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Daylight Study with Adaption of European Standard EN 17037:2019

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The objective of this thesis was to deliver study of daylighting simulation and its effectiveness when performed accurately. Furthermore, since a new European Standard EN 17037 about guidelines and recommendations of daylight in buildings was released in 2019, the thesis also studied the standard to understand better the design of daylight in European countries. Furthermore, a dance studio in Belgium was simulated to analyze how the new standard can affect daylight simulation.

The simulation required the use of several software tools, including Rhinoceros, DIVA, Grasshopper, and Ladybug plug-in. With these, combined with basic knowledge about daylighting and guidelines from the EN 17037, the thesis expected to demonstrate a picture of how daylight is assessed in reality. The results indicated a compliance with three out of four criteria in the EN 17037.

Keywords	daylighting simulation, sustainable, EN 17037, natural light

Contents

List of Abbreviations

CDD	Cooling degree days
DGP	Daylight glare probability
DHI	Diffuse horizontal irradiance
DNI	Direct normal irradiance
GHI	Global horizontal irradiance
HDD	Heating degree days
LRV	Light reflectance value
sDA	Spatial daylight autonomy
VLT	Visible light transmittance

1 Introduction

In 2019, Europe was hit by severe heat waves between June and July. Temperature records were set at 45 degrees Celsius in France and Italy, and at least two people died of the heat in Spain [1.] The world is getting hotter every day which results in a higher energy demand needed in households. In the building sector, the concept of degree days is used to calculate the needed energy for buildings. A degree day is calculated by comparing the outdoor temperature of a location to a base temperature, usually 15°C for heating degree day (HDD) and 24°C for cooling degree day (CDD). [2.] The higher the value of degree days, the colder or hotter the temperature, is consequently resulting in a higher energy demand for space heating or cooling. [3.]

According to the statistics from the European Union, the cooling degree days of Europe from 1988 to 2018 increased from 55.78 CDD to 91.60 CDD, or by 64.2%. For Finland, the increase was 69.4%. [4.] The world is turning hotter every year, and more energy is demanded for the cooling purpose. Therefore, it is expected to have a renewable energy source in order to avoid over-exploitation of fossil fuel. At the present, electricity is the second most consumed final energy in the EU (24.4%), second to natural gas, 59.1% of the consumed electricity is used for lighting. [5.]

As mentioned above, lighting alone consumes a significant amount of energy. To reduce that, a design strategy called daylighting can be applied in which designers maximize the use of natural daylight in order to reduce the amount of lighting fixtures in use. Daylighting is not a new concept in architecture but thanks to the development of today's simulation software, it has become a more reliable real-life tool. A proper design of natural daylight in living spaces can contribute significantly to the quality and availability of indoor lighting. In addition, natural light is reported to help people concentrate, and it has health benefits: it prevents depression and eye strain, and supplies vitamin D. [6.]

In 2019, the EU introduced the EN 17037:2019 standard that sets requirements on providing natural light into a building. Standards are set in four categories: daylight provision, view out, sun exposure, and glare protection. The aim of this thesis is to give an overall introduction into daylighting simulation, and the metrics used in it according to the guidelines of the EN 17037. A dance studio in Belgium is utilized as a sample case in order to study how daylighting can influence the architectural design and what benefits it can bring to the indoor comfort.

2 Daylight Study

2.1 Solar Radiation

Radiation from the sun is an almost endless source of energy that brings life to all creatures on earth and determines the climate. Every morning when the sun rises from the east, the earth receives 3.846x10^{26} watts of energy. In the form of radiation, there are three main ways of which sunlight can be captured on a surface: direct normal irradiance, diffuse irradiance, and global horizontal irradiance. [7.]

Direct irradiance is the solar beams radiating from the sun on a straight line and striking on a surface without any interruption. However, not all radiation that reaches the ground is direct radiation, but some of it is dispersed and reflected by molecules, particulates, or clouds in the atmosphere, and it reaches the ground as diffuse irradiance from many different directions. [8.] An intuitive example of diffuse radiation is the condition of daylight under an overcast sky or a cloudy day when the direct solar radiation hardly gets to the ground.

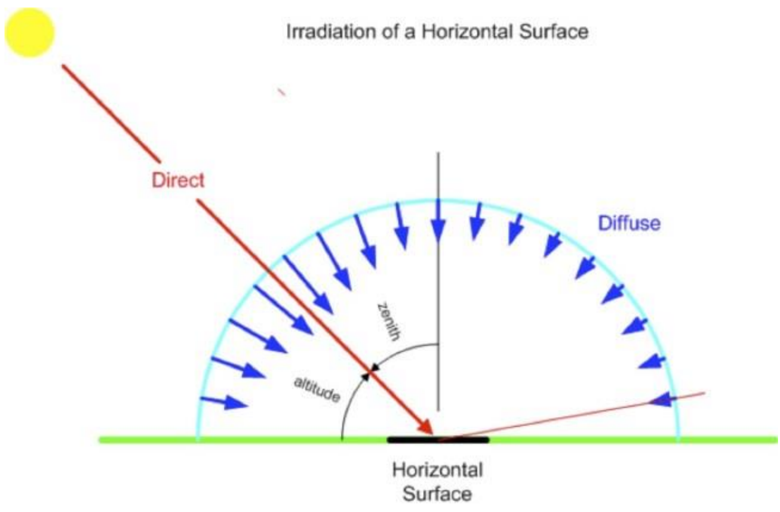


Figure 1. Different types of radiation striking on a horizontal surface [9].

Global horizontal irradiance is the total solar radiation that arrives on a horizontal surface, in other words, the total amount of direct and diffuse irradiance. Direct horizontal irradiance, shown in figure 1, is the value of direct normal irradiance after taking into account the zenith angle z. The formula for global horizontal irradiance is

$$GHI = DHI + DNI \times \cos(z)$$

where GHI is the global horizontal irradiance, DHI is the diffuse horizontal irradiance, and DNI is the direct normal irradiance. [10.]

Besides the different methods of how solar radiation reaches the earth surface, the way in which sunlight transfers heat and energy is also distinct. In general, solar energy travels as waves that vary in wavelength and consist of three main regions: infrared radiation, ultraviolet radiation, and visible light. This is called the electromagnetic spectrum (figure 2). These types of radiation are different in terms of wavelength, energy, and the way they effect on human awareness.

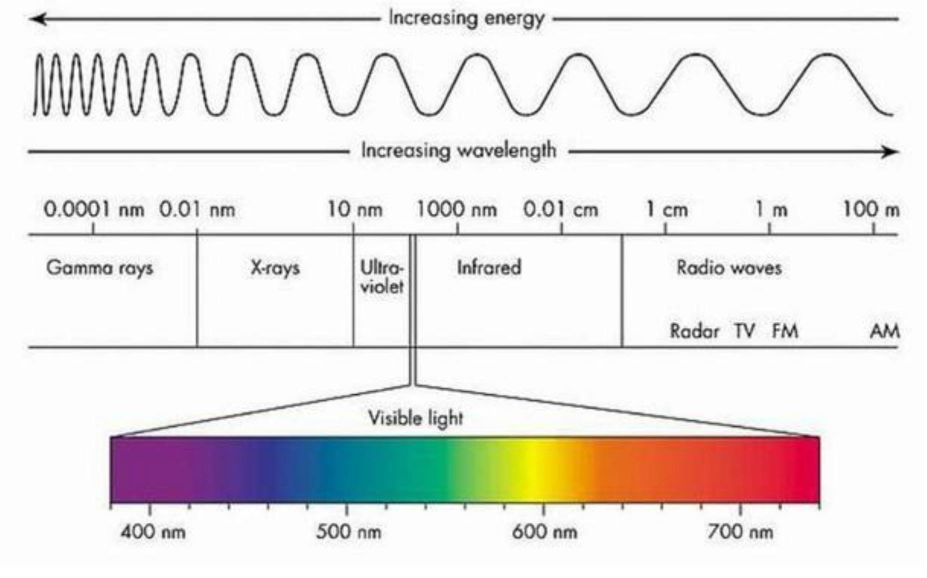


Figure 2. The electromagnetic spectrum [11].

Infrared radiation has the longest wavelength but transfers a lower energy. The waves of infrared radiation are invisible to the human eye. People perceive infrared radiation as heat. Ultraviolet radiation is the shortest type of radiation and like the infrared radiation, it is invisible to human beings. Ultraviolet radiation is the portion of sunlight that burns or tans the skin. Finally, visible radiation makes up the only visible portion of solar radiation. It falls between the infrared and ultraviolet in strength and wavelength. Visible radiation is what the architects will want to maximize in daylighting design. [11.]

2.2 Windows and Glazing

Windows are usually the place where daylight is collected. Window design and a smart choice of glazing can significantly improve the daylight quality of a space, and the owner's experience. One of the methods to effectively design windows is to wisely arrange the orientation of windows in order to maximize the daylight provision from the sun. Countries in the northern hemisphere might sometimes want to have bigger windows on the south façade where they can receive both daylight and heat gain during winter. However, more daylight does not equal with better lighting conditions. Too many windows on the south façade equals a greater risk for sun glare. Daylighting is a matter of balancing between daylight provision and glaring control. [12.]

