Chapter 2

Daylighting is More than an Energy Saving Issue

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Additional information is available at the end of the chapter

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Abstract

The focus in this chapter is to find adequate solutions to optimize daylighting of buildings. The climatic context is limited to Nordic European countries. As the knowledge of the positive impact of daylight on the human health increases and people spend most of their lives in buildings, the main objective is to create interiors with an optimum level of daylight for humans in a way which may also contribute to energy savings.

The solution for this complex task is showcased at a student's studio at the campus of the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The studio has been refurbished in 2016 by fundamentally changing design of the skylights. A high potential for energy saving for electrical light has been created since the light level has been increased two to three times, both in cloudy and sunny conditions. The light is evenly distributed creating good conditions for visual tasks. Additionally, the change of the colour of light from yellowish to white makes that the room appears as brighter, cleaner, more spacious and more open.

The new design was developed in the frame of the DayLighting project carried out by the Light & Colour Group at NTNU.

Keywords: daylight, sunlight, skylight, daylight factor, view out, aesthetical perception

1. Introduction

For many years the focus in daylighting research has been at daylight level and daylight distribution in buildings. By adjusting these two parameters with a control system of electrical light and shading devices, a substantial amount of savings in energy consumption can be made possible. But the subject of daylighting also includes other issues like: view out, visual comfort and accessibility of sunlight in interiors as important parameters of occupant's health, well-being and aesthetical satisfaction.

1.1. Daylight for health

Research shows that daylight is advantageous (vs. electrical light) for visual tasks if it is delivered in a comfortable manner. It may create even and intense illumination enabling ideal conditions for visual tasks such as reading. Daylight is also the best light source for colour discrimination. The variation of daylight during the day stimulates the visual system and conveys information about weather fluctuation and the passing of time. The view out through the window is important for orientation and for keeping in contact with the outdoor environment; as such it is one of factors influencing the mental health of occupants.

Daylight is also crucial for non-visual neural system that is stimulated by the light falling at the special type of light-sensitive neural cells in the retina called intrinsically photosensitive retinal ganglion cells (ipRGC) [1]. The nerve impulses conveying information about light detected by those cells contribute to regulation of hormone production and to adjustment of human circadian rhythm to the 24 h cycle. The circadian rhythm is decisive for good functioning of our body and brain. Daylight is the optimal light source for stimulation of the non-visual system since it has a very high intensity and a spectrum containing much light in the blue-green part of the visual spectrum to which the non-visual system is most sensitive. As the morning daylight exposure of ipRGCs is most effective for the circadian rhythm adjustment, high daylighting level in rooms where we stay in the morning, as e.g. bedrooms, is especially important. Finally, we may underscore that importance of daylight for the health of occupants should be considered including both, visual and non-visual systems, which are two separate nerve paths, both receiving impulses from the retina in the eye but processing them differently in the brain.

As the adequate light exposure during the day is important for sleep length and sleep quality, and adequate duration of sleep is important for cognitive activity as, e.g. learning, it is logical to expect that adequately daylit buildings may contribute to better performance of occupants. Such correlations were actually found.

1.2. Local climate

Considering daylighting solutions the local climate has to be taken into consideration, this topic is limited here to the region encompassing Nordic European countries.

Let us start with the most important parameter that has impact at other parameters, i.e. the position of the sun. It may be observed that three national capitals and other large towns in northern Europe have latitudes close to 60°: Oslo 59°54′, Stockholm 59°19′, Helsinki 60°10′, Bergen 60°22′ and Orebro 59°16′.

Even a momentary look at the sun diagram for one of those cities, e.g. Oslo, and the sun diagram for, say, Cairo, helps to find the most fundamental difference between daylight in the North and in the South, i.e. the prevailing height of the sun over the horizon. The sun moves straight

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up after sunrise in Cairo. In Oslo the movement is more horizontal; the elevation angle of the sun increases slowly over many hours and never reaches the area around the zenith. The highest position of the sun during the year in Oslo is 53.53°, the elevation angle at noon at the equinox is only 30.52°, while the two respective angles for Cairo are 83.37° and 60.33°.

