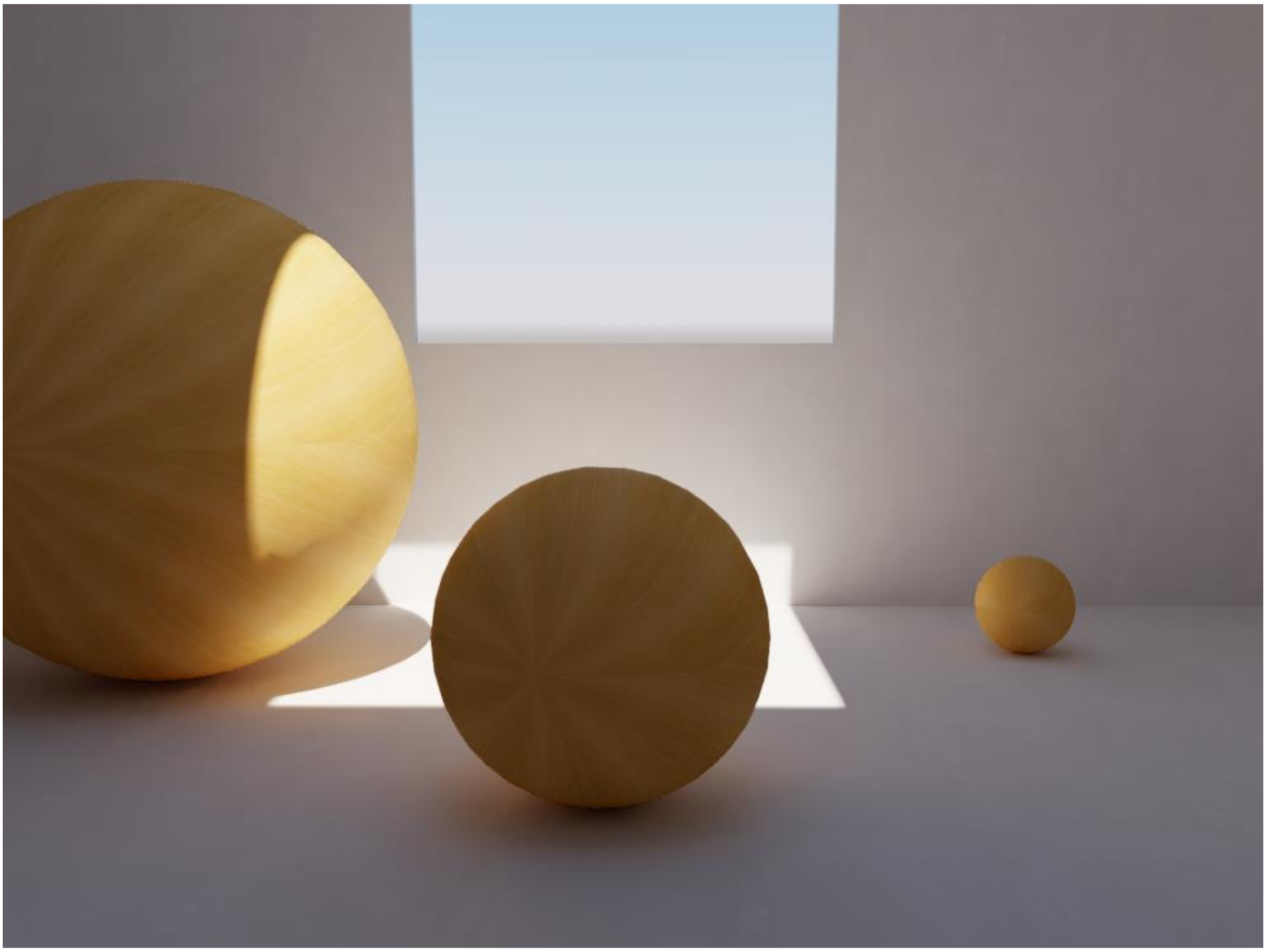
Harmonizing daylight

A study about finding the right balance

between vertical and horizontal daylight.



AALBORG UNIVERSITET

Aalborg University Copenhagen

2019

Semester No.: LiD10

Semester Project: Master thesis

Title: Harmonizing Daylight

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Abstract

This project investigates vertical and horizontal daylight source and how it provides lighting to a space, with the aim to develop data that can potentially provide a guideline for the optimal ratios between vertical and horizontal daylight in a given space.

An approach of building models in CAD-programs for evaluating different spaces and lighting ratios has been used and analyzed with reference to “The Scale of Light”. A template has been developed containing five parameters to support an objective and consistent rating of the different scenarios.

A preferred indoor lighting environment, with the use of vertical and horizontal daylight in a 1:2 ratio only, has been achieved for selected areas in a space.

Results has shown that only changing the numbers of windows, using the same total square meter of window area, has a huge impact on the outcome.

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Intro

Introduction

To make a good illuminated space you need to understand the importance of other factors than the quantity of light but also factors referring to the distribution of the light, which is relating to the light as shadows and ratio of light in a space. An overexposed room can cause glare and annoyance, leading to difficulties of identifying the texture of the surfaces and objects in the room. Today there is many ways to manipulate the daylight entering the room by using blinds, filters, or different glass-types, for example. Also adding mirrors or brighter finishes of the surface can make the room seem brighter.

The opening in a space also has a significant influence of how the space and objects appears. Where the sizes, locations, shapes, and orientation of the opening can change the outcome. To answer the question how can the ratio of vertical (V) and horizontal (H) daylight inflow in a space be investigated to support better perceived distribution of daylight in a space.

Mission

In this project the aim is to get the best possible distribution of the indoor lighting environment without any use of electrical lighting. The project will investigate if the qualities of light distribution of light has an effect in relation to the window areas and lux requirements according to the Danish Building Regulation, BR18.

Another goal of this study is to categorize and investigate the different parameters there is when working with light and try to use that knowledge gained into making a scheme. The scheme would act like a method of how to evaluate lighting designs.

The last goal for this study, is to find a method where it is possible to investigate the relationship between vertical and horizontal openings for daylight to enter.

What is good lighting

A lot of light is not necessarily the best solution. One needs to understand the importance of other factors than light, such as the distribution of light creating shadows and darkness, before one can design a good illuminated room.

Good lighting is very subjective and can vary a lot from person to person. However, lighting designer Hervé Descottes made a method of how to qualify the role of light in a space by dividing lighting qualities into six principles. These principles are-illuminance, luminance, color and temperature, height, density and direction. The principles will be used as an inspiration for how to qualify a lighting environment in this study[1].

Illuminance describes the quantity of light emitted by a light source that lands on a given surface area and luminance is the light reflected back to the human eye at the interface of two different materials. These gives a spatial understanding and what materials and surfaces that are present[2].

Color and color temperature has lesser importance in this study, since it is a daylight project where all the tests is situated in Copenhagen the 21st of March at twelve o'clock (spring equinox), making the color temperature, the latitude and time of the year in this study constants, meaning they are always the same throughout this study. However, daylight is always dynamic and that the color temperature will vary throughout the day, from cool mornings to warm sunsets.

The distribution of light can be concentrated in narrow areas or wide areas. Whereas narrow areas can be defined with parallel lighting, and wide areas using diffused light. The pairing of lights directionalities and its distribution gives the lighting designer many possibilities for rendering an object or a space.[3]

Knowing there are different needs to how the lighting environment should be and functions in different situations has high importance. In a shop at the window, for example, the purpose is to catch the attention of potential shoppers, were the lighting and purpose is completely different from the light at a hospital were the focus mainly is on health and on precise operations.

Therefore, good lighting is very complex. One must know the needs and the purpose of the space, furthermore an understanding of balancing the different parameters briefly mentioned above.

1 *Hervé Descottes, Architectural Lighting Design with Light and Space, P. 13*
2 *Hervé Descottes, Architectural Lighting Design with Light and Space, P. 14 and 30*
3 *Hervé Descottes, Architectural Lighting Design with Light and Space, P. 71*

Evaluating the light

Inspired of the Six Principles by Hervé Descottes, a scheme has been developed to support a harmonized approach for evaluation of scenarios. Some parameters from the Six Principles is used, but also new ones will be added. An example of how the scheme will work is shown below in *figure 1*. Each scenario will be evaluated on the following parameters-Materials/surfaces, Shadows, Light vs Darkness, Illuminance, and Impression by giving numbers from 1-5, with 1 being unacceptable, 2 bad, 3 neutral, 4 good and 5 excellent. This method helps to find the best lighting solution and makes it easier to compare the different scenarios. A brief conclusion will follow the evaluation of each scenario, to sum up and adding any further comments if needed. Why these parameters are used for evaluating the different scenarios and an elaboration of each parameter is explained in the next chapter.

Parameters/Scene	2.1	2.2	2.3
Materials/surfaces	3	4	4
Shadows	4	4	4
Light vs. Darkness	4	4	4
Illuminance	3	1	1
Impression	5	4	3
Total	**19**	**17**	**16**

Figure 1, example of the scheme

Factors of good light

Materials/Surfaces

This parameter is about identifying surfaces, objects in a space and their visibility as a three-dimensional object. How is the surface texture, for example, is the fuzz on the tennis ball showing, or the rough texture on a brick? The direction of the light beam and the direction of view can change the perception of the material, so can contrasts. Meaning, an object has a lower illumination than the backgrounds luminance, the object surface is reduced, making it harder to see details[4].

A material can be transparent, rough or smooth, and its reflectance has a value between zero and one. High reflectance materials could be white paper with and value of 0.8, while a perfect black surface has 0,

[4] *Peter Tragenza and David Loe, The Design of Lighting, P. 10-11*

meaning the surface has absorbed all the light. On matt surfaces the light hitting it will reflect in all direction, this is called diffuse reflection. The opposite is called specular reflectance, meaning the light hitting the surface will bounce off an angle equal and opposite to the incident angle. An example of this surface could be a mirror where its surface is glossy[5].

The criterion for getting a high score in the scheme, is that the materials and details of the objects in the space are easily identified.

Shadows

Shadows helps to support the understanding of three-dimensional objects form, its placement in a space and where the light source is situated.

The geometry of light sources and type of light has a huge influence on how the shadows will appear. For example, a uniform diffuse lighting causes bad shadow rendering and a single concentrated source produce a sharp shadow. A sharp shadow is very dark and much useful information may be hidden[6]. The crispness of shadows depends on the size of the light source, the larger the light source the lesser sharp the shadows get[7].

There is high variety of shadows, even though shadows are usually only referred to as “soft” or “sharp”. In a paper by Sophus Frandsen, he uses a more advanced type of scaling shadows. The scale comprises ten intervals and eleven types of shadows (*figure 2*). Scaling types 1-3 and 7-9 is defined as extreme and type 4-6 are defined as the preferred types. Type 4-6 is achieved when pairing diffused and parallel light sources. It is the shading size in the middle zone of the ball, that determines the intervals on the scale. A single concentrated light source produces a shadow like number zero and diffuse light like number ten, where the graduation extends over the entire surface of the ball[8]. By mixing light sources and adding more, it is possible to achieve the shadows between zero to ten.

The criterion for getting a high score in the scheme, is to have a variation of different shadows in the space, and objects expressing scaling type 4-6.

5 *Peter Tragenza and David Loe, The Design of Lighting, P. 23*
6 *William Lam, Perception and Lighting as Formgivers for Architecture, P. 67*
7 *Peter Tragenza and David Loe, The Design of Lighting, P. 7*
8 *Sophus Frandsen, The Scale of Light*

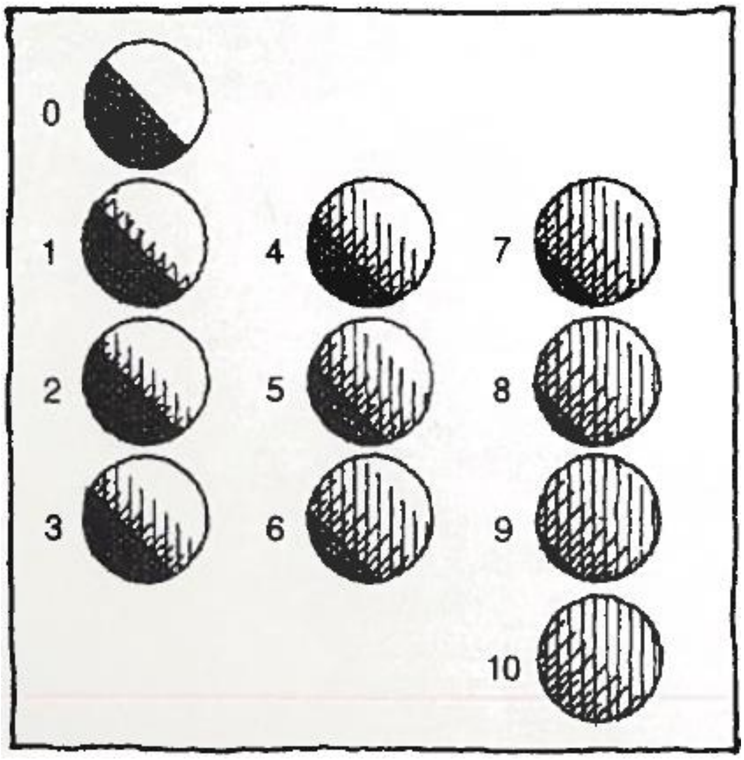


Figure 2, the scale of shadows

Light vs. darkness

In the retina, the neural layer in the eye, has two photoreceptor cells, called rods and cones. Rods are sensitive to changes in light intensity, where cones operate best in bright light and is sensitive to color. Rods and cones activity changes if the light level changes. Meaning rod cells gradually take over for the cones, when the light level goes from bright to darker. It is in this transformation, it is possible to discover new visual relationships in the shadow, that redefines the ways one perceives the surroundings. This happens even though it is dark, the eyes ability for always adapting to its surroundings, makes it possible to see[9]. In Japanese culture the writer Jun'ichiro describes the presence of shadows, as an essential part of their way of designing. Jun'ichiro believes, that dim lighting "*reveals the essence of a material, its delicate textures, nuanced form, and weathered patina beautifully illustrate how some objects and spaces are best seen and understood in the presence of feeble light and shadows*[10]*.*"

This parameter is about finding the right balance between dark and light. Hence studies have shown that rooms so dark that a person is not certain of the space nature, the space might be mysterious or frightening.

[9] *Hervé Descottes, Architectural Lighting Design with Light and Space, P. 16*
[10] *Hervé Descottes, Architectural Lighting Design with Light and Space, P. 17*

Furthermore, it was found, that office workers typically preferred that the chosen rooms had a mean wall illuminance of at least 30 cd/m^2 (around 200 lux) and a variability of the brightness[11].

The criterion for getting a high score in the scheme, is to have a good flow of bright and dark areas within the space, without making the space seems frightening nor too bright

Illuminance

Illuminance is the amount of light falling on a surface and is measured in lux. The longer the distance from the light source to the surface the lower the lux level gets. The illuminance describes the quantity of light in a space and must be controlled carefully for providing a light level for good visibility and safety[12].
According to the Danish Building Regulations (Br18), it is said that at least half of the interior floor plan, lit by daylight, must have a value of more than 300 lux for more than half of the daylight hours[13]. Moreover, the recommendation in classrooms and offices is between 300 to 500 lux[14].

The criterion for getting a high score in the scheme, is that the space fulfills the standards of lux level from Br18. Around 300-500 lux, below that is not acceptable.

Impression

A more subjective parameter, since light is more than just numbers and calculations. Variables such as-what is the user interpretation of the space, how does it the space make you feel, and how do you perceive the space is interesting for the lighting designer to know.
Unfortunately, this study is mainly using renderings/visualization in CAD-programs, when testing the different light settings, which makes it harder to tell about the feelings and the perception the space provides, than what a real-life model would do.

The criterion for getting a high score in the scheme, is to have a space were the user feels welcome and wants to stay in.

11 *Peter Tragenza and David Loe, The Design of Lighting, P. 96*
12 *Hervé Descottes, Architectural Lighting Design with Light and Space, P. 14*
13 *Br18, 18. Lys og Udsyn, § 379*
14 *Peter Tragenza and David Loe, The Design of Lighting, P. 109*

Vertical and horizontal light

The knowledge gained from investigating the previous parameters a pattern of how to make a good a lighting environment become clearer. Using only one light source would not be enough for achieving a high score in the scheme. Materials and surfaces for instance, would be harder to identify. With the use of only one light source, one is more dependent on the direction of the view and the light source for identifying the surface texture, than in a light scenario with multiple light sources. Since using only one light source, the light beam must fall at a glancing angle onto the material, before the texture is strongly revealed[15]. Hervé Descottes, says that "*the pairing of differing directionalities and distributions provides a lighting designer with many possibilities for rendering an object or space to different effect"* and continues explaining about the power of how to perceive an object, only by changing the type of light or direction of the beam[16]. A sidelit room can cause glare and discomfort. The light entering a room with only one opening on the side that side is dark, and the light mainly hits the floor near the opening and reflects light on ceiling also near the opening. This leads to an overall effect of increasing brightness from the back of the room to the front. Using only a horizontal opening, the surfaces below are very strongly lit[17]. Using a room with a combination of both vertical and horizontal openings and its outcome will be interesting to investigate further. The diffuse light entering from above mixed with the direct light from the side opening, provides the same kind of lighting as William Lam defines as the best conditions of illumination for most three-dimensional objects[18]. Knowing, that operating only with daylight, which is dynamic and varies depending on the weather, orientation and the time of the day and the year is harder to test than only the use of mechanical lights, where the conditions is static. However, the findings from this study could be an interesting addition for the lighting designer to include during the conceptual phase in a building process or for evaluating the light in an existing building.

Daylight VS. Electrical light

Besides the benefits of economy and health issues daylight provides, which will not be a factor in this study, there is several other benefits. Among others, the dynamic and movement daylight creates in a space is something high valued and affects how people behave and how they think. If a space looks the same at all time, it is not attractive, and generates mental images of an artificial environment[19]. Daylight is desirable,

[15] *Peter Tragenza and David Loe, The Design of Lighting, P. 10*
[16] *Peter Tragenza and David Loe, The Design of Lighting, P. 14*
[17] *Peter Tragenza and David Loe, The Design of Lighting, P. 14*
[18] *William Lam, Perception and Lighting as Formgivers for Architecture, P. 67*
[19] *Peter Tragenza and David Loe, The Design of Lighting, P. 102*

because of its illumination and spectral qualities coming from the window, but the window also provides the need of view. A view outside gives a lot of information that has high importance for people. Information such the weather, orientation and time of the day[20].

Of course, daylight is only available in the daytime hours, and support from mechanical light is needed when it gets dark.

Types of daylight

Sunlight, skylight and reflected light. These are the three types of lights and are referred to as daylight.

Sunlight is the most intensive type of light. The parallel rays directly from the sun, leave a precise and hard shadow figure, which is difficult to see through. The shadow constantly changes position depending on the time of the day and the year.

Skylight comes from the entire sky. It stretches from zenith down to the horizon. Depending on whether the sky is clear blue or cloudy, the light varies a lot in intensity. Skylight is the dominant daylight source in some regions.

Reflected light is the light being reflected from all the surrounding surfaces. The reflected light is always weaker than the light that hits the surface[21].

Modelling daylight

The best way of testing how the light in the space is perceived, is to build a mockup, which is a full-size model or build a smaller model in a fitting scale. Place the model outside, while documenting and observing the model, by taking pictures, notes and a stop-motion. There are both pros and cons when using this method. The light would be the most accurate, however, lighting designers is usually mostly interested in the two equinoxes' and two solstices. The two solstices happen the 21st of December and 21st in June. These are the days where the Sun's path in the sky is the farthest north or south from equator. The Sun is exactly above equator during the two equinoxes. By documenting the light these days, the lighting designer knows the range of light with the two solstices as the extremes and the equinox the average of light. When using CAD-programs where the technology is great, the lighting designer can do all these calculations and observations in short time. The method used in this study, is mainly CAD-programs. By defining the space, its surfaces and the texture of the materials, precisely renderings can be made.

[20] *William Lam, Perception and Lighting as Formgivers for Architecture, P. 23*
[21] *Torben Dahl, Climate and Architecture, P. 119*

Test 1

The test

To investigate how the distribution of vertical(V) and horizontal(H) daylight inflow and direct and diffuse light is affecting the appearance of objects in a space following experiment was carried out.

A model was made with two openings acting as the only light sources. A box of 10x10x3 meters was made in a scale of 1:20. The two openings, one on one of the sides of the box and one on the top side of the box, were cut out in three different sizes that easily could be changed. A diffused layer was placed on top of the top opening, so both diffused and direct light were present in the box

The purpose of this model is to investigate differences in how vertical (V) and horizontal (H) light, the room and the objects in the room changes when changing the sizes of the two openings. Moreover, the model is used to examine if pairing diffused light with parallel light, would optimize the impression of the three-dimensional form and keep the shadows.

The space

The box model is scaled 1:20 with two openings. One on the top of the model and one on one of the sides. Both sides with the openings is replaceable, so that it is possible to test various designs and size of the openings.

The three sizes of openings in a scale of 1:20:

0,75 m^2

2,25 m^2

4 m^2

The opening on the top of the model has a diffused layer filling the opening, and the opening on the side is without any filters.

The dimensions of the box are:

L50cm x W50cm x H15cm.

And when scaled 1:20 the dimensions of the box are L10m x H10m x H3m.

Figure 3, a ball and a hole for the camera is cut out

Materials and lights

- 5mm foamboard, double-sided white. Reflectance of 0.80

- Diffuser plastic sheet, estimated to 70% light transmission(*figure 4*).