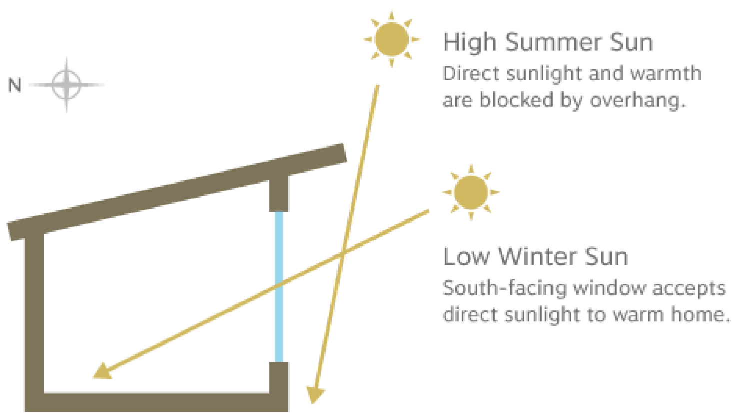


Figure 3. Overhangs prevent direct sunlight during the summer. [13.]

To overcome the problem of glare during the summer while still being able to maintain the heat gain received from the window in the winter, an appropriate design of overhangs can prevent most of the direct sunlight, and shade the room from excessive heat during the summer. Furthermore, because the sun is low during the winter, the risk of glare will be higher in the winter because sunlight can strike directly onto the surface of a window. A shading device or several trees outside can act as obstructions to block the direct sunlight from striking the room. Shading devices can be either internal or external, fixed or movable, and they can also serve as insulation as well besides daylighting purpose when being used as a sun screen (figure 4).

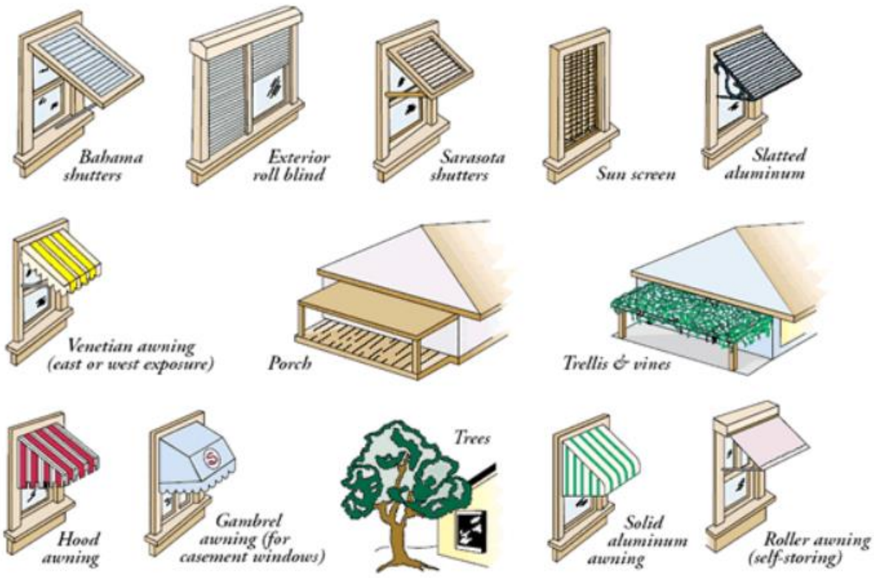


Figure 4. Strategies for window shading [14].

Another factor that can contribute to the daylight quality are the properties of the glazing. The characteristics of a glazing system include visible light transmittance (VLT), g-value, and u-value. The g-value determines how well the glazing absorbs solar heat, the VLT specifies the percentage of visible light transmitted through the window, varying between 0 and 1. A high VLT is desirable to maximize daylight. [14.]

2.3 Indoor Light Reflection

Light can come not only from direct sunlight but also from reflection inside a room. Therefore, a wise choice of interior light reflectance value can best benefit from the daylight collected from the outside. The ceiling, walls, floors, or furniture such as desks in an office can be painted in a color with a high light reflectance value. The interior lighting rules of LEEDv4 BDC (Building Design and Construction) recommend light reflectance values for interior surfaces of furniture. The recommendation is shown in table 1.

Table 1. Recommendation of light reflectance value [15].

Objects	**Light Reflectance Value**
Ceilings	At least 85%
Walls	At least 60%
Floors	At least 25%
Work surfaces	At least 45%
Movable partitions	At least 50%

The designers can choose painting products with high light reflectance values in order to increase the reflection of lighting in a room. On the other side, where there are risks of glaring, a lower reflectance value can be chosen.

2.4 Design Metrics

2.4.1 Basic Metrics

To design lighting comfort, one needs to understand the metrics of daylight measurement. There are several definitions and terms that need to be considered thoroughly. The first metric is luminous flux. It is the total amount of light emitted by a light source in all directions. Lumen is the unit for luminous flux and its symbol is ”lm”. [16.]

In contrast to lumen where light is measured in all directions, candela (symbol: cd), the unit of luminous intensity, is used to indicate the amount of light emitted by a light source in a specific direction. If lumen demonstrates how much a light source can emit, then candela means how far the light can travel. An example of candela is the light emitted by a laser where the measures are high in candela but low in lumen. There is a relationship between luminous flux and intensity. If a light source emits one candela uniformly in all directions, the flux can be calculated by multiplying the intensity by 4π. Thus, this uniform 1-candela light source emits 12.6 lumens in total. [16.] Figure 5 below demonstrates the relationship between luminous flux and luminous intensity.

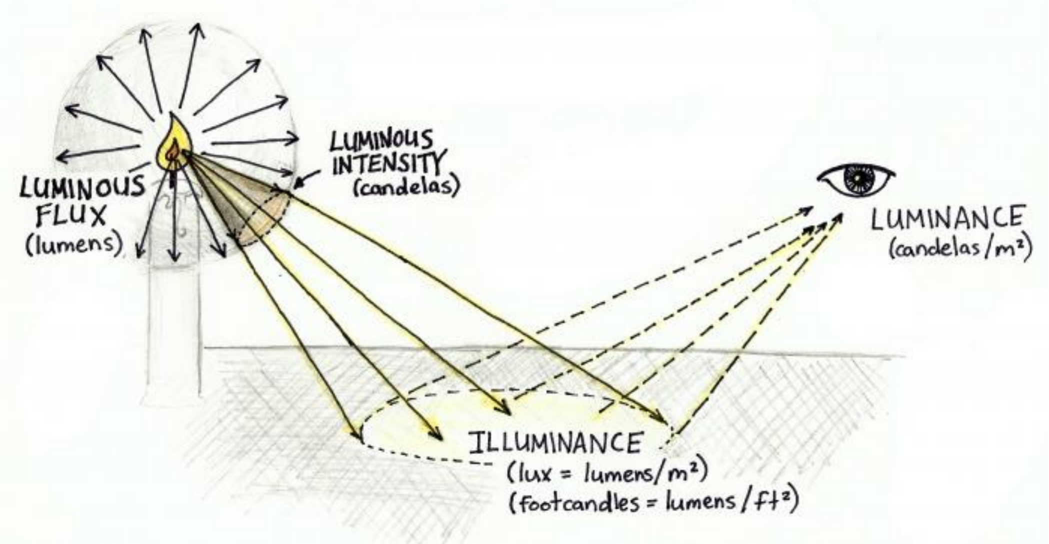


Figure 5. Luminous flux and intensity [16].

The most important measure for designers is illuminance. Illuminance is the total amount of luminous flux falling on a given surface, and it is measured in lux (lumen/m^2). It is used as a reference measurement in the performance of a light system. In daylighting study, the illuminance value is influenced by the outdoor illuminance emitted by the sun under different sky conditions, varying from sunny skies to intermediate or overcast skies. Different sky conditions result in higher or lower outdoor illuminance. The role of a designer is to make sure tenants can have an appropriate level of illuminance in occupied spaces, suitable for their preferred activity. [16.]

Although luminance might sound similar to illuminance, it indicates an opposite definition. Luminance describes the amount of light reflected from a surface and recognized by the human eye. The unit for luminance is candela/m^2 (cd/m^2). Luminance is what human eyes perceive when looking at an object, or when a camera is used. An image of an object is actually the luminance of it compared to the luminance of the surrounding environment. Because of that, luminance is also used as one of the factors determining the glaring of a space. The human eye can handle an extensive range of brightness; for examples the luminance value of the sun and the moon are: 1,600,000,000 cd/m^2 and 2,500 cd/m^2, respectively. [17.]

2.4.2 Daylight factor

Daylight factor is a metric used in daylighting design to understand how daylit an area is. It is the ratio between the indoor illuminance and outdoor illuminance under an unobstructed hemisphere of overcast sky. It is defined by the formula:

$$DF = \frac{Ei}{Eo}\; x\; 100\%$$

where DF is the daylight factor, Ei (lux) is the indoor illuminance, and Eo (lux) is the outdoor illuminance. [18.]

Although the sky conditions are constantly changing, the daylight factor method uses a typical type of overcast sky: a completely cloudy sky with a 100% coverage. Due to this, the method assumes that daylight is uniform from every orientation, regardless of time and location, at a typical low level of illuminance. In the daylight factor, direct sunlight is excluded and only diffuse light is taken into account. Designers usually use the overcast sky condition to calculate the worst scenario of daylight in an area. [18.]