Another interesting aspect is related to timing of the solar elevation angle. Since the position of the sun in Nordic countries is very low, the sun is near the horizon considerably longer than in countries situated at lower latitudes as, e.g. Cairo, 30°03′N. The very interesting question is how long can we expect the sun to be, e.g. between 0° and 10° above the horizon? The calculations of the percentage of daytime occurring during the first part of the year when the elevation angle of the sun is in intervals—(0°–10°), (10° –30°) and (over 30°)—were made with the help of the Solar Beam software [2] for Trondheim: 63°26′, see **Figure 1**. The results are also presented in **Table 1**.

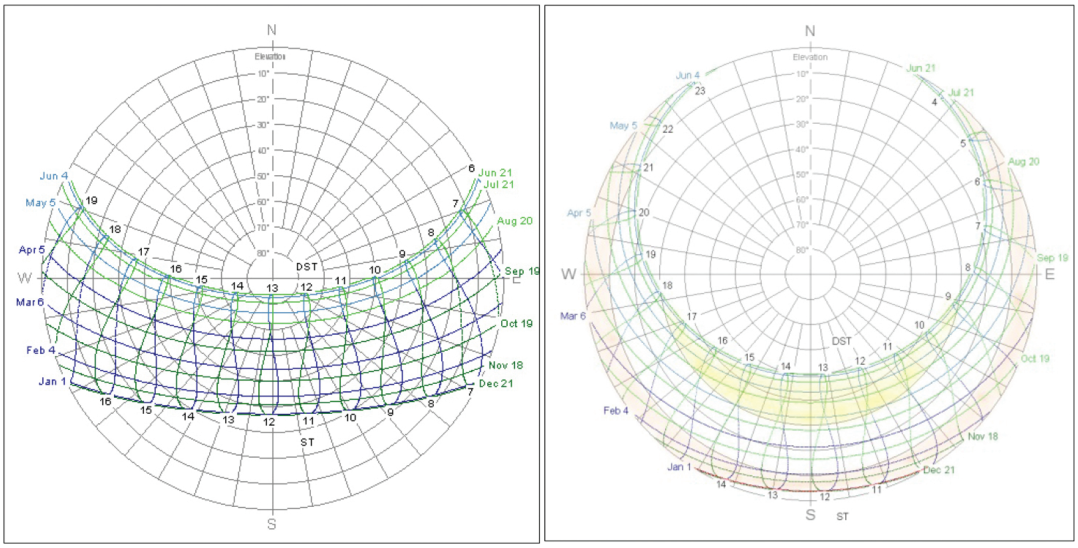

Figure 1. The sun diagram for Cairo and Trondheim generated using the Solar Beam software. The area of the Trondheim diagram representing 0–10° elevation angles of the sun is marked with red and the area representing elevation angles over 30° with yellow colour.

The highest elevation angle of the sun during the shortest day of the year, 21st of December, is only 3,35°. In the period from the 21st of December to the beginning of February the elevation angle of the sun will never reach 10°, this occurs first on the 3rd of February. After this day the number of hours when the sun is over 10° increases rapidly on a daily basis, but 30° sun elevation angle cannot be observed before the 30th of March.

The highest position of the sun in Trondheim is 50.01°. There are only four days during the year, 19th, 20th, 21st and 22nd of June, when the elevation angle of the sun is slightly higher than 50°; at 21st of June it lasts for 12 min.

The results are striking: the percentage of time during the year when the sun is between 0° and 10° is 35%. This means that for more than 1/3 of the whole daytime during the year we may expect a nearly horizontal light from the sun. The time when the sun is in the 0–10° angle interval is actually much longer than the time when it is over 30° (26%).

	0–10°	10–30°	30–50°	0–50°	Twilight
December 21–31	50.1	0	0	50.1	27.2
January	179.9	0	0	179.9	66.5
February	134.0	108.2	0	242.1	47.6
March	104.0	257.9	2.8	364.7	48.8
April	100.0	202.9	146.8	449.7	55.3
May	124.7	190.4	248.3	563.4	106.8
June 01–21	102.4	131.4	191.8	425.6	78.40
Together:	794.9	890.8	589.7	2275.5	430.42
	35%	**39%**	**26%**	**100%**	**19%**

Table 1. The time duration in hours when the sun is in the three elevation angle intervals, calculated monthly for the first part of the year in Trondheim.

