OPTIMISING DAYLIGHTING FOR HUSEBYBADET AT SAUPSTAD, NORWAY

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Master thesis, Spring 2020

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4 DESIGN

Trondheim, May 2020

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1. INTRODUCTION

Daylight is dynamic and ephemeral. It expresses the dimension of time while light and shadow's movements uncover the changing diurnal and seasonal cycles. Daylight and the ever-changing forces of sun, wind and weather help us to orientate. When coupled with passive solar and bioclimatic design strategies, daylight can reduce energy consumption and provide environmental benefits while heightening human comfort, health and well-being.

Daylight is an architectural medium and the most intangible materials. It symbolises the changing moods of the sky and qualities of place while interacting with the building forms, materials, surface textures, shades and reflectivity. The varied and changing material and atmospheric effects of daylight can stimulate the senses and further enhance our relationship with the surroundings.

1.1. GOAL

This thesis is focused on optimizing daylight conditions in Husebybadet. Two designs are proposed and analyzed. The designs attempt to balance technical, architectural and social aspects.

1.2. METHODOLOGY

Literature review is conducted in order to have a general understanding of daylight benefits, strategies and standard recommendations for light utilisation. Current building design is simulated and analysed in order to understand lighting demands, optimal light levels and to set parameters for lighting design. Two scenarios are developed using digital 3D modelling, sketches and daylight performance studies. Solutions are analysed using simulations. Annual daylight levels, glare occurrence probability and brightness dynamics are employed. Daylight factor is used to inform daylight provision under overcast sky, while annual glare probability simulation evaluate visual comfort in side lit spaces based on geographically-specific climate data.
A comparison of the quantitative results along with a qualitative assessment of aesthetic outcome determine the best design.

SIMULATION TOOLS

Study of daylight is conducted in DIVA and Revit, which are 3D and BIM software respectively. A plug-in Diva for Rhino is used, which is based on simulations engine Radiance.

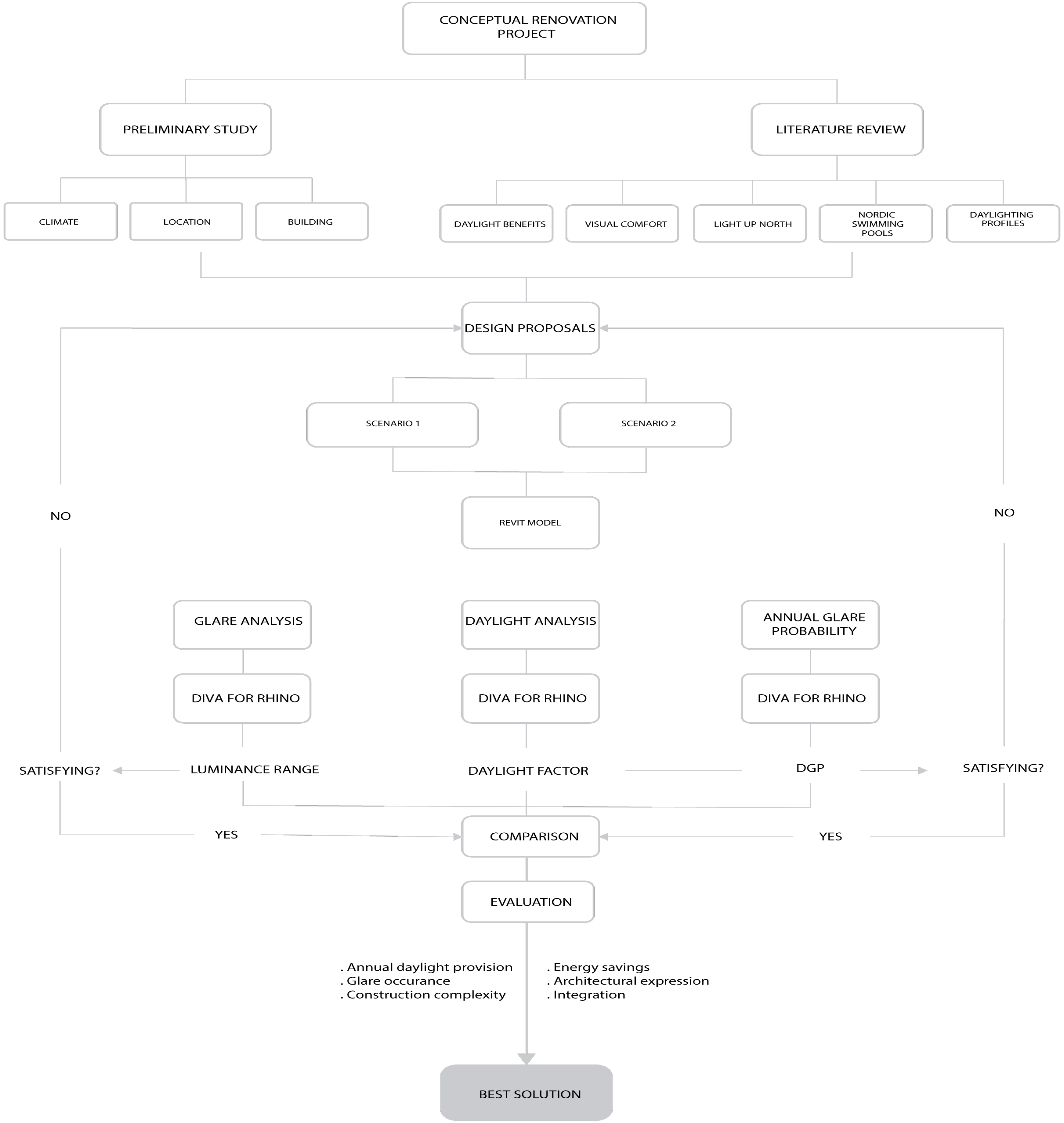


Fig. 1. Methodology diagram

2. PRELIMINARY STUDY

2.1. CLIMATE

According to the Koppen-Geiger climate classification system Trondheim has a subarctic climate that has severe winters with cool short summers. In summer there is a long daytime with high solar radiation. Whereas in winter the daytime is relatively short accompany with the dominant cloudy sky. Over the course of the year, the average temperature varies from -2.4°C to 13.4°C in winter and summer respectively. The average rainfall is 884mm annually, and average wind condition is 15m/s.

SUN

The length of the day in Trondheim varies extremely over the course of the year. The shortest day of the year last for 4hours 30minutes while the longest day lasts for 20hours 36minutes [1], meaning that the provision of sufficient daylight in winter is essential. The sun angle is low for a long period of time compared to places at lower latitudes. The sun's elevation angle is between 0°-10° during almost 35% of the daytime, while it is between 10°-30° during 49% of the daytime. Climate responsive design therefore should be adapted to the prevailing low sun inclination angles. (B. Szybinska Matusiak) On the 21st of December the shortest day of the year, the highest elevation angle of the sun is only 3.35°. The hours when the sun is over 10° increases after 3rd of February. The sun doesn't reach 30° until 30th of March and the highest position of the sun during the year is 50.01° on 23rd of June [2]. The presence of wide colour range and its transition is aesthetically appealing during winters. By percentage, the sun is in the south during 40% of the annual daytime. Although the sun position changes dynamically between seasons. In warmer season, the afternoon sun reaches north-west end of the day.

SNOW

The study of snow depth is limited due to the unknown factors like the layers accumulation rate and thawing time. However it is important to estimate it due to the presence of snow cover throughout more than half of the year in Trondheim. Snowfall is reported in liquid-equivalent terms, referring to the amount of liquid precipitation that is produced after melting snow. It is determined by the temperature profile of the troposphere and the surface temperature are important factors. The average snow to liquid ratio is 10:1, meaning that if 10cm of snow fell and that snow was melted it would produce 1cm of liquid precipitation in the rain gauge. Snowfall is reported in liquid-equivalent terms, referring to the amount of liquid precipitation that is produced after melting snow. It is determined by the temperature profile of the troposphere and the surface temperature are important factors. The average snow to liquid ratio is 10:1, meaning that if 10cm of snow fell and that snow was melted it would produce 1cm of liquid precipitation in the rain gauge. Average snow cover of at least 2.5cm happens between late October to end of April. During those days, snow cover maybe affecting transmittance of roof apertures. February in particular when predicted snowfall is highest and new layers accumulate on the old snow. Considering that possibility, during February actual depth of the snow can reach more than 1m.

CLOUD COVER

Snowfall is innately coupled with overcast sky. During winters, from September to April, overcast sky occurs for more than half of the time, with a little likelihood of clear sky. The sunlight availability is cloud cover dependent and the Nordic is categorised by low occurrence of sunny skies. In average, clear and mostly clear sky conditions happen 15% of the time throughout the year and 25% in summers. The cloudiest happen in January while the sunniest happen in May. Clear spring days also means more sunlight and lower temperatures compare to autumn as the warmth escape into the atmosphere in night time. (Fig.4) Being sheltered by the fjord, prevailing wind is mostly blowing from the west in summers and from the south in winters.

The combined climate factors is posting design challenges for sufficient daylight. In winters, diffused light resulted from the combination of cloudy sky, deep snow cover and short daylight. High snow reflectance offers light guiding surface. Besides, low inclined sun maybe harvested without being reflected from glass surface of window opening. Although control is needed to avoid glare and visual discomfort. Sun inclination in summers is critical because of the long daytime when solar altitude is low. The risk of glare is particularly high and consequently east and west orientation of window openings could be problematic.

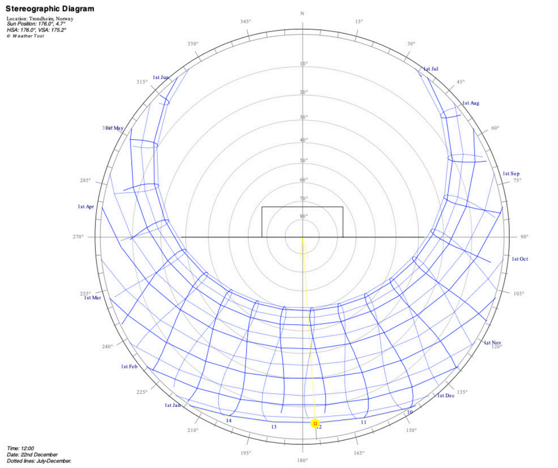


Fig. 2. Sun path diagram analysis based on Trondheim weather

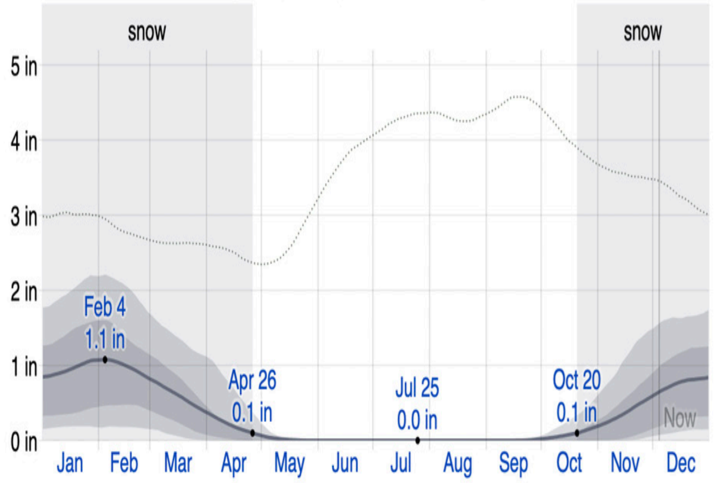


Fig.3. Analysis of average monthly depth of snowfall in Trondheim, based on weather statistics from: weatherspark.com

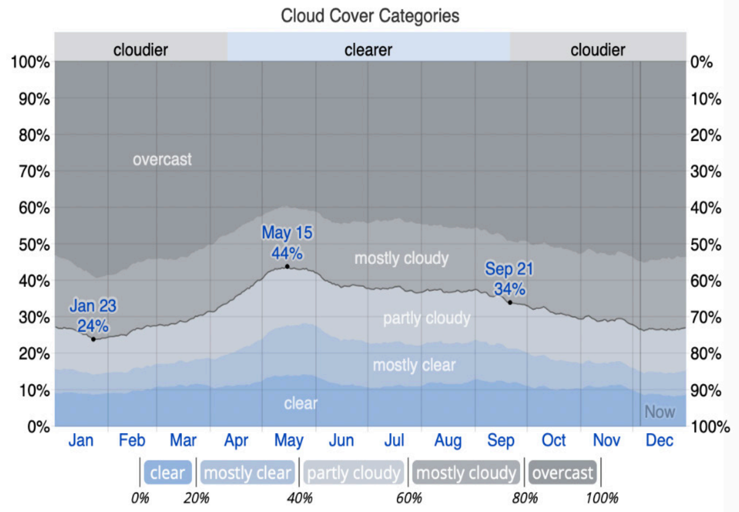


Fig.4. Percentage of time spent in each cloud cover band, categorized by the percentage of the sky covered by clouds in Trondheim. [weatherspark.com,2016]

2.2. PROJECT BACKGROUND

Husebybadet is a publicly owned swimming facility located in south west of Trondheim, with a distance of 12km from the city centre. It is architecturally part of Husebyhallen which was built in 1976-77 and expanded with bathing facilities and swimming pool in 1984. The building program includes a sports hall, a gym and a two swimming pools. It is designed as an arena for training and social interaction. See location of Trondheim on a map of Norway in Figure 5.

Trondheim Kommune has an intention to upgrade Husebybadet since 2009, as there is leakage issue at the pool as well as the lack of social zones for interaction. The pool is used for swimming, water gymnastics and baby swimming.

Location: Saupstadringen 13, 7078 Trondheim

Husebybadet is located in Saupstad, a district in Flatåsen in south of Trondheim. There are a school in an immediate proximity south from the plot. Study of shadows during equinox on 21st March, summer solstice on 20th June and winter solstice on 21st December are presenting the impact of the surrounding buildings.

Heimdal videregående skole is a few metres higher and is located on the south side of Husebybadet, therefore partly blocking sunlight availability for the 1st floor of the building during daytime in June. See Figure 8. On the 21st of December the 1st floor of Husebybadet is almost completely blocked by Heimdal videregående skole. Only a trace amount of sunlight could penetrate into the building from 8 to 11 o´clock.

SITUATION

The building is surrounded by pedestrian ways from the north and west, by a school from the south and by car parks from the east. In the west there are a few tall trees in a distance that may cast shadow on the elevation. They are visible from the building and somewhat affects access of low inclination direct sun to the west windows. However, the fact that the trees are leaf-less in winter may cause less problem in cold seasons.