For a long time, the daylight factor has been the most widely used method for determining the daylight quality. It is used to establish compliance with the building code or regulation, as well as to score credits within various building evironmental rating systems, such as BREAAM, LEED, and Greenmark. In spite of its dominance, the daylight factor is criticized for its many limitations. Because it is calculated under overcast sky, the daylight factor neglects the importance of location, and building orientation, and it provides no indication of glare. Therefore, researchers have introduced alternatives for the conventional daylight factor. Daylight Autonomy (DA) is a new metric, which was adapted by the European Standard EN 17037, it is discussed below in the next chapter 3. [18.]

3 The EN 17037:2019

European countries used to have different standards or building codes to deal with daylight in buildings. The EN 17037 is the first European Standard that addresses daylighting performance exclusively. The EN 17037 explains how to utilize natural daylight and how to limit glare, and gives metrics to be used for the evaluation and verification of the daylighting performance. The standard encourages designers to achieve more natural daylight, while still ensure other issues related to daylight design are under control. These issues are view out, exposure to sunlight, and protection from glare. According to the standard, the EN 17037 shall be used as a national standard or replace any existing standards across different European countries by June 2019 at the latest. [19.]

3.1 Daylight Provision

General

Daylight is important to the lighting needs of all type of buildings. Taking advantage of daylight can reduce the electricity bills, and natural lighting is considered necessary for the health and concentration of occupants. Therefore, the daylight provision chapter in the EN 17037 indicates a method of calculation and evaluation of daylight availability in a space. [19.]

According to the standard, the daylight provision must be studied under criterions of a reference plane within a space, for at least 50% of the available daylight hours. The reference plane is an imaginary plane which must be created by a software. The reference plane is supposed to be a working plane in a space, on which illuminance values, or daylight factor values, are calculated. This reference plane should be located at 0.85 m above the floor. A requirement of minimum target illuminance and target illuminance are set to achieve the desired daylight quality. There are two methods to evaluate the daylight provision: a calculation method based on daylight factors (method 1) and a calculation method of illuminance level that uses climatic data for a given site (method 2). According to the EN 17037, it provides three levels of evaluation: minimum, medium and high. Minimum target illuminance must be achieved in addition to target illuminance to ensure the uniformity of daylight throughout a space. [19.] Table 2 below shows the recommended levels for daylight provision.

Table 2. Daylight provision on a vertical and inclined surface [19].

Level	**Target illuminance** E_T (lux)	**Fraction of space for target level**	**Minimum target illuminance** E_{TM} (lux)	**Fraction of space for minimum target level**	**Fraction of daylight hours**
Minimum	300	50 %	100	95 %	50 %
Medium	500	50 %	300	95 %	50 %
High	750	50 %	500	95 %	50 %

In addition to the requirement mentioned above, the standard also implies a recommendation for the light reflectance value of interior surfaces. These are described in table 3.

Table 3. Recommendation of reflectance values for interior surfaces [19].

Surfaces	**Light Reflectance Value**
Ceilings	0.7 to 0.9
Interior Walls	0.5 to 0.8
Exterior Walls	0.2 to 0.4
Exterior ground	Usually 0.2

Unlike the LEEDv4 (table 1, chapter 2.3), the EN 17037 does not require reflectance value for the floors, but for exterior walls instead. The light reflectance values for ceilings and interior walls in both the LEEDv4 and the EN 17037 are relatively similar. [15.]

Evaluation methods

Method 1. Simplified method using daylight factor

The daylight factor is calculated on the basis of the ISO 15469:2004 for the overcast sky and for a reference plane at 0.85 m. After the daylight factors are calculated, the illuminance level must meet or exceed the target value and the minimum target value as defined in table 2. The formula for calculating illuminance values with the simulated daylight factors is:

$$Dt = \frac{\text{Illuminance level}}{\text{E v,d,med}}\ x\ 100\%$$

where Dt is the target daylight factor, exceeded for more than half of daylight hours and over 50% area of the reference plane, and Ev,d,med is the median diffuse horizontal illuminance given by the EN 17037. [19.]

The EN 17037 provides a list of median diffuse horizontal illuminance values for 33 countries of national members in the community of European Committee Standardization (CEN) . Table 4 below is an example of the median diffuse horizontal illuminance values for Finland, Sweden and Belgium. [19.]

Table 4. Mean diffuse horizontal illuminance ($E_{v,d,med}$) of Finland, Sweden and Belgium [19].

Nation	**Median Diffuse Illuminance** $E_{v,d,med}$	**D to exceed 100 lx**	**D to exceed 300 lx**	**D to exceed 500 lx**	**D to exceed 750 lx**
Finland	13,500	0.7 %	2.2 %	3.7 %	5.6 %
Sweden	12,100	0.8 %	2.5 %	4.1 %	6.2 %
Belgium	15,000	0.7 %	2.0%	3.3 %	5.0%

In short, the illuminance value can be easily calculated by multiplying the simulated daylight factor by the median external illuminance ($E_{v,d,med}$). If a designer in Finland is aiming at the target daylight factor of 2.2%, a minimum daylight factor of 0.7% must be achieved as well. Similarly, if the target daylight factor is 3.7%, the minimum daylight factor to be achieved is 2.2%, and so on.

Method 2. Detailed method using illuminance levels

The method using illuminance levels is the best solution for daylight provision. It requires simulation to use hourly sky and sun conditions acquired from climate data appropriate to the site. As similar to method 1, method 2 must be calculated on a reference plane of 0.85 m, where it must meet the target illuminance level for 50% of the daylight hours of the year, and on over 50% area of the reference plane. In addition, a minimum target level must also be met for 50% of the daylight hours, across 95% of the reference plane. [19.]

The minimum illuminance and target illuminance must comply with the requirements listed in table 2 at minimum, medium or high level, which corresponds to 300 lux, 500 lux or 750 lux, respectively. The calculation for this method should be carried out by using validated software. [19.]

3.2 View Out

General

The intent of the view out assessment is to ensure that occupants are given a visual connection with the outside surroundings. The view supplies information about the outdoor environment, weather and landscapes. In addition to the intent of giving a scene for viewing, a view to the outside is used to provide the occupants with refreshment and relaxation, especially in offices or hospitals, to prevent them to feel being trapped in a box, which can affect their work productivity or healing process. [19.]

There are three distinct layers to be considered for a view: a layer or sky, a layer of landscape, and a layer of ground. The view quality is assessed on the basis of the size of the daylight openings (for example windows), the width of the view, the distance from the view to the outside scene, the number of available layers, the quality of the environmental details of the view. [19.]

<u>Evaluation methods</u>

As explained above, daylight openings with a view outside can provide a connection with the environmental surroundings. The view should include layers of sky, landscape or ground. It is better to have a natural view instead of man-made environment. A view with a wide angle and distant view is preferred to a near and small sight. Furthermore, the quality of the view should be ensured with a clear and neutrally coloured glazing system. Table 5 gives a recommendation for three different levels of view out, from minimum to high, of which the high level is specifically suggested for high-rise buildings accommodated by people with limited mobility. [19.]

Table 5. Assessment of the view out [19].

Level of recommendation	**Horizontal sight angle**	**Distance to the outside view**	**Type of layers:** • **Sky** • **Landscape** • **Ground**
Minimum	≥ 14º	≥ 6.0 m	Must have at least land-scape layer
Medium	≥ 28º	≥ 20.0 m	Must have landscape and one additional layer (sky or ground)
High	≥ 54º	≥ 50.0 m	Must include all the layers

A horizontal sight angle is to determine the width of view out. It is assessed by calculating the angle from any reference points to the view openings. The reference points can be at any location in a space. [19.] The aim is to evaluate at which points, occupants can have a wide and distant view to the outside. Therefore, there can be many reference points ranging from minimum to high level of view out in an area. Figure 6 below is an example of how the horizontal sight angle is evaluated by the software DIAL+.

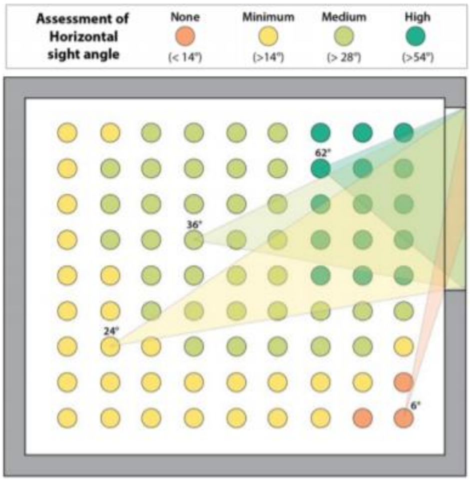


Figure 6. Horizontal sight angle at different reference points [26].

To ensure the quality of outside view, the glazing material of the view opening should provide a clear and neutrally coloured visibility. The evaluation provides three types of view (sky, landscape or ground) to be included, of which the landscape view is required in all three types (minimum, medium, high). The view can be examined by taking a photograph from a reference point indoors. [19.]

3.3 Exposure to Sunlight

<u>General</u>

Direct sunlight is a critical factor to the daylight quality of the interior of a building and it can contribute to the well-being of people. Direct sunlight is generally beneficial for most buildings throughout Europe, except for countries in hot climate. In some specific building types, like hospitals, schools, or nurseries, where sunlight is highly required for activities, minimum exposure to sunlight should be provided in at least one habitable space. Direct sunlight is considered valuable for physical health, such as providing vitamin D which helps build strong bones, healing skin conditions. Direct sunlight is also beneficial for mental health when during the winter, when the days are shorter and skies are dark, which can cause depression. Taking advantage of the short period of direct sunlight in a day can help stimulate the brain to create more serotonin and reduce excess melatonin. [20.]

