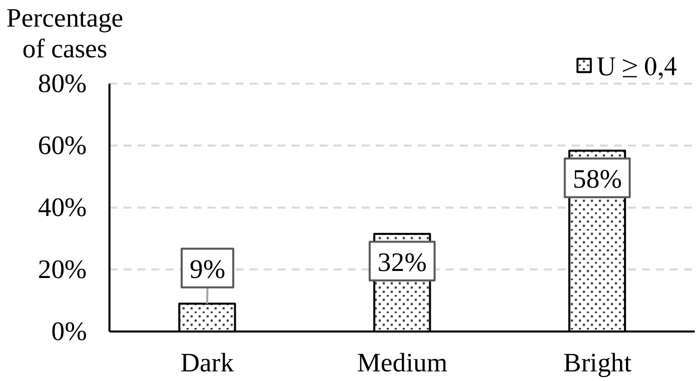

Figure 42. Cases complying with U ≥ 0,4 for different reflectance scenarios. All cases are included.

4.2.8 Window niche

The results on the window niche include cases of 15 % and 30 % WWR. The increase of the opening on the interior side of the wall due to the niche did not allow many large WWRs to be generated (large WWR + niche offset > façade area). The following figures show relative results per category.

Dynamic metrics

Cases complying with DA_{300} ≥ 50 % were equal for all window niche angles (Figure 43). Similar results were found for the other dynamic metrics.

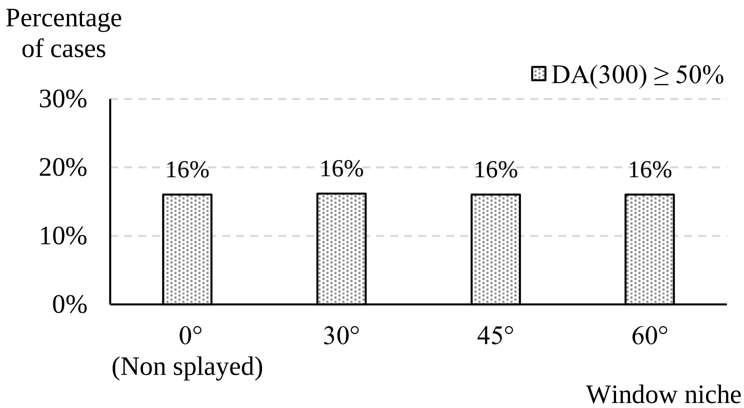

Figure 43. Cases complying with $DA_{300} \geq 50$ % for different window niche steps. Cases of 45 % and 60 % WWR are excluded.

Static metrics

The static metrics did not display significant changes when increasing the window niche either. Figure 44 shows the percentage of cases that comply with DF ≥ 2,1 %. The deviations stand for marginal differences that do not indicate an actual impact of niche.

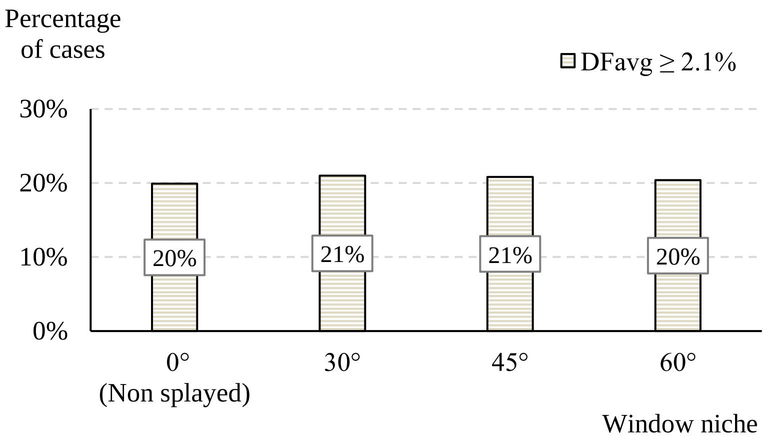

Figure 44. Cases complying with $DF_{avg} \geq 2,1$ % for different window niche steps. Cases of 45 % and 60 % WWR are excluded.