Fig. 5. Location of Trondheim, Norway

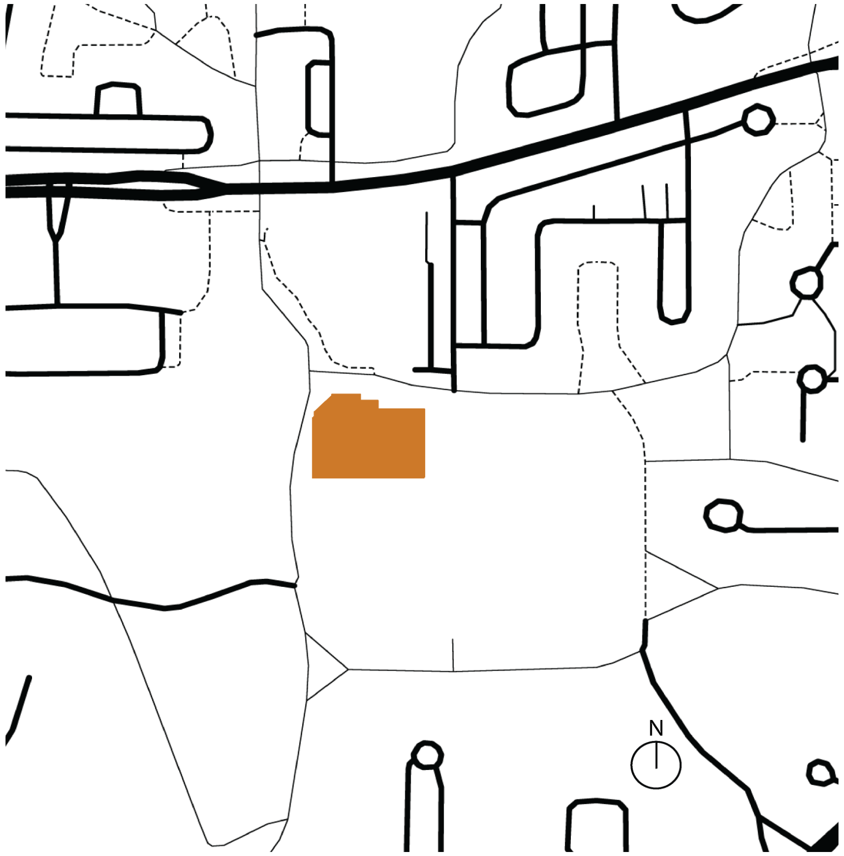


Fig. 6. Site map. Roads are in black. Husebybadet is in orange.

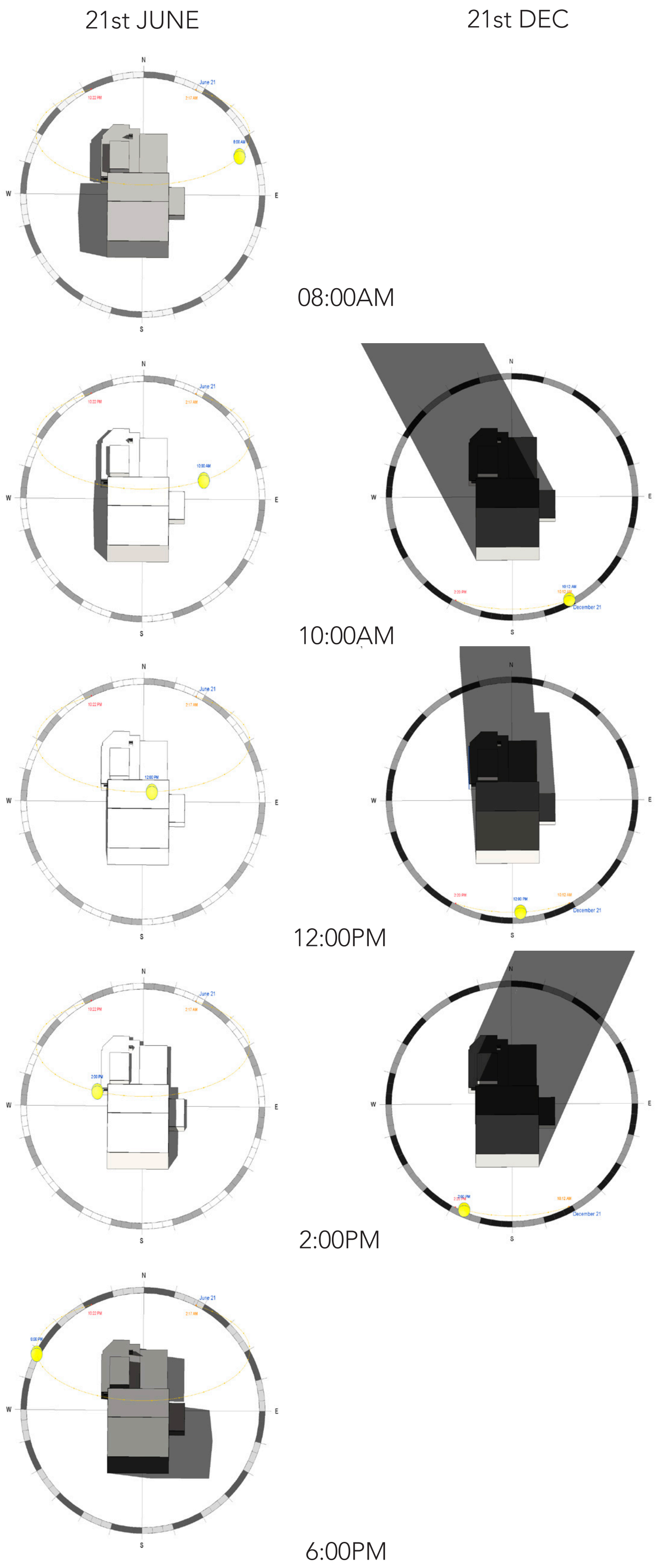
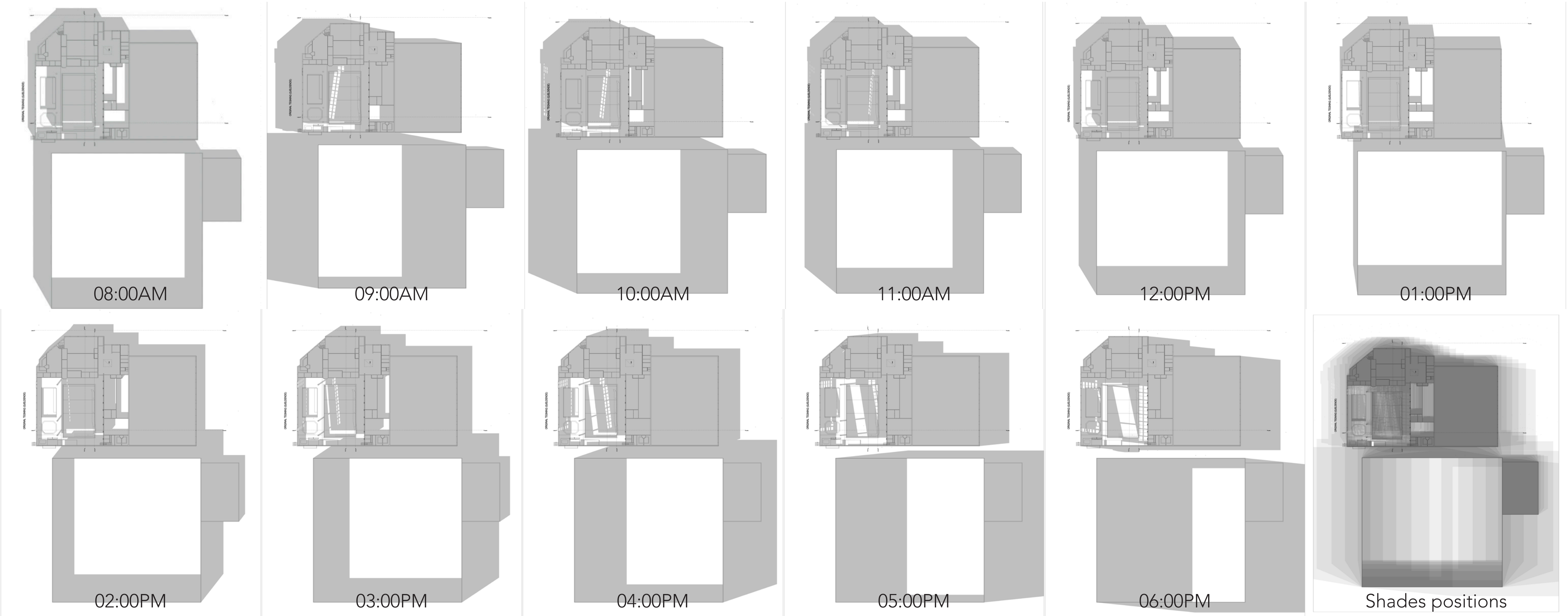


Fig. 7. Sun and shadow availability on the site

21st JUNE
SUMMER SOLSTICE
(1st floor)



21st DEC
WINTER SOLSTICE
(1st floor)

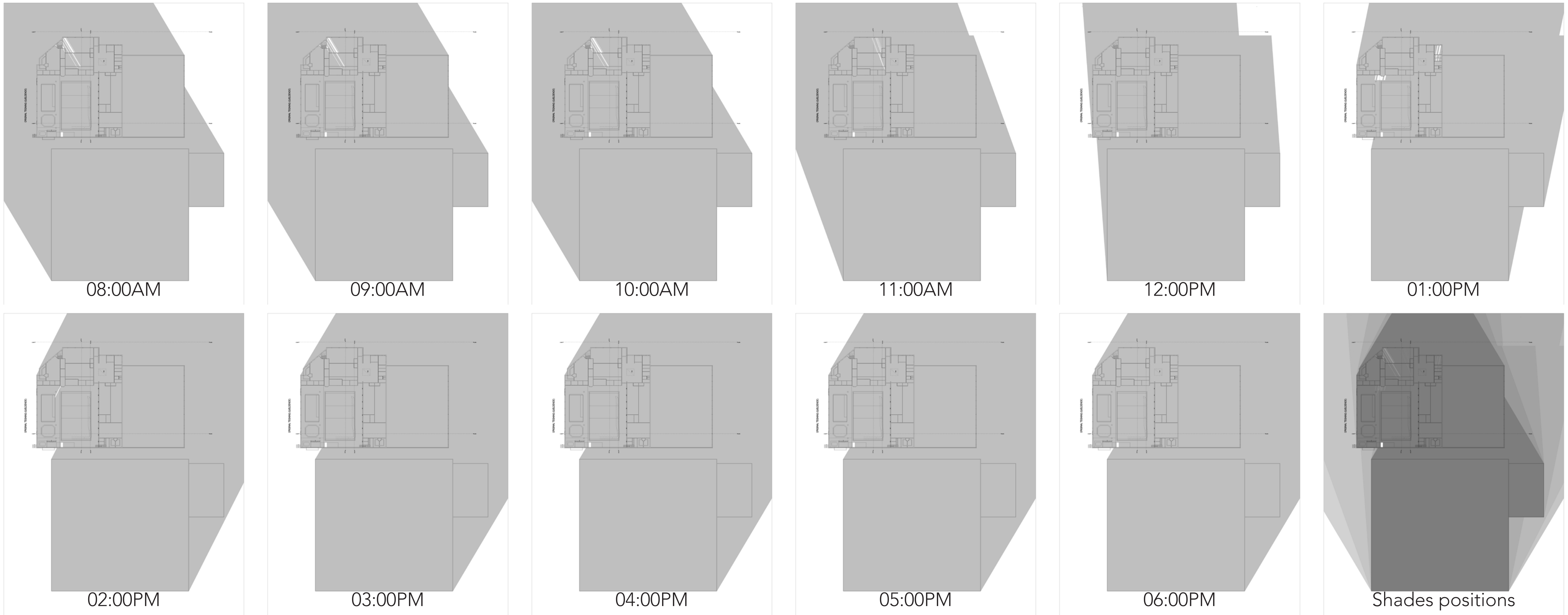


Fig. 8. Analysis of sun and shadow availability to the 1st floor on site

2.3. BUILDING ANALYSIS

Formation of interior spaces is the second most important factor in daylight provision after outdoor daylighting. Therefore, understanding the layout of the building not just enables understanding of daylight demands of the space but also the design of most appropriate openings.

Ground floor, first floor and roof plans present the current primary design of Husebybadet. Focal part of the project is marked with an orange dotted line on the first floor plan, where the proposals of new openings would be.

Building Design

Husebybadet is divided into two zones, due to different uses, construction demands, thermal zones and humidity content. The swimming hall complex is located in the west wing, while the sports hall is located in the east wing.
The main entrance of the building is in the middle of the north elevation. The entrance lobby leads through to the sports hall on the ground floor and a stair case up to the swimming hall on the 1st floor. Ticket office is located next to the staircase in the lobby. Behind the ticket office is a compact gym room without windows, and a hall way leads to the technical room.

The stairs leading to the 1st floor are connected to a common space that has an extruded trapezoidal prism with side-lit windows to allow daylight penetrate through. On the east side of the common space are the lifeguard´s office and kitchen, sunbed rooms, washrooms and storage rooms. On the south side are the female wardrobes and swimming hall, whereas on the west side is the male wardrobe.

The swimming hall is divided into 4 zones, including the 25m standard pool, therapy pool, children pool and the jacuzzi. On the north side of the swimming hall are the disabled wardrobes, lifeguard´s room and storage rooms.

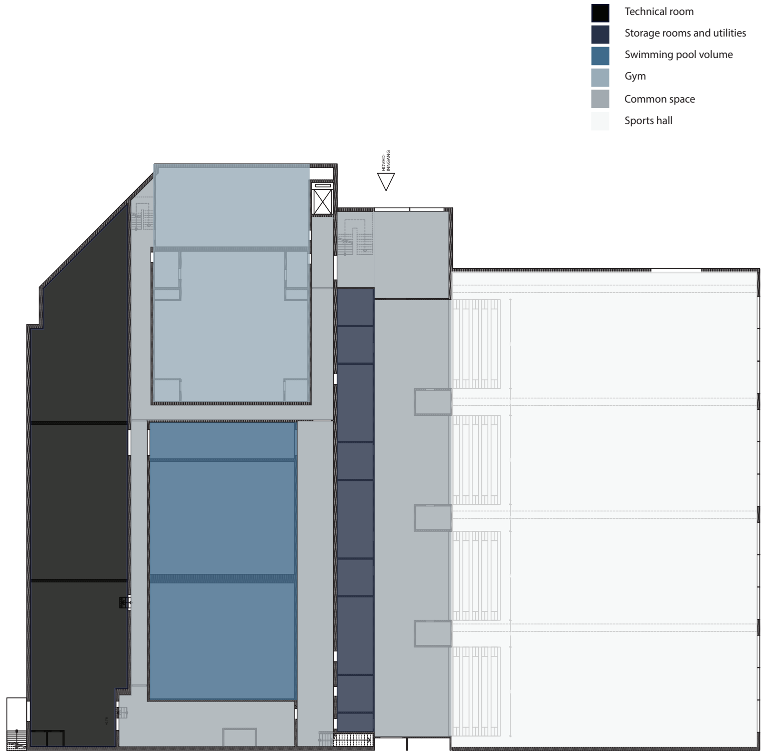


Fig. 9. Ground floorplan

Fig. 10. First floorplan

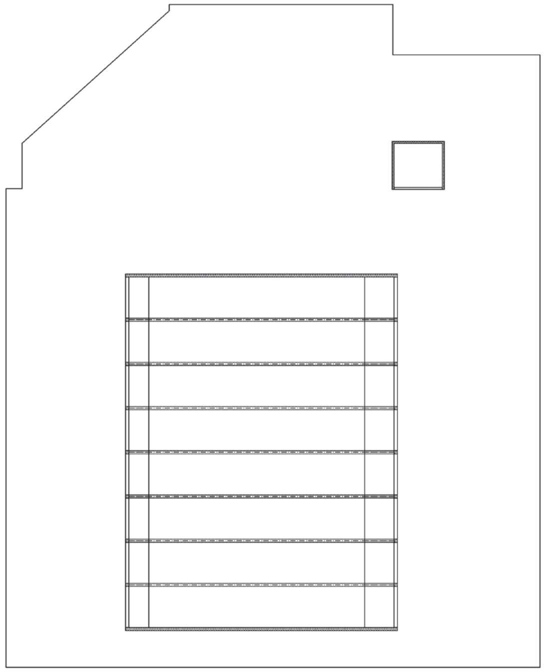
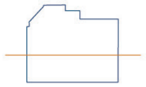