However, besides the benefit of sunlight, designers should also take into account the overheating issue during summer time in temperate climatic conditions. Possible thermal discomfort can be controlled by appropriate planning of shading systems. By balancing between the useful solar gain in winter and undesirable excessive sunlight in summer, buildings can contribute positively to the reduction of energy consumption for heating and provide comfortable living experience by solar shading devides in summer. [19.]

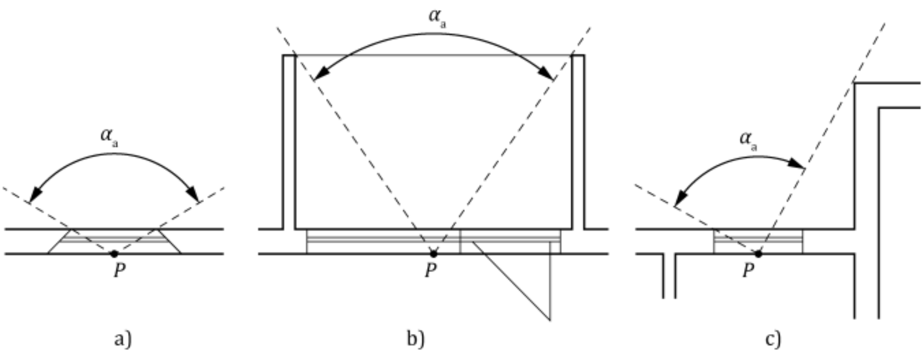
Evaluation method

Sunlight exposure is evaluated by checking if the sun is visible across the sky on a selected date and calculating the hours during which the building is exposed to direct sunlight. A space should receive a minimum time of possible sunlight on a selected date between February 1st and March 21st. When evaluating the exposure of direct sunlight on a building, at least one habitable space in the building should have a minimum level of exposure to sunlight. Table 6 indicates the recommendation for three levels of sunlight exposure. [19.]

Table 6. Recommendation for hours of sunlight exposure [19].

Level of recommendation	**Sunlight exposure**
Minimum	1.5 h
Medium	3.0 h
High	4.0 h

The EN 17037 requires the designers to identify a reference point P on window openings when performing the evaluation of sun exposure. [19.] Figure 7 and 8 below indicate the location of reference point P in plan view and section view.

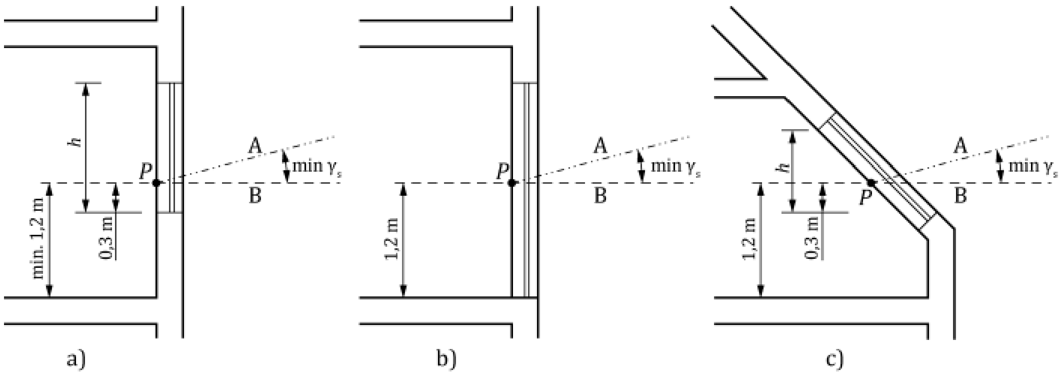


Key

a)	daylight opening with cut lining
b)	daylight opening in a loggia
c)	daylight opening shaded by own building construction
α_a	acceptance angle
P	reference point

Figure 7. Position of point P in plan view [19].

The assessment of sun exposure is conducted from point P, which is in the center of the width of an opening. Point P must be located at least 1.2 meters above the floor, and if there is a window sill, point P should also be 0.3 meter above it. [19.]



Key

a)	vertical daylight opening with a sill below 1,2 m above the floor
b)	vertical daylight opening starting from the floor level
c)	daylight opening located in an inclined surface
A	minimum solar altitude
B	horizon
γ_s	solar altitude
P	reference point

Figure 8. Position of point P in section view. [19.]

After identifying the position of point P, the fraction of the sky which is visible must be identified in order to evaluate if the sun can reach the reference point P on the selected date. In order to do that, all the surrounding buildings, that can act as a shading factor to the evaluated building have to be included in the calculation. [19.]

The assessment can be carried out by using appropriate software which is able to produce a 180-degree angle fish-eye type image. It is then used to compare the sky area free from obstruction to a sun path diagram (figure 9).

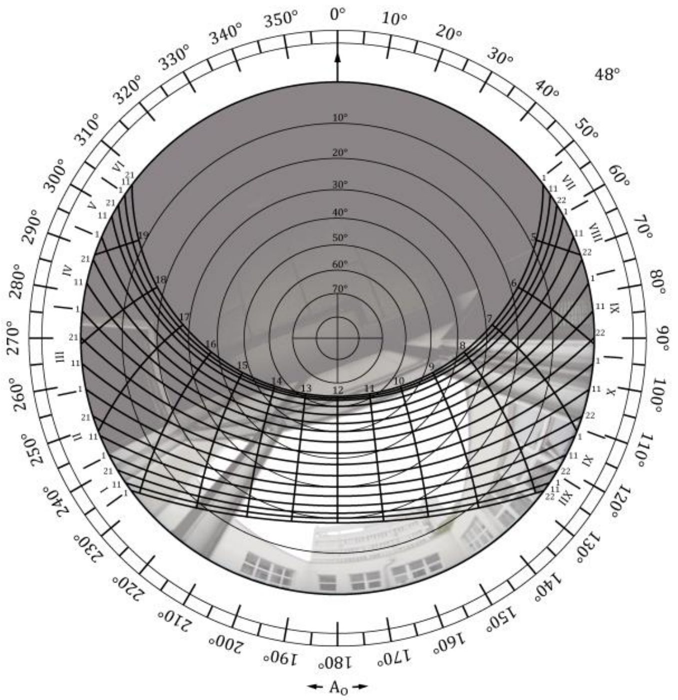


Figure 9. Fish-eye type image at point P overlaid by a sun path diagram [19].

In the image, the north direction and orientation of the sun path diagram shall be exactly determined. The center of the fish-eye type image produced by a software at point P should point at the sky vertically from point P. The sun path diagram can then be laid at point P over the image made by software.

3.4 Protection from Glare

General

Natural sunlight is beneficial and essential for the lighting quality of living spaces; however, too much daylight can unintentionally produce glare problems. Glare is defined as a negative sensation produced by luminance in the visual field that is so much greater than the luminance to which the eyes are adapted to that the luminance causes discomfort or reduces visibility. [19.]

Glaring is classified into two types. The first one is discomfort glare. It is defined by an instinctive reaction to look away from an intolerable bright source of light. An example of discomfort glare would be the lights of a meeting car in the dark. A similar problem is caused if one looks directly at the sun. [14.]

The second type of glaring is the disability glare. It happens when a light source interferes with the vision of objects, but not to the point of causing discomfort or making one look away. An example of disability glare is when one uses the smart phone outdoors. The luminance from the sunlight would be too high compared to the luminance from the smart phone. The contrast between the two sources of luminance makes it impossible to read the text on the phone. Increasing the screen brightness can overcome the problem. [14.]

Evaluation methods

Annual Daylight Glare Evaluation

To assess daylight glare, the EN 17037 introduces two methods: Annual Daylight Glare Probabiity (DGP) Evaluation and Simplified Glare Evaluation (SGE). The DGP is a new metric designed for daylight glare evaluation and it is believed to be the most reliable metric at the moment. The DGP combines several measurable physical quantities, including illuminance at eye level, luminance of glare sources, and solid angle of the glare source, with the glare experienced by subjects. [19.] The formula is

$$DGP = 5,87 \times 10^{-5} \times E_v + 9,18 \times 10^{-2} \times \log\left(1 + \sum_i \frac{L_{s,i}^2 \times \omega_{s,i}}{E_v^{1,87} \times P_i^2}\right) + 0,16$$

where E_v (lx) is the illuminance at eye level calculated on a plane perpendicular to the line of sight, L_s (cd/m^2) is the luminance of glare sources, P is the position index, ω_s (sr) is the solid angle, and i is the number of glare sources. [19.]

Table 7 below shows the DGP as a range of visual perception to describe the reaction of people towards the glaring intensity. The DPG ranges from imperceptible, which is the lowest level, to intolerable which is the highest level. [19.]

Table 7. DGP values in ranges of visual perception [19].

Criterion	**DGP**
Imperceptible glare	DGP ≤ 0.35
Perceptible glare	0.35 < DGP ≤ 0.40
Disturbing glare	0.40 < DGP ≤ 0.45
Intolerable glare	DGP ≥ 0.45

According to the EN 17037, the DGP should not exceed a threshold of 5% of the total time of occupation of a space. [19.] The evaluation is described below in table 8.