Consequently, the window niche had hardly any impact on the daylight metrics, both dynamic and static. The impact could be perceptible only at the first row of nodes that were included in the grid. To make this clearer, Figure 45 illustrates the DF distribution while altering the window niche. The illustrated case was a one-window case of 30 % WWR in the Center and Middle position of the façade. The T_{vis} was 0,50, the reflectance scenario were dark and the obstruction angle was 30°. The back end of the room was the same in all niche steps. Only a slight change can be noticed between the 0° angle and the rest of the angles, if one follows the 1,50 contour line towards the workstation (towards left). The same results were found for all other one-window cases. A room section illustrating these cases is provided in Appendix A (Figure A-1). The section is parallel to the window and shows the DF performance of the grid nodes closest to the window.

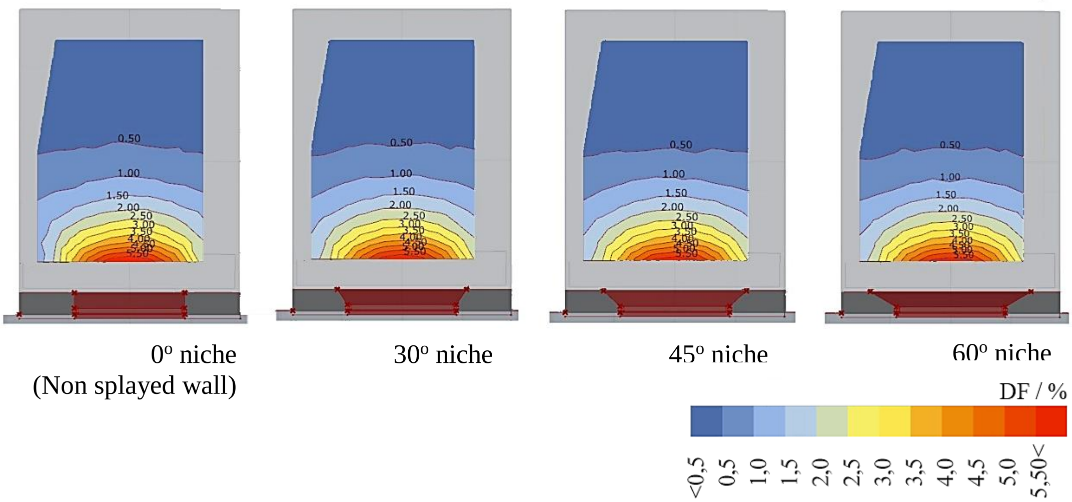

Figure 45. Illustration of DF distribution with contour lines for different window niche steps. All steps have: one window, center-middle placed, 30 % WWR, T_{vis} of 0,50, dark reflectance scenario, obstruction angle of 30°and non-splayed walls.

Another example of the DF distribution in the office, with two windows is illustrated in Figure 46. For all niche steps, the WWR was 30%, the T_{vis} 0,50, the reflectance scenario dark and the obstruction angle 30°. Once again, the impact of the niche was perceptible only very close to the window. Additionally the contour lines closer to the window seem smoother when the niche is 60°. Overall, it is shown that for an offset grid, a niche would only benefit the areas closer to the façade and between openings. A room section illustrating these cases is provided in Appendix A (Figure A-2). The section is parallel to the window and shows the DF performance of the grid nodes closest to the window.