Fig. 11. Roof plan



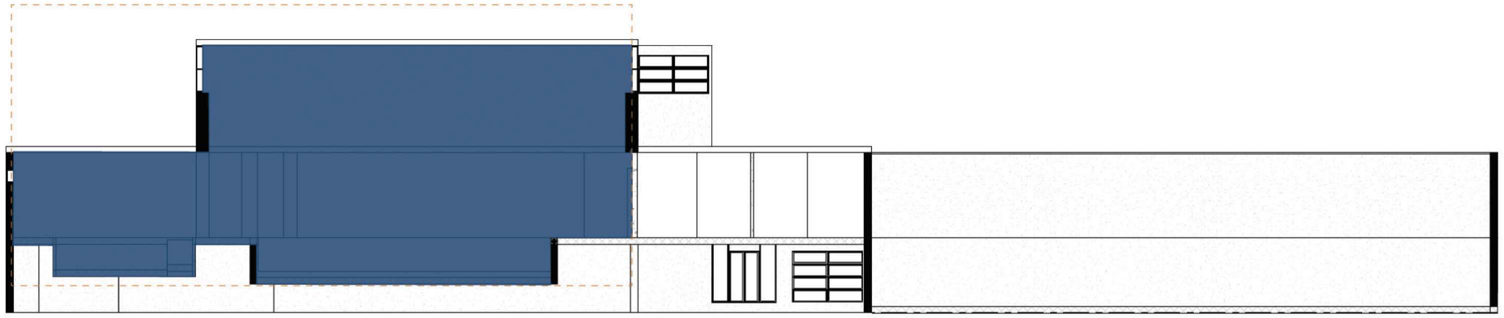


Fig. 12. Section, highlighted focused zone

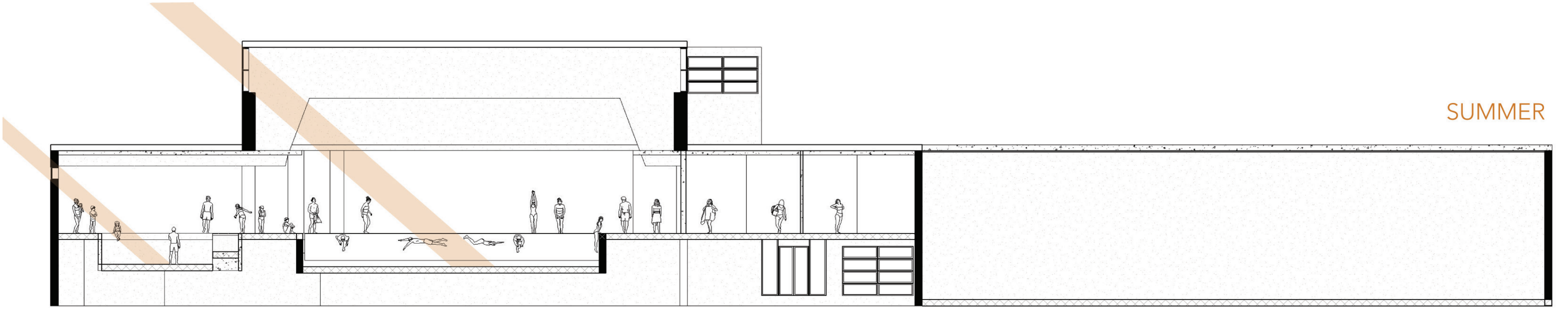


Fig. 13. Summer solar performance section

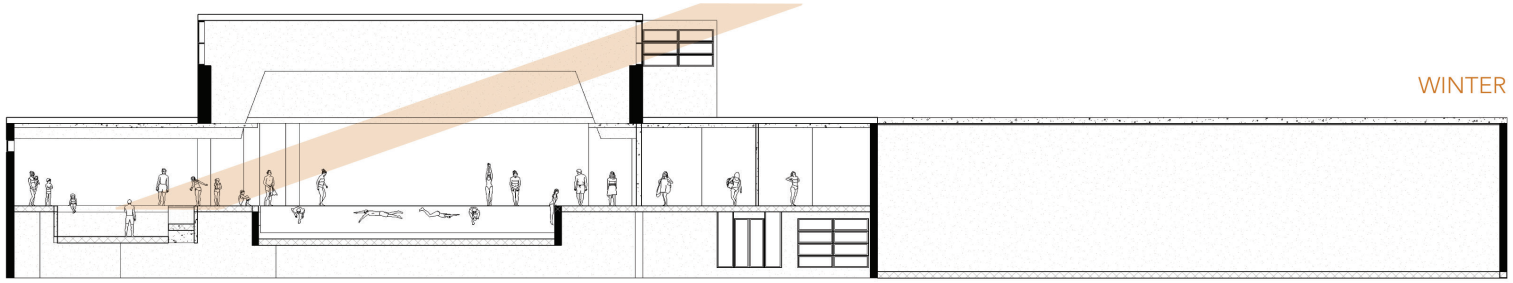


Fig. 14. Winter solar performance section

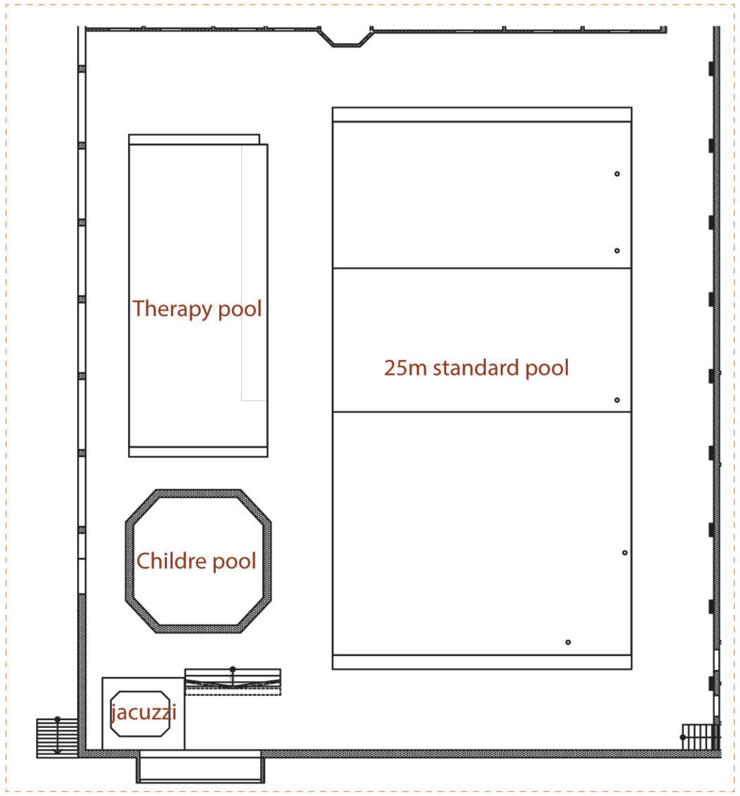


Fig. 15. Zoning of focused zone in first floor

3. LITERATURE REVIEW

3.1. DAYLIGHTING PROFILES

Daylighting can be profiled into six themes:
1) choreographed light
2) atmospheric light
3) sculpted light
4) structured light
5) material light
6) integrated light

Choreographed light

Choreographed light considers how daylight can be utilised to create a sequence of spatial and luminous events to celebrate the experience of place, climate, and program.


Fig.16. Detail of a ´driven void of light´reveals the large south-facing skylight with operable windows that admit light ad exhaust air.

Atmospheric light

Atmospheric light celebrates the qualities and moods of light particular to geographic location and latitude for a given program. The desired atmospheric qualities of light and darkness are closely linked to design intentions, experiential concepts and practical program goals.

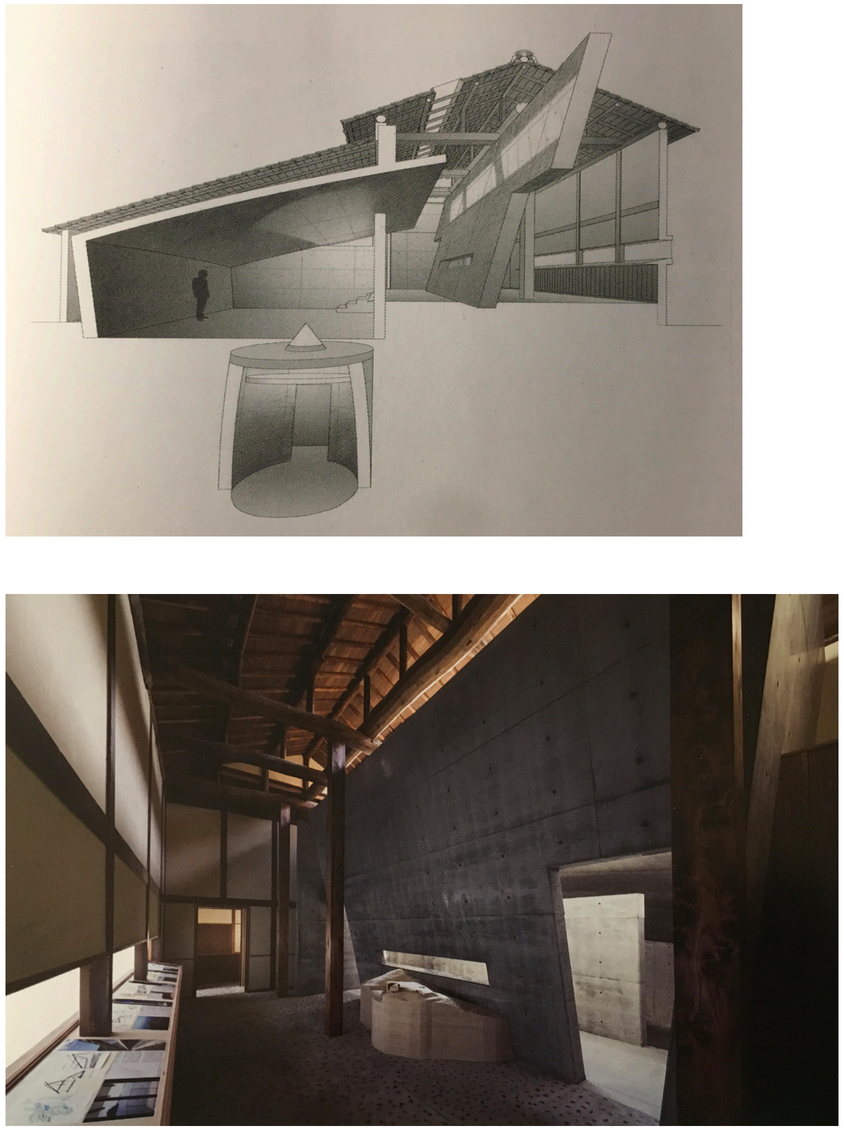


Fig. 17. The sextion perspective illustrates the nesting of galleries and underground meditation space within the reconstructed traditional timber frame house. A low translucent window and borrowed light illuminate the north gallery. A skylight in the south-facing roof admits daylight to the central gallery, while thin vertical and triangular windows provide direct sunlight in the south gallery. A conical skylight, hidden above a hovering ceiling plane, indirectly illuminates the walls of the underground meditation space.

Sculpted light

Sculpted light explores how architectural form can be shaped to support daylighting program and performance targets. The building massing, section, spatial organisation, envelope, and window detailing are inseparable from the quality, quantity, distribution, effectiveness and ecological


Fig. 18. View of an interior courtyard that provides daylight, natural ventilation, and views to the garden. Floor-to-ceiling glazing complements the toplighting and stack ventilation from the skylights. Direct sunlight and heat gain can be mediated by interior shades.

Structured light

Structured light considers the relationships between light and structure as it expresses design intentions and desired atmospheric qualities. The choice of daylighting strategies, form and detailing are inseparable from a

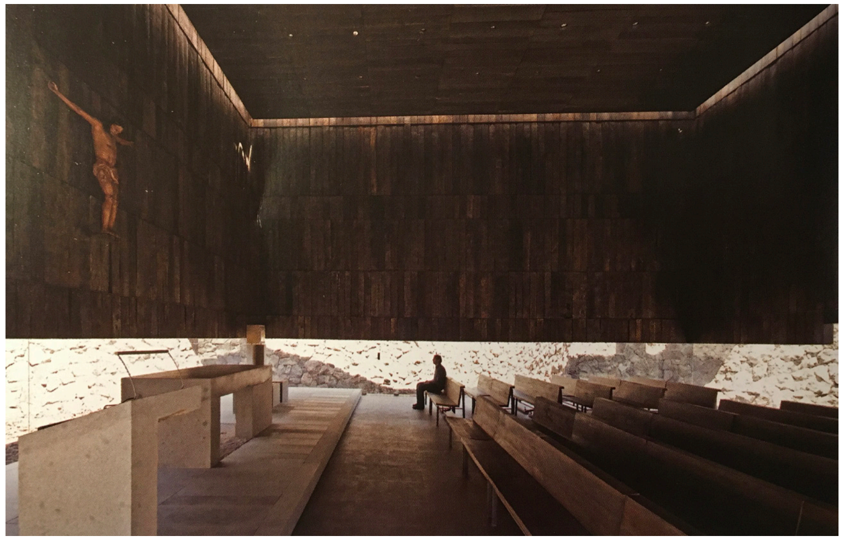


Fig. 19. Structural loads of the chapel are carried to exterior piers in the rock walls of the garden. From the interior, the rustic wood volume appears suspended inside the structural glass curtain wall. Sunlight reflected off the stone walls into the lower portion of the chapel through the glass facades is complented by a soft band of daylight from a narrow skylight at the top of the chapel.

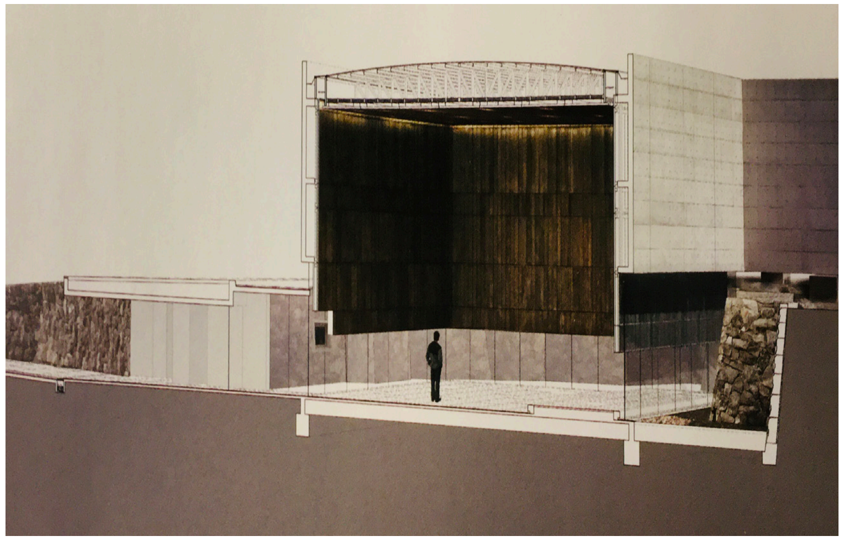


Fig. 20. The building section, concept diagram, and construction details illustrate the nested layers of structure and materials to create the illusion of a floating box within the volume of light. The dynamic movement of direct sunlihgt in the landscape contrasts with the quiet and mysterious darkness of the chapel.