- 2x Philips Hue bulbs, controllable CCT. Set to 5000k (daylight).

- Daylight outside 60.000 lux

Figure 4, Diffuser sheet

Method

The box was placed in a room with the side-opening facing 1.5m from a south facing window, just out of reach from direct sunlight. Furthermore, two electric light sources each on 4500K were used to support the light in the room giving the room a total of 520lux. Outside the light was measured to 60.000lux.

A hole for the camera lens was cut on the side across the side with the side-opening in a height of 1.70 meter (1:20) as illustrated on *figure5* and an object in wood was placed as seen in *figure3*

First, three pictures with only the top-openings was taken with three different size-openings and the lux levels measured, and then the same procedure was followed with only the side-openings.

Finally, a new test was performed, where both the top-opening and the side-opening were present, and all the 9 different scenarios was tried out and documented.

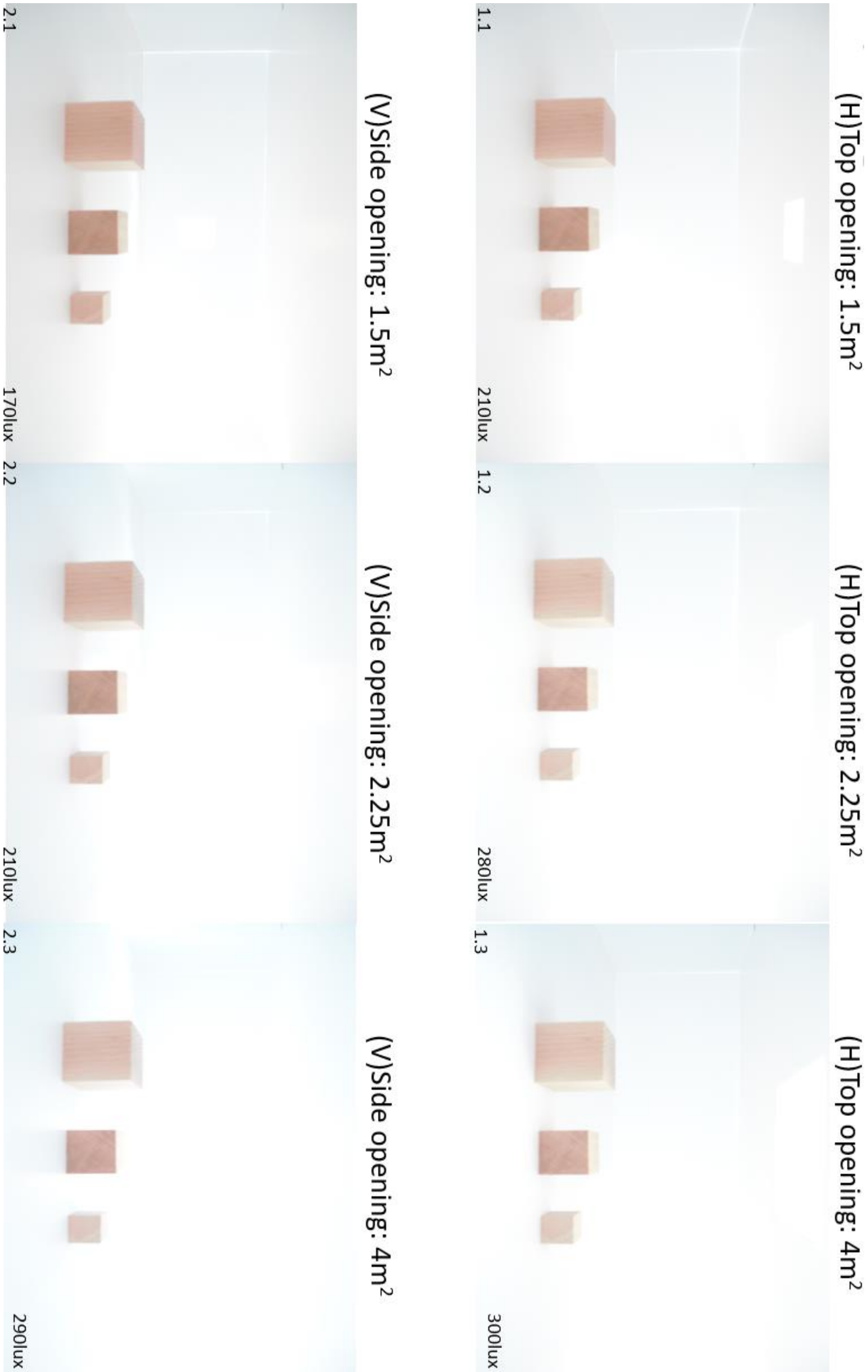
Then all the possible outcomes using both side-openings and top-openings were done and later put in a matrix and giving the different scenarios their own letter, for an easier comparison.

The first tests matrix has six different scenarios and will be numbered 1.1, 1.2, 1.3, 2.1, etc.…

and the second tests matrix has nine scenarios and will be numbered 3.1, 3.2, 3.3, 4.1, etc.…

Figure 5, the setup

Single openings



Evaluation

The scale used for evaluation is:

1 being unacceptable, 2 bad, 3 neutral/acceptable, 4 good and 5 excellent.

The criteria for each parameter are defined in the chapter "Evaluating the light".

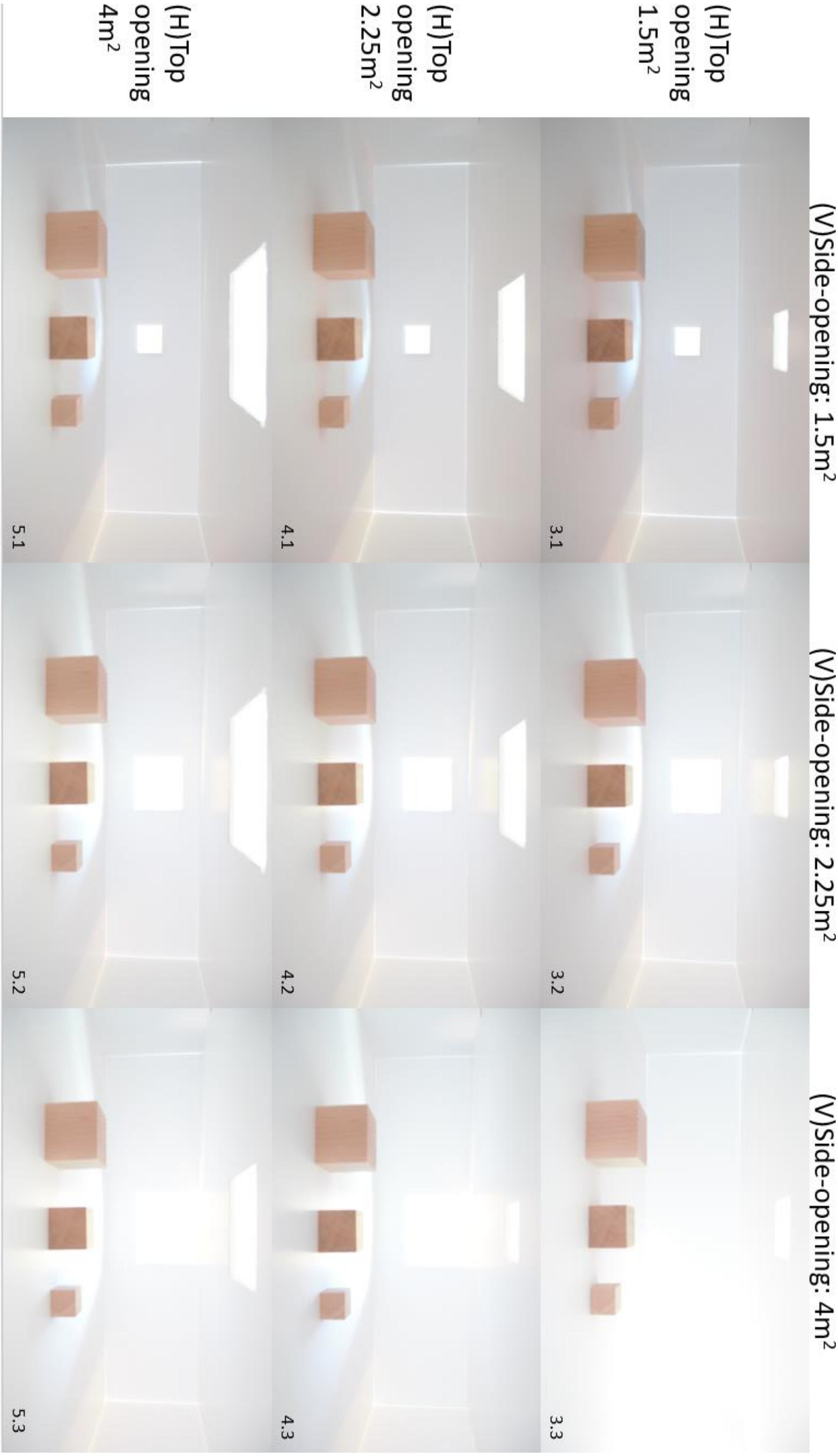
Table 1

Parameters/Scene	1.1	1.2	1.3
Materials/surfaces	2	2	2
Shadows	1	1	1
Light vs. Darkness	1	1	1
Illuminance	1	1	3
Impression	3	1	1
Total	**8**	**6**	**8**

Table 2

Parameters/Scene	2.1	2.2	2.3
Materials/surfaces	2	1	1
Shadows	1	1	1
Light vs. Darkness	1	1	1
Illuminance	1	1	1
Impression	3	1	1
Total	**8**	**5**	**5**

Double openings



Evaluation

Table 3

Parameters/Scene	3.1	3.2	3.3
Materials/surfaces	3	2	1
Shadows	1	2	1
Light vs. Darkness	2	1	1
Illuminance	-	-	-
Impression	4	3	2
Total	**10**	**8**	**5**

Table 4

Parameters/Scene	4.1	4.2	4.3
Materials/surfaces	3	2	2
Shadows	1	2	2
Light vs. Darkness	2	1	1
Illuminance	-	-	-
Impression	4	3	2
Total	**10**	**8**	**7**

Table 5

Parameters/Scene	5.1	5.2	5.3
Materials/surfaces	3	2	2
Shadows	1	2	2
Light vs. Darkness	2	1	1
Illuminance	-	-	-
Impression	4	3	2
Total	**10**	**8**	**7**

Findings

Due to a little too high exposure setting on the camera and only using cubes and not having balls too as the objects for comparison, it is difficult to find any significant results. The combination of different types of objects will lead to a higher understanding of how the room, the light, the shadows and the texture would be perceived. Also, if using balls, the shading could have been compared to Sophus Frandsen's shading scale. The light coming from the top openings provide a higher lux level, than what the equivalent side opening does when only using one opening at the time. Even though, there is a diffused layer covering the top opening. The joints of the box not being completely tight, causing light leaking inside the box and resulting in a higher exposed environment. No lux level was measured in the second part of the test; therefore, the blank result is shown in the scheme.

The shadows are hard to define; however, the details and materials of the objects is easy seen.

Conclusion

Add balls to the project and use a different light-setup in a CAD program to simulate the daylight better. The diffused layer on top of the box obscures the opening, which makes the opening act like one big diffused luminaire. This means it is hard to tell whether the light entering the space is daylight or electrical light, and the shadows is therefore not visible. Additionally, the opening losses the function to provide orientation, when the opening is covered. The lack of orientation and questioning whether the light is daylight or mechanical light, which is very important for the quality of light, has too high importance to extrude and therefore it can be concluded, that the diffused layer will not be present in the next tests.

Test 2

The test

A new setup with the use of the CAD-programs Revit and VELUX Daylight Visualizer. The matters of the size opening as in Test 1 will be tested again, but with more details, since the CAD-programs are able to simulate the daylight easier than how it was done in Test 1. The findings from this test is expected to lead to a clearer result and therefore get a better understanding of how to make a good lighting environment. The standards from the Danish Building Regulations will set the frame of which light scenario there can be used in a building project.

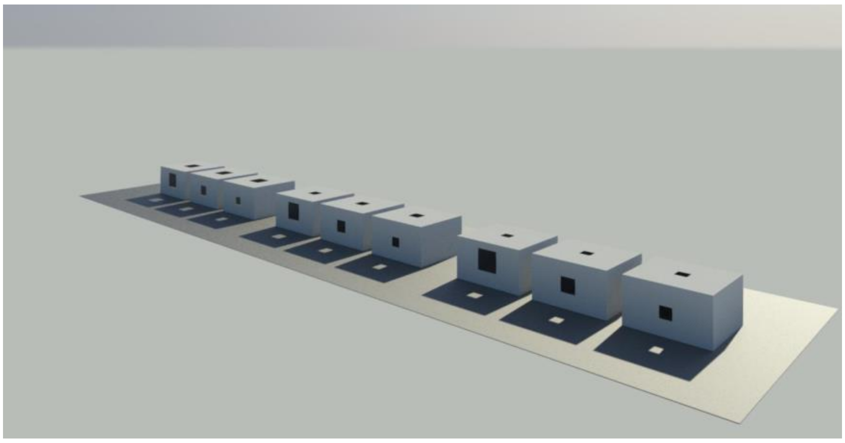


Figure 6, the situation of all the scenarios

Method

The different light scenarios was built in Revit and imported to VELUX Daylight Visualizer (*figure 6*).
The simulations are at 21st of march at 12'oclock (spring equinox), situated in Copenhagen, with the side openings facing north.
The same matrix and numbering as in Test 1, is used again to simplify and get a better comparison of the nine new different scenarios. The window area and the percentage of the floor area for each model is represented in table 6. A visualization of how the naked eye will perceive the rooms (*figure 7*). After pseudo colors is added to each visualization to indicate the lux level in the spaces (*figure 7*).

Table 6, The total opening areas and floor percentage

Scene/dimensions	Side opening(V)m2	Top opening(H)m2	Total openings m2	Percentage of floor area
1.1	0.56	0.56	1.12	4.5
1.2	2.25	0,56	2.81	11.2
1.3	4	0,56	4.56	18.2
2.1	0.56	2.25	2.81	11.2
2.2	2.25	2.25	4.50	18.0
2.3	4	2.25	6.25	25.0
3.1	0.56	4	4.56	18.2
3.2	2.25	4	6.25	25.0
3.3	4	4	8.00	32.0

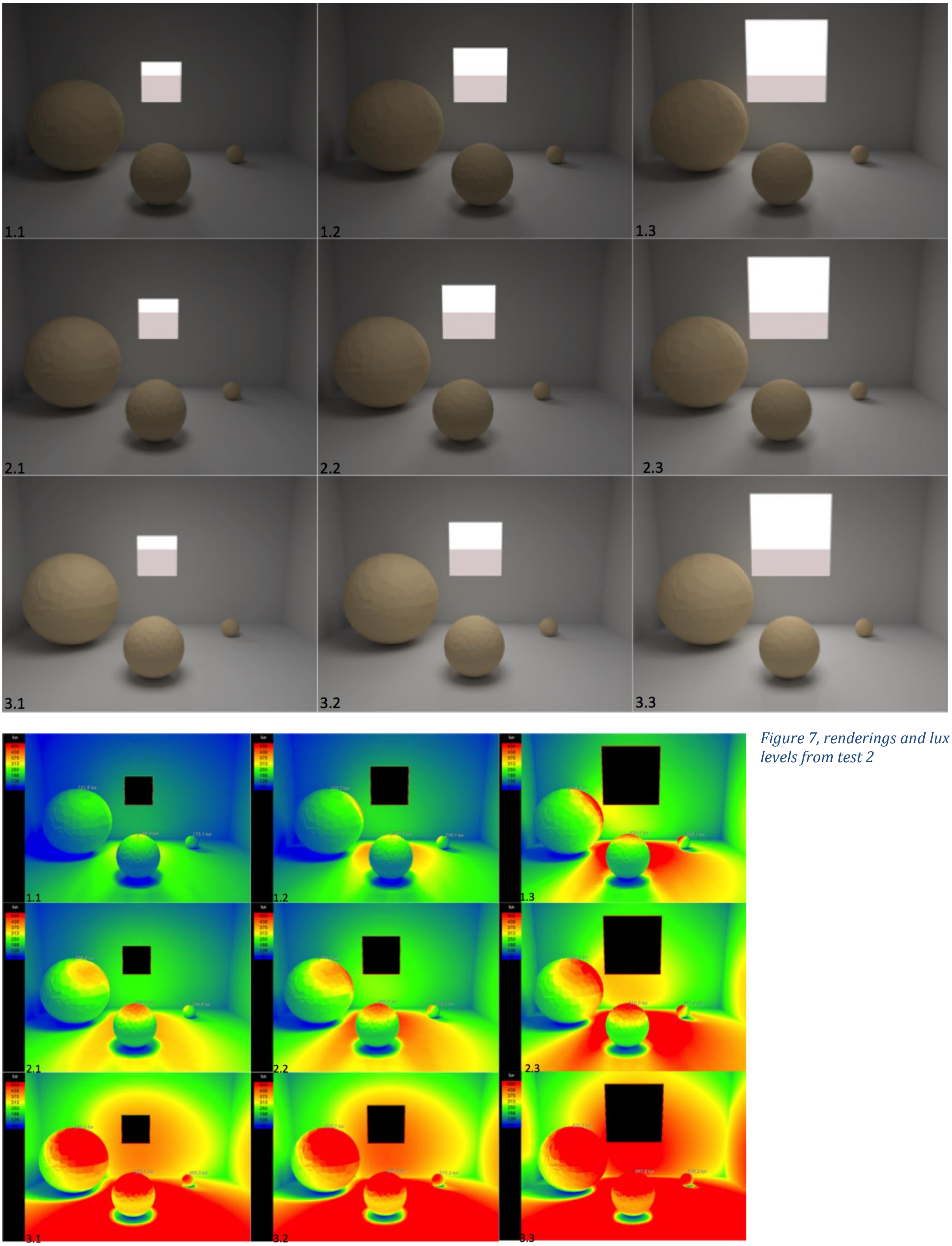


Figure 7, renderings and lux levels from test 2

Evaluation test 2

Table 7, having small horizontal opening

Parameters/Scene	1.1	1.2	1.3
Materials/surfaces	2	3	3
Shadows	4	4	5
Light vs. Darkness	2	3	4
Illuminance	1	1	5
Impression	2	2	4
Total	**11**	**13**	**21**

Table 8, having medium horizontal opening

Parameters/Scene	2.1	2.2	2.3
Materials/surfaces	3	4	4
Shadows	3	3	3
Light vs. Darkness	2	3	3
Illuminance	5	4	4
Impression	2	4	4
Total	**15**	**18**	**18**

Table 9, having large horizontal opening

Parameters/Scene	3.1	3.2	3.3
Materials/surfaces	3	3	3
Shadows	2	2	2
Light vs. Darkness	2	2	2
Illuminance	2	2	2
Impression	2	2	2
Total	**11**	**11**	**11**

Result

If comparing the lux levels to the Danish Building Regulations, then it can be concluded that the results documented in pictures 1.1, 1.2, 2.1 and 2.2 does not fulfill the standards.

Since the lux level should have a minimum of 300 lux.

Another standard that needs to be followed, is that the openings should be at least 10 pct. Of the entire floor. Which in this case means, that the openings combined should be 2.5m^2 or more, since the floor is 25m^2. This leads to only scenario 1.1 being not relevant (*figure 8*).

1.2 and 2.1 are very close the BR18 10pct. requirement, but their scores (11 and 15, respectively) are only medium.

The best scoring scenarios are in 1.3, 2.2, and 2.3, this indicates that an optimal indoor lighting environment requires openings closer to 20pct. of the floor area. Also, vertical light appears to be on the highest importance for an optimal score. This needs to be further investigated before anything can be concluded.

What is next

To find an easier way of finding the right ratio between to openings providing horizontal and vertical light. Another factor, such as how the different spaces will appear if adjacent buildings were placed in the whole CAD-model and therefore adding more reflected light and more realistic to the everyday living, could be interesting to investigate. However, this would make the study to broad, where the main aim is to find the balance between two light sources.