The availability of the sunlight is also strongly dependent on the cloud cover. To look at the frequency of sunny skies a map was generated with the help of the Satel-Light [3], see **Figure 2**.

The analysis made so far shows the typical features of daylight in the Nordic countries:

1. Dominating low solar elevation angle during the year.
2. Long periods of twilight and white nights in the time period close to summer solstice, midnight sun at places north of the Arctic Circle.
3. Rather low frequency of sunny skies during the year, especially during winter.

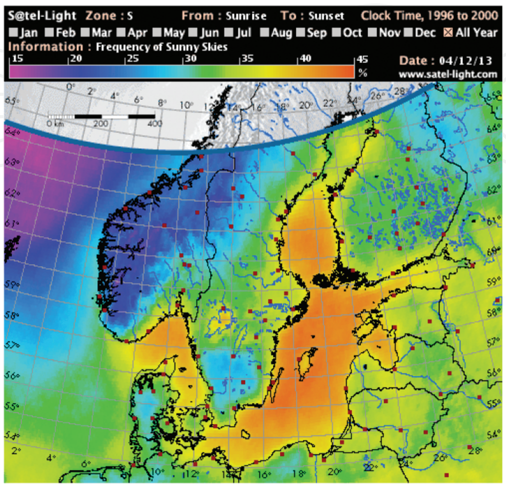

Figure 2. Frequency of sunny skies in North Europe.

2. How to utilize daylight?

A new method of harvesting daylight in the Nordic climate was developed during the retrofitting of a studio located at the campus of the Norwegian University of Science and Technology in Trondheim, Norway. The room is located on the third floor of a three storey building called Lavblokk Sør. The building is situated immediately south of a high raise 13 storey building, representing its largest exterior obstruction (**Figure 3**).

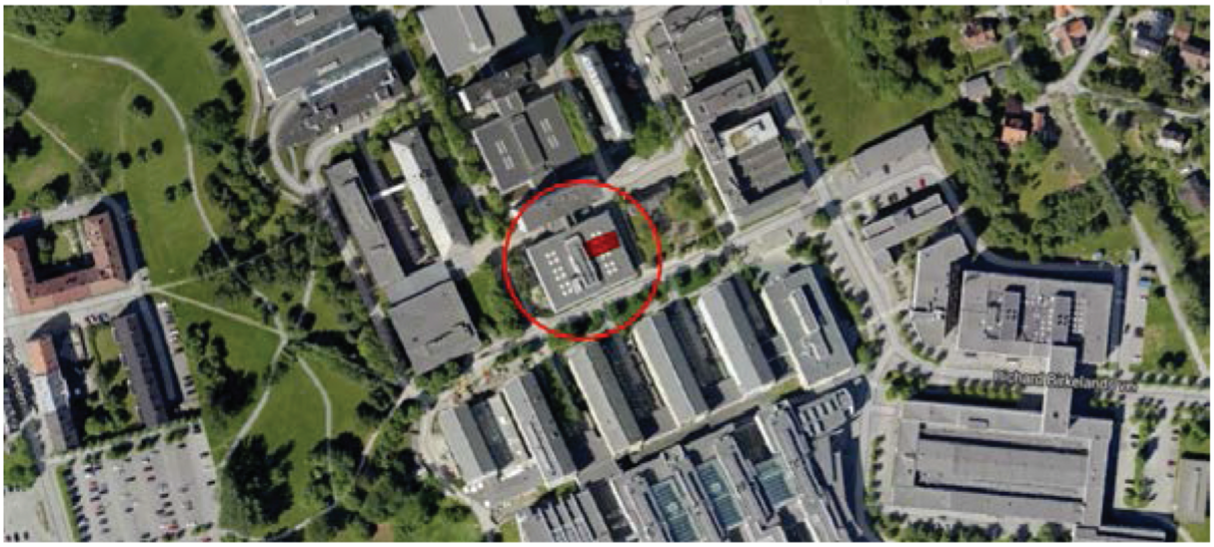

Figure 3. NTNU campus. The studio is marked by a red rectangle within the red ring.

The room is 8.2 m × 14.3 m, a total of 117 m^2 and has a height of 3.4 m, as shown in **Figures 4** and **5**. It is one of eight student studios at the Faculty of Architecture. The students use them as permanent working places; the typical visual tasks are drawing, making sketch models and of course reading and writing both in the analogue and digital format.