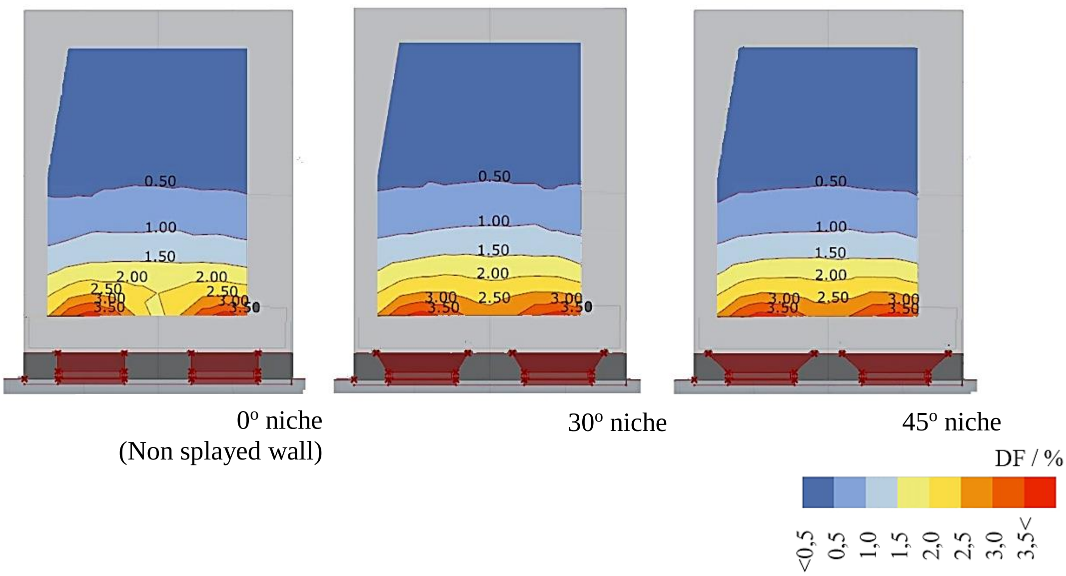

Figure 46. Illustration of DF distribution with contour lines for different window niche steps. All steps have: two windows, placed in the center with distance equal to their width, 30 % WWR, T_{vis} of 0,50, dark reflectance scenario, obstruction angle of 30°and non-splayed walls.

4.2.9 Obstruction angle

The presented results include all parameter iterations i.e. all orientations, window sizes, reflectances etc.

Dynamic metrics

Figure 47 shows the impact of the obstruction angle on the DA_{300}. When the obstruction angle was 60°, hardly any office achieved $DA_{300} \geq 50$ % at the workstation area and no case reached it at the office room grid. For a 30° obstruction angle, 26 % and 7 % of the cases achieved a $DA_{300} \geq 50$ % at workstation and office room grids respectively. The percentage of cases increased significantly when there was no obstruction, the increase being more dramatic for the office room grid (from 7 % to 40 %).

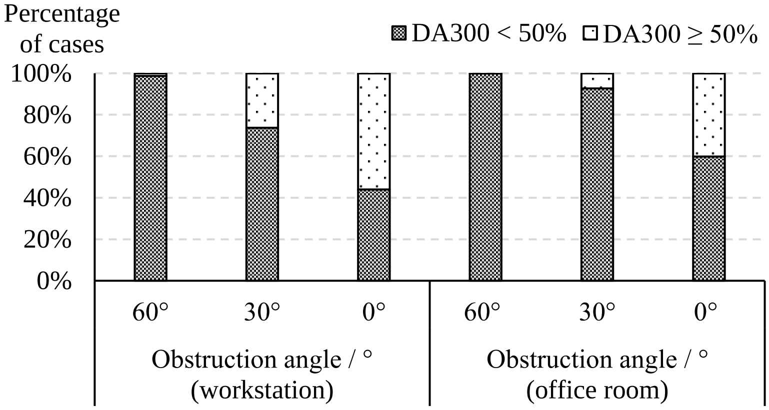

Figure 47. Cases complying with $DA_{300} \geq 50$ % for different obstruction angles. All cases are included. The results of the workstation grid are shown in the left part and of the office room grid in the right part.

Static metrics

The effect of the obstruction angle on the DF_{avg} is presented as boxplot diagrams in Figure 48. The DF_{avg} was found inversely proportional to the obstruction angle. The effect was considerably more evident for larger WWRs.

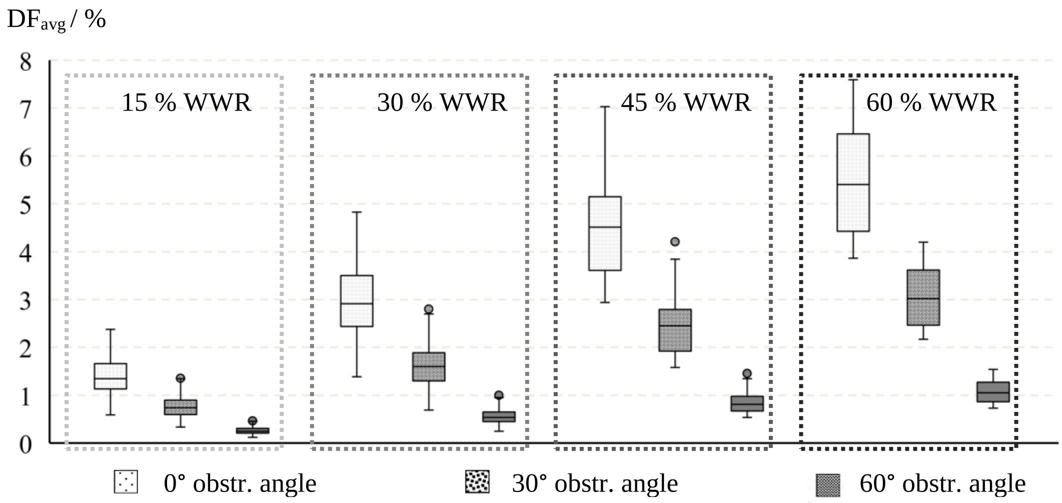

Figure 48. Boxplots of DF_{avg} ranges for different obstruction angles the window sizes. All cases are included.