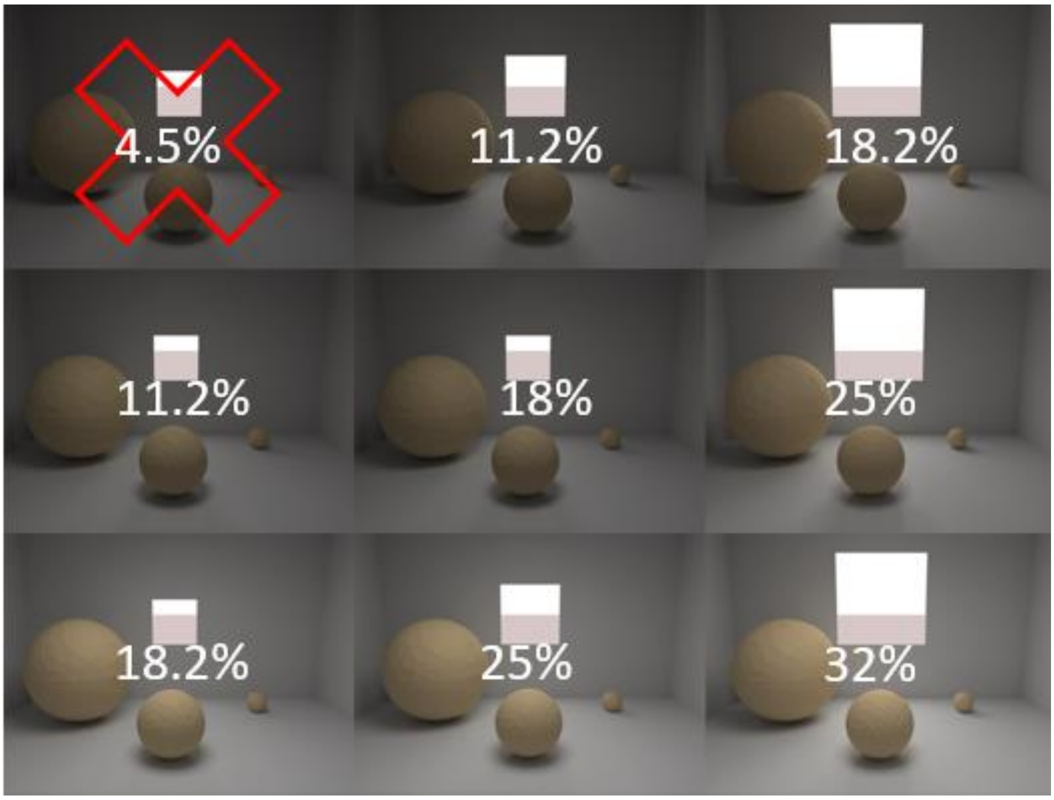


Figure 8 opening area as percentage of floor area, with indication of compliance with BR18

Test 3

The test

In this test the aim is to find an easier and a better defined standard when starting a new building project. This will help people in the building industry to have a guideline of how much horizontal and vertical daylight the project needs for making a good indoor lighting environment.

Ratios

New openings are made to simplify the standards when starting a new building project. The following ratios that will be tested is 1:2, 1:4 and 1:6 on both sides, meaning that the side opening is respectively twice as big, four times as big, and six times as big as the top opening. The total openings are based on the dimensions of a 5x5m (25m^2) interior floor. This means that the total opening areas has a total of 2.5m^2. The opening area of each of the scenarios is shown in *figure 9*

Scenario	Side opening(V)m2	Top opening(H)m2	Total openings m2
1.1, 1(H):2(V)	0.83	1.66	2.5
1.2, 1(H):4(V)	0.5	2	2.5
1.3, 1(H):6(V)	0.35	2.15	2.5
2.1, 1:1	1.25	1.25	2.5
3.1, 1(V):2(H)	1.66	0.83	2.5
3.2, 1(V):4(H)	2	0.5	2.5
3.3, 1(V):6(H)	2.15	0.35	2.5

Figure 9, The dimensions for every scenario

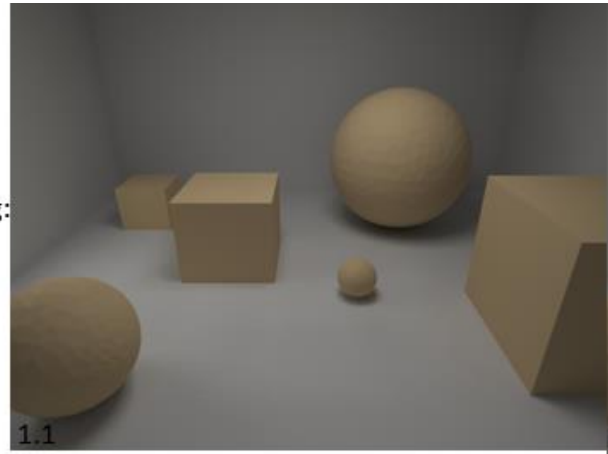
Method

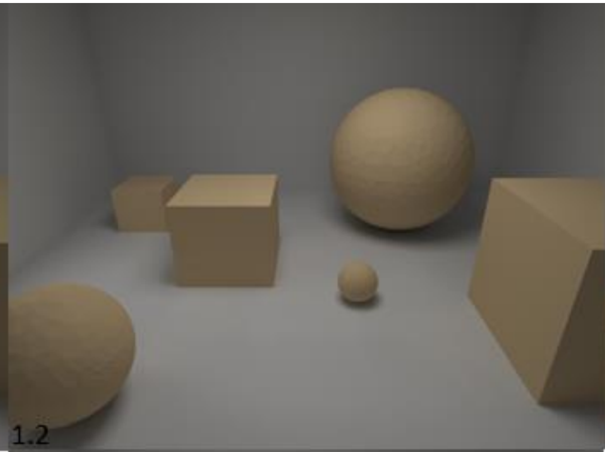
Velux Daylight Visualizer is used and rendered at spring equinox (21st of march, 12am). Also, a pseudo color render will be made. Different ratios between a horizontal opening and a vertical with a total square meter opening of 2.5m^2, is calculated and will be tested and compared to each other. The scenarios will be numbered just as the previous tests, meaning 1.1, 1.2, 1,3, etc.

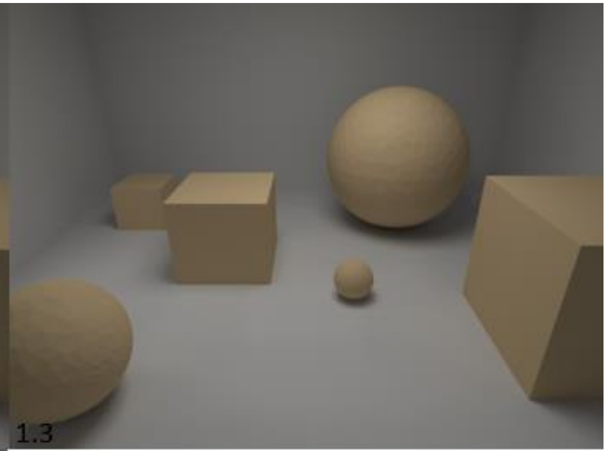
In the first scenario, 1,1, the ratio between the side opening and the top opening is 1:2. This means, that top opening is twice as big as the side opening. Scenario 1.2, the ratio is 1:4 making the top opening four time as big as the side opening. In 1.3, the ratio between top and side opening is 1:6, making the top opening six times bigger than the side opening. Next is 2.2, here the ratio is 1:1. That means that the top opening and side opening is the same size and still with a total square meter opening of 2.5m^2. Last 3.1, 3.2 and 3.3 has the same ratios as being used on scenario 1.1, 1.2 and 1.3. But here it is the side opening being two, four and six times as big as the top opening.

Test 3

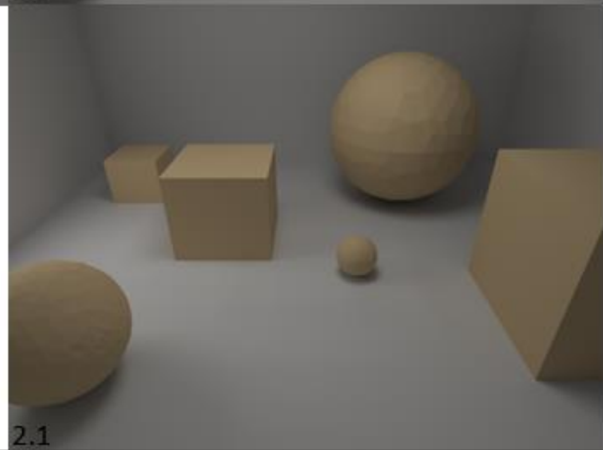
Big horizontal opening:
1:2, 1:4 and 1:6



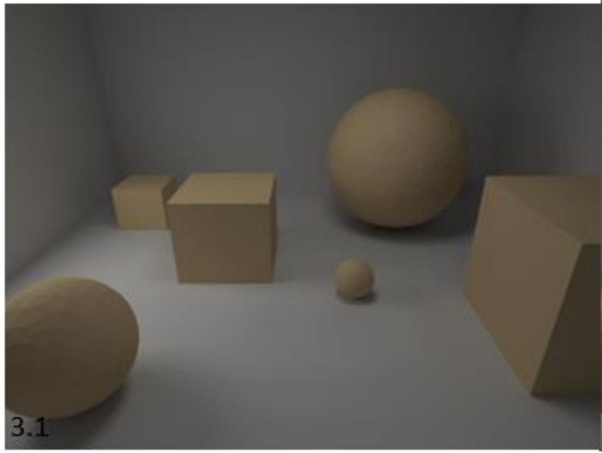


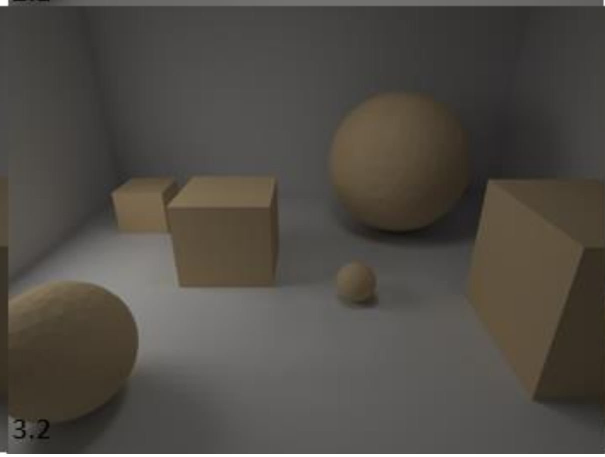


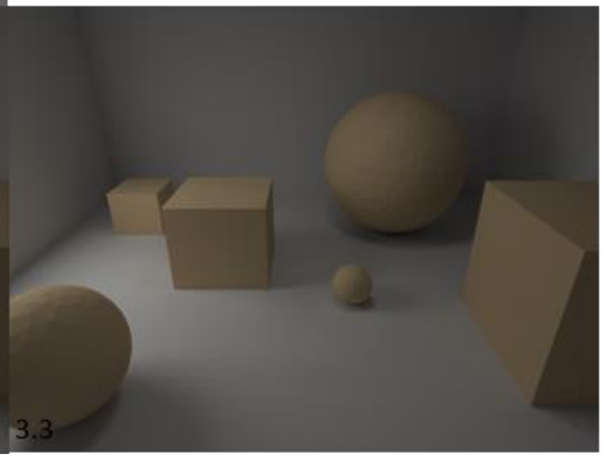
Side (V) and top opening (H), in same size: 1:1



Big vertical opening:
1:2 1:4 and 1:6

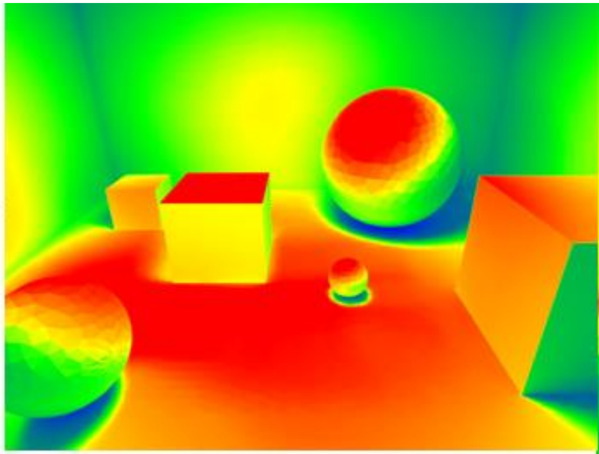
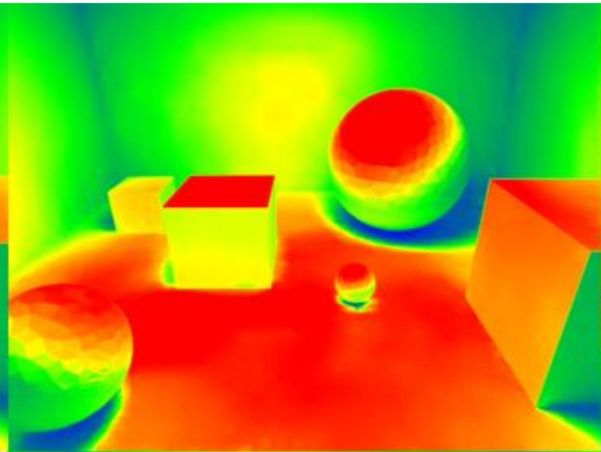
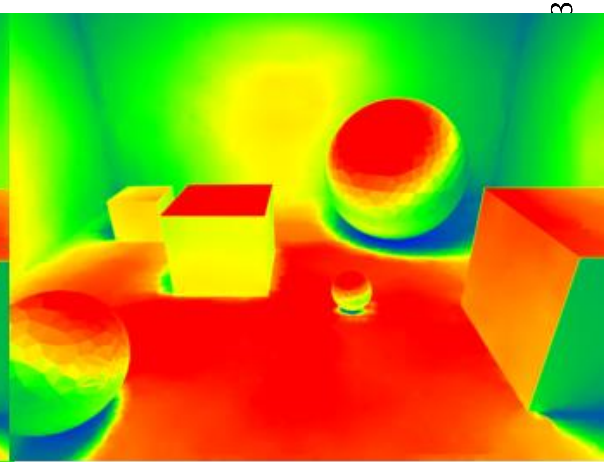




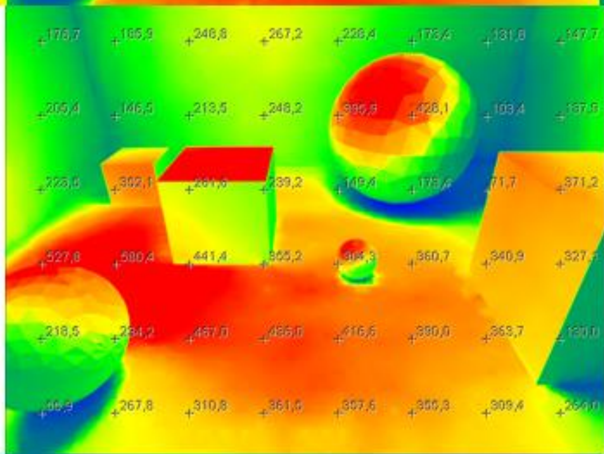


Test 3

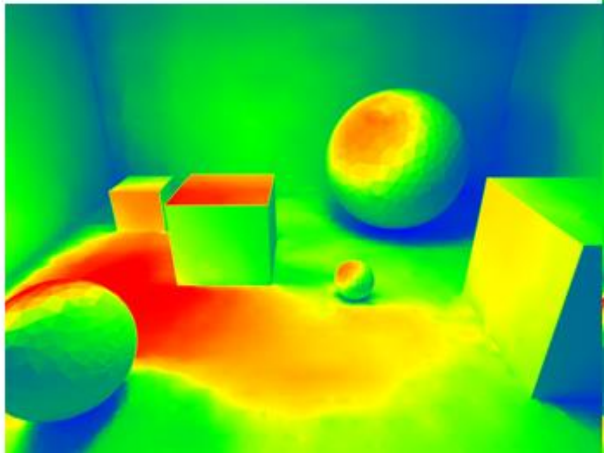
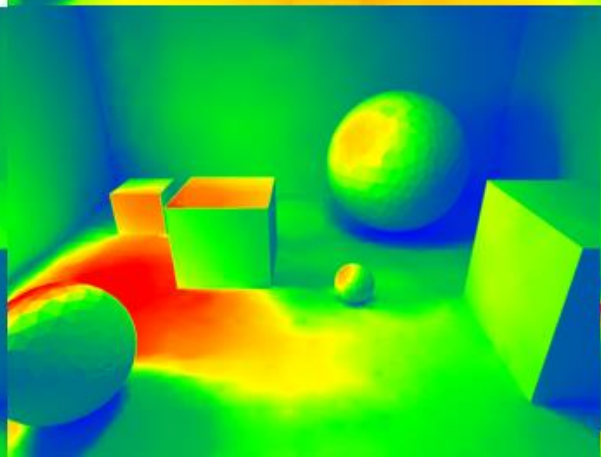
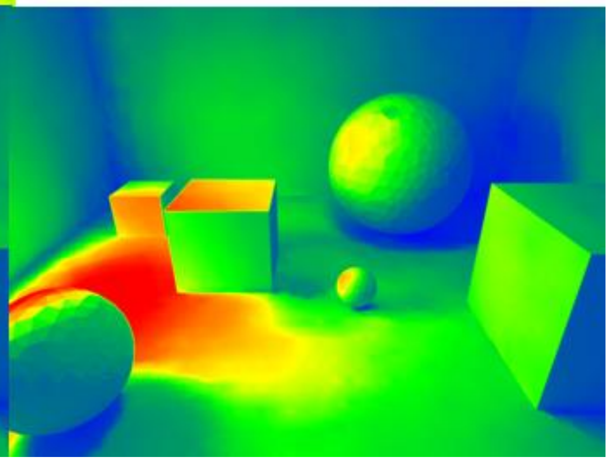
Big horizontal opening:
1:2, 1:4 and 1:6

Side (V) and top opening(H), in same size: 1:1



Big vertical opening:
1:2 1:4 and 1:6

Evaluation test 3

Table 10, result with scenarios having bigger horizontal opening than vertical opening

Parameters/Scene	1.1 1(H):2(V)	1.2 1(H):4(V)	1.3 1(H):6(V)
Materials/surfaces	5	5	5
Shadows	2	2	1
Light vs. Darkness	2	2	1
Illuminance	2	2	1
Impression	2	2	2
Total	**13**	**13**	**10**

Table 11, result with scenarios having equally big horizontal opening and vertical opening

Parameters/Scene	2.1 1:1
Materials/surfaces	3
Shadows	3
Light vs. Darkness	4
Illuminance	2
Impression	5
Total	**17**

Table 12, result with scenarios having bigger vertical opening than horizontal opening

Parameters/Scene	3.1 1(V):2(H)	3.2 1(V):4(H)	3.3 1(V):6(H)
Materials/surfaces	3	2	2
Shadows	4	5	3
Light vs. Darkness	4	3	1
Illuminance	3	2	2
Impression	5	4	2
Total	**19**	**16**	**12**

Result

In the scenarios having bigger horizontal opening than vertical opening, the spaces are very overexposed. The high quantity of light results in high detail levels on the objects in the spaces. The surface materials are easy recognizable. The synergy between darkness and bright is very poor in scenario 1.1, scenario 1.2, and especially in scenario 1.3. Almost every wall is lit up, and the few shadows present in the scene a hard shadow on the lower segment on the balls and the cast shadows in the place. The over lit spaces could lead to discomfort and glare for the user situated in the space.

In scenario 2.1 the objects are easier to identify, and there is a bigger variation of shadows and shading tones both on the objects and the cast shadows. Looking at the big in the right corner, the shading size in the middle segment has a gradient of shading tones and are what Sophus Frandsen would categorize as a type "5" in "The Scale of Light".

The same level of light quality is present in scenario 3.1 and scenario 3.2. Having ratios 1(V):2(H) and 1(V):4(H), respectively. The quantity of light drops rather drastically when vertical openings are the dominant light source. There is a nice synergy between darkness and light, in the three scenarios (3.1, 3.2, and 3.3). Almost every shadow type and tone are present, showing on the cast shadows from the objects and on the objects.

What is next

Based on the results, the ratios 1:1, 1(V):2(H) and 1(V):4(H) has the highest scores and therefore the ratios there will be investigated further in this study.

Test 4

The test

The aim of this test is to see if there are any significant changes when the number of openings changes to three, both on the side and on the top. The total square meter opening remains at 2.5m^2(10pct.). The light settings used in previous tests is still the same. Using Velux Daylight Visualizer to render the different scenarios and then evaluated with the use of the same scheme.

The test is based on the ratios 1(V):4(H), the ratio 1(H):4(V), and the ratio 1:1. The number of openings is 1x1, 2x2, and 3x3, meaning that each ratio containing three scenarios each.

Figure 10 shows the numbers and sizes of each opening on the three different ratios being tested.

The dimension of the openings is (using rounded up numbers):

	1(V):4(H) (1.1, 1.2, 1. 3):	1(H):4(V) (2.1, 2.2, 2. 3):	1:1 (3.1, 3.2, 3.3):
1x1	1.1 Side: 0.7m x 0.7m Top: 1.4m x 1.4m	2.1 Side: 1.4m x 1.4m Top: 0.7m x 0.7m	3.1 Side 1.1m x 1.1m top 1.1m x 1.1m
2x2	1.2 Side: 0.5m x 0.5m Top: 1m x 1m	2.2 Side: 1m x 1m Top: 0.5m x 0.5m	3.2 Side 0.8m x 0.8m top 0.8m x 0.8m
3x3	1.3 Side: 0.4m x 0.4m Top: 0.8m x 0.8m	2.3 Side: 0.8m x 0.8m Top: 0.4m x 0.4m	3.3 Side 0.65m x 0.65mtop 0.65m x 0.65

Figure 10, the number of openings and their sizes is measures. The calculations of 1(V):2(H), 1(H):2(V), and 1:1 is showed above

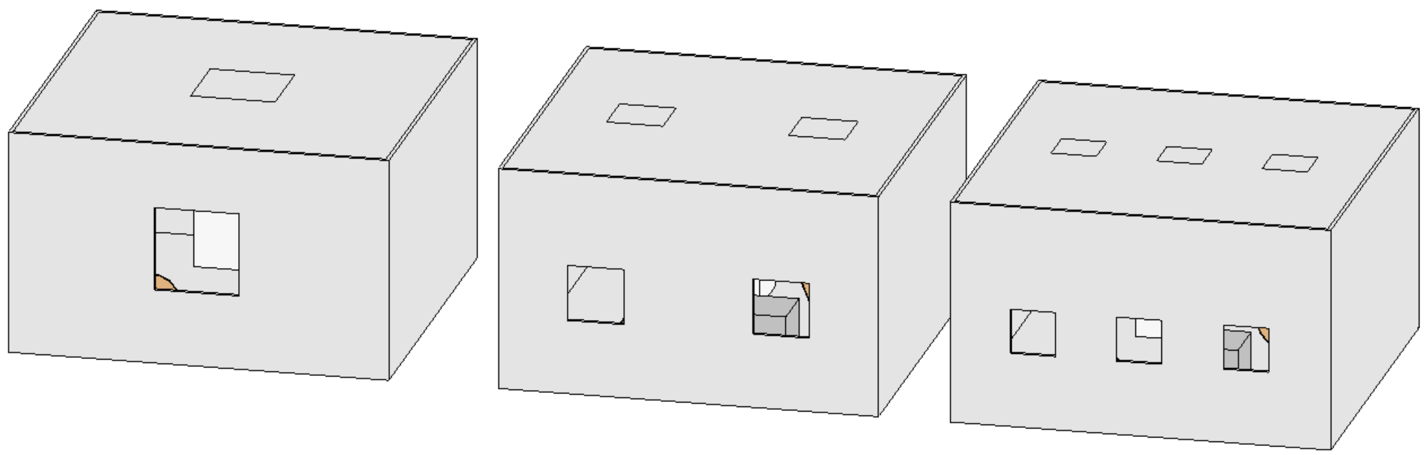


Figure 11, how scenario 3.1, 3.2, and 3.3 looks like

Method

Each scenario will be evaluated by using the same scheme used in previous tests. Furthermore, to simplify the evaluation an additional estimate of the quality of the light in each scenario is obtained by applying shadow type numbers, according to the Scales of Shadows by Sophus Frandsen, to the big ball in the corner to the far right of each scenario.