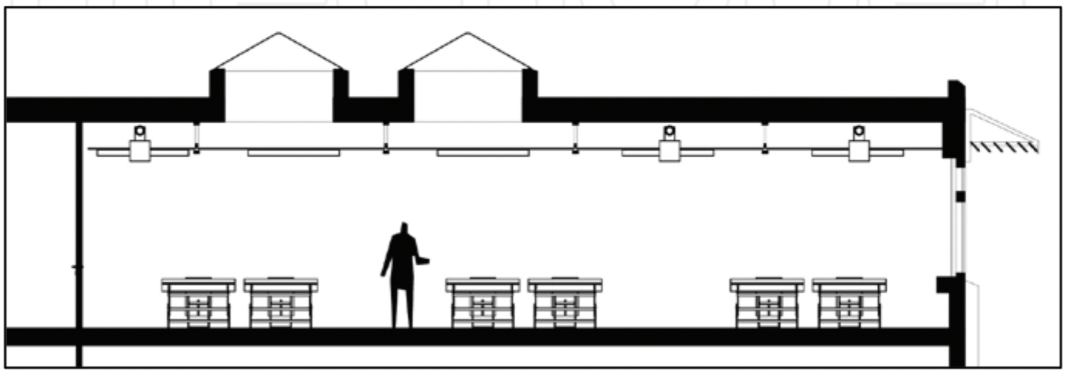

Figure 4. The cross-section of the room.

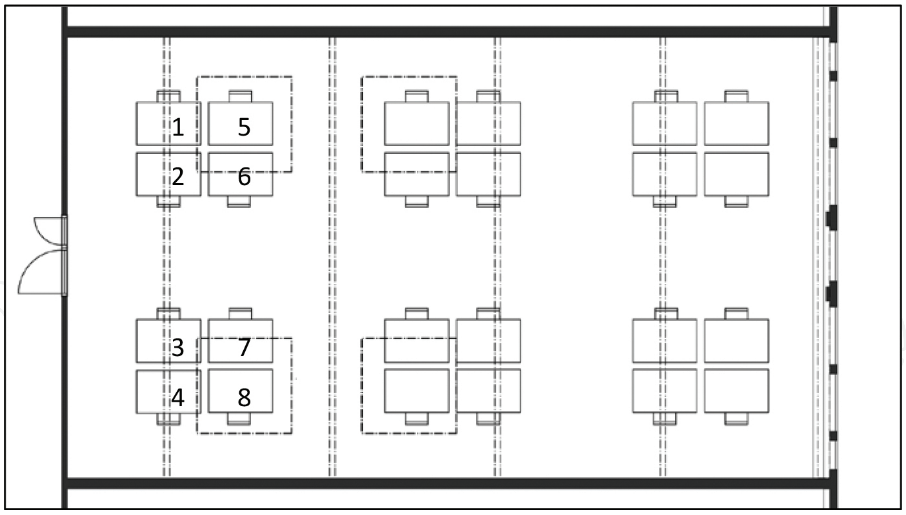

Figure 5. The layout of the room with drawing tables for 24 students. Location of skylights is marked with dashed squares. The dashed lines represent steel beams.

The roof construction is made of steel beams situated across the room, as shown in **Figures 4** and **5**. There are four skylights in the rear part of the room. The original idea behind skylights was to deliver daylight in the rear part of the room and to protect against direct sunlight falling at working areas. This was achieved by the usage of translucent acrylic sandwich elements in the pyramid-shaped skylights. Skylights are square in plan 1.8 m × 1.8 m; the height of vertical walls surrounding each roof opening, the well, is 0.85 m.

The acrylic sandwich elements diffuse sunlight very well, but they have also a negative feature, namely, the total transmittance of light is low, i.e. sandwich elements transmittance is 30–40% depending on the thickness of material, something that limits daylight penetration during cloudy weather which, as was shown in introduction, occurs in Trondheim quite often.

After including this refurbishment project in the research activity of the Light & Colour Group, specifically in the DayLighting project carried in international cooperation, in the frame of IEA Task 50 "Advanced solutions for retrofitting of lighting systems" [4], the scope of the project has been widely extended.