Table 8. Recommendation for glare protection [19].

Level of glare protection	**$DGP_{e\ <5\%}$**
Minimum	≤ 0.45
Medium	≤ 0.40
High	≤ 0.35

An example of the use of DGP is a simulation of annual glare probability for an office space, open from 8 am to 5 pm (9 hours). The aim was to achieve a high level of glare protection. The calculation established the total occupation times (9 hours x 365 days = 3285 hours) and the DGP ($DGP_{e < 5\%}$ = 5% x 3285 h = 164 h). Thus, the DGP value must be less than 0.35 and less than 164 hours.

Simplified Glare Evaluation

The SGE method requires an assessment of solar protection devices for three different options: opaque solar protection devices, such as blinds, shutters, and roller shutters; see-through solar protection devices made of textile, film or perforated opaque material; non-diffusing glazing with low light transmittance to admit less daylight, such as electrochromic glazing. [19.]

All three types of devices are assessed with three parameters. The first parameter is a sunshine zone that classifies evaluated devices in two sunshine zones either H for locations with more than 2100 annual sunshine hours or L for locations with less than 2100 annual sunshine hours). The second parameter is the size of daylight openings of which are divided in window with either large or small openings. The final parameter is the distance to the daylight opening which is 1, or 2, or 3 meters from the observer to the solar protection device. In this thesis, the glare in the study case was assessed with a software method that used DGP evaluation. Therefore, the simplified method will not be discussed in more detail. A full assessment for the three types of solar protection devices in respect to the three parameters is included in the EN 17037. [19.]

4 Dance Studio Project – Case Study

4.1 Project Overview

The project studied in this thesis is a dance studio in the capital city of Brussels, Belgium (figure 10). A consult on daylighting for the architectural design was required for the project. The company offering the consultation is Boydens Engineering, a building services and sustainable engineering office. At the time of writing of this thesis, the project was at the early design stage so detailed information was not yet provided by the architects.

To understand the availability of daylight in the dance studio and to provide the architects with necessary information, a basic daylight simulation was performed. Figure 11 below is the preliminary interior design of the dance studio with a baffle ceiling system, windows on the west wall and a sliding door on the south wall.

Figure 10. Location of the project in Brussels [21].

Figure 10 shows the location of the dance studio captured by Google Map. In the photo, north direction is pointing upward.

Figure 11. Interior design of the dance studio.

The architectural drawing had a flaw, instead of one array of windows there should be two, one at the top and the other at the bottom. However, the picture is the only one there is and it is still useful to understand the design of the baffle ceiling. Figure 16 in chapter 4.3 has the correct arrangement of windows.

4.2 Project Software

The dance studio project required the use of several software tools. They were

- Rhinoceros 5.0
- Grasshopper
- DIVA
- Ladybug

These are discussed below.

Rhinoceros 5 (figure 12) was used for drawings and 3D modelling in the project. Rhinoceros 5, simply known as Rhino or Rhino3D, is a powerful 3D modelling software. It allows the users to import almost any kind of file extensions, for example sketchup, autocad, DXF, DWG, 3DS. Thus, the engineer can work simultaneously and efficiently with the architect to answer questions about technical specifications. [22.]

Figure 12. Rhinoceros version 5.0 [22].

Grasshopper (figure 13) is an open-source graphical programming language developed by the same company that created Rhinoceros. With other software tools, users are usually less able to interfere with the algorithm. However, Grasshopper is built as a programming language; therefore, it allows users with a great potential to manipulate their calculation procedure. Programs in Grasshopper are created by dragging components onto a canvas. The greatest advantage of Grasshopper is that it allows multi-objective parametric simulations, for example the development of a unique program capable of optimizing the different variables of a building by simulating hundreds of possible envelopes, geometry, glazing placement, and the like. Grasshopper is a free-to-use tool and is included in Rhino 6. [23.]

Figure 13. Grasshopper – Algorithmic modelling for Rhino. [23.]

DIVA (figure 14) is a plugin designed for daylighting and energy modelling which can be used in both Rhino and Grasshopper. The plug-in provides a series of environmental performance evaluations, including radiation maps, climate-based daylighting simulation, annual and point-in-time glare analysis, LEED daylighting assessment, thermal single-zone energy and load calculations. In this thesis, DIVA was used for simulations of daylight autonomy and annual glare analysis.

Figure 14. DIVA for Rhino – Environmental Analysis for Building [24].

Ladybug (figure 15) is an open-source plug-in for Grasshopper to help a designer to create environmentally-aware architectural designs. The name ”ladybug” refers to the assumed ability of ladybugs to forecast weather.

Figure 15. Ladybug tool for Grasshopper [25].

The users need to import a standard EnergyPlus Weather file (*epw) into the tool and ladybug will provide a series of environmental 3D graphics, including the sun path, wind rose, radiation rose, radiation analysis, view analysis, and shadow studies. In this thesis, ladybug was used for simulation of sunlight exposure. [25.]

4.3 Simulations and Results

The simulations for the dance studio were performed for two cases. Case 1 is the original design and case 2 (modified design) has some changes to improve its performance. Figure 16 below is the 3D model of the Studio modelled with Rhinoceros for the simulation.

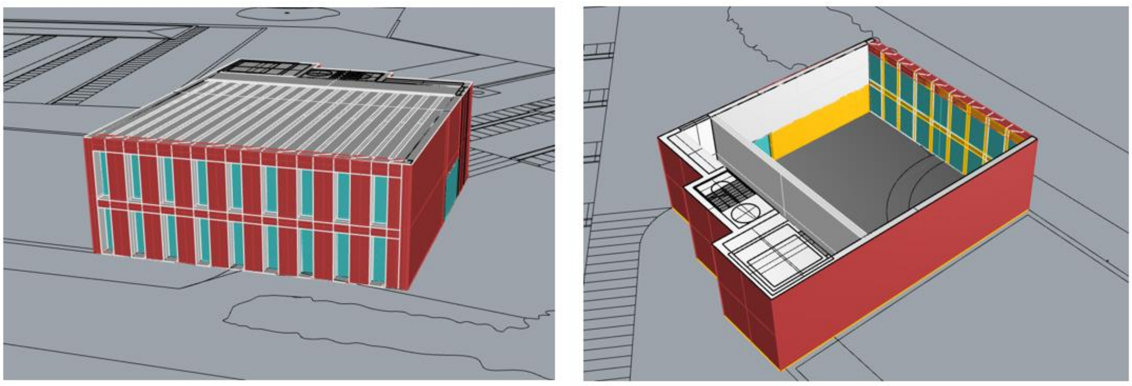


Figure 16. 3D model of the Dance Studio.

The materials used in both simulation cases are consistent and have the same light reflectance and visible light transmittance values listed in table 9 below.

Table 9. Light reflectance and visible light transmittance values of the building.

Room Properties	**LRV**	**VLT**
Ceiling	80%	
Baffle Ceiling	80%	
Interior Wall	80%	
Exterior Wall	35%	
Floor	20%	
Sliding Door	50%	
Glazing		70%

4.3.1 Original Design

Daylight provision

The daylight factor and daylight autonomy were simulated with the DIVA software. The engine that DIVA uses for the calculation is called Radiance. Radiance is an algorithm that uses backward ray-tracing algorithms. Light rays are traced back from the measured point to the light sources taking into account all inter-reflection between the surfaces of the objects in the space. There are several parameters in Radiance; however, for a new user, the most important parameter is the ambient bounces. It indicates the number of diffuse bounces included in the calculation. The more bounces set, the more accurate the simulation can get. The number of bounces can be set from 0 to 7. When the ambient bounce is set to 0, the ambient calculation turns off, and only direct sunlight will be considered. Setting the ambient bounces to a higher level will result in a longer running time for the software. [24.]

Since the dance studio is designed with a baffle ceiling system, light rays will be reflected significantly from the ceiling. Therefore, it is necessary to set the ambient bounces to a sufficiently high level in the simulation to ensure that the path of the light rays is computed thoroughly. The simulation was performed with four ambient bounces.

Method 1 (Simplified method): Daylight factor

Simplified daylight factor method was first used to evaluate the daylight quality of the dance studio. The dance studio is aiming at the minimum level as described in table 2 (chapter 3.1) for Belgium. Therefore, the minimum daylight factor is 0.7% and target daylight factor is 2.0%. These values must be over 95% and 50% of the space respectively. Figure 17 below shows the result of daylight factor simulated by DIVA for Grasshopper.