Finally, an evaluation of the lux levels will be performed.

Top opening area four times as big as side opening area

1(V):4(H)

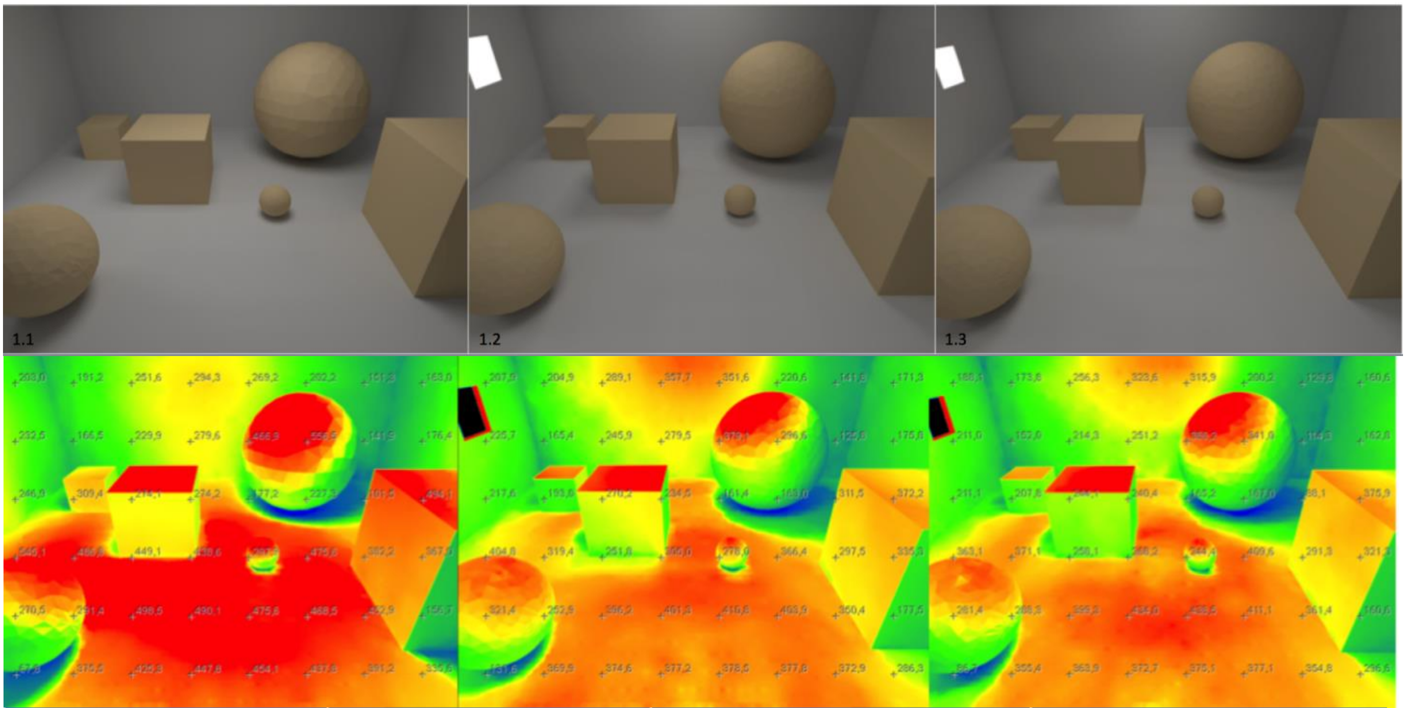
All scenarios fulfill the standards from the Danish Building Regulations.

Scenario 1.1: The big ball in the far-right corner is given a type 5

Scenario 1.2: The big ball in the far-right corner is given a type 8

Scenario 1.3: The big ball in the far-right corner is given a type 9

1x1 opening 2x2 opening 3x3 opening



Parameters/Scene	1.1	1.2	1.3
Materials/surfaces	5	5	5
Shadows	2	2	2
Light vs. Darkness	2	2	2
Illuminance	2	2	2
Impression	2	2	2
Total	**13**	**13**	**13**

Side opening area four times as big as top opening area

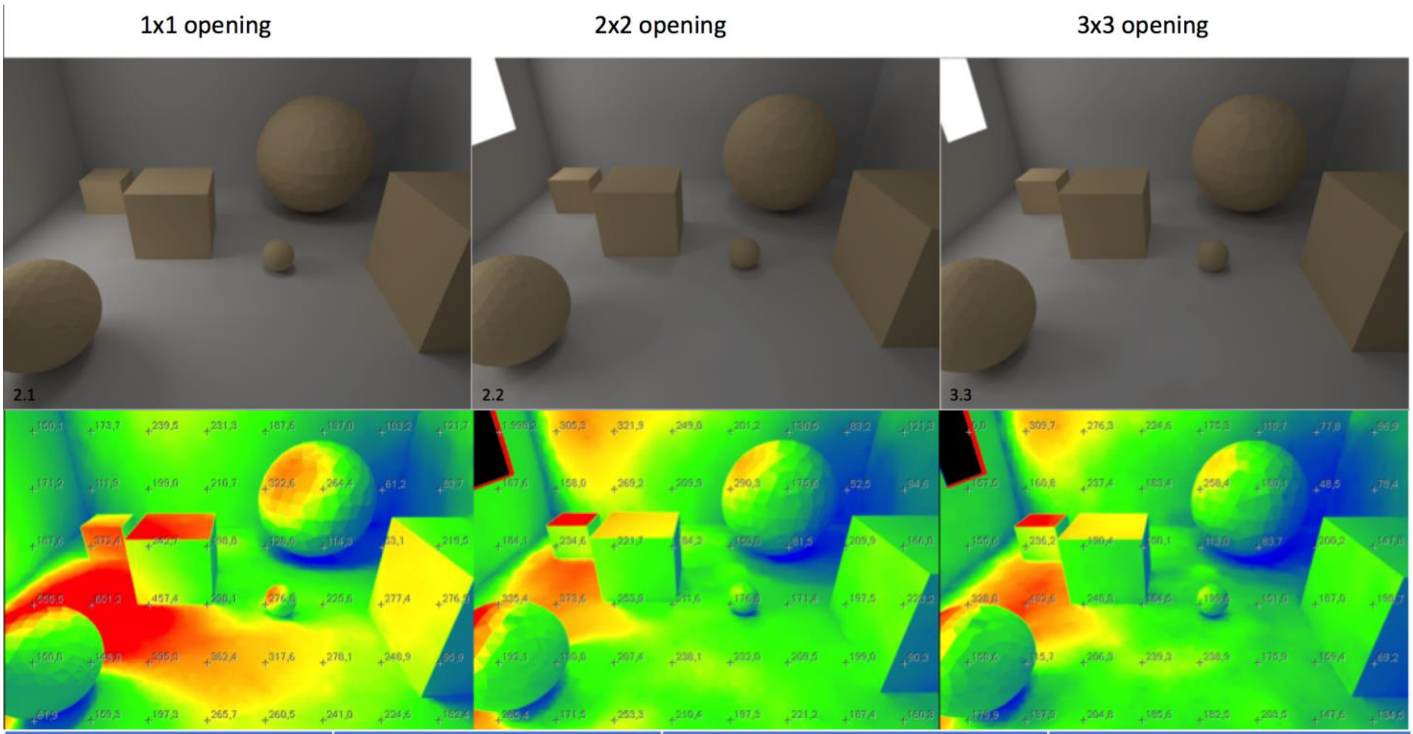
1(H):4(V)

Only scenario 2.1 fulfill the standards from the Danish Building Regulations.

Scenario 2.1: The big ball in the far-right corner is given a type 6

Scenario 2.2: The big ball in the far-right corner is given a type 7

Scenario 2.3: The big ball in the far-right corner is given a type 8



Parameters/Scene	2.1	2.2	2.3
Materials/surfaces	3	4	4
Shadows	4	4	4
Light vs. Darkness	4	4	4
Illuminance	3	1	1
Impression	5	4	3
Total	**19**	**17**	**16**

Equally big side and top openings

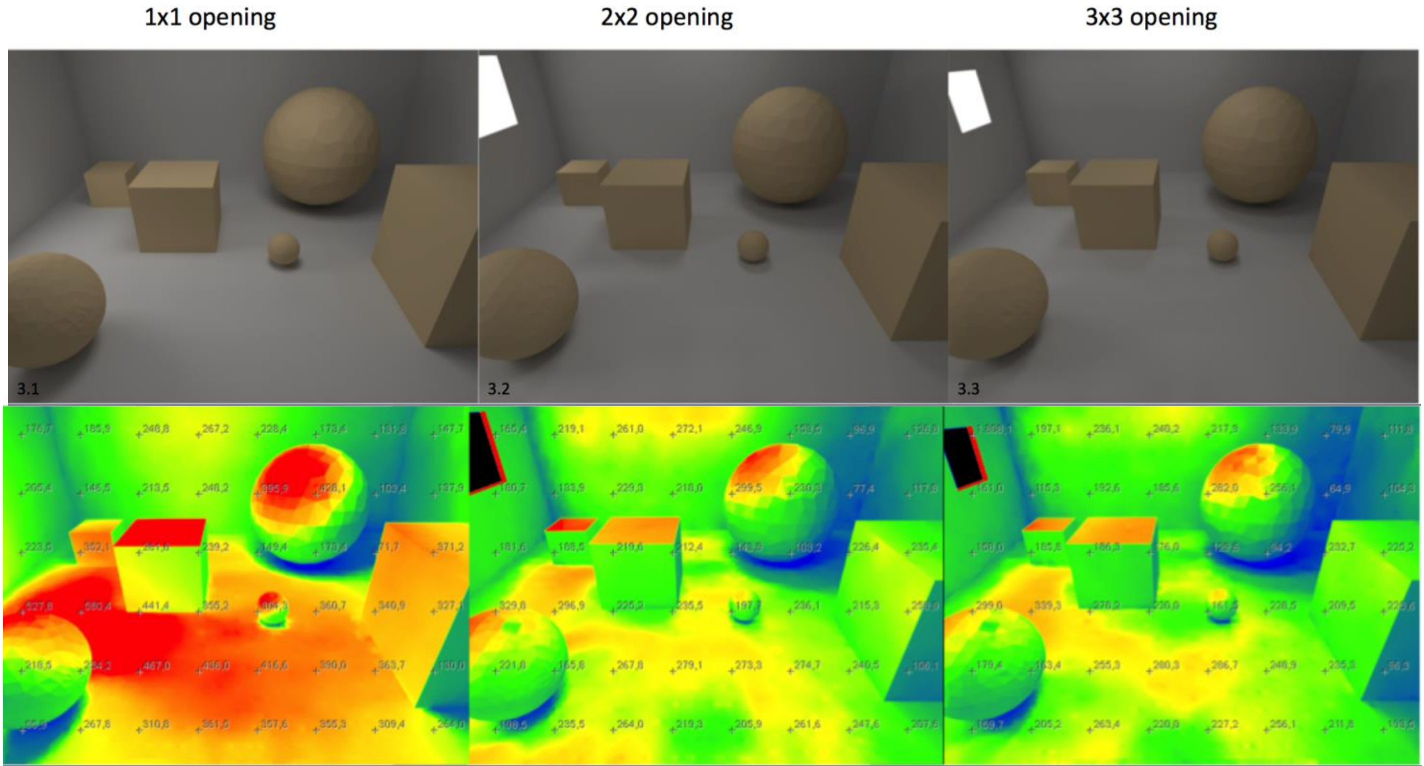
1:1

Only scenario 3.1 fulfill the standards from the Danish Building Regulations.

Scenario 3.1: The big ball in the far-right corner is given a type 4

Scenario 3.2: The big ball in the far-right corner is given a type 5

Scenario 3.3: The big ball in the far-right corner is given a type 7



Parameters/Scene	3.1	3.2	3.3
Materials/surfaces	3	2	2
Shadows	3	3	3
Light vs. Darkness	4	3	3
Illuminance	2	1	1
Impression	5	4	3
Total	**17**	13	**12**

Findings Test 4

In general, the more windows added to the space, the more uniform the light gets. Also, the quantity of light drops with the number of openings, even though the total opening area remains unchanged.

All the scenarios with the big horizontal openings give a high detail level and easy recognizable materials. But they lack in shadows and shadow types and present with a dull expression.

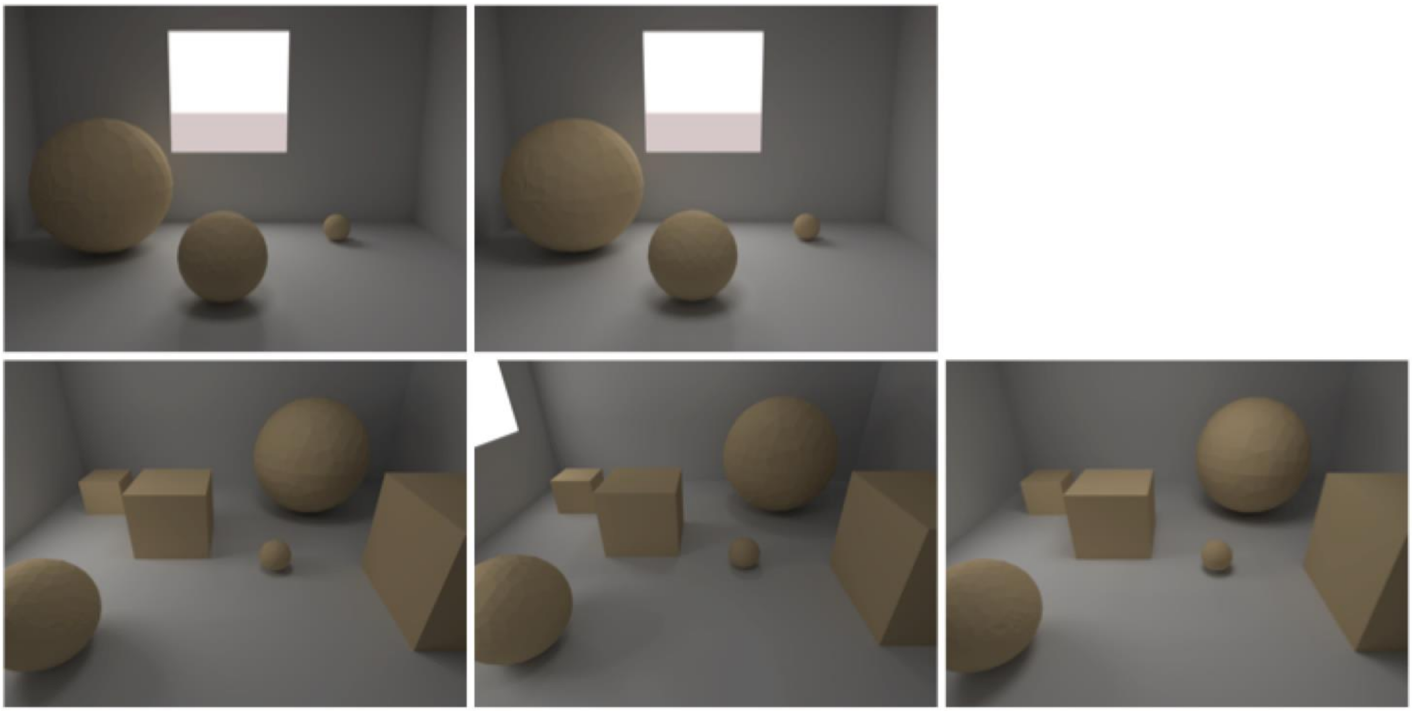
Big vertical openings the detail level is a bit lower than for the horizontal openings, but still good. However, the synergy between light and dark is nice and the shadow graduation on the objects provides a good impression of the objects three-dimensional form.

Many of the same qualities as described for big vertical openings is seen in scenario 3.1 with the vertical and horizontal openings of equal size. For scenario 3.2 and 3.3 the scores drop a little as more openings are added. However, the Type numbers given are still acceptable.

Sub-discussion

Summary

A clear result has not been found. Regarding exact ratios between vertical and horizontal openings. The scenarios with the highest scores and which fulfills the standards are scenario 1.3 and 2.3 from Test 2, and scenario 2.1, 2.2, and 3.1 from Test 4 (shown beneath in that order). With 1.3 from Test 2 with the highest score.



A pattern is starting to show, where the scenarios having a big vertical opening has the higher scores. Meaning parallel lighting entering from a vertical angle paired with a less powerful horizontal light are preferable. A space with dominating horizontal light has resulted in uniform light which makes the space seem dull and less inviting.

Sub-conclusion

This study has examined several parameters and their influence on the lighting in a room. The parameters examined are material/surfaces, shadow, light versus darkness, illuminance and impression. The parameters are examined under different combinations of vertical and horizontal daylight. The emphasis of the study has been on the balance between the horizontal and the vertical light sources. While it is not possible to build a rule with regards to the ratios between the light sources it is however clear from the study that a space with a dominant vertical light source, supported by a secondary light source, is the preferable lighting scenario. The high scores in the scenarios Test 2: scenario 1.3 and 2.3 and Test 4: scenarios 2.1, 2.2 and 3.1 supports this observation.

In Test 2 it was concluded that a space having more vertical light than horizontal light was preferable, and that having a space with equally big side and top openings was too bright (3.3, score: 11, Test 2). But now when looking at 3.1 in Test 4, where the sides is equally big too, the score is much higher, scoring 17 points. The reason could be that the total square meter opening in Test 2 has a total of 4.5m^2(18 pct.), where in Test 4 the total is 2.5 m^2 (10 pct.) and therefore less light coming in.

Also, the study supports the standards as they are defined in the Danish Building Regulations, that openings must account for at least 10% of the floor space. In this study the scenarios with a bigger side openings and smaller top openings generally score in the high end. Also, the Danish Building Regulations requirement of a minimum of 300 lux is supported by this study. In all scenarios were the lux requirement was not met, the score was also low.

In this study the theoretical maximum score is 25, however in reality this score is not obtainable since some of the parameter, for instance shadow and material/surfaces, will work against each other. Taking this into account the maximum scores of 19 obtained in this study is considered very high and witness of some good lighting scenarios.

In the following study, the focus will be on the quality of light and less on the quantity, meaning that the parameter “Illuminance” will either have less importance or will be eliminated entirely when evaluating. Furthermore, the ratio 1(V):2(H) between the roof window and side window, has been set, and will be the only ratio examined in the following tests. The following tests will reflect a realistic environment, containing furniture and building materials.

Test 5

The test

In Test 5, the findings from the tests in previous tests has been taking into consideration. The ratio 1:2, having the side total opening area twice as big as the total top opening area, will be the ratio which will be tested further.

The aim of this test is to see if the light quality will remain the same as previous ratio 1:2 tests, but now using a more realistic scenario. Meaning that Test 5 is performed, using typical building materials and furniture situated in a typical classroom.

The case and its dimensions

The walls and the ceiling have a matte white painting with a reflectance of 0.840. The floor has a linoleum finish with a reflectance of 0.595. The furniture (chairs and tables) is made of wood. Furthermore, the openings have windows in it with a transmittance of 0.69 with the side openings facing north. The interior windowsill has a depth of 175mm also coated with a matte white painting with a reflectance of 0.840. The dimensions of the classroom are based on the recommendations from Den centrale Rådgivningstjeneste for Skolebyggerier which is 2.5-3m^2 pr. student[22]. In this case the class has a total of 20 students giving each student 3m^2 space, resulting in a classroom with a total floor surface area of 60m^2 and a height of 3 m. Likewise, in the tests from previous tests, where the total of window openings must be at least 10pct. of the total floor surface area, the same guideline will be used again in this test. The total window area is calculated to be 6m^2. Again, the ratio 1:2 is used, therefore the side windows area will always have a total of 4m^{2,} and the top window area will always have a total of 2m^2.

Method

Different window combinations will be tested, but always with same total of window areas. The space is situated in Copenhagen and the different light scenarios will be tested in VELUX Daylight Visualizer on the 21st of March at 12 o'clock p.m. only using daylight with no adjacent buildings and rendered in an eye height of 170cm. The side windows are facing true north, like in the previous tests.