The main objectives of the refurbishment project were to:

- Keep the energy consumption for heating at the same or lower level. It should be mentioned that since the climate in Trondheim is rather cold and a high rise building is situated to the south, there was no need for cooling in the studio.
- Maximize the provision of daylight, both sunlight and diffuse light from the sky; this is to enable a reduction of energy consumption for electrical lighting.
- Create good visual conditions for all occupants in the room in any daylight condition.

The scope of the project was originally limited to replacement of dirty old acrylic sandwich elements with two-layers low-energy glass (**Figure 6**).

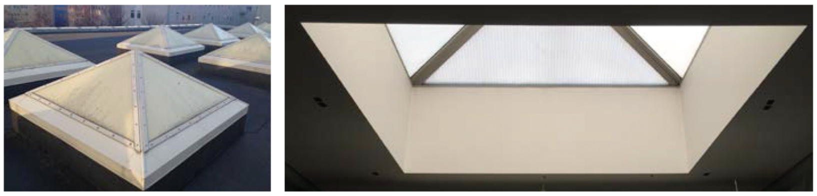

Figure 6. Existing skylights from the outside and from the inside.

To minimize the energy consumption for heating three-layers low-energy glass was chosen instead of two-layers such that the U-value of the new glazing, specified at the middle of the glass, has been 0.9 W/m^2K.

The estimated transmittance of old sandwich elements is in the range 20–40% depending on the dirt thickness and age (yellowing of material) while the transmittance of the new glazing oscillates around 70% depending on maintenance frequency. To maximize the daylight provision the low-iron glass was chosen to keep the light transmittance of the glazing at the topmost level (about 4% increase comparing to the standard glass).

The vertical well walls have been covered with highly reflective mirrors, R = 96%. Such a solution ensures that all of the light hitting surfaces of the mirrors is reflected down, i.e. not a single ray is reflected back to the atmosphere. This is especially important in the location with dominating low sun.

The most challenging task was to ensure the visual comfort. The sunlight passing through the glazing and reflected from mirrors would create patches of strong sunlight in the interior. The patches would move in the room as the sun moves on the sky. The crucial question was how to distribute the sunlight in the room and at the same time keep the skylight transmittance at topmost level?

To obtain the most promising solution different alternatives were tested in a scale-model study carried out in the Daylight Lab. at NTNU, Light & Colour Group. The alternatives assumed utilization of perfectly transparent acrylic plates which have been perforated with holes made with the Laser Cutting Machine accessible at the workshop at the Faculty of architecture, NTNU.

After the idea of scattering sunlight with the help of perforated acrylic plates proved to be successful, a long design process followed. A suspension system for hanging the plates exactly at the level needed to be aligned with the ceiling plates had to be designed. The size of the acrylic plates had to be selected according to the dimensions of the skylight well. The thickness of the plates had to be chosen according to the size of the plates and the size of the holes and the distance between the holes had to be adjusted according to the thickness of the plates.

The result of this project is shown in **Figures 7** and **8**. Pictures were taken with a Nikon D600 camera with the fish eye EX DG positioned at the entrance to the room about 2.0 m above the floor. Two rooms were photographed, the renovated room (on the left-hand side) and the neighbouring room that has not been renovated (on the right-hand side). A series of 11 low-dynamic range pictures were taken and combined afterwards into high-dynamic range HDR pictures. The HDR pictures visualize a room in a way that is much more similar to the way human visual system perceives it, especially regarding lightness of surfaces.

It is clear that the general light level in the retrofitted room is significantly higher, both in the overcast and sunny conditions. This may be observed comparing the right and the left picture but also by looking at the high situated windows in the partition wall. The windows appear as darker than the wall if seen from the renovated room creating impression that we are looking into a darker room to the right; a contrary impression is created if the same windows are seen from the room which was not retrofitted.

Additionally, the renovated room appear as cleaner, since the yellowish shade had been removed. Interestingly, the brightest spots in the renovated room are at acrylic panels, even very gentle sun patches on side walls appear as darker.

Figure 7. Fish eye HDR pictures of the studio under overcast sky conditions, the new solution to the left, old one to the right.

Figure 8. Fish eye HDR pictures of the studio under clear sky conditions, the new solution to the left, old one to the right.