Material light

Material light explores natural light as a dynamic and ephemeral building material that interacts with architectural space and material surfaces to influence the resulting luminous quality of space in time.

Fig. 21. Detail of the sheltering brick wall that wraps the perimeter of the center. Glazed Danish bricks of varying sizes and view openings create a sense of shelter while allowing glimpses of the surrounding community and landscape.

Integrated light

Integrated light explores opportunities to couple daylighting with architectural form, passive design, and innovative technological systems to integrate

Fig. 22. Expansive translucent skylights with exterior shading louvers capture north light and provide an even distribution of daylight in the entry lobby. Piano Pavilion, Kimbell Art Museum, Fort Worth, Texas, USA; Renzo Piano, Renzo Piano Building Workshop.

3.2. DAYLIGHT BENEFITS

Sufficient daylight is both important and beneficial to our health, well-being and environmental performance. Light enable our vision and sufficient natural light offers desirable visual conditions. Besides, light regulates our circadian rhythm. Most animals and organisms, including human have built-in clock in the brains that regulate the timing of biological processes and daily behaviour, known as circadian rhythms. It is responsible for the synchronisation of the body with the day-night cycle. (B.Norton, 2017)

Light also regulates our attentiveness and sufficient illuminance leads to healthier visual and mental conditions. When we are exposed to sunlight directly, vitamin D is produced and arouse the production of serotonin which affect our moods. (J. Lowdon, 2011, G.W. Lambert, 2002) Prolonged exposure to poor daylighting and insufficient sunlight would lead to 'Seasonal Affected Disorder', SAD in short. Though patients could recover quickly by being exposed to natural light.

People spend 90% of their time indoors on average, which is a considerable amounts of time. (European Commission, 2003) In Trondheim, where the climate is cold, people stay indoor for a significant amount of time to shelter themselves from weather conditions, which may risk themselves from adverse consequence if there's insufficient daylight.

3.3. VISUAL COMFORT IN SWIMMING HALLS

Recommended daylight factors:

Sports buildings	swimming pool, pool surface	2%
	pool surrounds	1%
Offices	general offices	2%
	typing computers	4%

(S.V. Szokolay, 2014)

3.3.1. GLARE

The International Commission on Illumination (CIE) define glare as a condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme contrasts.

Glare is either caused by a saturation effect or by excessive contrast. Discomfort glare and disability glare can be distinguished depending on the magnitude of the effect. Saturation glare occurs when the average luminance of the field of vision is more than 25000cd/m2. For instance, on a white sandy beach (Rho = 0.9) with full sunshine (100 000 lx), giving 28600 cd/m2) or looking directly into a bright light source.

Discomfort glare

Discomfort glare is a condition when the glare sources are not too bright which are merely an annoyance and do not directly interfere with vision. Discomfort glare results in difficulty in seeing a task. The influence scale ranges from imperceptible to intolerable. It can also cause headaches or fatigue on people which are often not measurable directly (Reinhart, 2011).

Disability glare

The higher the luminance of the glare source, the higher the disability glare. Disability glare impairs the vision of objects without necessarily causing discomfort. Generally, if discomfort glare limits are met, disability glare is typically not a major concern (NS-EN-1246-1, 2012).

Glare assessment indices

The 3 most common glare indices for calculating discomfort glare from daylight and electric light in buildings are:

- UGR (CIR Unified Glare Rating) – used to calculate glare from artificial lighting
- DGP (Daylight Glare Probability) – used to calculate glare from daylight
- Luminance contrast ratio

(Dubois, 2016)

Daylight glare probability (DGP)

DGP is an illuminance-based measure that describes the percentage of people disturbed due to the level of vertical eye illuminance (Wienold, 2006). It's a metric to predict the appearance of glare in a daylit room. The results evaluation from the experiments indicates good correlation between the DGP and the user's response. The DGP matric can be applied to both high dynamic range (HDR) photographs of daylit scenes and HDR renderings generated using daylight simulation software like Radiance. DGP is applicable to any daylit indoor space that are primarily side-lit and where the expected tasks are comparable to office tasks, whereas it is non-applicable to situations where vertical illuminance is not a decent indicator for the glare perception. With regards to measurement of visual comfort it was found that DGP gave poor agreement with occupant report of discomfort glare in open-plan space with skylights (Isoardi, 2012)

Luminance contrast ratio

Luminance contrast ratio is the ratio between the higher luminance, LH, and the lower luminance, LL, that define the feature to be detected. It can be an alternative to measure glare in sports halls while DGP is not suitable for open plan space with skylights. The luminance contrast ratio between foveal and near peripheral or far peripheral vision can be described by the equation below:

$$C=L_H/L_L$$

Where
L_H: Greater luminance [cd/m2]
L_L: Lower luminance [cd/m2]

Luminance within the visual field should be controlled and balanced to avoid glare or excessive luminance ratios. To achieve visual comfort, luminance ration should not exceed certain threshold.

	Visual requirement		
Location	Low	Moderate	High
Between work zone and its close surrounding	Between 1:10	Between 1:5	Between 1:3
Between work zone and surrounding zone	Between 1:20	Between 1:10	Between 1:5
Between a window and nearby walls	<100:1	<50:1	<20:1

Table. 23. Recommended luminance ratio in the visual field. (Osterhaus, 2002 and Dubois, 2016)

Table 23 presents suggestion of luminance ratios specified for a location and a level of requirement in the visual field. The visual requirements depend on the visual task. High visual requirement is for tasks require high concentration and accuracy, while low requirement is for visibility of large objects.

Though it is not easy to define the work zone in a swimming pool when swimmers move around the pool area. It is reasonable to define the pools as work zones and thus the whole hall as surrounding zone which include the windows.

To conclude, there are two ways to calculate the luminance contrast ratios in swimming hall:

I. Contrast ratio between luminance values of any points in the HDR image, the brightest and the darkest
II. Contrast ratio between luminance values of a target object like a swimming board, and any point in its surrounding zone which is 30° around the view direction.

3.4. LIGHT UP NORTH

The rare ray of sunlight in the Nordics makes it essential to harness the scarce daylight. Prevailing cloudy skies imply that design should permit greatest amount of diffused light from both clouds and clear sky. Overcast skies is formulating natural light to be monochrome, which is to be balanced by interior design decisions.

Harvesting daylight in winters is insufficient in achieving optimal indoor light levels, the use of electrical light is consequently relatively usual. Artificial light is commonly used during daytime for raising illumination and balance out the dark outdoor conditions. Mixture of natural and electric light is a situation often seen in public buildings and offices globally. Daylighting design for buildings in high latitude should deliberate integrating artificial light as part of the architectural design.

3.5. NORDIC SWIMMING POOLS

3.5.1. GENERAL DESIGNS

As mentioned before, it has been common to build sports halls without windows in the old days, swimming halls are not an exception. This could be due to design practicality as well as energy saving purposes. However, due to the update of building regulations, the design of modern swimming halls have started to integrate more passive strategies and achieve a balance between utilising natural daylight, energy saving and enhancing well-being purposes.

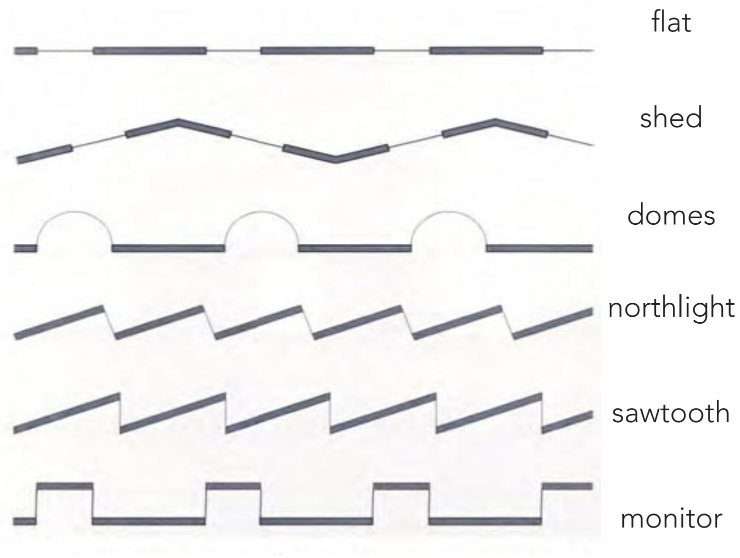


Fig. 24. Different overhead openings for daylight

Fig. 25. Pirbadet, Trondheim, Norway

Fig. 26. Aalto Alvari swimming hall, Finland

3.5.2. CURRENT DAYLIGHT STANDARDS

The inclusion of daylight in sports hall is debated. Norwegian sports halls have been traditionally built without windows, swimming pool is not an exception. There are currently no specific requirement for daylight in swimming pool, according to research.

TEK10, the Norwegian building code requires rooms for permanent residence to have adequate access to daylight. Daylight requirement can be verified either by an average daylight factor of 2% in the room as minimum, or by the room's glass area that represent at least 10% of the floor area. It is noteworthy that for public buildings, all work areas and public space are counted as room for permanent residence. (TEK 10, 2011)

It is unclear if a swimming hall is counted as permanently occupied space. Yet, TEK 17 defines permanently-occupied space as a space where people would stay continuously for more than an hour or two in a day. The swimmers and the coaches could train inside the pool for several hours a day and students from surrounding schools may have swimming classes that last more than an hour. Therefore, windows for providing sufficient access to daylight is a necessity to rooms for permanent occupation.

BREEAM-NOR (2016), a British environmental certification system, requires a minimum of 2.2% daylight factor for non-residential buildings above latitude of 60°.

3.6. EXAMPLES OF POOLS WITH DAYLIGHT STRATEGIES

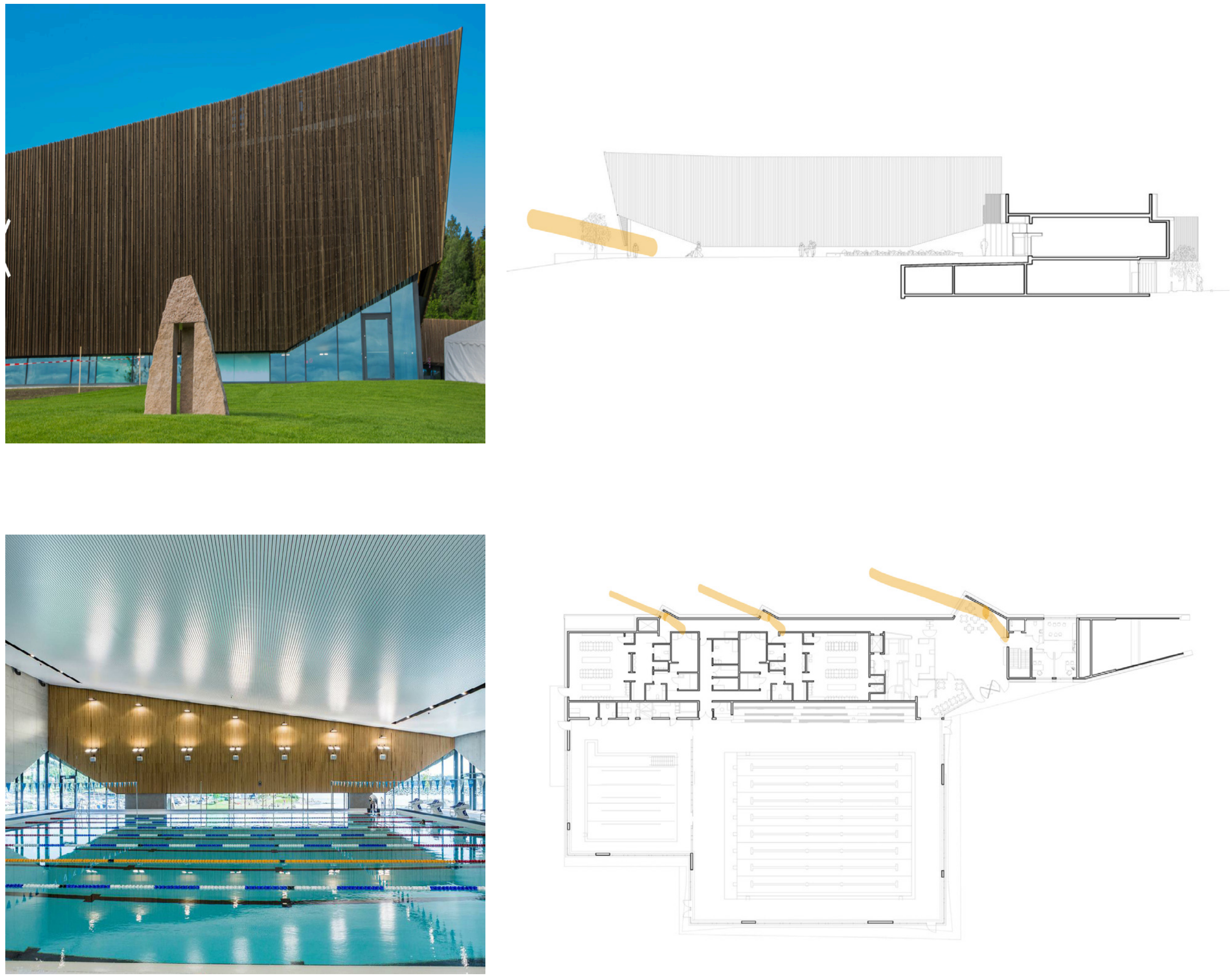


Fig. 27. Holmen svømmehall, Norway. Daylighting diagram.

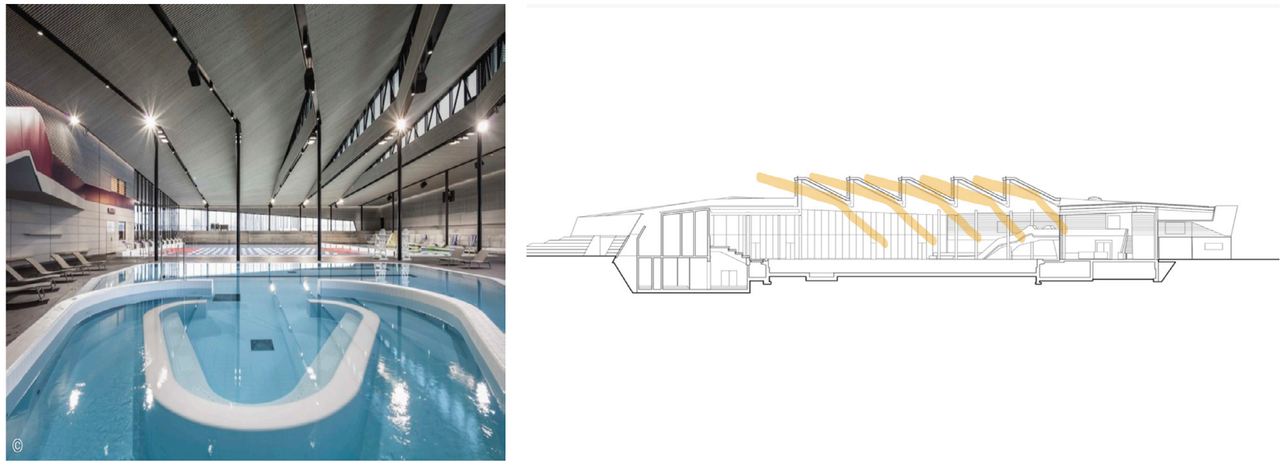


Fig. 28. Aquatic Centre Sourcéane, France. Daylighting dia-

Fig. 29. Terme Olimia Spa, Slovenia. Daylighting diagram.