4.3 Combined results

Figures 49 and 50 show the effect of four independent variables i.e. reflection, obstruction, orientation and transmittance, on the daylight performance in terms of $sDA_{300/50\%}$ (area illumination) and DGPs (visual comfort). The 'y' axis indicates percentage of cases that achieved each benchmark. The benchmark in Figure 49 is the nominally accepted level of $sDA_{300/50\%} \geq 55$ %. The benchmark in Figure 50 is $DGPs_{(95\%)} > 0{,}40$ or $DGPs_{(5\%)\ avg} > 0{,}42$, which corresponds to cases with disturbing and intolerable glare. There is a correlation between the two figures. For all independent parameters, with the exception of orientation, increased $sDA_{300/50\%}$ resulted in increased glare probability. This was not true for orientation parameter, where the west orientation included the most cases with glare, although the south included the most cases with high $sDA_{300/50\%}$. This could be attributed to the lower sun altitude seen by western façades compared to north one, which included the glare sensor (located at observer's eye).

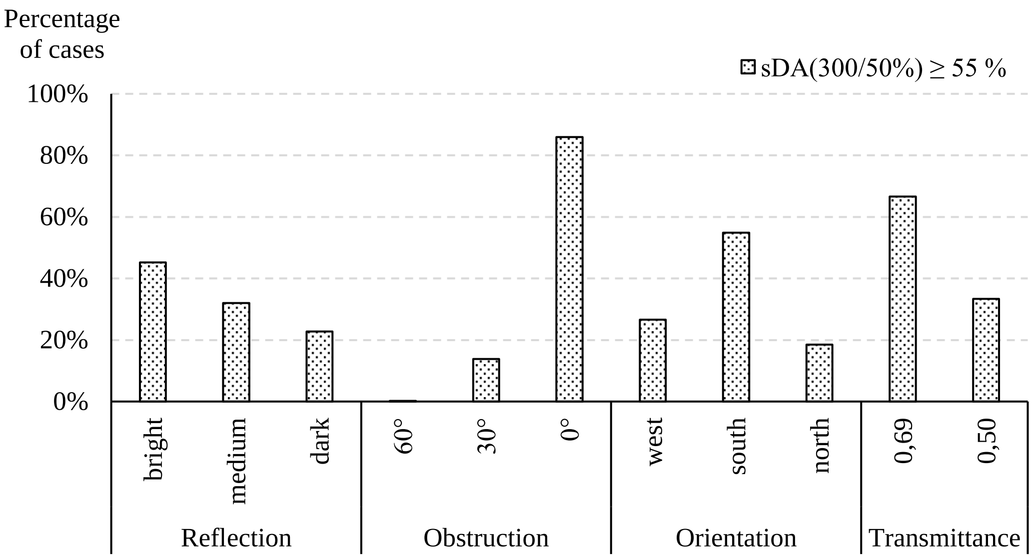

Figure 49. Cases complying with $sDA_{300/50\%} \geq 55$ % for different independent variables. All cases are included.