3. Potential for energy savings

The refurbishment project is not completely finished; the next step will be the replacement of the electrical light system. New LED-luminaires will be fixed underneath the steel beams and will be connected to a daylight-responsive control system. This will allow theoretically the highest possible energy saving for lighting.

The results of illuminance measurements taken in June 2016 at the middle of each numbered desk, see **Figure 5**, both in sunny and cloudy conditions are presented in **Table 2**. For cloudy conditions both illuminance and daylight factor (D) values are presented.

On average the light level is increased by two to three times both in sunny and cloudy conditions. We predict similar values for intermittent sky, i.e. more than doubling of the light level. The daylight factor was increased from 2.1–2.3% in the room with the old solution to 4.8–6.9%.

	Sunny		**Cloudy**			
	New (lx)	**Old (lx)**	**New (lx)**	**D**	**Old (lx)**	**D**
1	3145	1655	1306	6.3%	454	2.2%
2	3485	1795	992	4.8%	435	2.1%
3	3490	1760	1154	5.6%	433	2.1%
4	3110	1730	1417	6.9%	456	2.2%
5	3960	2015	1252	6.1%	472	2.3%
6	4300	1900	982	4.8%	462	2.2%
7	7535	1820	1109	5.4%	431	2.1%
8	4445	1765	1327	6.4%	458	2.2%

Table 2. Illuminance measured on eight desks situated closest to the entrance.

In sunny conditions, while the sun elevation angle is about 48°, the light level in the room with old skylights oscillates between 1600 and 2000 lx, in the room with the new solution it is around 3100–4400 lx. The variation in sunny conditions is higher as a very small percentage of light is allowed to pass directly through the acrylic panels creating a little brighter area (7535 lx).

As the light level in the room with old skylights is rather low, doubling of this value makes daylight illumination much more adequate to the needs of the users (300–3000 lx). This means that the time of the daylight level on desks higher than 300 lx has been radically increased, giving large potential for energy saving for lighting.

4. The importance of the view out of the window

The research conducted by Ne'eman et al. [5] shows that acoustic, heating, lighting, outside view, ventilation, air conditioning and the design of work space are among the most important physical environmental factors affecting worker satisfaction. Daylighting and outside view, both conveyed by windows, are the most important factors for achieving worker satisfaction. The view out is especially important for well-being since it gives the possibility to keep contact with the outside environment continuously [6, 7].

The existing hypotheses and research findings about preferences for view may be categorized into three groups: the need for information about the outside environment, the need for aesthetical experience and the need for restoration and health [8].

The need for visual information is well described by Lam [9]. A typical window conveys information about location, time and weather conditions, but also about activities and events outside the building. If the need for visual information is not satisfied, the ability to focus on a work task is seriously limited.

The need for aesthetical experience has been explained by the evolutionary aesthetics [10, 11] claiming that perceptions of beauty are evolutionarily determined, i.e. places and landscapes which people consider beautiful are typically found in settings that are likely to support survival of the human's genes. This theory together with the prospect-refuge theory proposed by Appleton [12] may explain why natural landscapes and well-kept buildings are generally preferred.

The need for restoration and health can be explained by the attention restoration theory [13]. Natural environments have qualities that in combination seldom occur in other types of environments. They give a feeling of being away and they create a sense of extend, i.e. what is seen is a part of a larger area. In addition, natural environments create a sense of fascination meaning that they encourage exploration, attract attention and hold it effortlessly [14, 15].

Consequently, for the evaluation of the view out, two categories of descriptors should be considered:

- the content of the outside view discussed previously, i.e. qualitative descriptors, and
- the extent to which the view is actually available from a given point in the interior, i.e. quantitative descriptors.

Both types have impact on the view quality, see **Tables 3** and **4**, but the responsibility may be allocated to different professional groups. Architects designing a single building have responsibility for most quantitative descriptors, as e.g. the width of the view from a given place in the building as well as the possibility to see the view layers: sky, landscape and the ground. To a certain degree they may decide about the view distance, e.g. by choosing the location of the building on the site. Additionally, architects may attempt to include a nice landscape element in the views from many rooms. However, there are urban and landscape planners and municipalities who decide about the distance between buildings, width of the streets, size of town squares and have responsibility for creation of attractive urban or rural landscapes, i.e. are decisive for the qualitative descriptors.