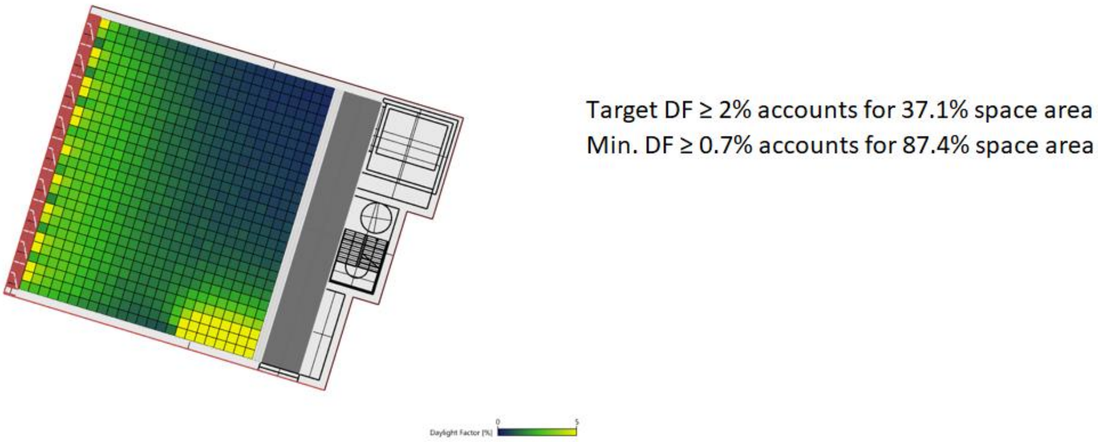


Figure 17. Daylight factor value for the original design.

The result; however, does not comply with the requirement of at least 50% for target DF and 95% for minimum DF. Therefore, with this simplified method the project does not achieve the minimum recommendation level for daylight provision.

The second method used to evaluate the daylight quality of the dance studio was the detailed illuminance level method. Similar to the daylight factor method, the aim is a minimum level of daylight provision. Therefore, the target illuminance is 300 lux and the minimum illuminance is 100 lux. These values must be achieved in over 50% of the space for at least 50% of the daylight hours. The unit used to describe this is called spatial daylight autonomy (sDA). sDA (300 lux, 50%) = x % means the space achieves at least 300 lux per calculated grid point for at least 50% of daylight hours and throughout x% of the simulated area. Figure 18 below is the result of the illuminance level simulated by DIVA.

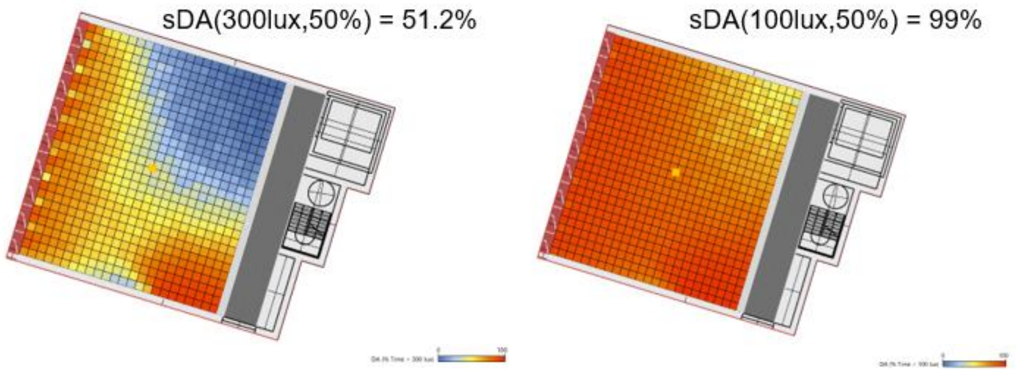


Figure 18. sDA for target illuminance of 300 lux (left) and minimum illuminance of 100 lux (right) for the original design.

The figure shows a sDA value of (300 lux, 50%) = 51.2 % and (100 lux, 50%) = 99 %. This result complies with the requirement in table 2 in chapter 3.1 for the minimum illuminance of 100 lux and target illuminance of 300 lux. Therefore, the space achieves the minimum recommendation level for daylight.

View Out

There are three criteria to comply with when evaluating the view out: the width of the view, distance to the view outside, and the number of view layers. In this dance studio case, the horizontal sight angle was evaluated at two reference points, one in the middle and one in the back-left corner. These two points were chosen to represent the locations furthest from the window openings. In other words, they represent the worst case for the width of view criterion. The results of the width of view are shown in figure 19 below.

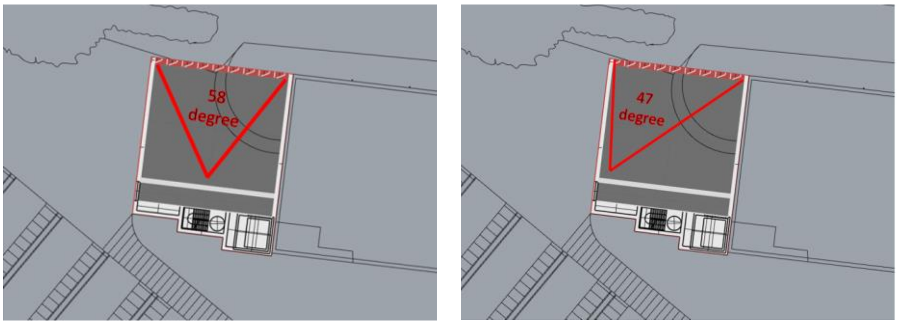


Figure 19. Horizontal sight angle at two reference points.

At two reference points, the width of view is shown as the angle of 58 and 47 degree, these values are equivalent to high and medium level respectively, according to table 5 in chapter 3.2.2. Overall, the dance studio has medium level width of view according to the assessment.

The criteria of *distance to the outside view* and *number of layers* were evaluated with the help of Google Map (figure 20).

Figure 20. Distance to the outside view [21].

In figure 20, the calculated distance is 25 meters and the view to the outside contains layers of landscapes and the sky. Therefore, the dance studio complies with the medium level of the criteria distance to the outside view and number of layers.

<u>Exposure to sunlight</u>

The windows of the dance studio are located on the west facade of the building and, due to the architectural design, the wall facade provides a lot of shading to the window openings. Therefore, the building receives very little or even no direct sunlight during the time period required by the EU 17037 for sun exposure evaluation (a day between 21st Feb and 21st Mar). Figure 21 below is a fish-eye type image, result for the sun exposure evaluation.

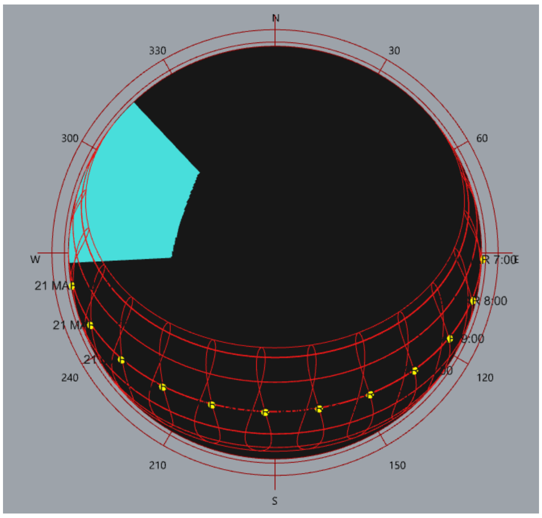


Figure 21. Fish-eye type image for the sun exposure evaluation of the original design.

The simulation was performed for the date of 21st March. The figure shows that no direct sunlight would be captured on that date. This result does not comply with any of the recommendation levels shown in table 6 in chapter 3.3.2.

Protection from glare:

Figure 22 below shows the result of the DGP for the original design. The simulation was performed with DIVA software.

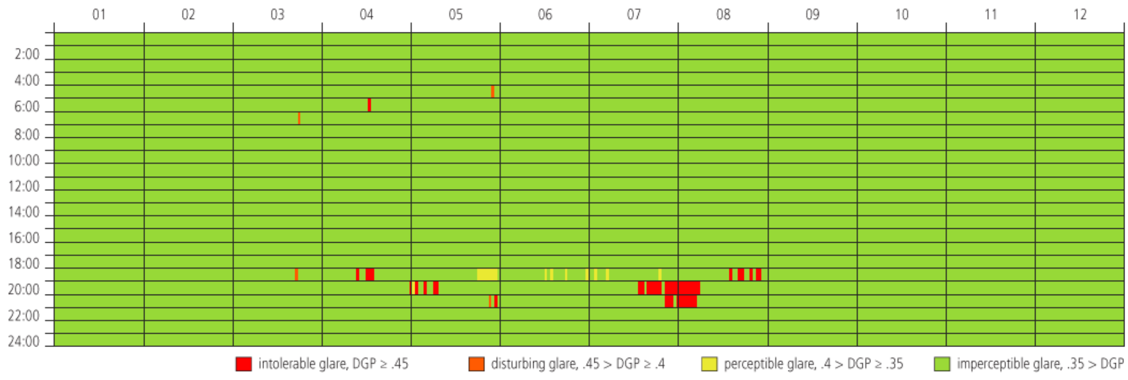


Figure 22. DGP values simulated by DIVA for the original design.

The result in figure 22 shows that there are risks of glare, mainly between 6pm and 9pm, especially during the summer time (July and August). This is because the windows are located on the west facade and during the summer the sun sets late in the evening, resulting in more risk of glare. The DGP result is evaluated according to the EN 17037 as shown in table 10 below.

Table 10. Summary of DGP values according to glare protection recommendation level.

Level of glare protection	**DGP**	**$DGP_{e\ <5\%}$**
Minimum	≤ 0.45	0.88
Medium	≤ 0.40	0.92
High	≤ 0.35	1.21

The DGP value of below 0.35 accounts for 1.12% of the occupied time. This result complies with the requirements for high level of glare protection listed in table 7 and 8 in chapter 3.4.2.