4. DESIGN

4.1. DESIGN CRITERIA MATRIX

A design matrix for daylighting is made to identify both visual functions and task-oriented conditions. It is a pre-design tool describing design concept and logging project goals. The swimming hall on the 1st floor, which is the focused zone, is divided into 5 sub-zones with different lighting demands. The overall lighting concept is then reviewed, which is referring to the atmosphere and ambience that is desired in each zone. Then architectural conditions are listed, and the light quality is specified. Sunlight exposure probability is projected, followed by how natural light being harvested to the space. The main activities are then identified to design coordinate target. Typical recommended minimum daylight factors for rooms with side lighting are derived from Mitchell's Introduction to Building (Osbourn & Greeno, 2013).

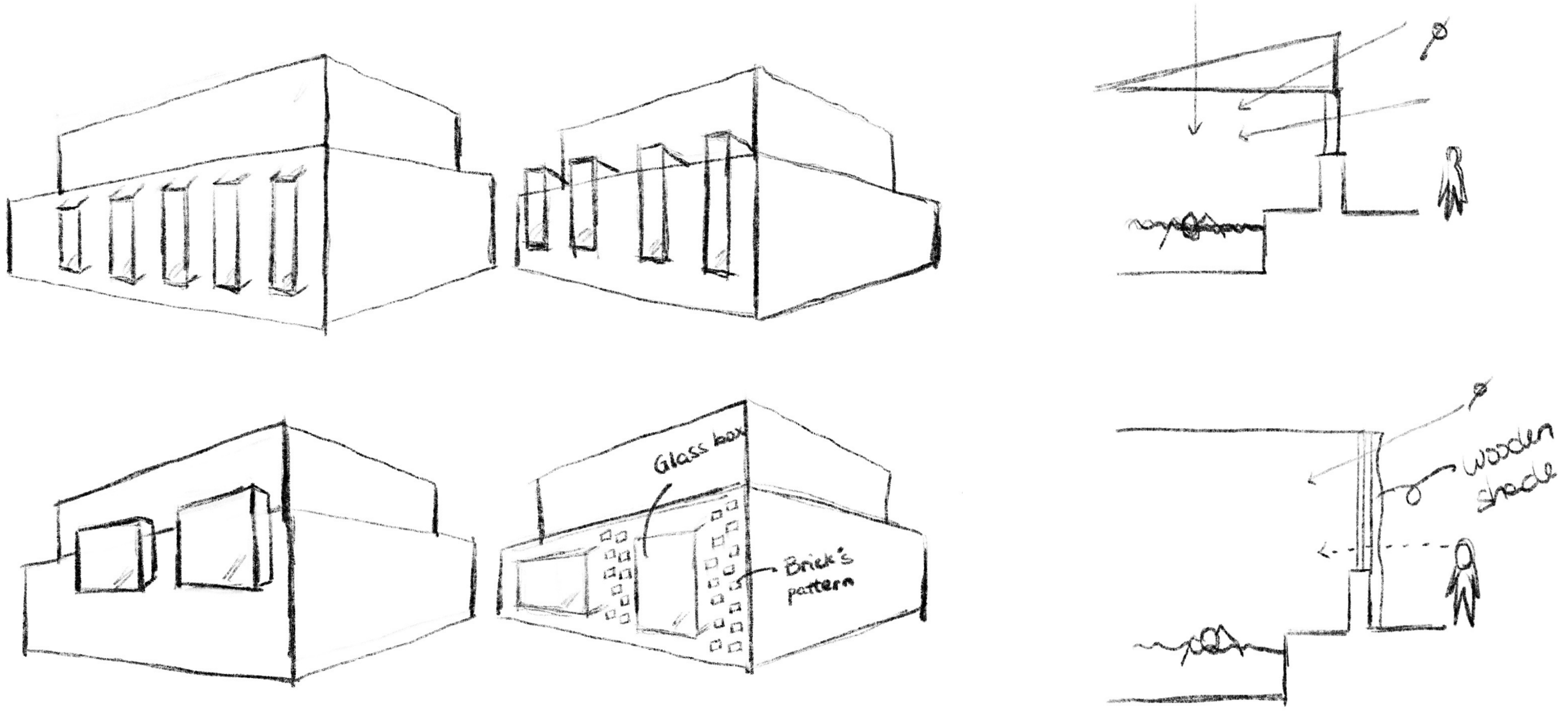


Fig. 30. Digital hand sketches of different design alternatives during the design process

		DESCRIBE CONDITIONS						COORDINATE TARGET		
SPACE		Overall light concept	Architectural conditions	Light quality	Sunlight exposure	Daylight – harvest	Activity	Light level required	Min D required	DGP e<5%
1st floor - swimming hall	Main pool	Modern, overall bright feeling	Skylight openings	Diffused, bright	√	Top-lighting	Swimming	300-500 lux	4.5%	<0.35
	Therapy pool	soft	Largely glazed wall,	Controlled sunlight	√	West window	Water aerobics, swimming	200-400 lux	4.5%	<0.35
	Massage pool	Warm, calming, soft	Access to west window indirectly	diffused	X	West window	Relaxing, bathing	200 lux	2.4%	-
	Children´s pool	Playful, warm, modern	Open plan to allow direct eyesight	Diffused, controlled sunlight	√	West window	Playing	200-300lux	2.4%	<0.35
	Lifeguard room	Welcoming, encourage alertness	Glazed room to allow direct eyesight to the pools	Diffused, bright	X	Window in swimming hall	Observing	500 lux	4.5%	-

Fig. 31. Design criteria matrix

4.2. DESIGN ANALYSIS

Primary design of Husebybadet was methodically analysed in terms of daylight provision. The building was modelled in Revit and Rhino, based on sections and plans. (See Figure. 10 and 12)
Daylight factor was simulated 75cm above the ground. Studied zones respond to the ones listed in the Design Criteria Matrix (Fig. 31), where target daylight factors are described. Basing on a grid 50x50cm, daylight factor levels from 0% to 50% are coloured using gradient ranging from blue to red.

The focused zone on the first floor (Fig.10) is divided into four sub-zones, including the 25m standard pool (main pool), therapy pool, children pool and massage pool (jacuzzi). The 25m standard pool is located on the east side of the hall, with entrance situating on the north. Above the pool, is an extruded ceiling structure with larger and deeper windows on the east and west. Ambient daylight factor 3.8% in the main pool is sufficient for performing task like swimming. Therapy pool has fairly acceptable light levels for water aerobics. Although light is distributed less evenly by the west side of the hall due to the variation of window sizes. Ambient daylight factor 2.1% in the therapy pool is just sufficient enough to meet the target. The children pool has an ambient daylight factor of 2.7%, which is a good light levels for playing. The massage pool (jacuzzi) has an ambient daylight factor of 0% which is too dark for even task like relaxing in the water.

4.3. OPTIMISATION

The first lighting problem to solve are insufficient daylight levels in the massage pool area. Improvement can be made by either introducing new windows to the west façade or introducing artificial lighting to the corner. South façade could also be an option to introducing larger windows, however, the neighbour building might create shadow that could potentially block the light penetrating through. Another problem to solve is the uneven distribution of daylight on the west side. Improvement can be made by introducing larger windows with the same size. This can both introduce more daylight to the therapy pool and children pool but also allow views to the outdoor.

Fig. 32.North-west facades of Husebybadet

Fig. 33.North-west and west facades of Husebybadet

Fig. 34.Entrance of Husebybadet

Fig. 35.Interior of the existing swimming hall

WEST GLAZING SHADING

Daylight factor simulation have shown that spaces around the main pool with west facing windows above are slightly over-lit. For visual comfort, there is a risk of glare occurring in the positions facing west glazed façade. As large glazing is a sophisticated solution which allows visual connection between outdoor and indoor, hence, the concept of plentiful glazing is retained and shading alternatives are studied.

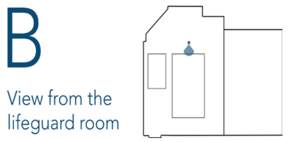
GLARE

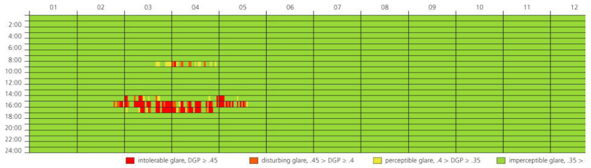
View from the lifeguard room is chosen to measure annual glare probability due to the higher west windows. Lifeguard room or area in front of the lifeguard room is frequently occupied by either lifeguards or swimming teachers, therefore should provide most comfortable condition. In figure. 36, the view from the lifeguard room. Annual DGP simulation represented by a graph is showing that in March, April and May glare is intolerable between 14:00 and 17:00. Figure 36 shows that on the first floor glare is intolerable between 14:00 and 17:00 in late February, the whole March and April and first half of May.

SHADING

A solution is tested at 21st of March, when DGP is 100% at the lifeguard room and glare is intolerable. Shading should provide optimal daylight level while minimising glare.

One way of blocking the sun is the use of automated translucent roller blinds. DGP reduced from 100% to 24%. However, the disadvantage of such blind is that annual daylight levels in the main pool is decreased from 3.8% to 2.5%. Despite that, it is still believed to be the most positive solution. Automatic translucent roller blinds can block sun when needed and succeed in lowering DGP to imperceptible level. The blinds do not have to shade the whole window height and can hang half way of the window, so view to the sky is kept even during shading.

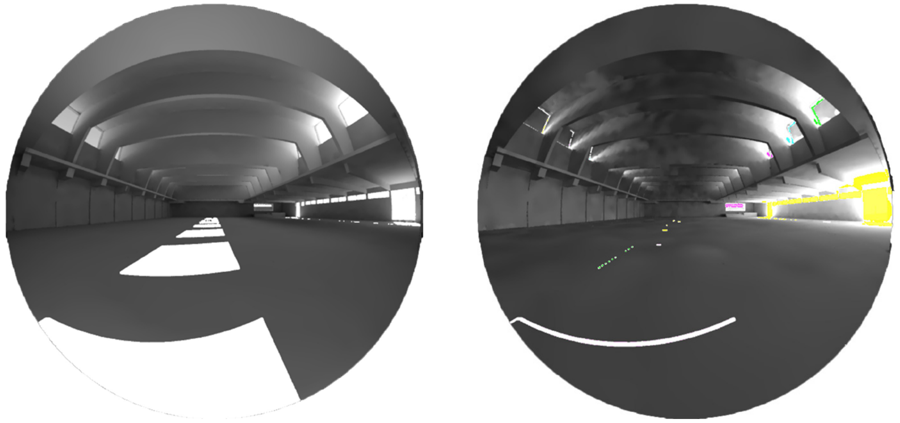




21st March, 16:00

No Shading

Automated translucent roller blinds



DGP: 100
Intolerable glare

DGP: 24
Imperceptible glare
Improvement: 76%

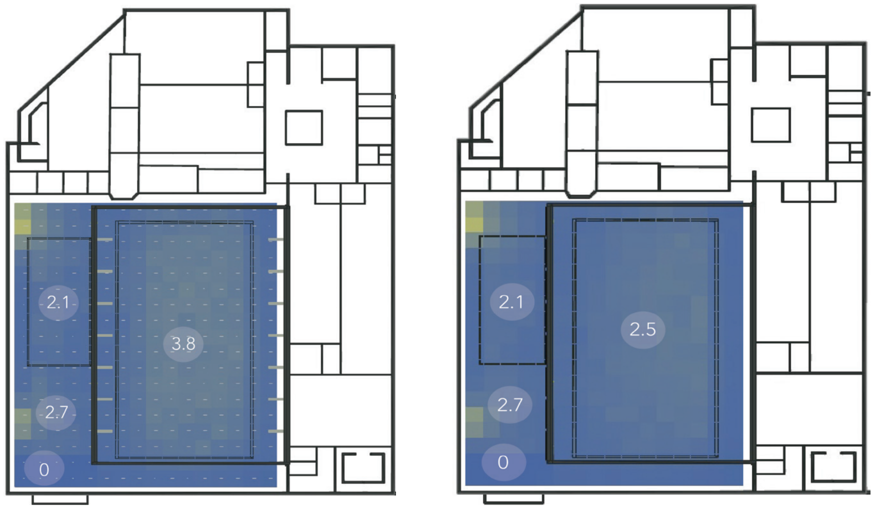


Fig36. Point assessment of view from lifeguard room and shading affecting daylight factor

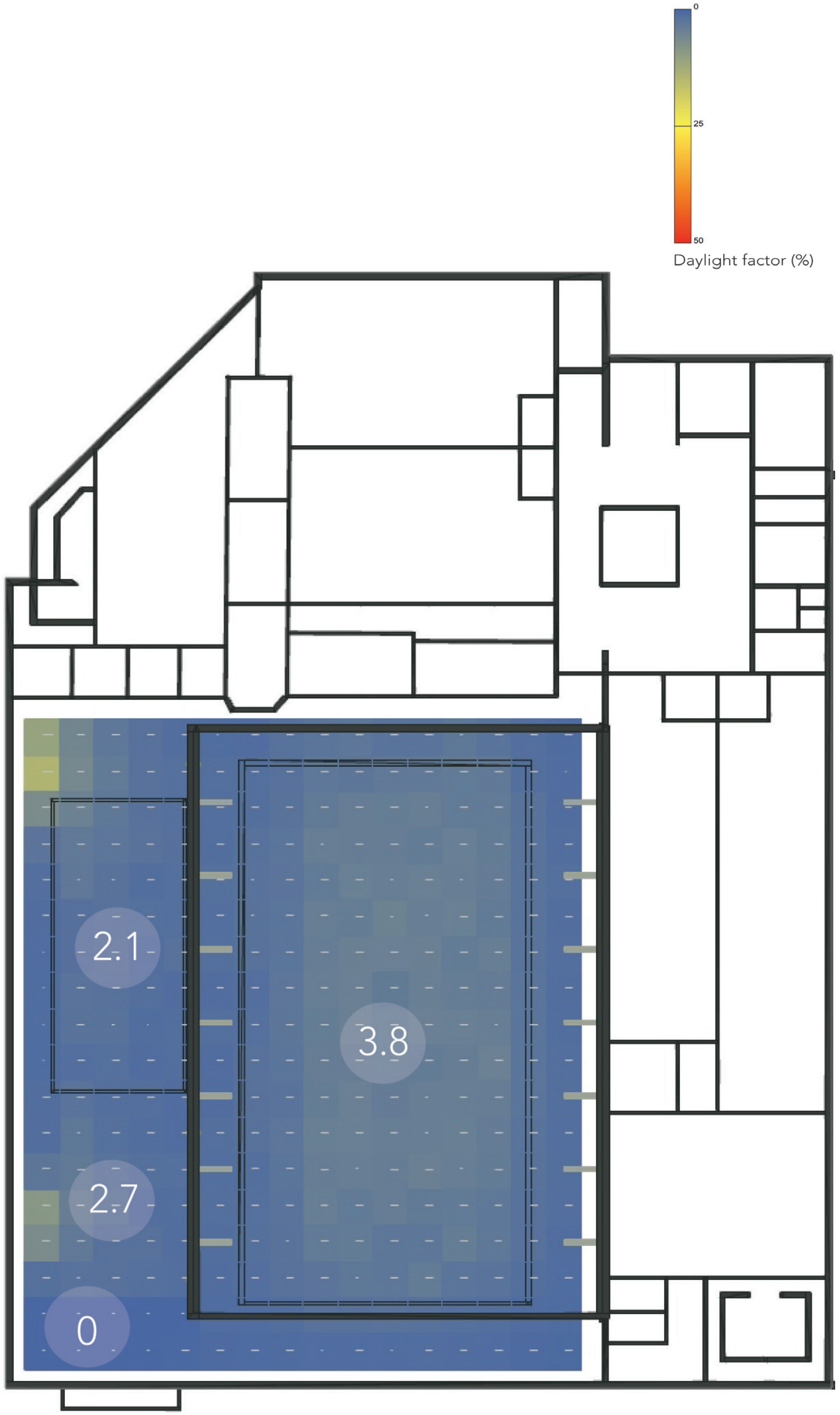


Fig. 37. Daylight factor on the first floor

4.4. DYNAMICS OF BRIGHTNESS

Husebybadet primary design is systematically analysed in terms of visual comfort such as glare. Analysis is performed using luminance false colour maps of five camera views, which are named A, B, C, D and E. Their positions are noted on the reference plan, see Fig. 38.