The scenarios will be evaluated using the scheme as used previously containing the same parameters. Furthermore, each scenario will be discussed and evaluated.

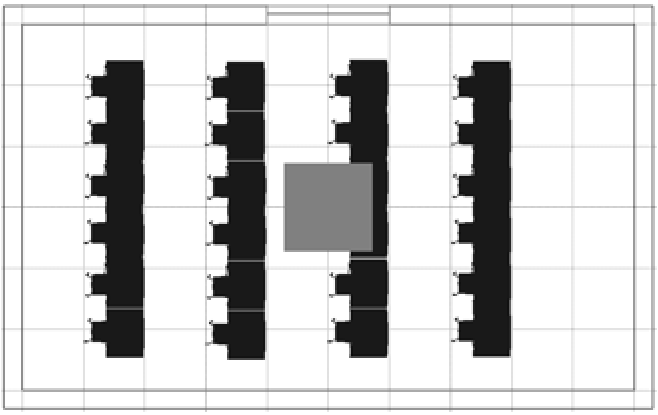
When evaluating the scenarios will be examined in pairs, each pair having equal number of side windows. Meaning scenario 1.1 against 1.2, 2.1 against 2.2, etc. Following up with a conclusion including all scenarios.

[22] https://www.dlf.org/loen-og-vilkaar/arbejdsmiljoe/fysisk-arbejdsmiljoe/normalklasserum

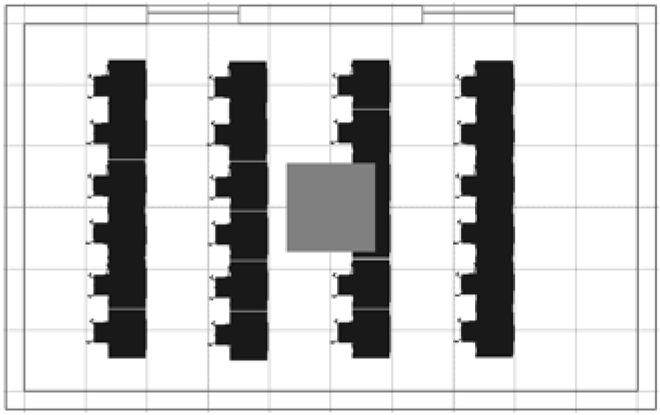
The spaces

Eight different light scenarios will be tested. All with a total floor surface area of 60m^2(6mx10m). The dimensions, the placement, and number of windows is illustrated below in *figure 12*.

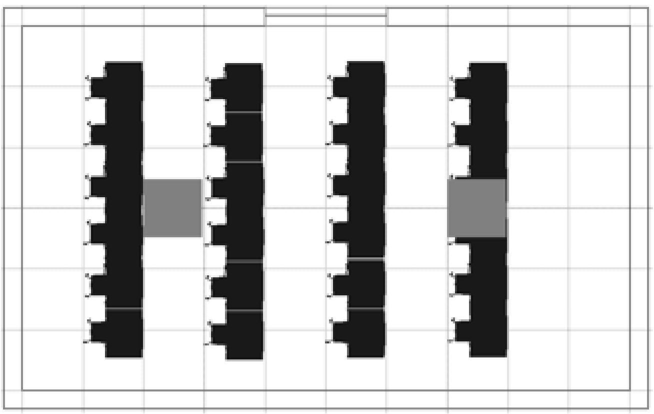
1.1
One side window 4m^2(2mx2m)
One roof window 2m^2(1.4mx1.4m)



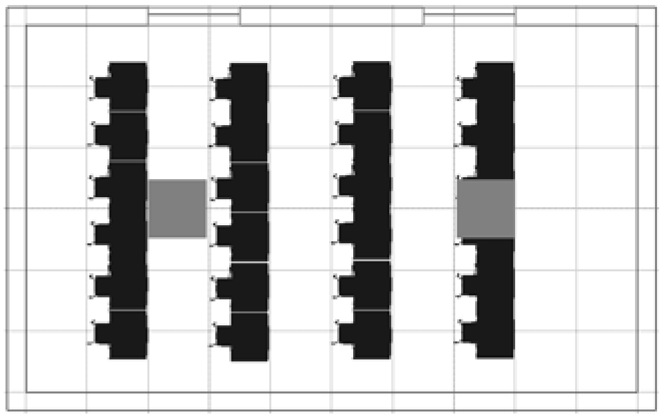
2.1
Two side windows 4m^{2}of each(1.4mx1.4m)
One roof window 2m^2(1.4mx1.4m)



1.2
One side window 4m^2(2mx2m)
Two roof windows 2m^2 of each(1mx1m)



2.2
Two side windows 4m^{2}of each(1.4mx1.4m)
Two roof windows 2m^2 of each(1mx1m)



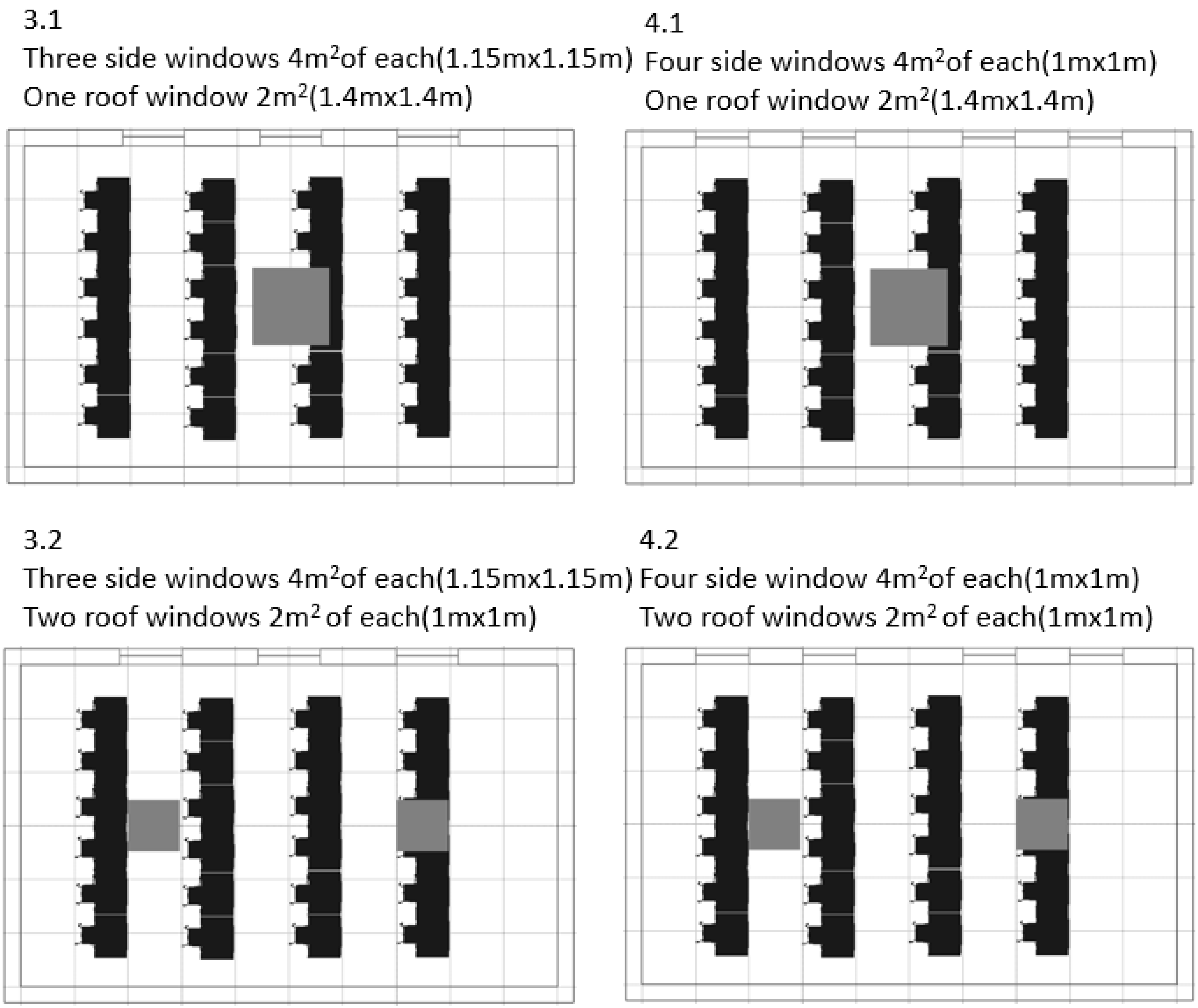
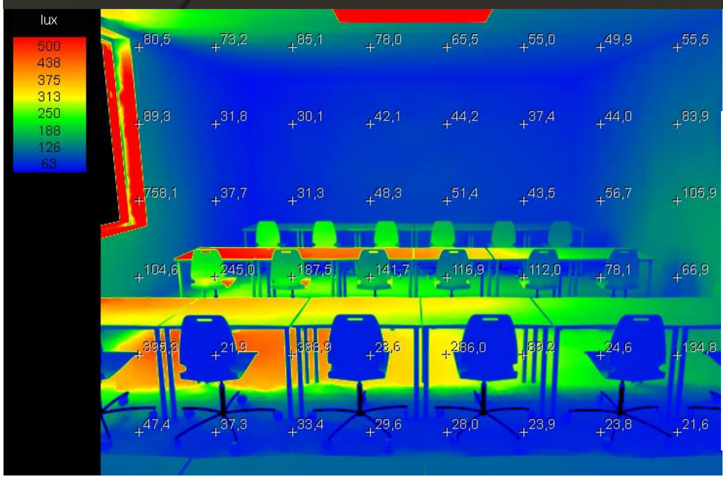
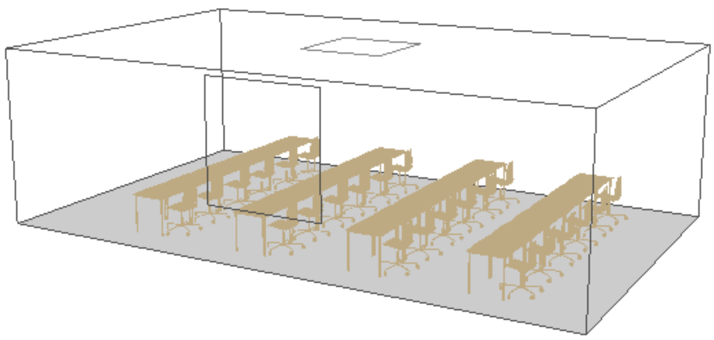


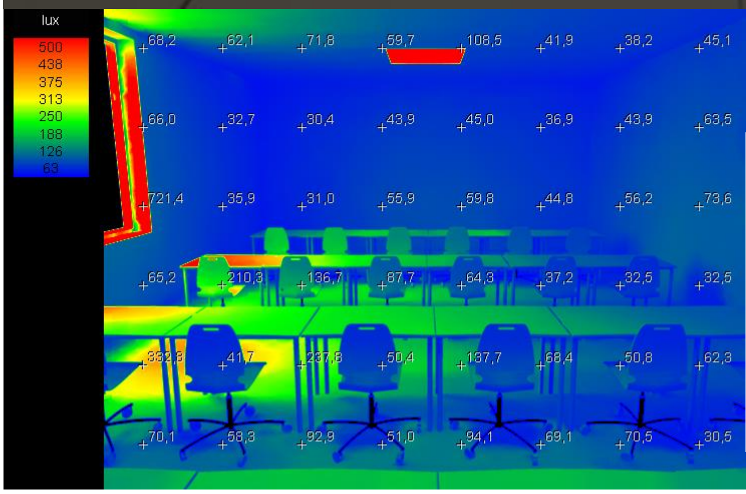
Figure 12, placement and sizes of the windows

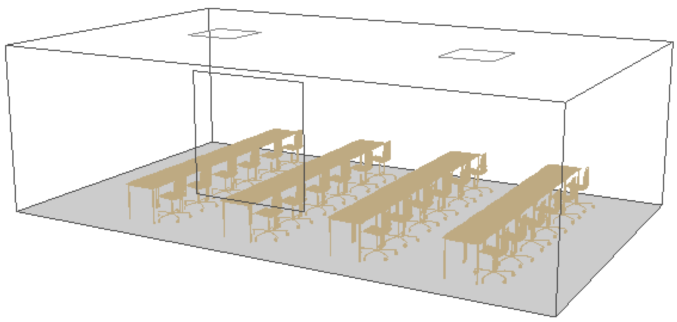
1.1, One side window and one roof window





1.2 One side window and two roof windows



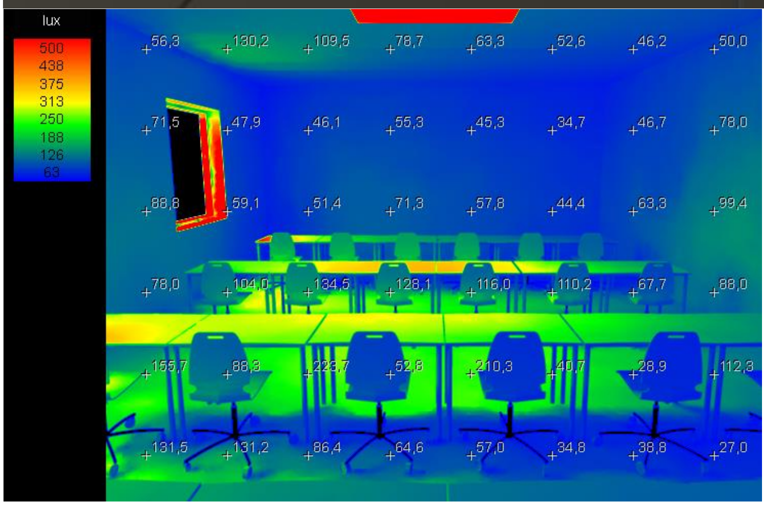


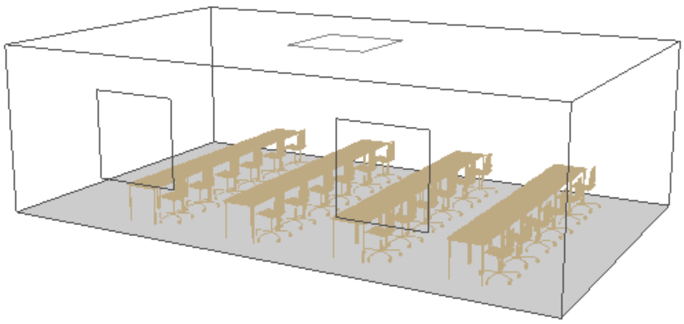
Parameters/Scene	1.1	1.2
Materials/surfaces	4	2
Shadows	2	4
Light vs. Darkness	2	3
Illuminance	2	1
Impression	2	3
Total	**12**	**13**

Findings, 1.1 and 1.2

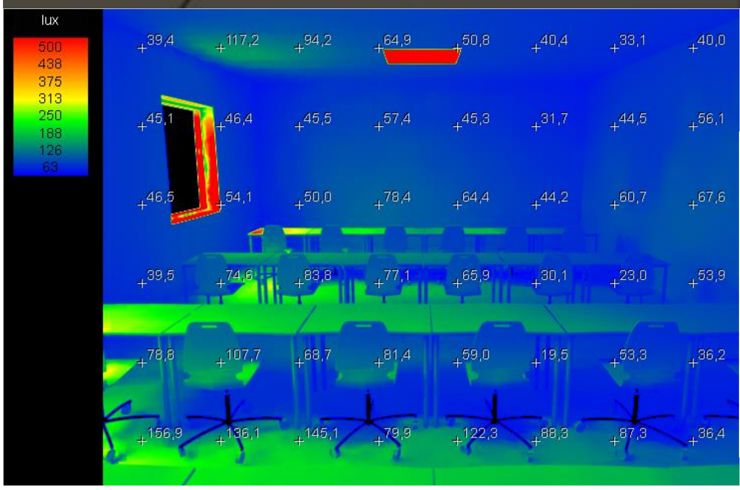
When using only one side window for the daylight to enter, the distribution of light in the room will be very poor leaving many dark spots and only one well illuminated spot at the window opening. This outcome is also present when using only one roof window, where the spot beneath the roof window has a higher illumination than the rest of the room. This leads to very high contrasts in the room, with very sharp shadows. In particular in scenario 1.1. when comparing the shadows under the tables on each scenario, the scenario 1.1 only has one kind of shadow, which is a very dark and sharp shadow, where in scenario 1.2 the shadows are more nuanced and gradually going from light to dark tones. This gradient is shown on the floor, going from the side window where the shadows are brighter to the opposite wall where the shadows are darker. Total sharp and dark shadows is also present near the legs on from the tables. The reason why 1.2 does not get the highest score in” shadows” is that these preferable shadows is only present in the middle of the room. Again, the illumination in the middle of the room in scenario 1.2 has a really high quality of light, meaning objects are easy to identify, there is a vast gradient of shadows and the materials, such as the wood on the tables, the linoleum on the floor, and the matte white paint on the walls are easily identified. However, this quality of light lacks everywhere, but in the middle of the room.

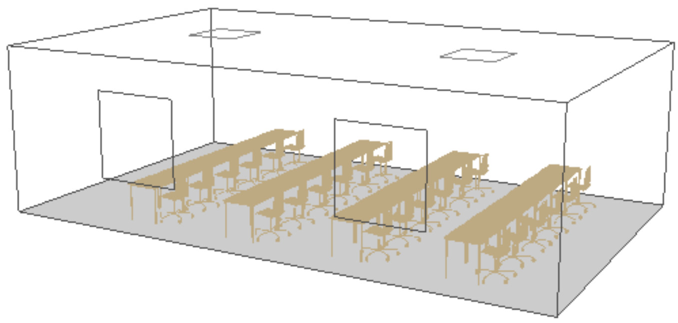
2.1, Two side windows and one roof window





2.2, Two side windows and two roof windows



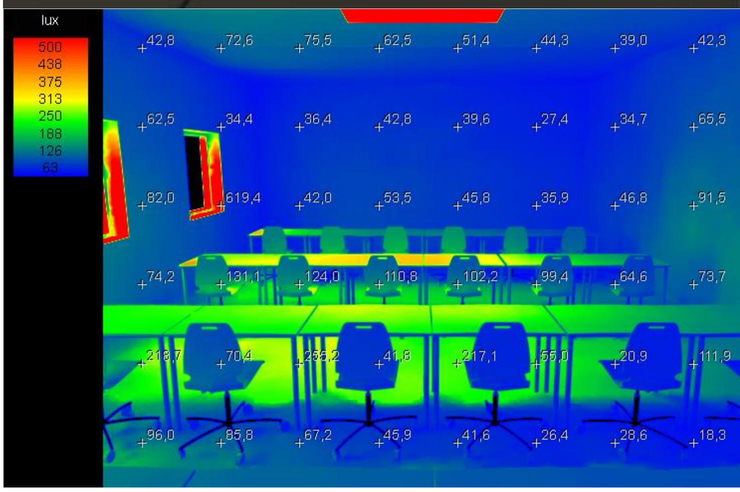


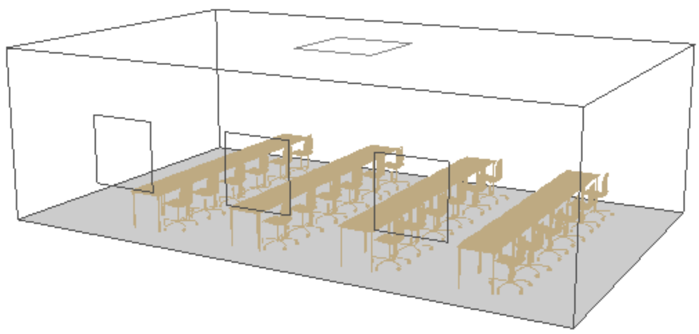
Parameters/Scene	2.1	2.2
Materials/surfaces	5	1
Shadows	5	2
Light vs. Darkness	4	1
Illuminance	2	1
Impression	5	2
Total	**21**	**7**

Findings, 2.1 and 2.2

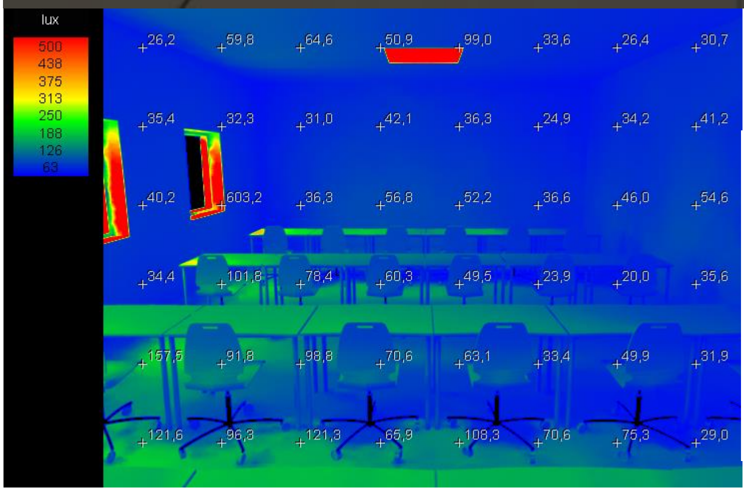
Scenario 2.1 scores a high score in every parameter but" Illuminance", where the lighting setup does not fulfill the standards from the Danish Building Regulations. However, the materials and the different surfaces is easy identified. The Shadows has a vast variety of tones and types, leading to a great synergy between light and darkness, which results in an overall good impression of the room and delicate material surface.
It is interesting that adding another roof window, causes almost every parameter do drop drastically. The quantity of horizontal light entering the room is lesser than what it is when only using one roof window, even though the total window square meter is unchanged. Looking at scenario 2.2 the room is perceived as dark, the shadow types and tones lacks in variation. When a space is dark like in 2.2 it is difficult to recognize the surface textures and materials.