Descriptor	View quality Sufficient	Good	Excellent
Width of the view (glass)	> 14°	> 28°	> 54°
Outside distance of the view	> 6 m	> 20 m	> 50 m
Number of view layers: - sky - Landscape (urban and/or nature) - Ground	At least landscape layer is included	Minimum two layers are included	All layers are included
Environmental information: - Location - Time - Weather - Nature - People	Time, weather and basic info about location	Time, weather, location and nature or people	All

Table 3. Assessment of the view out, quantitative descriptors.

Descriptor	View quality Sufficient	Good	Excellent
Content and Quality of landscape: - urban low quality, as e.g. toward concrete walls, parking plot, etc. - urban middle quality - urban high quality, e.g. an attractive square or with attractive elements as, e.g. historical buildings, fountains, sculptures, etc. - natural/rural low quality, as e.g. monotonous rural landscape - natural/rural middle quality - natural/rural high quality, e.g. varied and including beautiful elements as lakes, well-shaped trees/bushes	Natural/rural –low or urban middle	Natural/rural -middle or urban high	Natural/rural -high or urban high
Composition: - poor balance between landscape elements, e.g. more than ½ of the view is toward one dominating element - good balance - very good balance between landscape elements	Poor balance but at least the central part of the view is free from undesired elements.	Good balance and the central part of the view is free from undesired elements.	Very good balance and the view is free from undesired elements

Table 4. Assessment of the view out, qualitative descriptors.

It is preferable to divide the view out quality into classes, e.g. sufficient, good and excellent, see **Table 3**. For a good view it is recommended that the width of the view (window glass only) from the observation place in the room is larger than 28°, the mean minimum outdoor distance to other buildings/constructions is minimum 20 m and minimum two of the three view layers are included. If the evaluation of those metrics is difficult, it may help to consider if the view conveys environmental information about time, weather, location and nature or people, see the last row in **Table 3**.

As discussed previously, for a view to meet the occupants' needs for environmental information, for aesthetical experience and for restoration there are expectations to the quality of the view. Interesting question is then, how people evaluate quality of the view from their usual occupancy places. In the research study performed in a previous work [8] in Trondheim, Norway, over 100 subjects were visited at their work places and asked to evaluate the quality of the view out. The quality was best predicted by the view distance, the number of view layers, the quality of the landscape/elements and the composition of the view. This is a new finding showing that the aesthetical experience may be more important than assumed previously. Occupants appreciate the possibility of looking towards beautiful and well-maintained buildings and towards well-kept parks and gardens. It appears also that a certain degree of complexity is preferred. A variation in composition of green areas with different shapes and/or colours of trees and shrubs is preferred. Regarding buildings, a certain variation of forms and shapes is preferred compared to ordinary plain walls made of one material.

Anyhow, even if the view contains a beautiful element, like for example a cathedral, the important question is how much of this element is actually included in the view? Another question is if there are unwanted elements, like e.g. a poorly maintained building, in the view? With other words, how is the composition of the view? Where the liked and disliked elements are positioned, at the central or peripheral part of the view? A good method to find it out is simply to take pictures from the place under consideration. **Table 4** gives additional guidance regarding the qualitative descriptors.

It has to be mentioned that it may be also indirect determinants that influence people's perception such as glare, colour rendering of glazing, contrast and clarity of the image which may have impact on the final evaluation of the quality of the view.

5. Daylight and aesthetics

Experience-based knowledge gathered by generations of architects and building planners tells us that daylight has a profound impact upon the aesthetic ambience of the interiors. However, can this be scientifically proven? A full-scale study with mock-up rooms build in the Room Lab at NTNU in 2014 [16] examined the impact of window size and room reflectance on the perceived quality of a small room, and the correlation between various architectural quality attributes, as shown in **Figure 9**.

Figure 9. Pictures of the mock-up rooms.

The mock-up rooms were visited in the randomized way by a number of carefully selected subjects. Statistical analysis of their answers led to the following conclusion: "overall, the rooms with larger windows and lighter walls obtained higher ratings for all the studied architectural quality attributes, suggesting that high levels of daylight are crucial in order to achieve a more pleasant, exciting, complex, legible, coherent, spacious, open and spatially defined room." Additionally, it turned out that the window size was more important for the aesthetical judgement than the surface colour; on average the black room with the largest window scored higher than the white room with a small window. As this study was limited to rather small rooms, achromatic colours and overcast sky conditions, more research is needed for generalization.