TIME

Three different dates are selected, including winter solstice 21st December, spring equinox on 21st March and summer solstice on 21st June. Annual DGP simulation is produced for each view. It is studied if the method of measuring useful range of discrimination links with the DGP.
For winter and spring, only 12:00 o´clock under overcast sky condition was studied. For summer three different times: 08:00, 12:00 and 16:00 were studied.

CAMERA VIEWS

View A is focusing on the east and west windows affecting visual condition of a person working on the ramp next to the jacuzzi. Analysis proves the source of glare mainly coming from the east windows in summer mornings and west windows in summers afternoon. View B shows the view of a lifeguard standing outside the lifeguard room, looking towards the south side of the swimming hall. The glare is mainly coming from the south facing windows next to the jacuzzi. View C is showing the view of a person standing next to the therapy pool facing towards to east. It could refer to a teacher of water aerobic lessons. Glare is mainly coming from the east windows in early mornings of summers. View D shows a view of a person relaxing in the jacuzzi, looking forwards north east of the swimming hall. Glare mainly occurs from the east windows in early mornings of summers and from the west windows in the afternoons of summers. Lastly, view E indicates a view from the sitting area.

LUMINANCE MAPS ANALYSIS

Realistic renderings are investigated to measure if the views are within the useful range of discrimination. An average luminance of the scene

Fig. 38. Primary design concept, luminance false coulor maps analysis

is measured on false colour maps, which becomes an adaption level for the view. It is a simplified version of real life condition as our eye can adopted by changing focus point fast which define adaption level. However, analysing visual comfort mainly in top lit space is still the most ideal technique.
In figure 38, luminance maps analysis are shown. The view on the top left corner is referring to 12:00 in the noon on 21st of December. Adaption level is the number shown in white. Then, useful range of discrimination is read from the graph (Fig. 39) and written under the view. To evaluate each view, extreme luminance values at points are defined and evaluated. The points that lay within the useful range of discrimination are marked with green frames, whereas the points that are out of range are marked with red frames. Often the points with extreme high ratio to adaption level are out of range. Next, views that are significantly out of visual comfort are marked with dotted orange lines.

USEFUL RANGE OF DISCRIMINATION ANALYSIS

Luminance of light sources and working planes were defined. The ratio among them and an average luminance of the view was found. Luminance of the instant task and nearby surface in the view should not be extremely dark or bright.
Based on the luminance adaptation level, discomfort is likely to occurred at 08:00 in the summer morning of view A, B, C and E. The sun is shining directly to the water surface through the windows and create reflection to the walls, which are the immediate surroundings of the observer. Also, in the summer at 16:00 at view A, B and E, there is an extreme contrast between the window high luminance and water surface. In winter, light sources in most cases are perceived to be too bright compared to the dark interior with small windows. Further, the highest ratios were found in spring at 12:00 in view B (116:1) and in summer at 12:00 in view B (64:1). This indicates exposure to sunlight presents a broad range of high luminance leading to glare.
To precisely evaluate visual comfort analysis, a second step was conducted. Views that have not fallen out of the useful range of luminance were found. After that only seven views out of twenty five were in a useful range of discrimination.

GRAPH RESULTS

Results acquired during the analysis were transformed into a log-log graph based on the original graph from the book Daylight Design of Buildings. All cases are described by the time and season. The most severe glare happens during summer solstice. The worst conditions occur in the morning at the C camera view. Perceivable extreme luminance value is about 6000cd/m2 above the threshold. It is because of the sun position being almost perpendicular to the geometry of the window openings.

NEW DESIGNS

Assumptions from the analysis of primary design are used to create guidelines for the new scenarios for roof and side-lit lighting. Winter discomfort can be reduced by

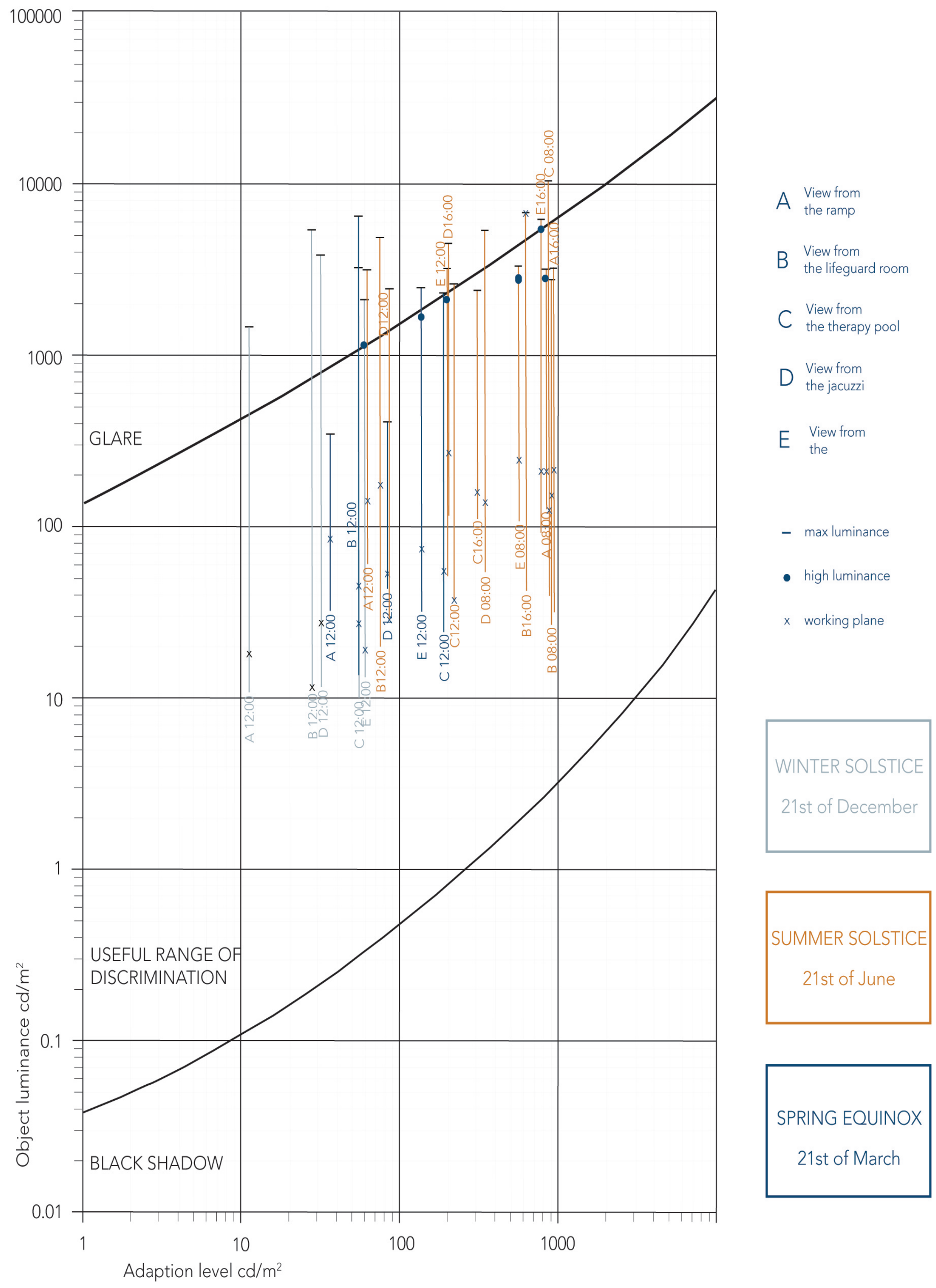


Fig.39 . Visual comfort evaluation at five camera views, represented on a luminance dynamic graph

4.5. DESIGN PROPOSAL - SCENARIO 1

Scenario 1 attempts to enhance and maximise daylight provision, offer good visual circumstances for swimming hall users, ensure glare free environment and enable passive solar heating.
The concept is based on enlarging east and west facing window openings in the extruded structure as well as adding roof apertures. The windows were originally placed behind a thick concrete wall structure in the extruded structure, which limits daylight penetration through the building. Whereas the new design converts the concrete wall structure to glass, which double the size of window openings. Making a total glass area of 269m2 in the extruded structure. Windows on the west façade have also been optimised, making a total glass area of 104m2. Besides, roof apertures have also been added to allow roof lighting.

Daylight levels are sufficient, apart from the massage pool (jacuzzi) which is not getting any improvements. (Fig.45) Window glasses are large and some are placed higher up, installing shadings may therefore be complex. However, large glazing allow view to the sky. Interior is pleasing and modern, but lack a vibrant expression. The large window openings in west façade allow connection to the outdoor.

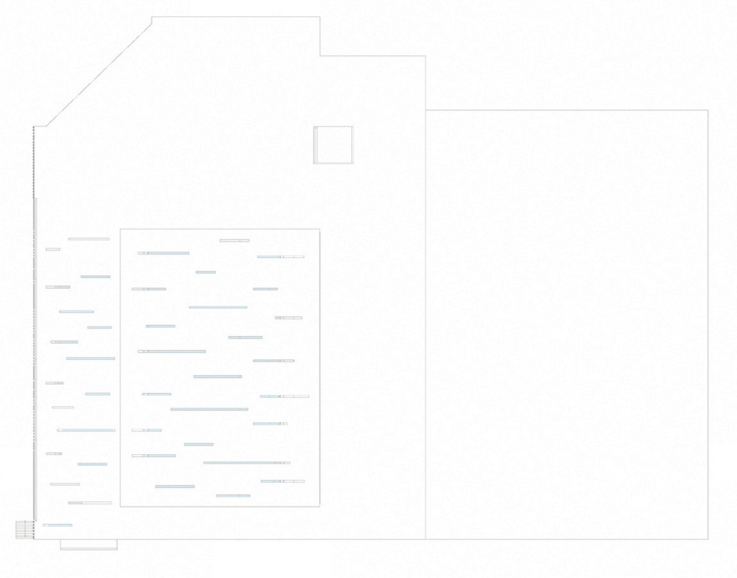


Fig. 40. Roof plan of scenario 1

Fig. 41. Render of scenario 1. West facade.

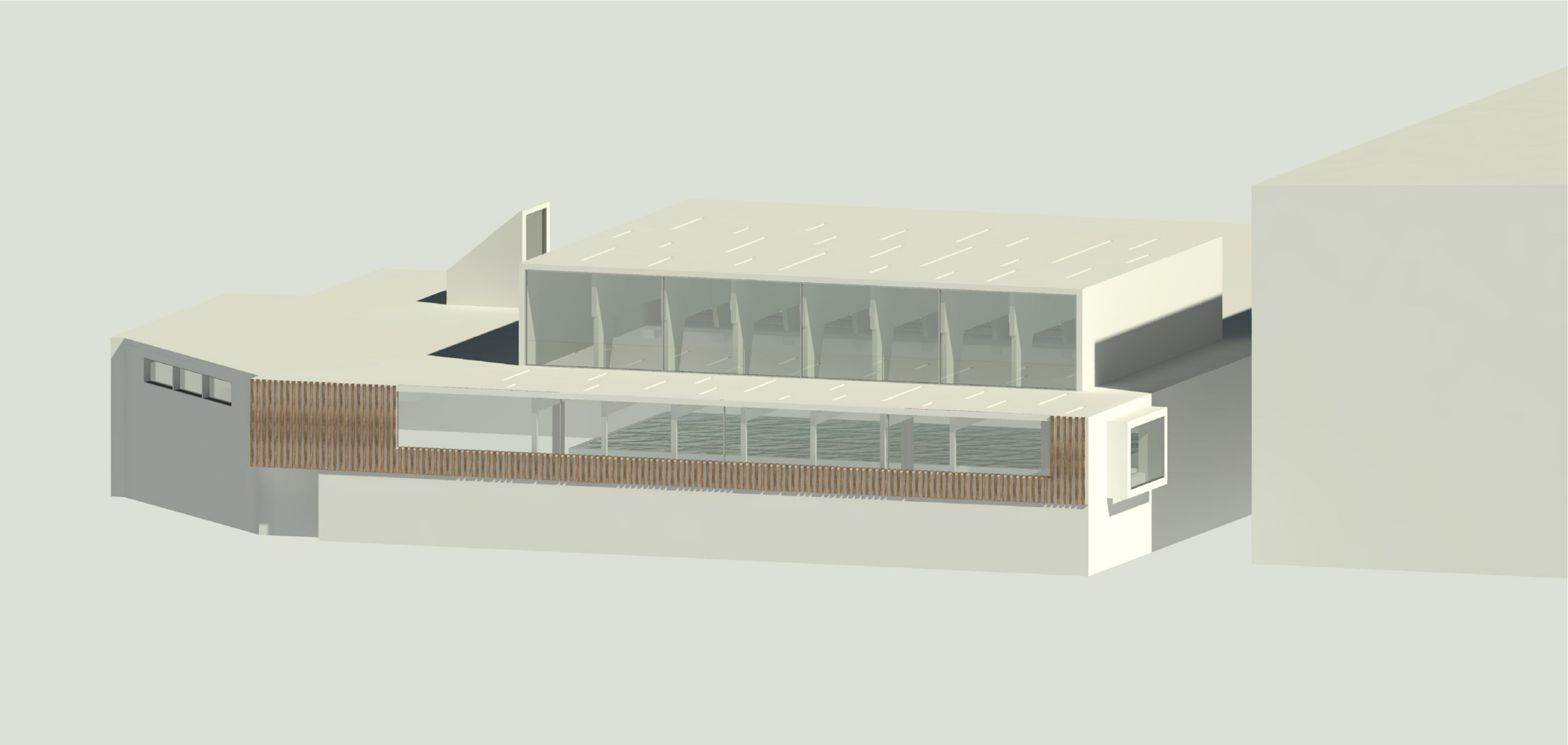


Fig. 42. Render of the whole Husebybadet from west facade.