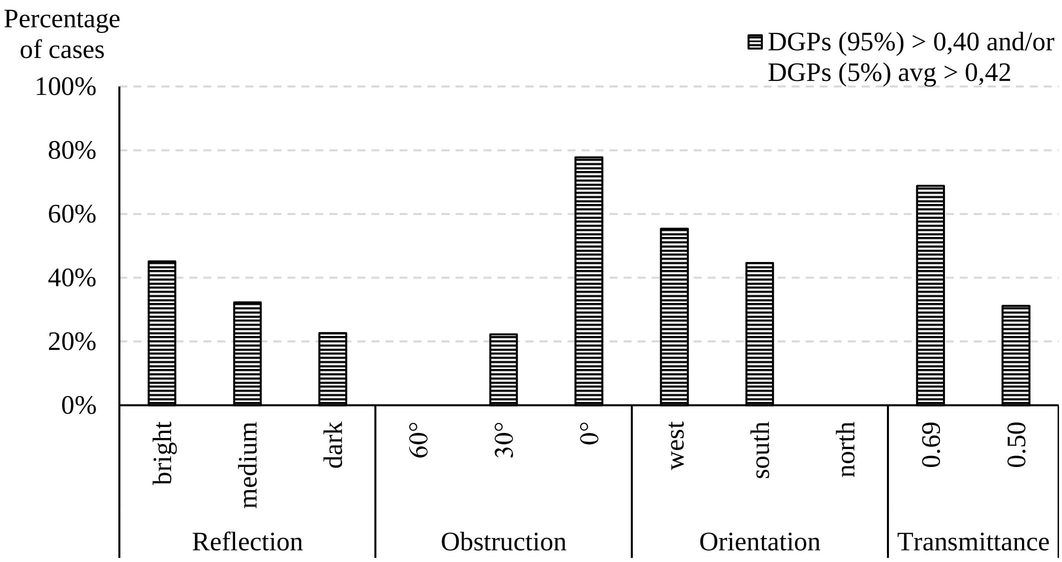

Figure 50. Percentage of cases that have disturbing or intolerable glare rating for different independent variables. All cases are included.

5 Discussion

In the first chapter of the result section, some static metric correlations were presented. The DF_{median} (median DF) was found equivalent to DF_p (point DF) and also equal to about 78 % of the DF_{avg} (average DF). The correlation between these metrics was high (high R^2 values) indicating a stability in the results and in geometric light relations within the space. These correlations are limited to the case of a simple rectangular room illuminated by window(s) on one side. Further study of arbitrary room layouts and multiple façades could establish a more generalized correlation between these metrics. However, as the rectangular is considered the most typical shape for cellular offices, it could be argued that the DF_{point} is a satisfying daylight indicator, since it relates to DF_{median}. In addition, the correlation between the DF_{median} and DF_{avg}, was in accordance with results from Christoffersen and Mardaljevic (2017) who demonstrated that side-lit spaces always have lower DF_{median} than DF_{avg} values.

A consistent outcome was that when illuminance levels increased, the uniformity decreased, as it normally corresponded to more brightness closer to the façade than at the back of the room. The exception to that was the effect of interior surface reflectances. When the surfaces had higher reflectance values, both uniformity and illuminance levels increased, the impact being greater for the former metric.

It is important to define the workstation position from an early stage, so that no direct glare sources are included in occupant's visual field. For this study, the condition of not having direct glare sources was created to estimate glare probability by only assessing the illuminance on a fixed point of view, using DGPs. However, even in absence of direct glare from outdoors, some cases still confronted glare problems when the illuminance levels increased. This occurred mainly for unobstructed, large window sized offices that faced south or west. A movable shading element could overcome these issues, if applied during discomfort hours, but this was beyond the scope of this report. It was found that a north facing office or offices with obstruction angle of 60^o did not experience any glare problems regardless of the other independent variables.

The workstation area achieved higher illuminance values than the overall office area. The placement of the workstation closer to the exterior façade was the obvious reason. For the south **orientation,** the difference between front and back parts of the room was lower than for other orientations. For north and west orientations, the workstation area achieved considerably higher DA_{300} scores than the office area. This can be attributed to the direct solar rays that illuminated the back of the room more in the case of a south facing room.

The **glass transmittance** influenced the climate-based metrics significantly (DA_{300} and sDA_{300} doubled when T_{vis} increased from 0,50 to 0,69). Static metrics also showed a high increase. However, there was more glare probability and a decrease of illuminance uniformity.

A high **window position** was shown to improve the daylight performance. However, a high position is not always possible due to construction limitations (HVAC ducting, electrical installations). In such cases when the window must be placed lower, it is advisable to place it in the middle of the façade, instead of closer to side walls. This improves the illumination of the overall space without compromising the illumination of the workstation.

Concerning the **window shape**, the square window was the best performing. When the opening was straightened horizontally or vertically (2:1 or 1:2), for a given window size, the overall daylight performance was reduced to some extent. It was shown that when window height is equal to window width the space is better illuminated, especially for low WWRs. A squared window can contain the glazing unit in a shorter frame length. This is also better for energy efficiency, as the frame U-value is higher than the glazing U-value, and the linear thermal bridges are larger for lengthy frames.