Another full-scale experiment was carried out in a small office room situated in one of high rise buildings on the NTNU campus to find out the aesthetical preferences of four different daylighting systems: venetian blinds (WB), high reflecting blinds (HRB), hybrid (included electrical light also) light shelf (HLS) and mirrored light shelf (MLS) [17], **Figure 10**. Results from MANOVA indicated that both the daylighting systems and the type of sky had an effect on the aesthetical attributes, and the significant interaction effect suggested that the aesthetical perception of daylighting systems depends on the type of sky. The room equipped with the high reflecting, i.e. specular, blind system, which created even and rather strong illumination, was evaluated highest by participants, i.e. as the most pleasant, exciting, coherent, spacious, legible and the one making the room most spatially defined, under both clear and overcast sky conditions.

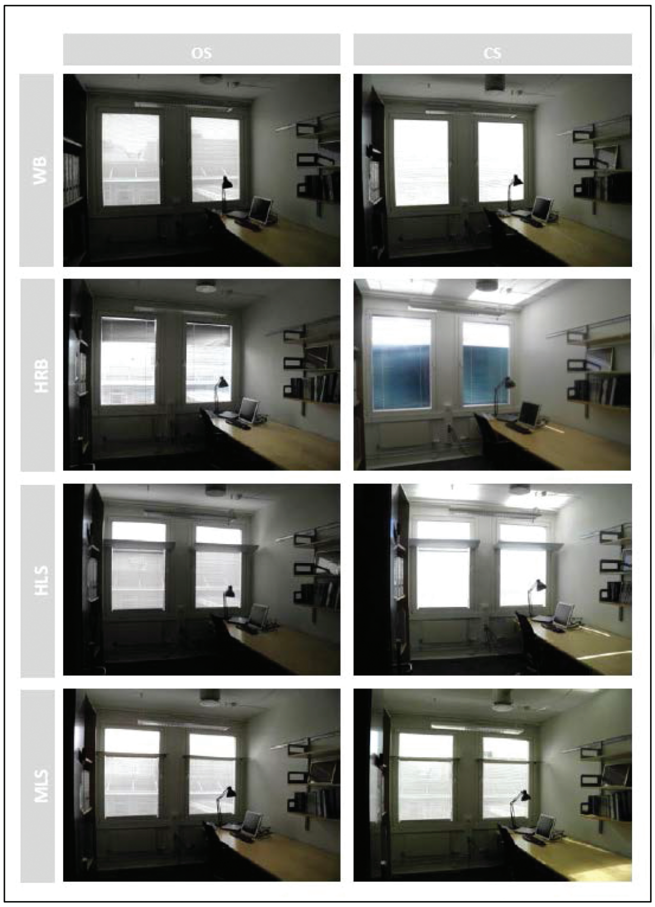

Figure 10. Pictures of the studied office rooms with the eight different stimuli.

6. Conclusion

The most prominent question in the study of daylighting is how to create rather high daylight level in cloudy conditions and avoid uncomfortable sunlight in sunny conditions in the same space. This is especially problematic when intense sunlight causes discomfort when shone on human bodies and distracts our view on computer screens. Sun shading devices are usually used to solve this problem, but this will cause the overall light level in the room to diminish and electrical light has to be used.

The new system developed by the Light & Colour Group at NTNU [18] in Trondheim is based on the strategy of maximal penetration of daylight through the skylight, aided by vertical mirrors on the walls of the skylight well, which is scattered in the room using perforated acrylic plates. The results observed showed evenly distributed light of high intensity providing comfortable working conditions and significant energy saving when the use of electrical lighting is reduced. For high sun elevation angles which happen at the middle of the day during summer, sun patches may occur, especially on the side wall, but then they are weak and does not cause discomfort. In fact, they add luminance contrasts in the room and in this way increase

http://dx.doi.org/10.5772/65866

esthetical experience. As the studied room has rather large windows towards trees, the good view is also ensured.

Our research confirms that there is clear potential for energy saving for lighting by utilization of daylight directly for illumination of interiors using canny designed skylights.

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