4.3.2 Modified Design

With the original design of the dance studio, the project achieves minimum level for daylight provision, medium level for view out, non-compliant sun exposure, and a high level of glare protection. However, the daylight provision requirement was just achieved by a very small margin which is not a safe result. Therefore, a modified design was created to enhance the performance of the dance studio (figure 23).

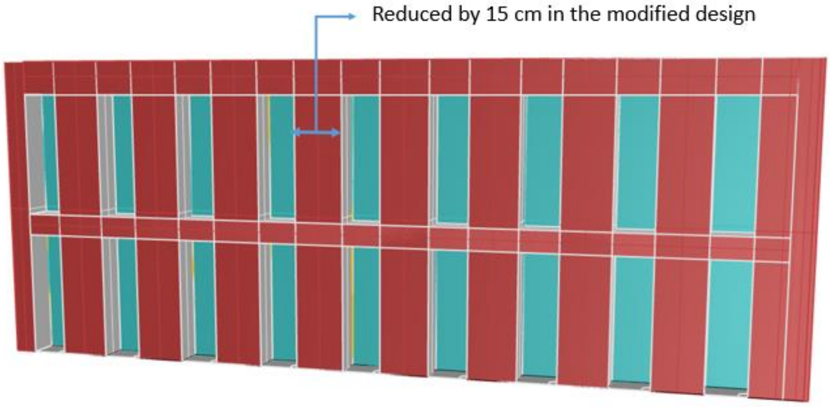


Figure 23. Building facade after reducing the exterior column area.

The design was optimized slightly in order to improve the performance in daylight provision, and to see if the sun exposure can also be improved to an acceptable level. The idea was to reduce the exterior area on the west facade by 15cm in order to increase the daylight provision and strive for direct sunlight exposure.

Daylight provision

The result acquired by the simplified daylight factor method shows compliance with the minimum recommendation level for daylight provision (figure 24). By reducing the facade column area, the window could admit in more daylight than in the original design. However, the daylight availability is still not enough to fulfil the requirements for the medium level of daylight provision, shown in table 2, chapter 3.1.

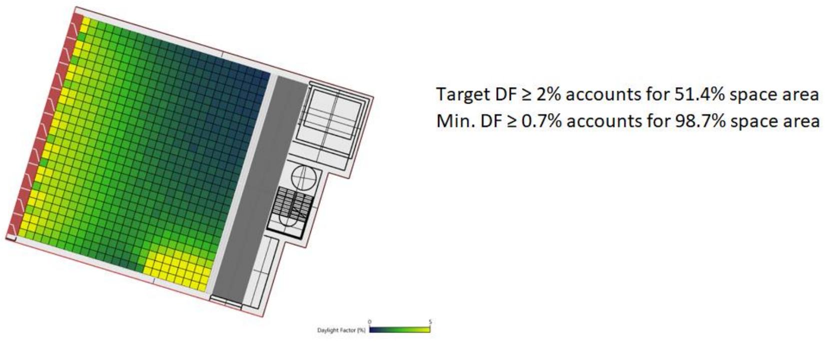


Figure 24. Daylight factor value for the modified design.

The result acquired by the detailed illuminance level method also shows an improvement in daylight provision compared to the original design (figure 25). However, like the simplified method, the result of the detailed method could not comply with the requirements for the medium level of daylight provision in table 2, chapter 3.1.

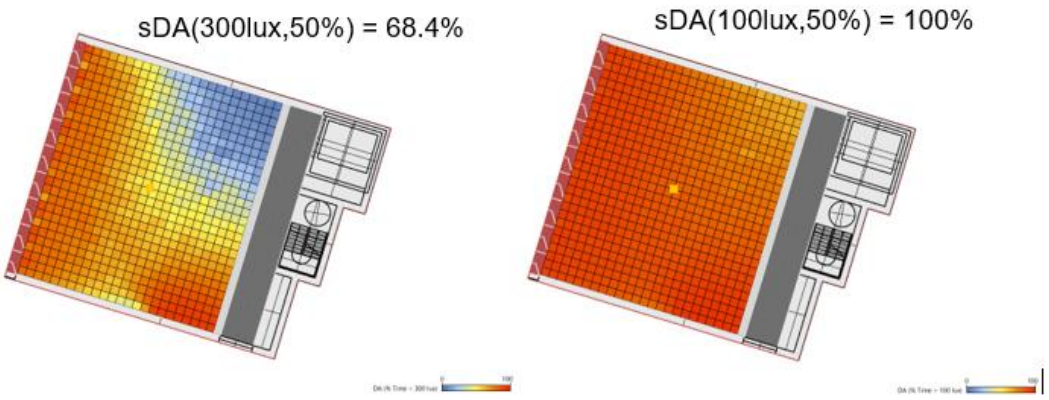


Figure 25. sDA for target illuminance of 300 lux (left) and minimum illuminance of 100 lux (right) for the modified design.

The results of daylight provision from both the simplified and detailed method for the modified design were improved. The EN 17037 provides strict requirements for daylight provision; therefore, although showing an improvement with a safe result, the modified design could not achieve the medium level.

<u>View out</u>

The results of the assessment for view out in the modified design is similar to that of the original design in the criteria for view out width, distance to outside view, and number of layers. The modified design also achieved medium level of recommendation for view out.

<u>Exposure to sunlight</u>

Similar to the original design, a fish-eye type image was created for the sun exposure evaluated, with the use of Ladybug. The simulation was performed for the date of 21st March.

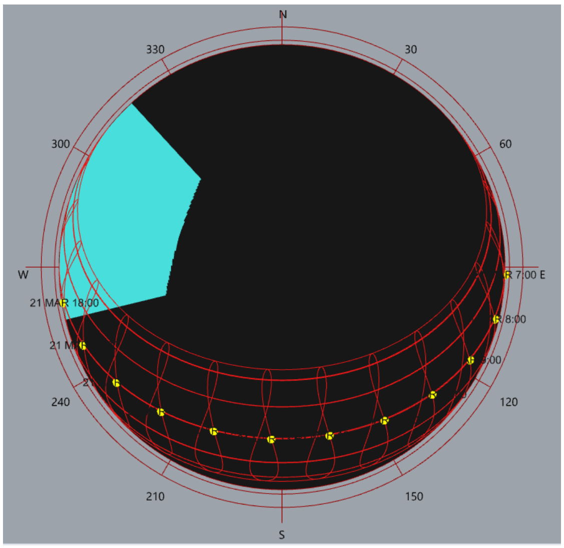


Figure 26. Fish-eye type image for the sun exposure evaluation of the modified design.

When the window openings are increased in the modified design, the space is able to receive more direct sunlight during the daylight hours. However, the sun exposure time is less than one hour. Unfortunately, this still does not comply with the minimum level, at least 1.5 hours of direct sunlight a day. Therefore, the project is still not compliant with the EN 17037 for sun exposure.

The reasons for the lack of direct sunlight from the main windows might be the wish of the architects to avoid most of the sunlight. This is suspected because, first, the windows were placed on the west facade where they can only receive sunlight at the end of a day and mostly during the summer. Second, the design of facade columns blocks most of the available sunlight. Third, a sliding door was designed on the south facade (figure 11, chapter 4.2). This door can be opened or closed at any time of a day to attract the needed sunlight, if necessary.

Glare protection

In the modified design, reducing the number of facade columns allows more daylight, while increasing the higher risk of glare. Figure 27 below shows the result of the DGP for the modified design. The simulation was performed with DIVA software.

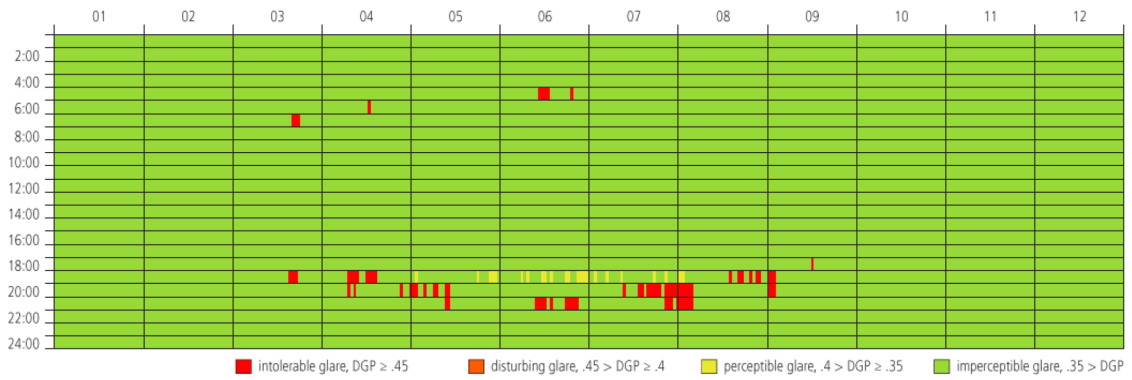


Figure 27. DGP values simulated by DIVA for the modified design.

The result in figure 27 shows more times in the evening exposed to glare compared to the original design. However, the building still manages to maintain a high level of glare protection as described in table 11 below.

Table 11. Summary of DGP values according to glare protection recommendation level for the modified design.

Levels of glare protection	**DGP**	**$DGP_{e\ <5\ \%}$**
Minimum	≤ 0.45	1.45
Medium	≤ 0.40	1.45
High	≤ 0.35	1.90

The DGP value of below 0.35 accounts for 1.90% of the occupied time. This result complies with the requirements for high level of glare protection listed in table 7 and 8 in chapter 3.4.2. A summary table of simulation results in the original and the modified design is listed in table 12 below for comparison.