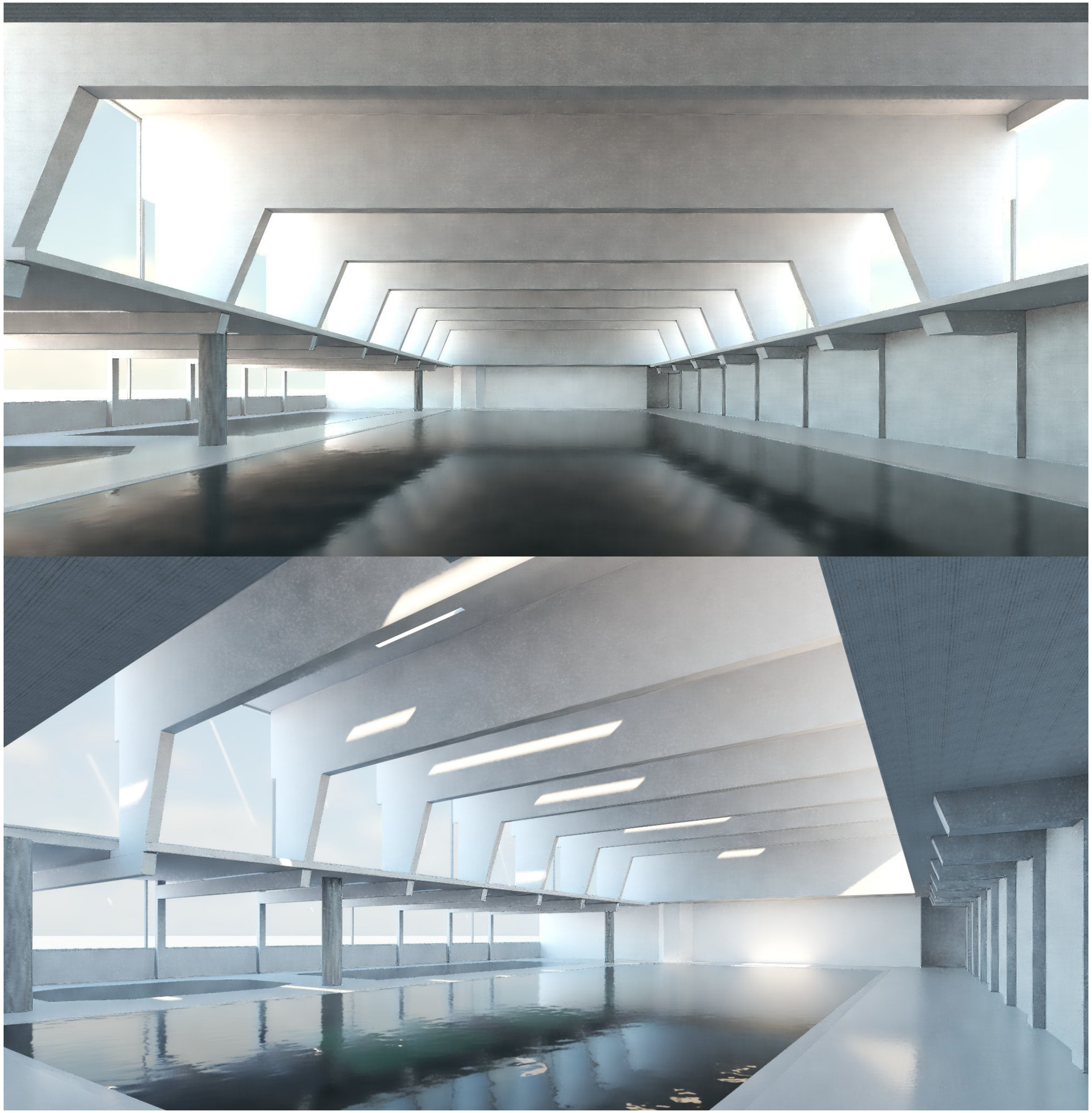


Fig. 43 & 44. Renders of scenario 1´s interior.

Fig. 45. Daylight factor on the first floor. Scenario 1.

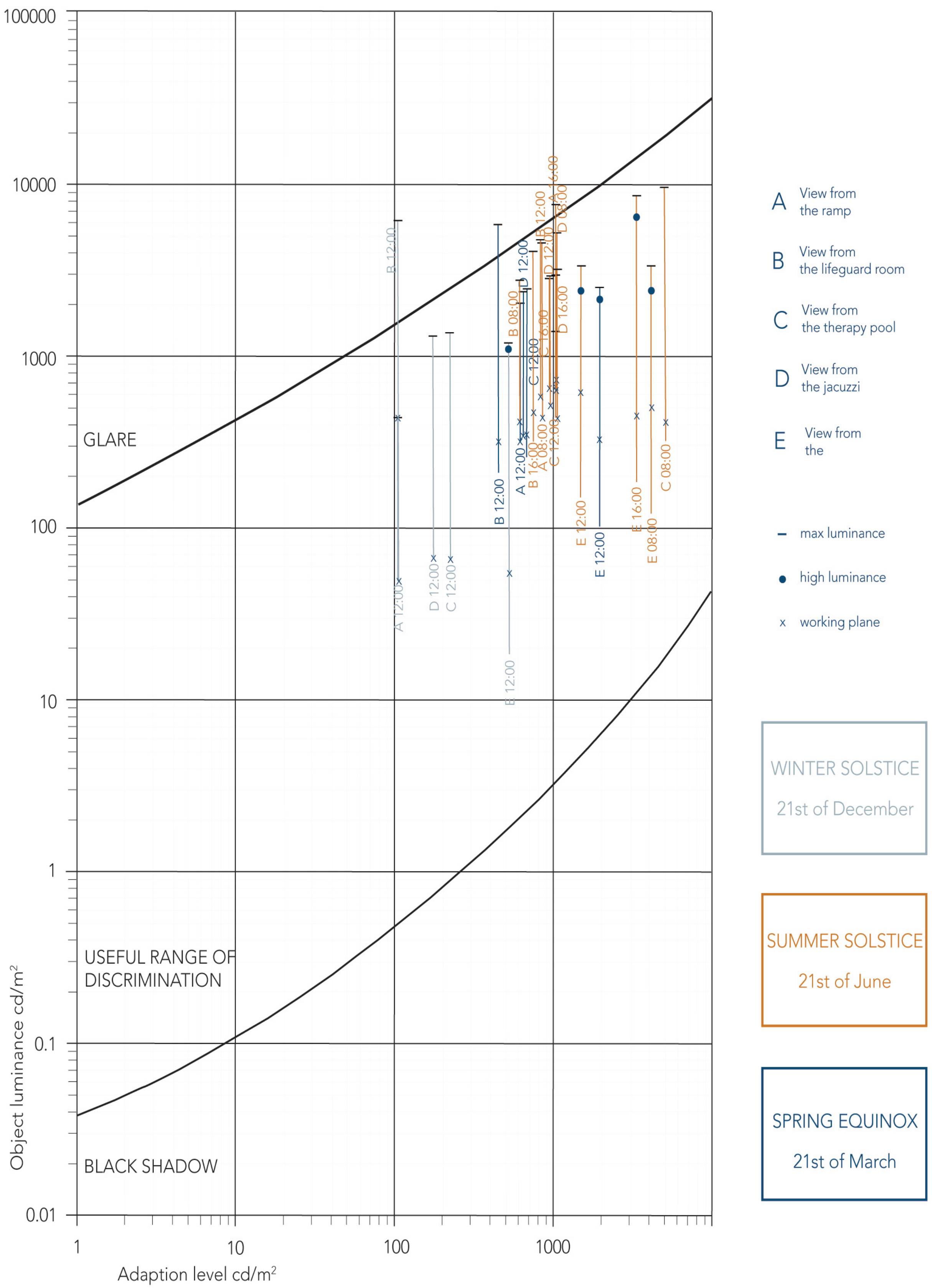


Fig. 46. Scenario 1, luminance dynamics graph

VISUAL COMFORT ANALYSIS

Twenty one views out of twenty five analysed have no signs of disturbed visual comfort. A few of the worst conditions causing glare occur in the winter view D and view B at 12:00. This is due to the low sun angle causing sunlight illuminating through the high windows openings. It is highly possible that window openings placed higher up have higher risk of perceivable glare, particularly when camera is placed on the working level, illuminated by large openings surfaces that are close to the observer and when we can see sky via the windows.

Glare also occur in the spring and summer view D at 12:00. When the camera is placed in the darker zone, the contrast from the puddles of light results in a less comfortable visual environment.
The benefit of scenario 1 is that luminance of the visual task is generally higher than in the primary design. Also, views present higher adaptation levels in average.

Fig. 47. Primary design concept, luminance false coulor maps analysis.

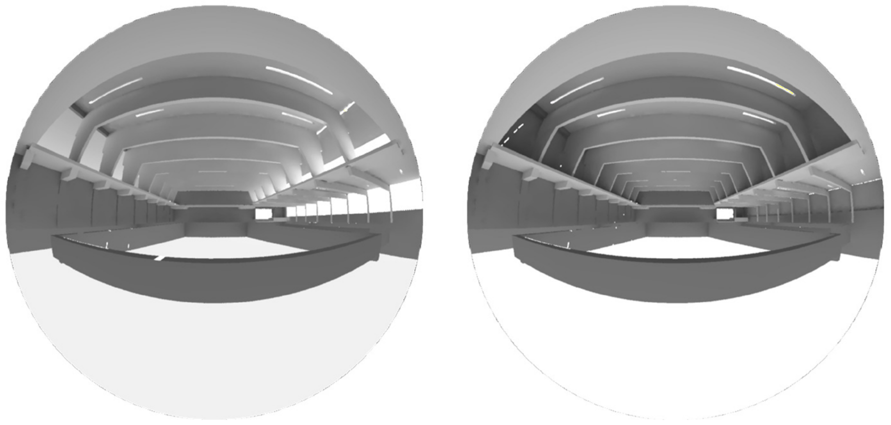
B

View from the lifeguard room

21st March, 16:00

No Shading

Automated translucent roller blinds



DGP: 100
Intolerable glare

DGP: 34
Imperceptible glare
Improvement: 66%

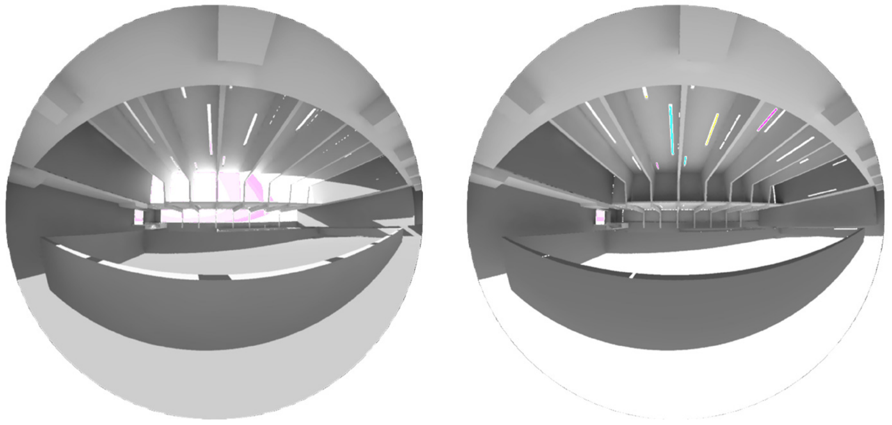
E

View from sitting area

21st March, 16:00

No Shading

Automated translucent roller blinds



DGP: 46
Intolerable glare

DGP: 32
Imperceptible glare
Improvement: 14%

Fig. 48. Point assessment of views from lifeguard room and from sitting area. Shading affecting daylight

WEST GLAZING SHADING

Daylight factor simulation have shown swimming hall´s spaces adjacent to west are over-lit. In terms of visual comfort, there is also a risk of glare occurring in positions facing west glazed façade. As the large glazing opening is visually pleasing and that visual connection between the indoor and outdoor is vital, the concept of large glazing is kept and shading alternative is examined.

GLARE

Two locations are chosen to examine annual glare probability due to the west windows. First one is from the lifeguard room where space is frequently occupied by lifeguards or swimming teachers, therefore should offer most contented conditions. Second view is located by the sitting area for audience such as parents who wait for their children during swimming lesson.

In figure 48, with the view from the lifeguard room. Annual DGP simulation represented by a graph is showing that from late February to May glare is intolerable between 07:00 and 10:00 as well as late February to early October glare is intolerable between 14:00 and 18:00. Fig. 48 shows view from the sitting area where glare is intolerable between 15:00 and 1900 from mid-February to early June, and occasionally in August and September.

SHADING

A solution is tested on 21st March, when DGP is 100% at the lifeguard room and 46% at the sitting area, and glare is intolerable. Shading should offer ideal daylight levels while minimising glare.
One way of preventing light causing glare is the use of automated translucent roller blinds. DGP reduced from 100% to 34% and from 46% to 32%. However, the disadvantage of such blind is that general annual daylight levels in the swimming hall is decreased by half, from 16% to 7.5% in the main pool for instance. Despite that, it is still believed to be the most positive solution. Automatic translucent roller blinds can block sun when needed and succeed in lowering DGP to imperceptible level. The blinds do not have to shade the whole window height and can hang half way of the window, so view to the sky is kept even during shading.

SCENARIO 2

4.6. DESIGN PROPOSAL - SCENARIO 2

In scenario 2, design objectives are the same as the one specified in scenario 1, plus this one tries to deliver a more expressive, vivacious and transparent expression. Design follows similar principle as scenario 1, but with higher window glazing ratio. The extruded structure is transformed into a glass box, creating a 360° connection to the sky. The west façade has a large window opening, gladded with wooden strip panels on the exterior for glare protection and privacy purpose. Geometry of the wooden strip gladding is in a wavy shape, imitating the wave of water. Besides, privacy issue is important in Husebybadet, due to the high percentage of female minority group users.

Daylight levels are sufficient in the proposed design, as shown in Fig. 53. There is an increase in daylight factor in the massage pool (jacuzzi) from 0 to 7. However, there is also a decrease of daylight factor in some zones despite the uniform distribution of light.
Scenario 2 shows how viable is perceivable glare in Husebybadet. Lights bouncing from the water surfaces results in a higher luminance values, which is observable while comparing with primary design with lower luminance.
Electrical light could be integrated in the west part of the hall where the ceiling is lower to increase the daylight factors.

Fig. 49. Render of scenario 1. West facade.