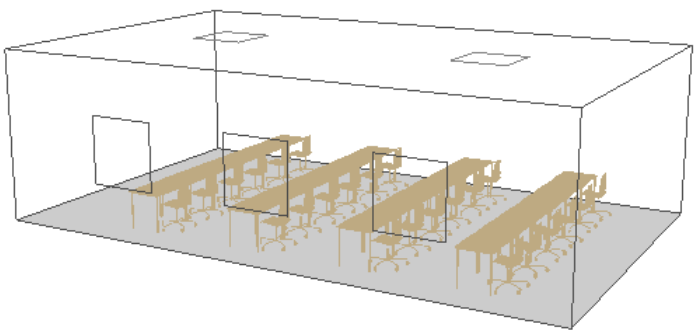
3.1, Three side windows and one roof window





3.2, Three side windows and two roof windows





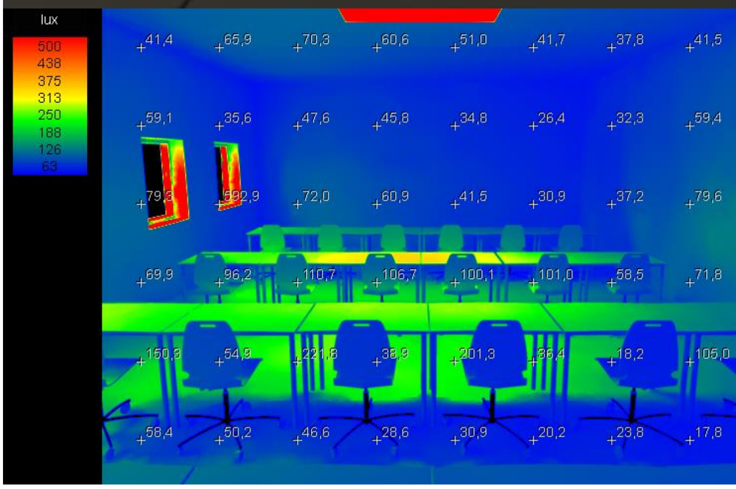
Parameters/Scene	3.1	3.2
Materials/surfaces	3	1
Shadows	3	2
Light vs. Darkness	3	1
Illuminance	2	1
Impression	3	1
Total	**14**	**6**

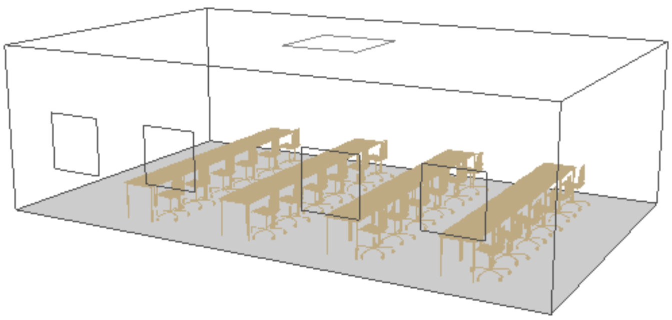
Findings, 3.1 and 3.2

Scenario 3.1 is slightly darker than scenario 2.1, which makes the materials less easy to identify and the detail level lower. The synergy between light and darkness is still present, which has a positive influence of the high score in" Impression".

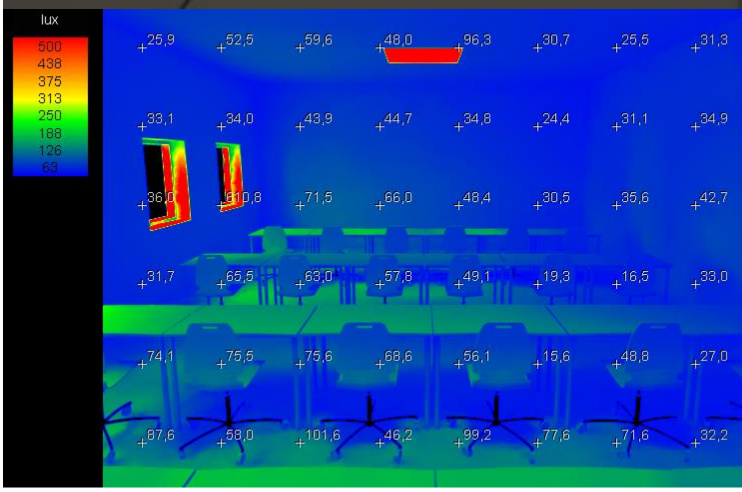
3.2 has become even darker than in scenario 2.1. The materials, surfaces, objects, and textures are close to indistinguishable due to the lack of light. The total score in scheme tells that this lighting setup is far from acceptable.

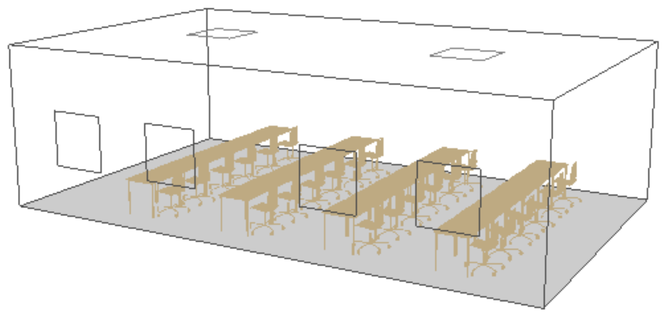
4.1, Four side windows and one roof window





4.2, Four side windows and two roof windows





Parameters/Scene	4.1	4.2
Materials/surfaces	3	1
Shadows	2	1
Light vs. Darkness	2	1
Illuminance	1	1
Impression	3	1
Total	**11**	**5**

Findings, 4.1 and 4.2

4.1, using four side windows and one roof window, the light drops significantly in quality and quantity. The total window square meter spread over four windows distributes less vertical light than 1.1, 2.1, and 3.1. The space is dark and seems dull. The materials and surfaces are less delicate. However, there is still some variations of shadow tone gradient, light and darkness.

Looking at scenario 4.2 every parameter has the lowest score possible. The room is too dark to define materials, shadows, textures, etc.

Findings from test 5

The scores drop significantly when adding more side windows than three. When using two roof windows the quantity of light in the room is less when using one roof window- The lack of light entering the rooms is resulting in overall bad scores. 2.1 and 3.1 having respectively two side windows and one roof window and three side windows and one roof window, has the highest scores. The balance of horizontal and vertical daylight entering the spaces is better for these two scenarios than the rest of the scenarios and for these two scenarios the quantity and quality of light is as preferred. Meaning the two spaces are not only better illuminated, but also the synergy between light and dark is good, the types of shadows, sharp and soft, is present and has a gradient of different tones too.

The balance of using horizontal and vertical daylight is good in both scenario 1.1, 2.1 and 3.1. However, in scenario 4.1 the balance has tipped over to a dominant horizontal light, that makes the light in the room uniform. This is a very interesting finding, considering that scenario 1.1, 2.1, 3.1, and 4.1 all have one roof window and multiple side windows and the outcome changes when moving from a scenario with three side windows to the scenario with four side windows.

Conclusion

To better support a conclusion, especially about the flow of light and the shadows, it is decided to apply objects to the scene. The objects (balls) will make it easier to define the quality light based on evaluations of shadows and light on and around the objects. This will be Test 6

In Test 6 the parameter “illuminance” has been removed, since all the different outcomes using ratio 1(V):2(H) has showed that they do not fulfill the minimum lux standards that is required from the Danish Building Regulations. Another reason to eliminate “Illuminance” is that this project strives to find the optimal balance between the amount of horizontal and vertical daylight entering a space. This balance of light is defined by the quality of light and not the quantity.

Test 6

The test

A big variation of light was shown in the test 5, which equals a potential variation in the quality of light too. The idea of this test is to evaluate the quality of the light, by placing a ball on the middle desk on each row in the classroom (illustrated in *figure 13*), and afterwards render close-ups on each ball. Sophus Frandsen's method of scaling types of shadows will be performed for each ball. Each ball will have its type number written directly on the rendering.

Method

Again, the different lighting scenarios is tested in VELUX Daylight Visualizer on the 21st of March at 12 o'clock p.m. only using daylight with no adjacent buildings. The eye height level is 140cm. above the ground, since the viewing perspective is now set from a sitting person, and the side windows facing true north.

Figure 13, cross section 2.2

The ball

The ball has a diameter of 30 cm. and is made of polystyrene which is often used as insolation in building constructions. Polystyrene has a reflectance of 0.920 and has a rough texture. The texture of polystyrene has a characteristically appearance. Below (*figure 14*), a picture of a natural polystyrene ball, and the ball as it is represented by Velux Daylight Visualizer.

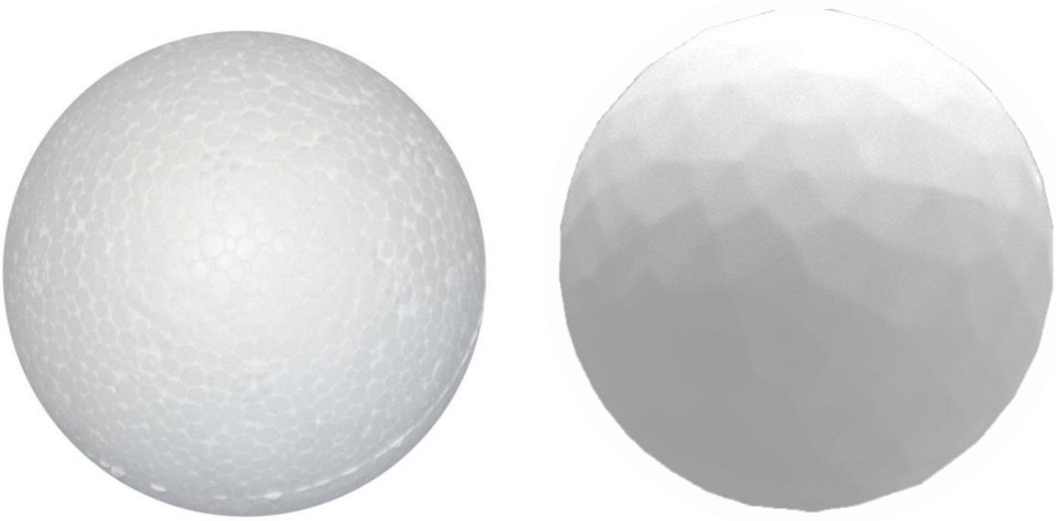


Figure 14, Polystyrene ball, natural appearance. Polystyrene ball, in Velux Daylight Visualizer

The scale of shadow, Sophus Frandsen

The scale of shadows is now the only evaluation point. The perception of the objects under evaluation, is to some degree inspired by Cuttle and the flow of light – while the reporting for each scenario will be exclusively according to Sophus Frandsen's scale.

Brief description of the method

The dotted lines in *figure 15* indicates the borderlines of each area. Sophus Frandsen divides a sphere into three areas: Area 1, the top segment that revives light from the light sources and has none shadow. Area 2, the zone in the middle receiving varying amount of light also called semi-shadow. Area 2 also has the decisive role of scaling the shadow. Area 3 is in the bottom of the sphere, receiving no light from the light sources, meaning there is full shadow[23].

Type 1-3 is a result of a lighting setup with predominantly parallel light which makes the objects looking protruding and has a high detail level. Type 7-9 occurs in diffused light. The objects seem very dull and the lack of shadows means lack of three-dimensional form. Sophus Frandsen says that these two extreme types is more or less reserved for artistic purposes, where type 4-6 is for everyday use, in this case a classroom. The kind of shadows in type 4-6 can only be achieved using both diffused and parallel lighting. These types as Sophus says:" demonstrate *their middle-of-the-way qualities."* They are" neither *dramatically three-dimensional nor dull and flat[24].*"

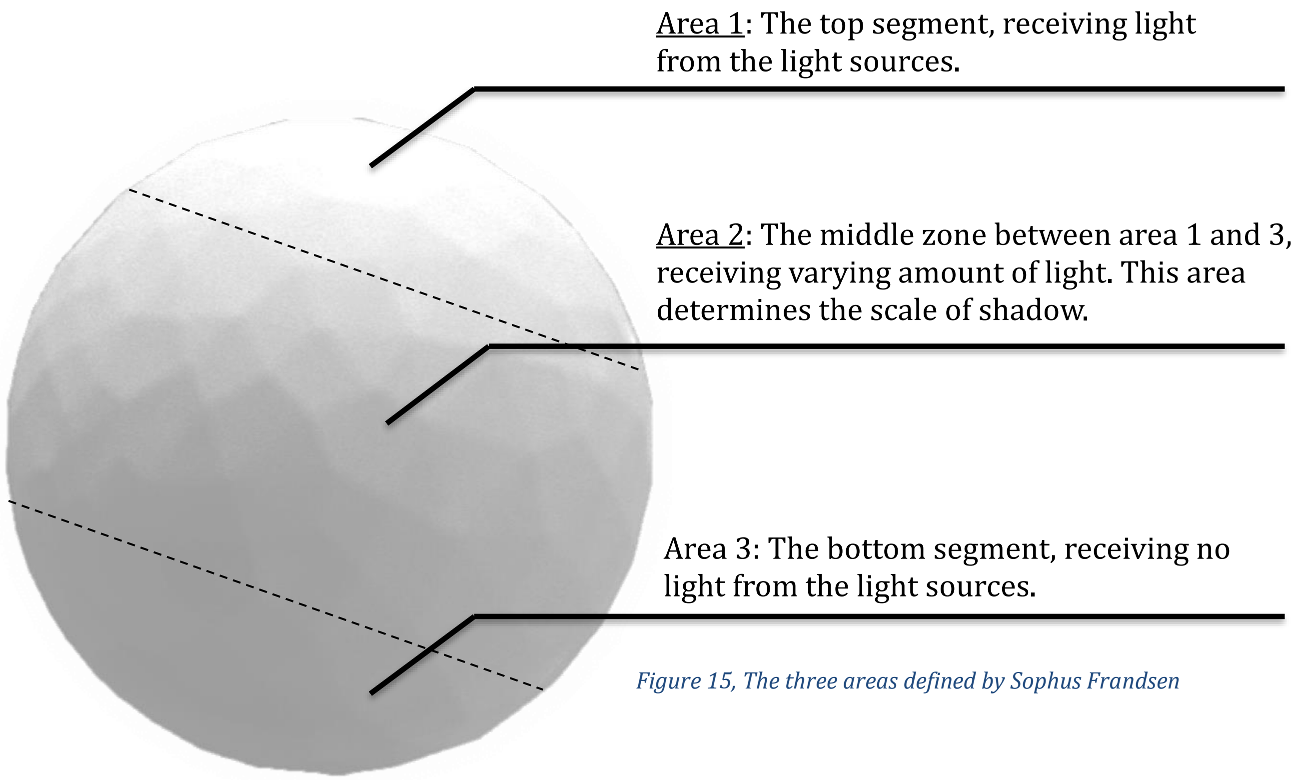


Figure 15, The three areas defined by Sophus Frandsen

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[23] Sophus Frandsen, *The Scale of Light*
[24] Quote of Sophus Frandsen, *The Scale of Light*

Scaling the shadow

Figure 16 shows the process of the method, where the ball is categorized as a type ”5”, according to the scaling system. This is determined only by looking on the shading size of area 2. Again, type 4-6 can only be achieved by combining diffused with parallel lighting. An illustration of how the evaluation is shown at the bottom of this page. By making a line where area 2 starts and stops and copy those lines into the balls in the scaling system, the type of shadow gets easier to define.

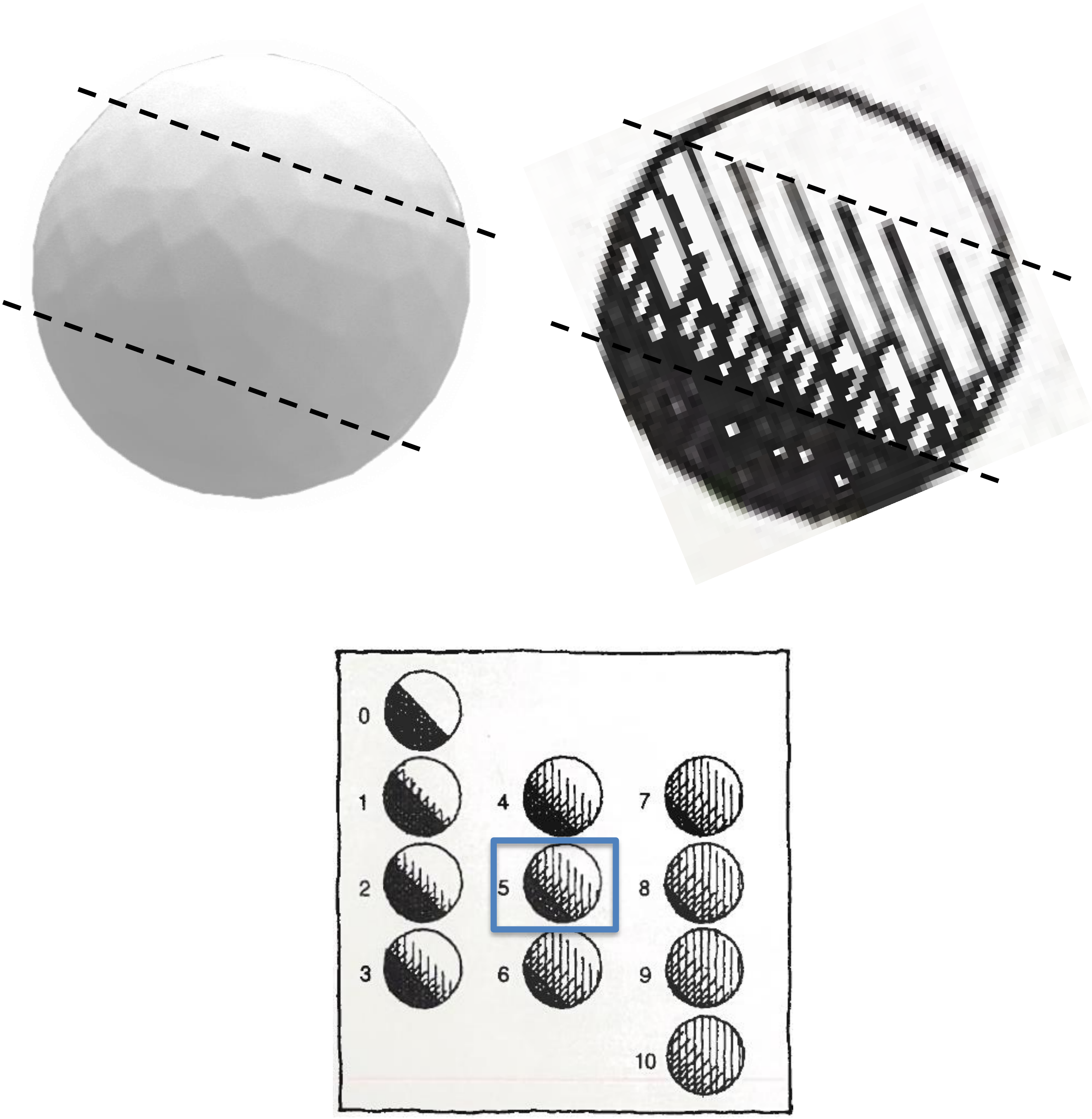
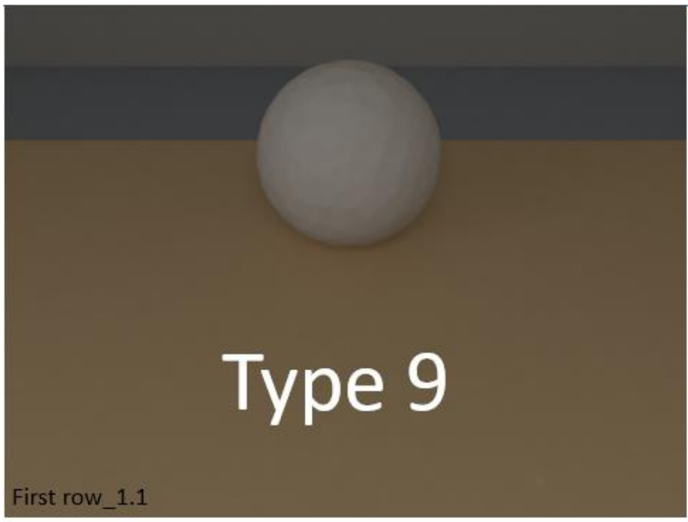
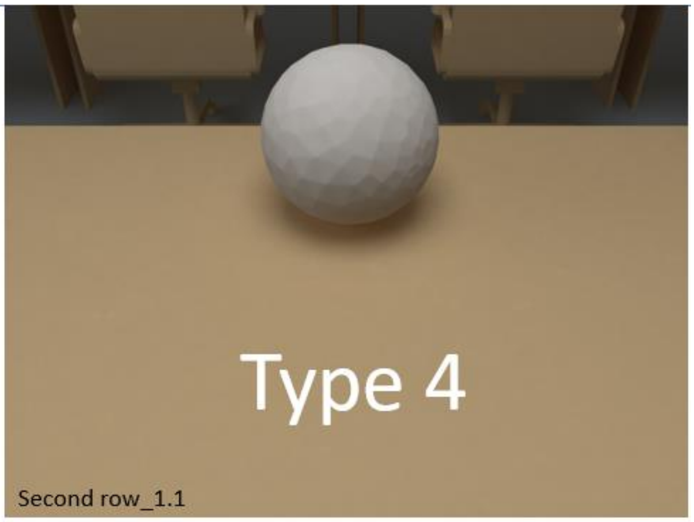