One of the most effective parameters to increase daylight level, as measured by the DF and DA, was the **window size**. The larger WWRs outperformed the smaller ones by far. The larger benefit was observed when increasing WWR from 15 % to 30 %. The benefits would decrease though for high obstruction angles. For a 60° obstruction angle, increasing the WWR from 15 % to 60 % would only yield a 1 % increase in the room DF_{avg}. This shows the implications of urban planning on the performance of office spaces. In a dense environment, high WWRs (that increase the heating demand) do not supply potential daylight.

As the **number of windows** increased, for the same WWR, the space illuminance decreased. Moreover, for two-window cases, the daylight levels decreased when the intermediate distance between them was longer. The horizontally arranged windows performed better than the vertically arranged ones. Consequently, the current trend of using long vertical windows is not justified, according to the results found here. Horizontal arrangements would not only provide a better view out due to intrinsic horizontal shape of our visual field, it would also provide better daylighting in the space and energy savings. It should be pointed out that these parameters could only be applied in small window sizes due to restricted exterior façade area. It should also be noted that the frame width was kept constant for all window sizes. This effectively means that splitting a single window of a given WWR into two windows, corresponds to a significantly larger frame area and thus higher heating loads.

The **surface reflectances** proved to be fundamental for daylighting. The brighter the surfaces, the deeper the daylight propagated in the room. This was evident for both dynamic and static metrics. The most interesting finding was that this was the only parameter increasing both illumination and uniformity simultaneously. In addition, surface reflectance was equally beneficial for any obstruction angle, unlike other parameters. It should be noted though, that interior office walls are never completely empty, as in this study. Shelves or other furniture may reduce the average wall reflectance and this should be accounted for by design teams when simulating office spaces.

The iterations of **niche** had no effect on the daylight metrics for the assessed room geometry. The thickness of the external wall was assumed 410 mm though, which makes this finding case specific. The impact was perceptible only in the first row of grid nodes that were closest to the window. Grid points should have also been monitored closer to walls and more specifically towards the window in order to have a more precise illuminance distribution exactly after the light passes through the glazing. If the grid was not offset 0,50 m parallel to the window, the impact would be probably more evident.

The provided exemplary illustrations showed that uniformity could not increase with this strategy. The DF distribution at the back of the room was not affected by the niche design, to help increase it. It should be noted here, that this study only considered sensor-point evaluation, not view-based. Splayed walls could display higher overall luminance that could be captured by a fisheye rendering of the scene. As more of a matter of visual comfort and perception rather than quantitative value, a luminance based analysis towards the exterior wall would be more informative in these terms.

Finally, the **obstruction angle** was influential on both the workstation and the overall room illuminance. Lower obstruction angles proved to be necessary to increase illumination at the back of the room. The effect was most perceptible when analyzed with respect to the different window sizes. An increased obstruction angle, which actually corresponds to a very dense urban context, could make the window size of low importance as it diminishes the daylight performance to a great extent. When the obstruction angle had a moderate value of 30^o, the window size impact was more significant. When there was no obstruction, all window sizes significantly affected daylight level as measured by DF and DA. More often though, there is an urban context with surrounding buildings or vegetation that obstruct some part of the window.

6 Conclusions

This thesis aimed to provide information on daylight performance of side-lit offices with different fenestration configurations, sizes, glazing types and inner surface reflectances. Different parameters regarding window design were studied to evaluate their impact. What was concluded after this research can be summarized in the following points:

- For side-lit spaces of simple geometry, the DF_{point} was approximately equal to the DF_{median}.
- For side-lit spaces of simple geometry, the DF_{median} was approximately equal to 78 % of the DF_{avg}.
- An obstruction angle of 60° made it impossible for designs to reach a DF_{avg} of 2,1 % or a sDA of 55 %.
- Splaying the niche had no effect on daylight levels as measured by DF and DA for the investigated wall thickness of 410 mm.
- For smaller window sizes (WWR = 15 %), it was found that a single square window was the best performing solution compared to a vertical or horizontal window with the same surface area.
- The vertical shaped windows were the worst performing ones in terms of DF and DA, while the horizontal windows were the second best performing solutions.
- Arranging windows along the horizontal axis showed to be better overall solution than arranging them along the vertical axis.
- Highly (along the vertical axis) placed windows performed consistently better. Middle (along the horizontal axis) placed windows performed better for the overall illumination of the office.
- The reflectance of interior surfaces was the only parameter that increased both daylight illuminance and uniformity simultaneously.