Table 12. Summary of simulation results in original and modified design.

	Original design		Modified design	
	Results	Level	Results	Level
Daylight provision	Daylight factor method: + Target DF≥2% = 37.1% + Min DF≥0.7% = 87.4% Illuminance level method: + Target sDA = 51.2% + Min sDA = 99%	Minimum	Daylight factor method: + Target DF≥2% = 51.4% + Min DF≥0.7% = 98.7% Illuminance level method: + Target sDA = 68.4% + Min sDA = 100%	Minimum
View out	Width of view: medium Distance to outside:medium Number of layers: medium	Medium	Similar to Case 1	Medium
Sun exposure	0 hour	Not compliant	Less than 1 hour	Not compliant
Protection of glare	DGP≤ 0.35, $DGP_{e<5\%}$ = 1.21%	High	DGP≤ 0.35, $DGP_{e<5\%}$ = 1.90%	High

Overall, the modified design improved the performance of the dance studio in daylight provision with the higher daylight factor and sDA values. However, the modified design failed to achieve the minimum level of sun exposure. Therefore, only three out of four criteria from the EN 17037 were achieved in the dance studio project.

5 Conclusion

The thesis discussed daylighting simulation, and provided basic knowledge that designers need to be familiar with before doing any simulation. To perform a proper and detailed daylight simulation, there are many techniques, and experience is required from the simulators. In general, the summary for daylight simulation can be listed as following.

- There are three main types of solar radiation: direct radiation, diffuse radiation and global radiation. The sun can be hidden in an overcast day which results in very little or no direct sunlight, but daylight is still able to make its way into a building as diffuse or reflected radiation.
- Depending on the wavelength and energy, sun radiation is either infrared, ultraviolet, or visible light. A wise choice of window glazing can, for example maximize visible light for better natural light and minimize the infrared to prevent overheating.
- High demand of daylight will result in a risk of glare. Therefore, a suitable shading system should be carefully studied and simulated.
- Daylight factor is the most widely-known metric for evaluation. However, it also exposes several drawbacks. Therefore, new metrics for daylight evaluation, for example spatial daylight autonomy (sDA), have been introduced and used in some countries, for example the United States.

Regarding to the simulation software, most of them use an engine called Radiance. Radiance allows light rays to be traced back from the measured point to the light sources taking into account inter-reflection between the surfaces of the objects in the space. Users can decide the number of times a ray of light bounces in the simulation, depending on the complexity of the design and degree of accuracy. A higher number of bounces can provide better quality but the simulation will take longer. Ideally, it would be wise to test with a low number of bounces first to understand if the result is what the designers expect.

The thesis can work as basic guidelines for anyone looking for some base knowledge in the field of daylighting. If properly carried out, the combination of daylighting, and energy dynamic simulation together can provide a significant improvement in building performance.

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Appendix 1. Autocad drawing of the Dance Studio

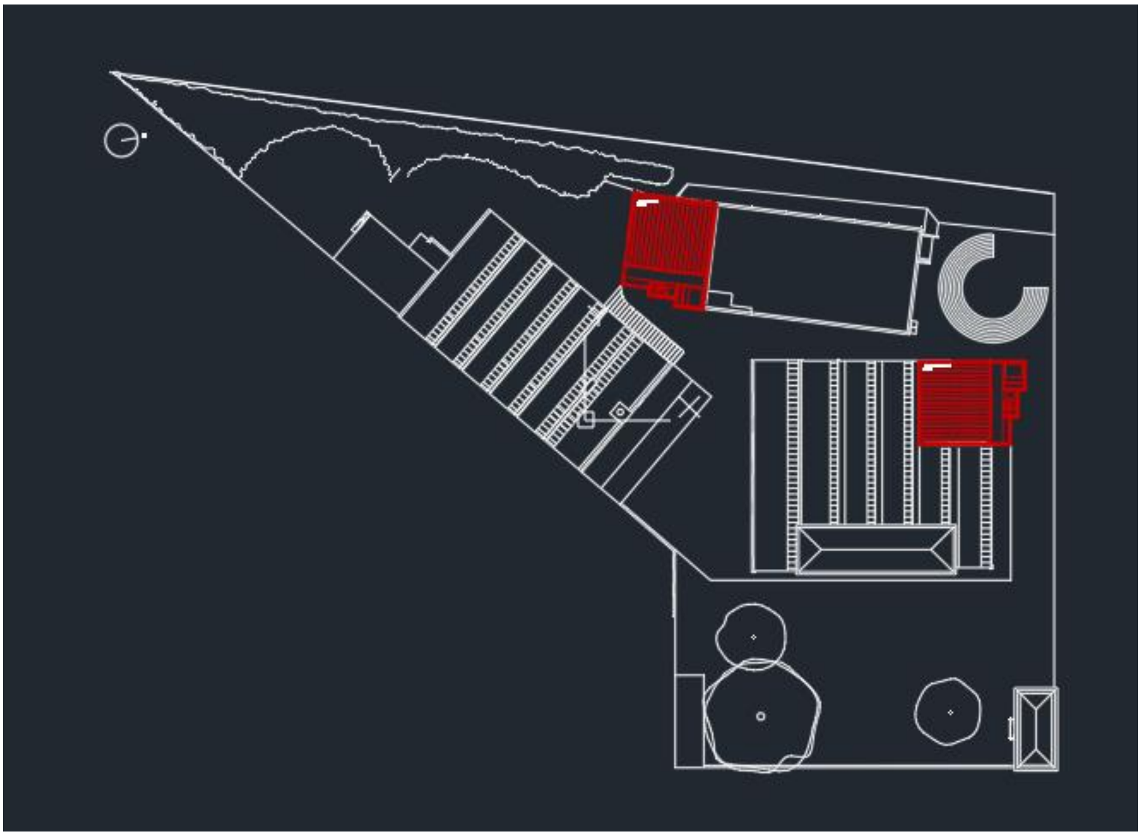

Figure 1. Site layout of the dance studio project.

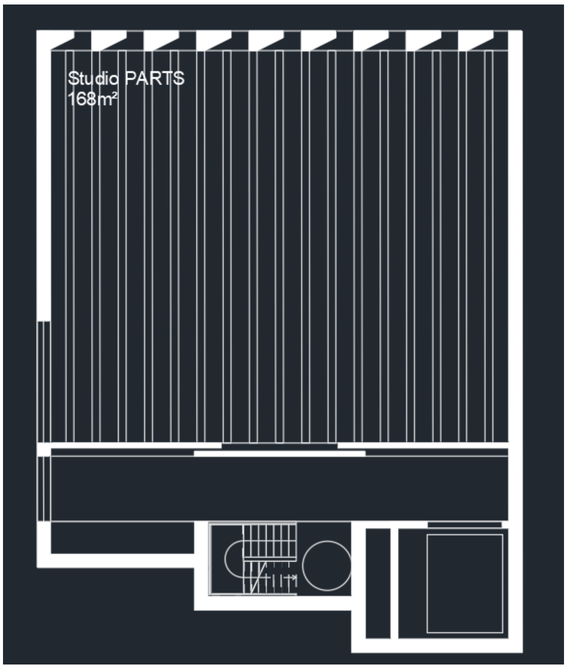

Figure 2. Floor plan drawing of the dance studio room.

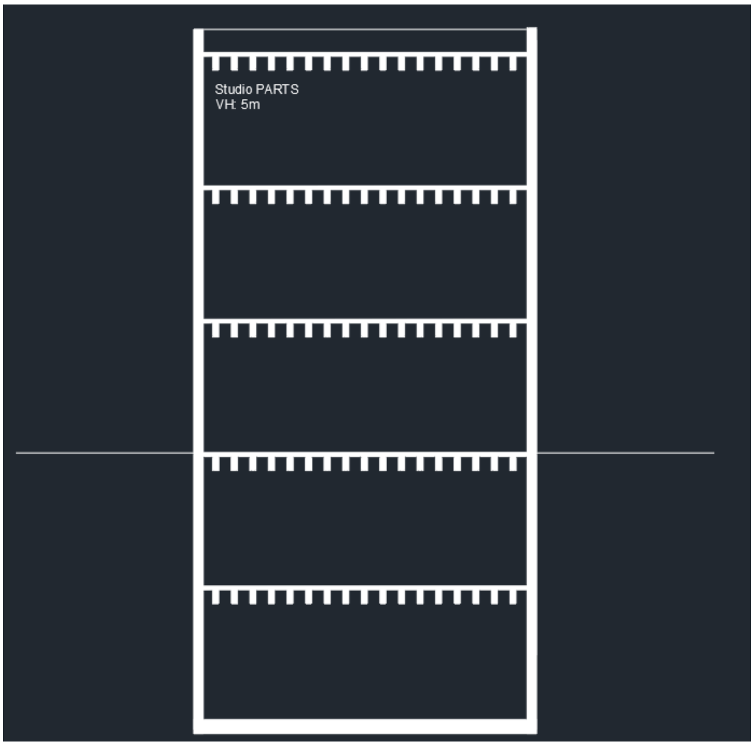

Figure 3. Section drawing of the dance studio room.