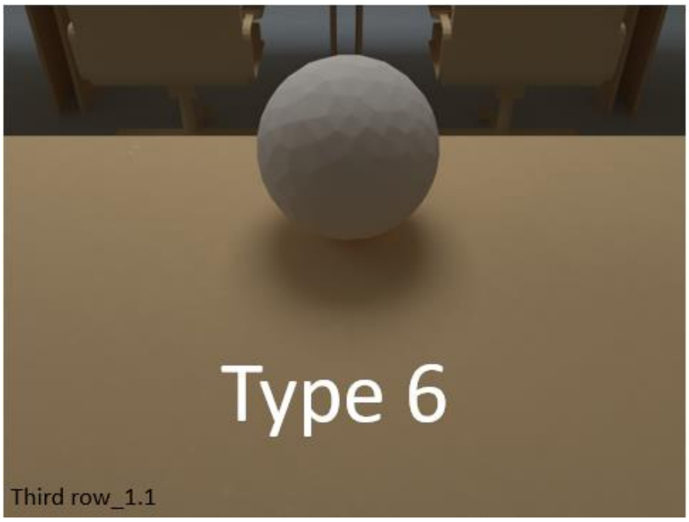
Figure 16, The process of type numbering

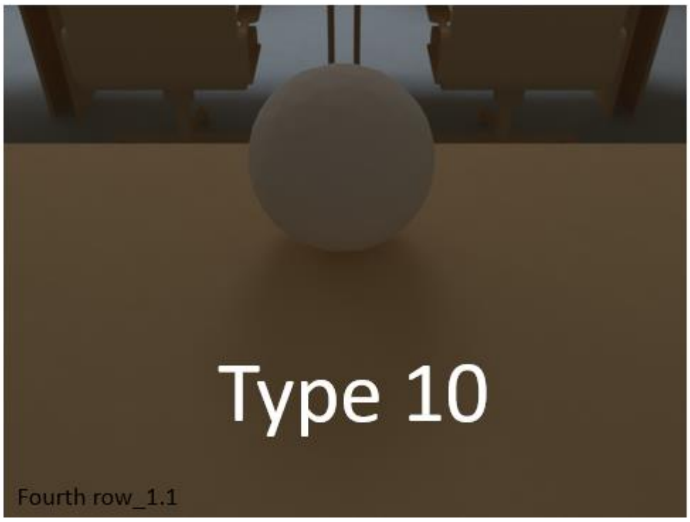
One roof window

1.1, one side window and one roof window

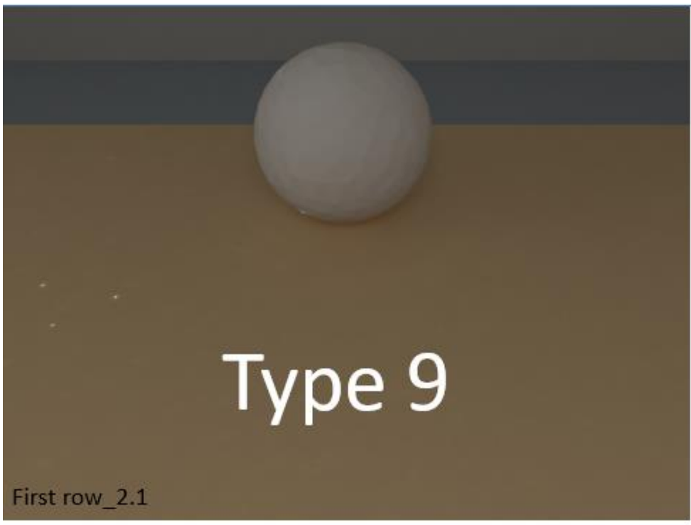


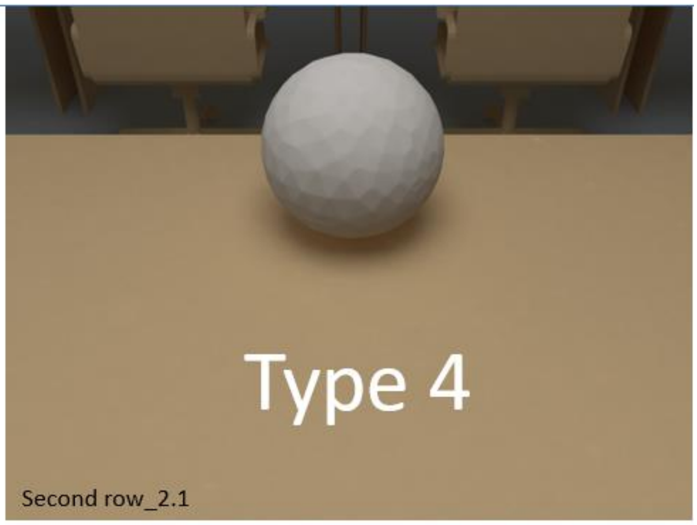


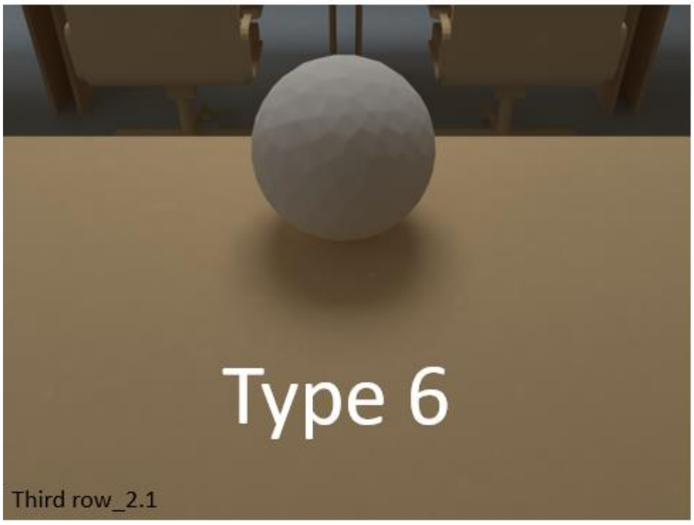


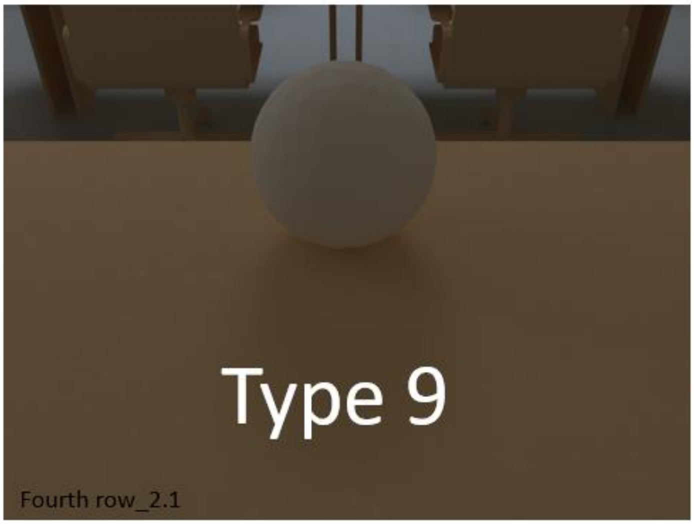


2.1, two side windows and one roof window

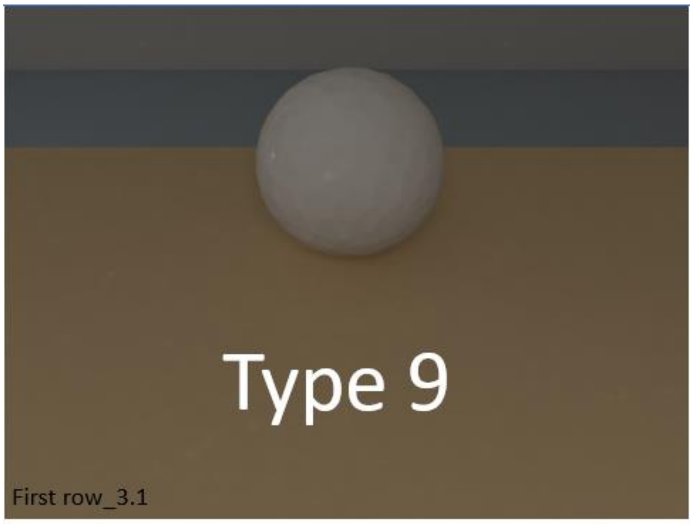


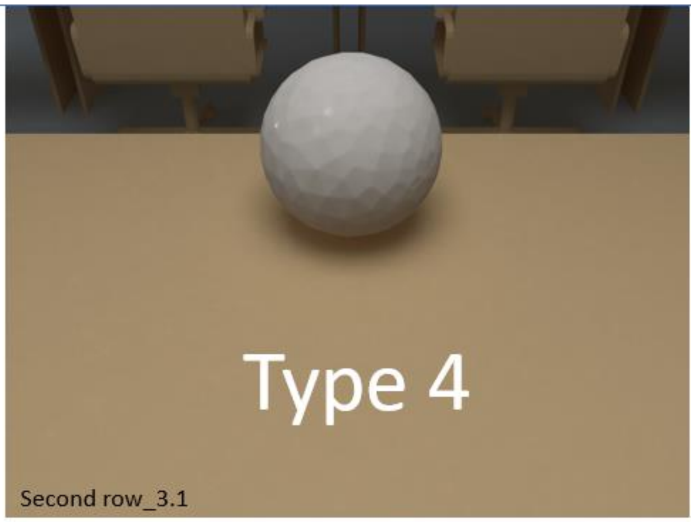


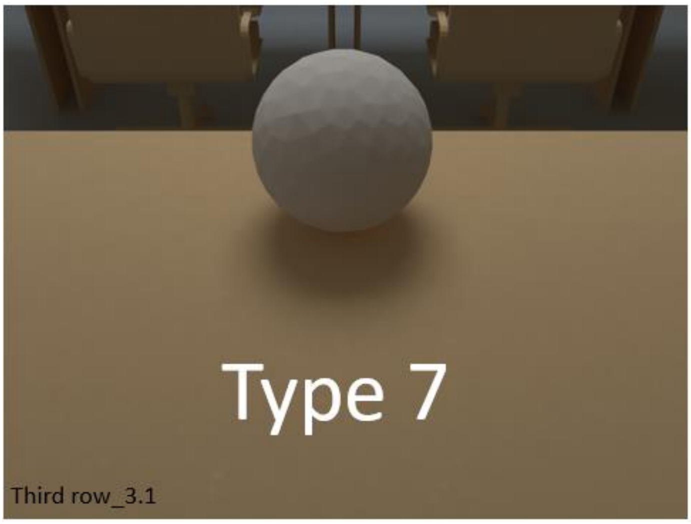




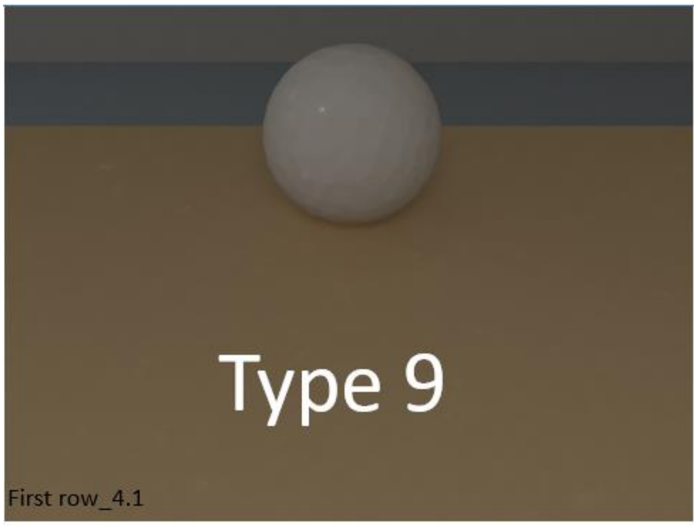
3.1, three side windows and one roof window

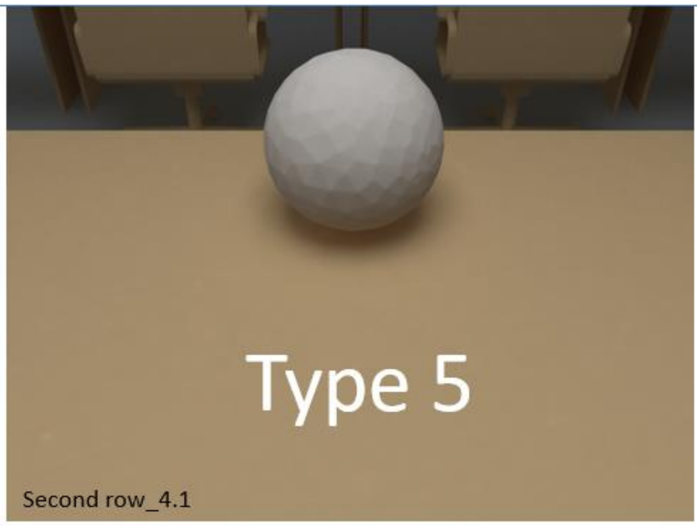


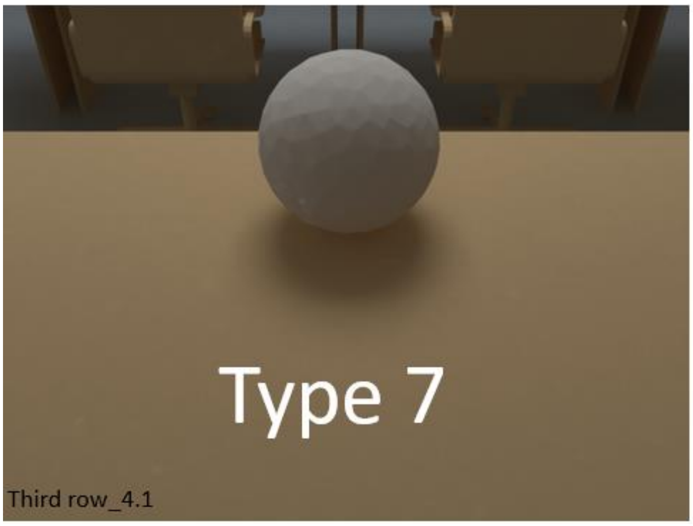


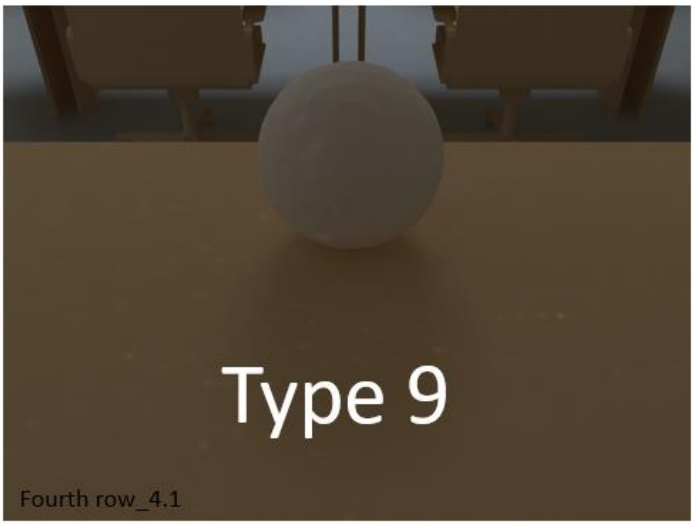


4.1, four side windows and one roof window









Findings from the four scenarios using one roof window and varying side windows

The given type numbers from all scenarios, having one roof window and multiple side windows, tells that the light quality in each scenario differs very little from each other. Even though Test 5 showed that the illuminance in the rooms dropped rather significantly the more side windows added to the room.

In each scenario both first and fourth row has what Sophus Frandsen categories as extreme type numbers. The low illuminance on these objects is caused by the balls only reviving reflected light bouncing from all the surfaces and furniture in the room. However, the light those two balls receive is not the same.

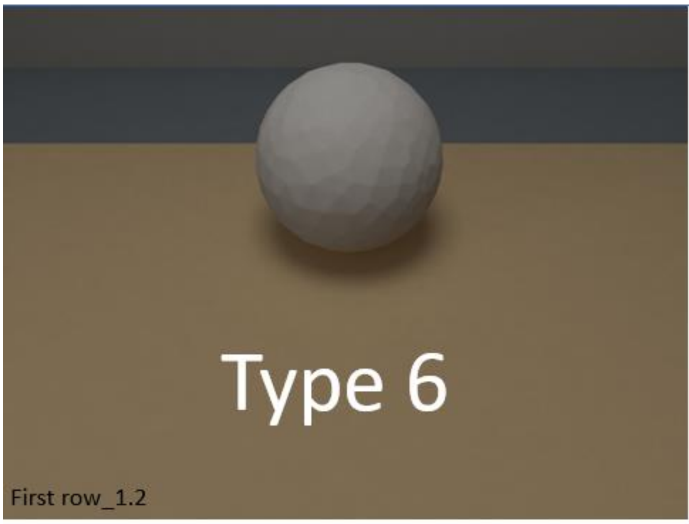
The ball in the first row has a non-cast shadow and s shading graduation that extends on the whole surface of the ball, which indicates a predominant diffused light, causing the ball to seem dull and flat, and lacking three-dimensional form.

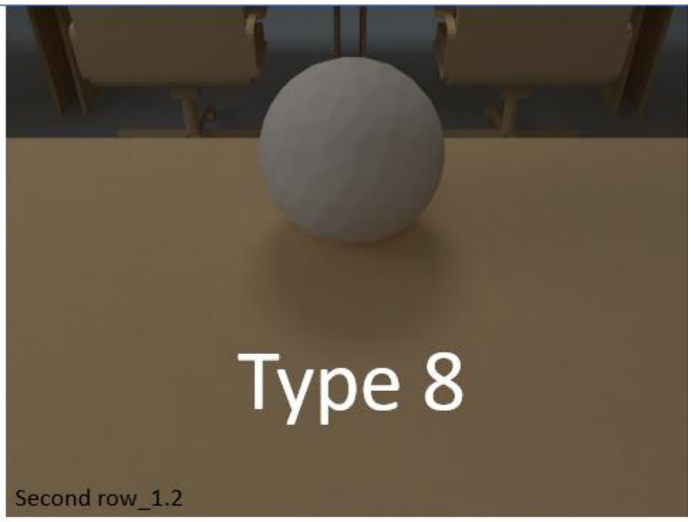
The ball in the fourth row the type is hard to define, since the ball receives almost no light coming from the camera's point of view (pointing towards east). From this angle the borders between the three areas, as defined by Sophus Frandsen, are hard to define, and it appears as only full shadow. Turning the camera's point of view towards south, a mixture of lights would probably occur, and a type numbering can be made.

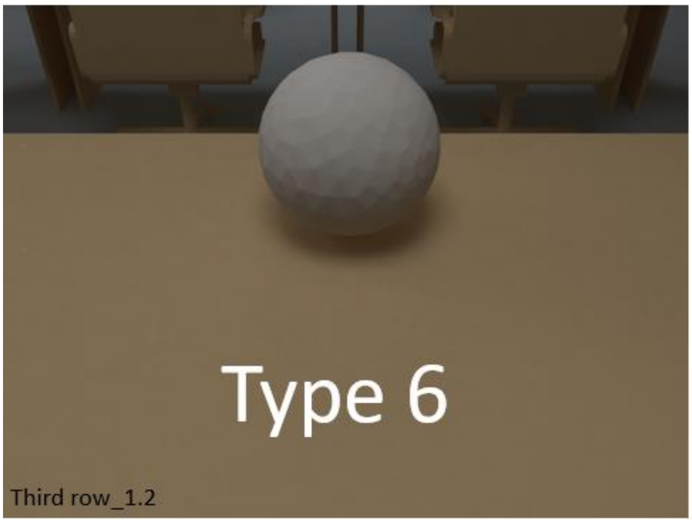
The balls on the second and third row have a very nice representation of three-dimensional form. Especially seen on the ball on the second row. The quality of light here, is almost as high as it gets. The borderline between the three areas are not sharp ones and the graduation shading tone on the ball is very smooth. The wooden surface on the table is also easier recognizable compared to the tables on the first and fourth row.