Summary

Several parameters affecting daylight were investigated for an exemplary cellular office in Lund, Sweden. The main goal was to evaluate the impact of each parameter to the daylight conditions and provide some key conclusions that could be taken into consideration at an early design stage.

Initially, a literature review was conducted in order to specify the key independent variables and the dependent variables to monitor the consequent effects on daylight levels. The studied independent variables were: orientation, window shape, window size, window position, number of windows, glazing transmittance, window niche, reflectance of the surfaces and obstruction angle. The dependent variables were both dynamic and static metrics.

The evaluation of the design alternatives was conducted through simulations to produce daylight performance data. Each parameter was iterated between two to four discrete steps, leading to a total of 11.124 assessed cases. Typical values and data attained from literature review were used to define parameters that did not change throughout the study, such as the assumed road width.

The study provided information on daylight metric correlations, impact of separate parameters on the daylight metrics and combined results. Benchmark compliance made it easier to comprehend and arrange the research findings.

Overall, highest compliance rates were achieved for larger, highly placed windows in the middle of the façade. Window glazing transmittance and obstruction angle were shown to affect illumination significantly. On the other hand, splaying the wall around the window proved to have no quantitative impact on office daylighting for the studied room. In terms of window number and shape, it was concluded that single squared-window solutions performed better.

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Appendix A

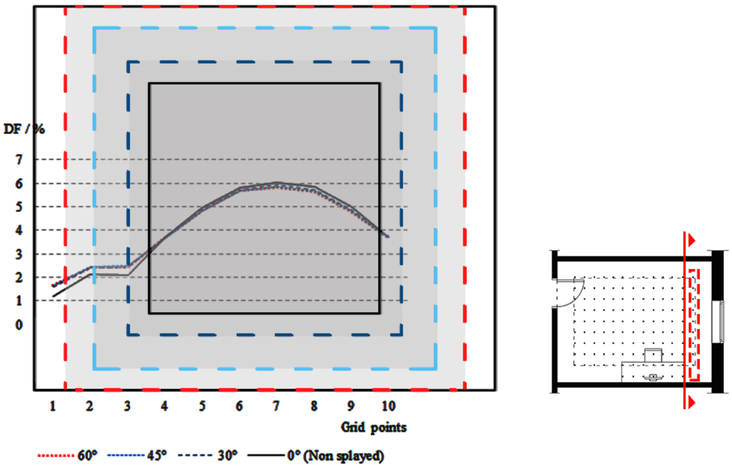

Figure A-1. Room section parallel to the window. The vertical axis shows the DF scores of the first row of grid points (y axis) as the small plan indicates. The coloured lines show the niche steps and the corresponding DF performance. All steps have: one window, center-middle placed, 30 % WWR, T_{vis} of 0,50, dark reflectance scenario, obstruction angle of 30°and non-splayed walls.

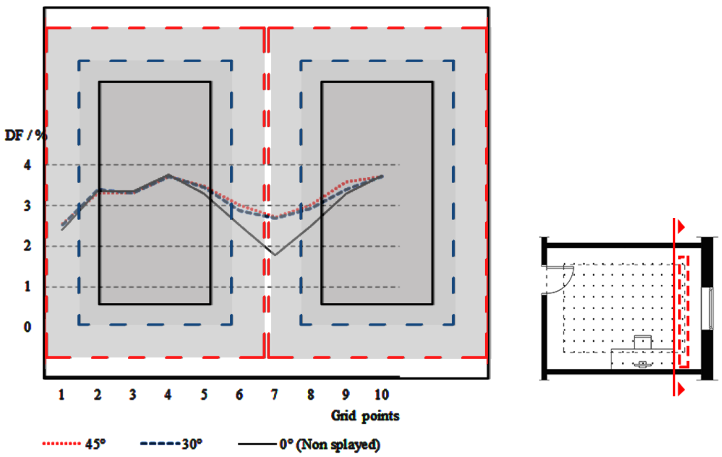

Figure A-2. Room section parallel to the window. The vertical axis shows the DF scores of the first row of grid points (y axis) as the small plan indicates. The coloured lines show the niche steps and the corresponding DF performance. All steps have: two windows, placed in the center with distance equal to their width, 30 % WWR, T_{vis} of 0,50, dark reflectance scenario, obstruction angle of 30°and non-splayed walls.

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