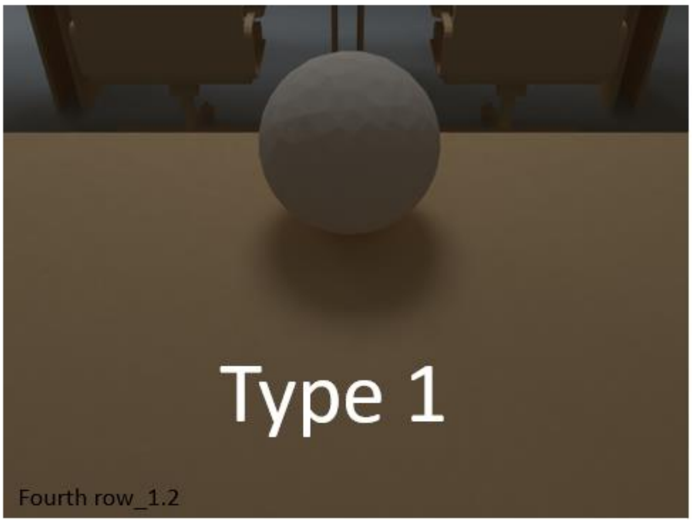
Two roof windows

1.2, one side window and two roof windows

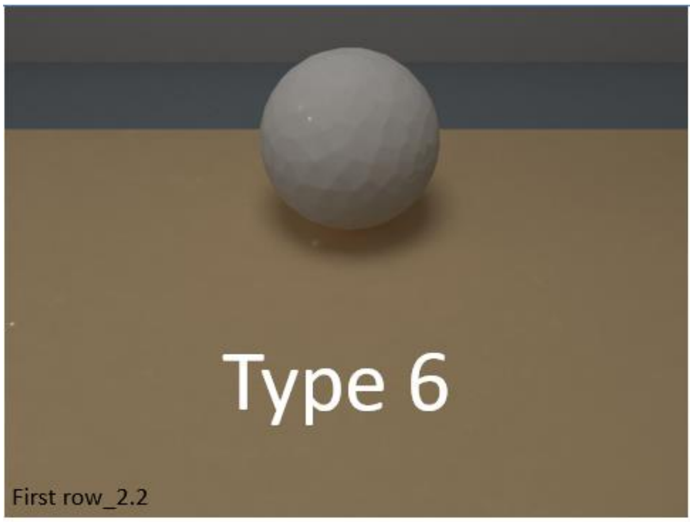


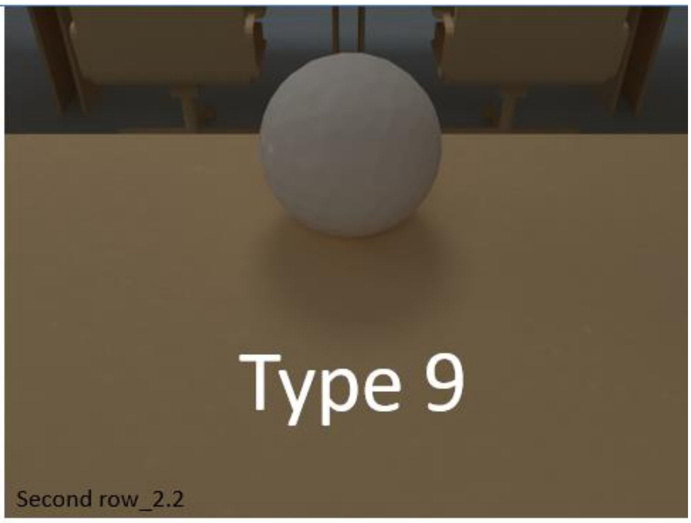


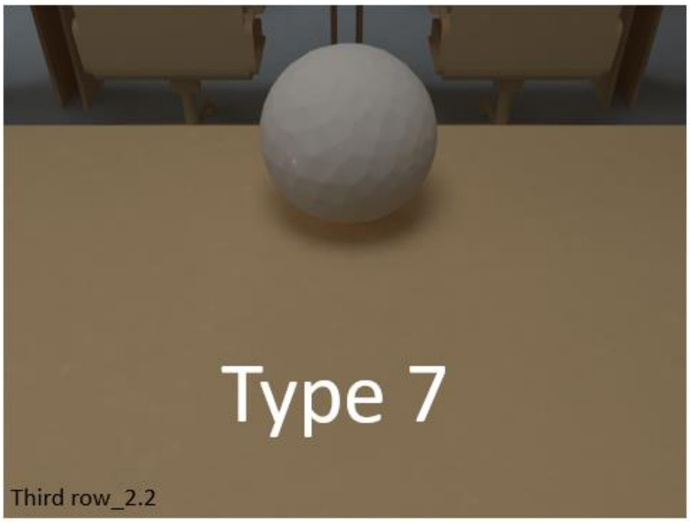


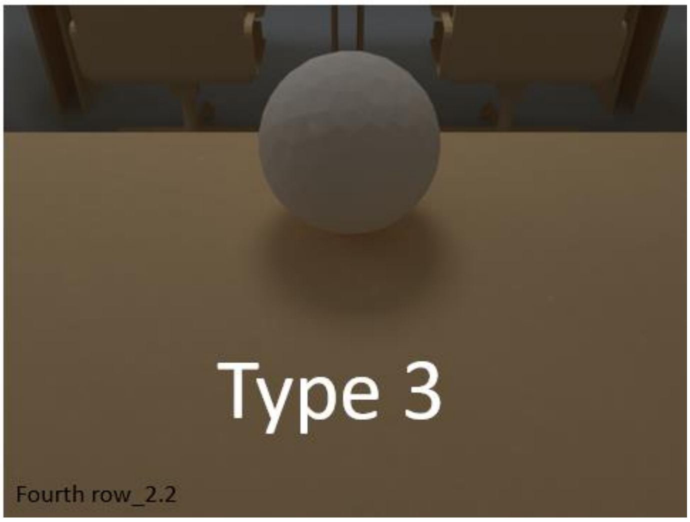


2.2, two side windows and two roof windows

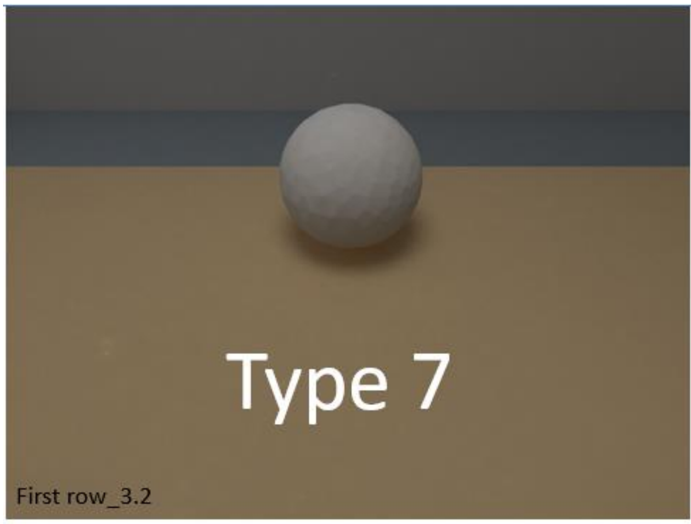


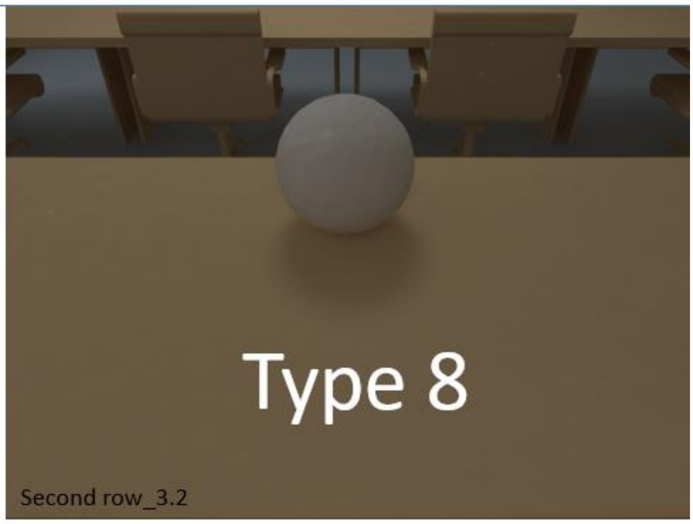


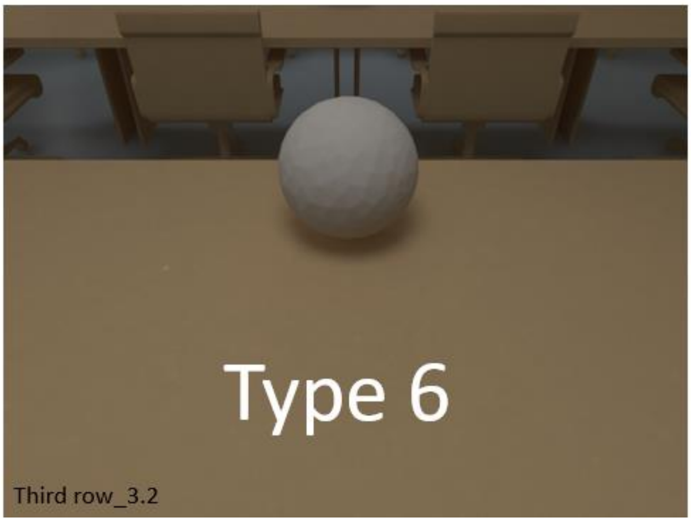


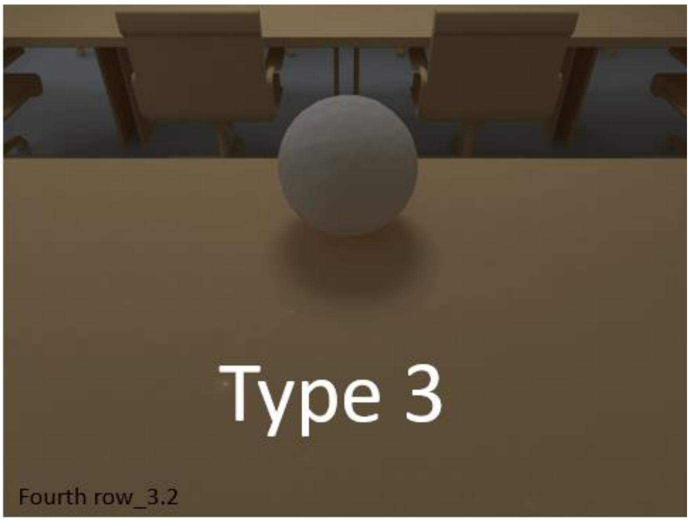


3.2, three side windows and two roof windows

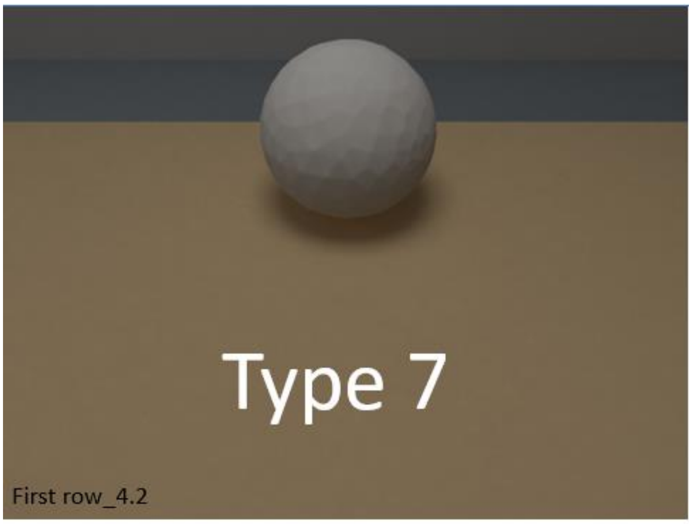


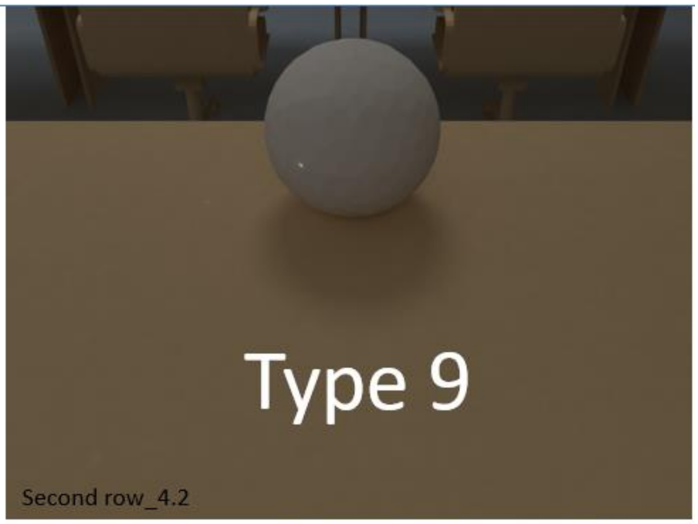


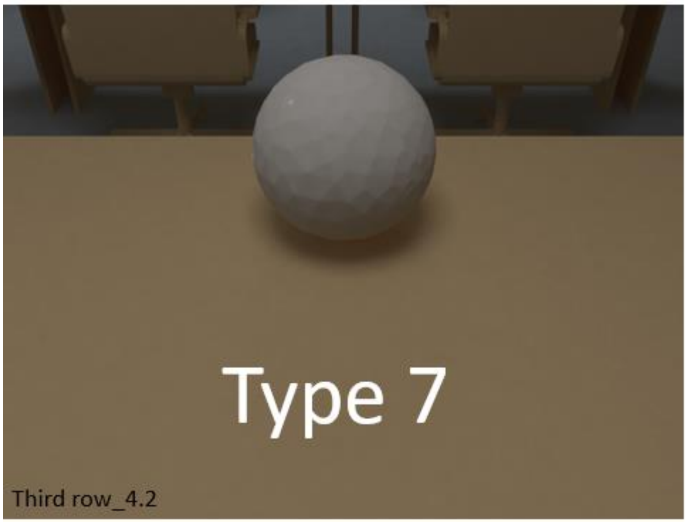


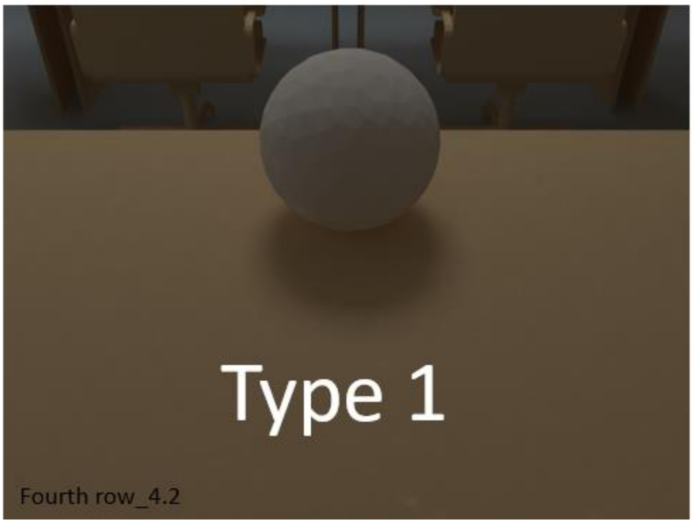


4.2, four side windows and two roof windows









Findings from the four scenarios using two roof windows and varying side windows

Overall, the balls in all four scenarios having two roof windows looks more dull and flat, than the balls in the scenarios only having one roof window. The balls given type numbers in every scenario indicates that the light balance is slightly tipped towards a dominance of diffused lighting. The diffused light causes a uniform lighting environment. There is a low variety of shadow types and the graduation extends over the entire surface on the majority of the balls, especially on the balls on the first row in both scenario 2.2 and 3.2. Some of the balls, like them on the first and third row in scenario 4.2, have full shadow in the bottom segment. This means that the rooms are not entirely dominated by diffused light, since only parallel lighting creates hard shadows.

Every ball on the fourth row in each scenario has been given an extreme type number (types 1-3), opposite to the extreme type numbers (types 7-9) given to the remaining rows. Compared to the balls in the other rows all balls in fourth row has a greater area of full shadow, with a gradient to softer shading tones. All the balls in the fourth row are hard to categorize, since none of them fits exactly into the scaling of shadow system. Which is why there is a possibility that their given numbers could be discussed.

Conclusion including all Test 6 scenarios

Using the ratio 1:2 between roof and side window areas, it has not been possibly to reach a combination where the light in the entire space is satisfying. The scenarios having only one roof window (1.1, 2.1, 3.1, and 4.1) have most non-extreme types with explicit representation of the balls three-dimensional form and surface details, as seen in most second and third row scenarios. For the second and third row in scenario 1.1 and 2.1 the right balance between horizontal and vertical daylight has been found using a 1:2 ratio and only one roof window, however this balance does not extend to the entire space. This is a good starting point and further studies should expand on these findings. The alternative scenario having two roof windows are all less optimal.

The outcome of all scenarios changes more drastically when changing the number of roof windows, than when changing the number of side windows. The result indicates, that using roof windows with openings of $1m^2$, the best possibly result is a type number 6 in the scale of shadow system. For objects directly and almost directly under the roof window of $2m^2$, the type numbers vary in the desired range from 4-6. This finding leads to a possibly conclusion for optimal result, that the roof windows should as a minimum be approximately $2m^2$ in a $60m^2$ space. The results also indicate that more than one roof window of $2m^2$ is needed for optimal lighting environment of the entire space. However, this solution will jeopardize the 1:2 ratio, which has been basis for these tests.

Discussion

The results presented in this thesis shows that with combinations of vertical and horizontal light it is possible to create lighting environments of high quality. When adhering to the BR18 minimum requirements with regards to window openings it has not been possible to reach the minimum lux requirements of the BR18 in the class room setting investigated, however in another model where openings in the range of 11% - 32% of the floor area was investigated several scenarios in the range of 18% - 25% were evaluated as providing lighting of a high quality and they also easily met the BR18 requirements with regards lux requirements. It is interesting that in the same test the scenarios with the largest top opening all met the lux requirements, but still all scored overall low partly due to over exposure. This, together with similar findings in other tests, calls for further investigations of the horizontal light sources. These investigations should investigate the critical ratio, between vertical and horizontal light, the optimal number of roof openings and the placement of these roof openings.

The findings and methodology from the tests in this thesis could be used in initial building design phases to ensure that tasks are placed in the rooms where the light is optimal for a specific activity, but also as an inspiration not to use the BR18 to plan for the minimum of required window openings, but plan for additional footage with window openings distributed between horizontal and vertical sources to created spaces with a high quality of daylight and a minimum requirement for additional electrical lighting.

The methods used in this thesis has been a combination of the use of a commercial available CAD program, Velux Daylight Visualizer, the method, Scale of Shadow by Sophus Frandsen (Test 6) and then a relative objective and fast method for comparison between scenarios a table that allows for evaluation of the parameters; material/surfaces, shadows, light versus darkness, illumination and impression. The Velux Daylight Visualizer is good for at looking at uniform hard balls without texture, for type numbering of objects and defining whether the light is parallel, diffused as well as for defining the light balance. It has proven possible to use a modern CAD tool in combination with the method Scale of Shadow developed by Sophus Frandsen in the period 1979 – 1982. However, should small details, like hair on a tennis ball, be included in the simulations, as Sophus Frandsen did in his tests, then more powerful CAD-software, like 3DSMax should have been used. For the purpose of the tests in this study the Velux Daylight Visualizer has provided the data needed. Also, the Scale of Shadows method has been a good tool and added additional information for evaluation of the quality of light in Test 6. With regards to the table created for objective evaluation of the different scenarios that are investigated in this thesis the perception is that it has been easy to work with and that it does support the selection process by providing a total score which can be used for ranking of scenarios.

Final conclusion

With regards with the aim to create the best possible indoor lighting environment without the use of electrical light it is concluded that this has been successfully achieved.

In Test 2 with openings corresponding to approximately 20pct. of the floor area, which evaluates combinations of medium and large side- and top-openings it has been possible to create an indoor lighting environment of very high quality (ranging in scores between 18-21) in the entire room (scenarios 1.3, 2.2, and 2.3).

Likewise, in Test 5 and Test 6 with openings totaling 10% of the floor area, in accordance with BR18, it was possible to create areas of very high light quality and object renderings. This was achieved in scenario 2.1 (two side openings and one top opening) which score 21 for the entire room and scores of type 4 and type 6 in "The scale of shadows" (on second and third row respectively).

In Test 5 and Test 6 where all scenarios are according to the standards from BR18 it has also been possible to create spaces with good lighting qualities. For instance, scenario 3.1 (one top window and three side windows), whereas all the scenarios having two roof windows are all less optimal. This indicates that the size of each top window is of importance even though the total opening area remains unchanged. Meaning that when adhering to the BR18 standards it is important to consider how the openings are distributed.

With regards to the BR18 lux requirements it is demonstrated in Test 5 that in a classroom with openings corresponding to 10% of the floor area, it is not possible to reach the required 300 lux in any of the combinations of vertical and horizontal light that has been examined. Even though some of the scenarios (see above) were documented to have a high quality of the light. In Test 2, where the opening areas exceed the BR18 requirements the 300 lux is achieved in the scenarios 1.3, 2.2 and 2.3. The opening areas for these scenarios are between 18- 25%. Similarly, the requirement for 300 lux is met, even more pronounced, in the scenarios 3.1, 3.2 and 3.3. Opening areas for these scenarios are between 18 – 32%. Interestingly however the illuminance in these last three scenarios were all evaluated low (a score of 2) due to overexposure. The three scenarios were the scenarios with the largest top openings ($4m^2$). These observations suggest that by introducing total opening areas of approximately twice the minimum requirement of the BR18, the 300 lux requirements can be achieved. The observations also suggest that there is limit with regards to the size of or the percentage of top openings which when exceeded will create a less desirable lighting environment. These effects together with the observation above that the size and distribution of the top windows should be further investigated. Similarly, limits were not shown for the vertical light.

Sophus Frandsen's scale of shadow, has been used in Test 6 and the evaluation is that the method is a good tool for analyzing objects, lights, and shadows in a space. By categorizing the shadows, he invites for an intuitive and numerical method to use. In addition, a table with qualitative and quantitative parameters was established to support, comparing, and selecting scenarios. The evaluation is that the method was a good support for evaluating the light in a space.

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