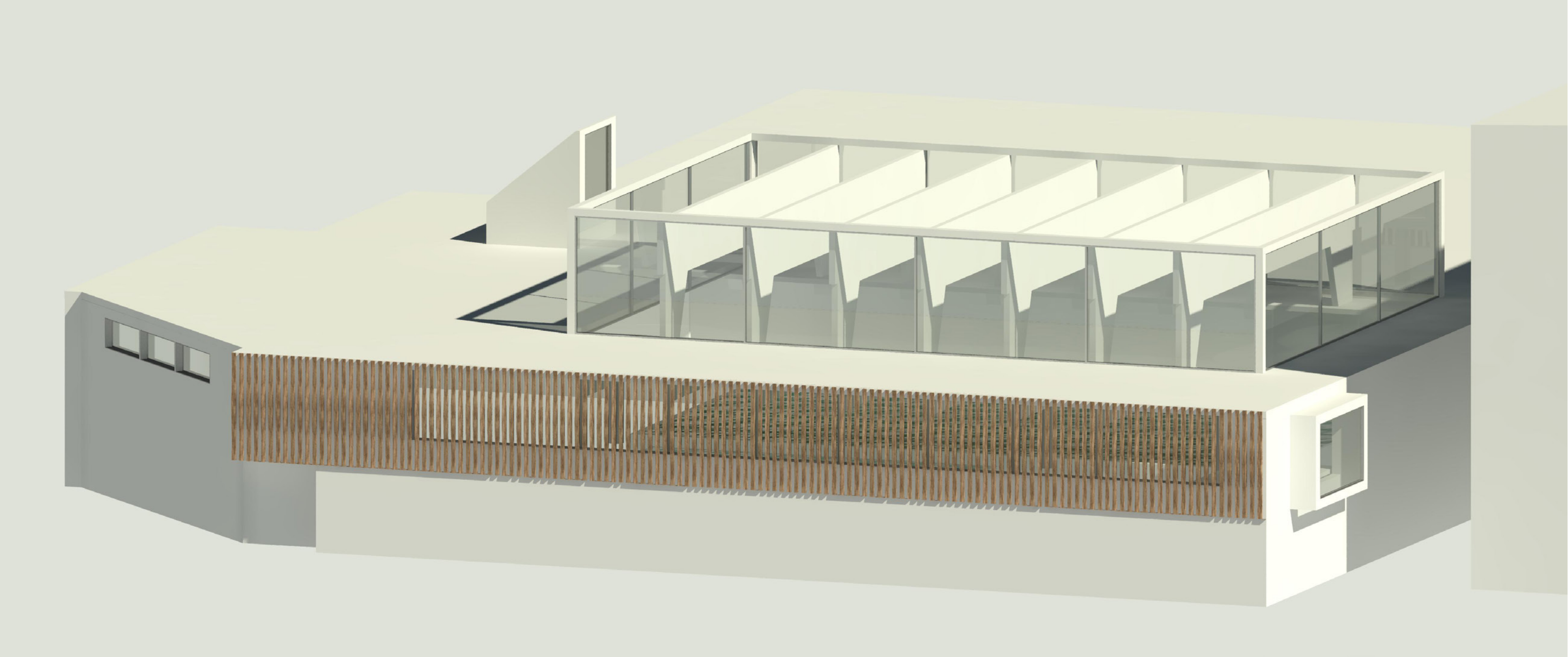


Fig. 50. Render of the whole Husebybadet from west facade.

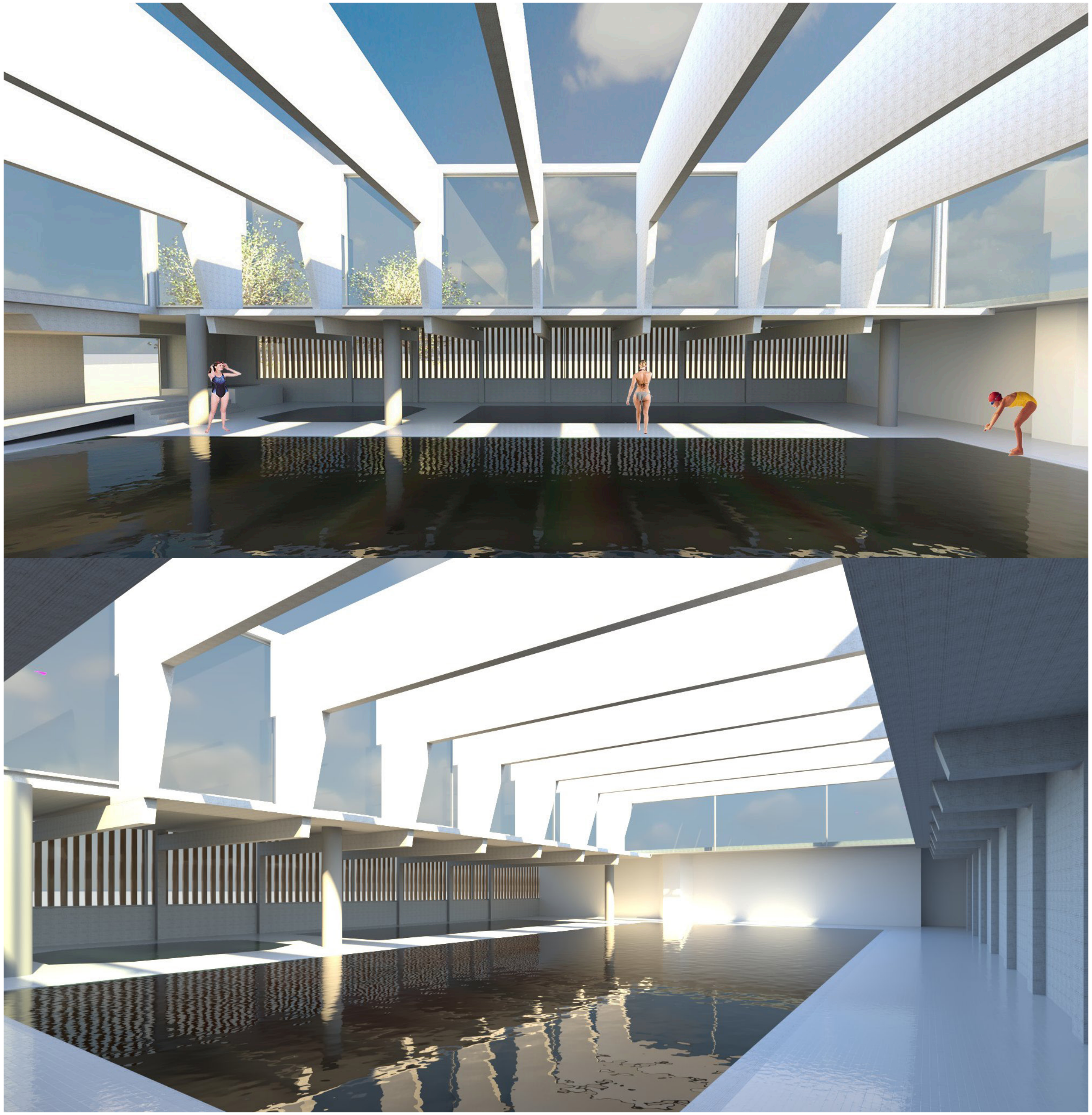


Fig. 51 & 52. Renders of scenario 2´s interior.

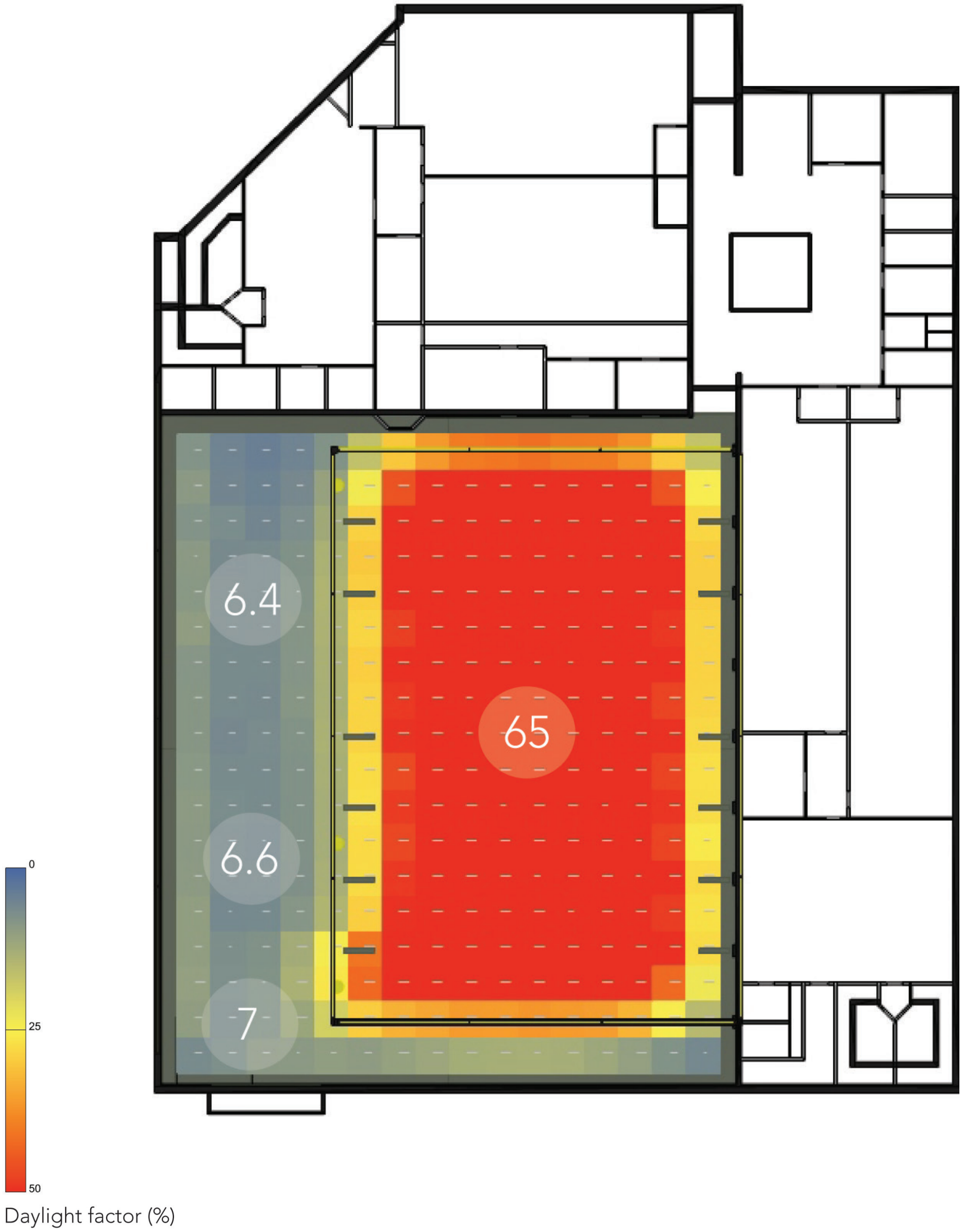


Fig. 53. Daylight factor on the first floor. Scenario 2.

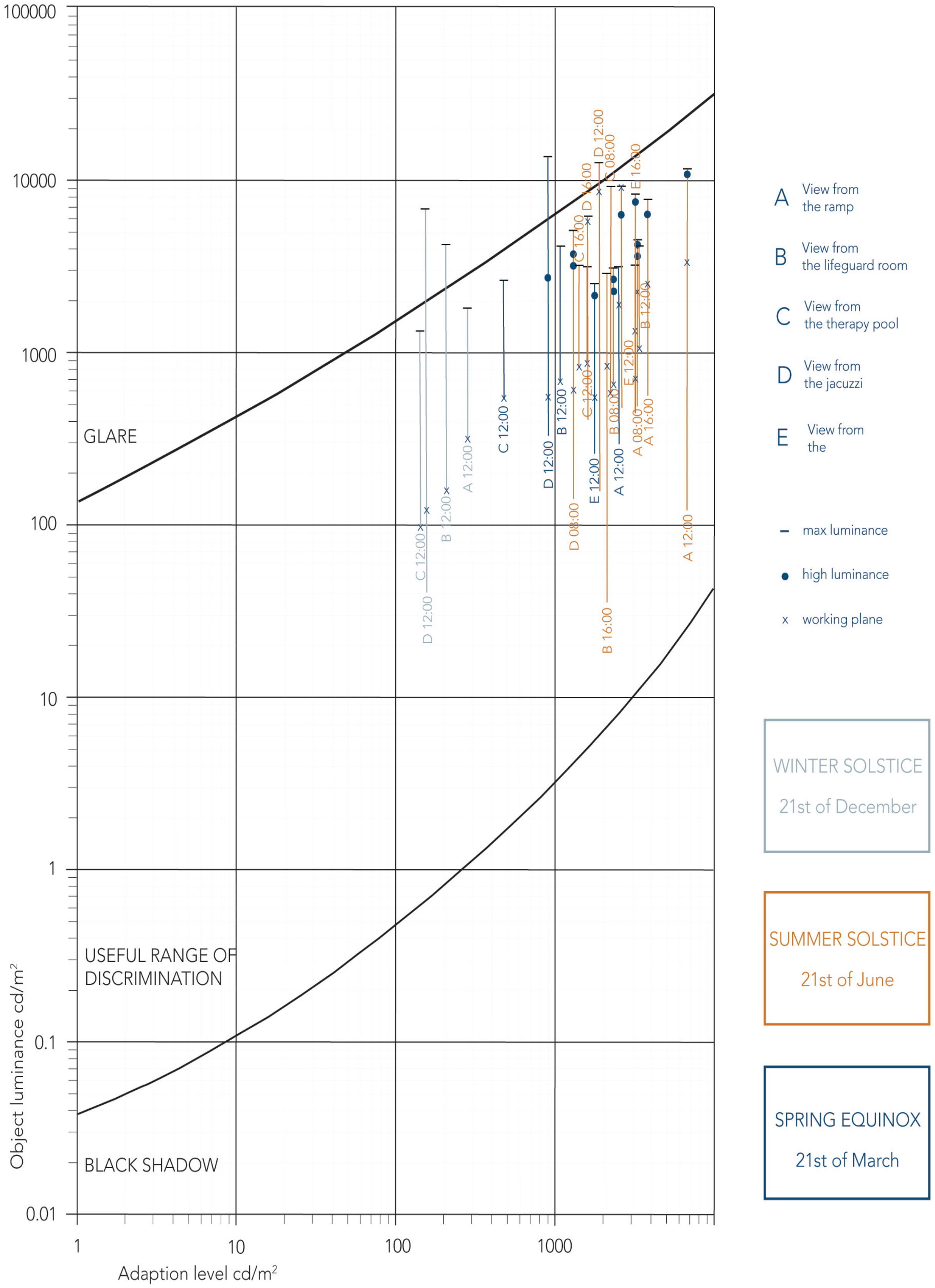


Fig. 54. Scenario 2, luminance dynamics graph

VISUAL COMFORT ANALYSIS
Luminance false colour maps was constructed in order to compare the full spectrum of views between scenario 2 and primary design. Analysis shows that four out of twenty five cases result in perceivable glare. In scenario 2, worst condition occur in the spring and summer at 12:00 in view D. Extreme luminance values and adaptation levels are higher than the ones in the primary design. Luminance dynamic graphs is used again to measure how far above the glare threshold the luminance values are.
Results plotted to the graph makes it clear that abundant amount of direct sunlight entering the interior causes negative visual sensations to some viewvers. There are less points at a time when glare occur compared to the primary design. Yet, some of the ones occurring are more serious which the extreme values are further from the useful range of discrimination.

NEXT STEPS
Concept should be further developed in order to reduce visual negative sensations in the swimming hall. The use of semi-transparent shading could soften extreme glare. However, because of the constantly changing weather in Trondheim and the nature of light dynamics, it is difficult to program the best automatic shading.
The use of electrical lighting should be further evaluated and placement should be carefully designed to balance out the brightness dynamic during the time when there is no daylight. This is particularly important for the long dark winters.

Fig. 55. Primary design concept, luminance false coulor maps analysis.

5. SCENARIOS EVALUATION

Scenarios are compared with the primary design in a table Fig. 59.Scenario 1 receives best grade in daylight provision, due to high and even daylight factors across the hall. The difference in daylight factor can be seen in the Fig. 58. Scenario 1 main advantage is that the glazing ratio balances out daylight harness and solar gains. Scenario 2 provides much higher daylight in the main pool area, where the daylight factor can be compared to an outdoor pool. Yet, good control of glare could offset the extremely high daylight factor. The down side is that large glazing ratio will cause huge energy loss during winters and overheating in summers.In terms of visual comfort comparison of the number of views out of the useful range of discrimination is in Fig.57. How often glare occur and how severe it is are the two main questions. Table with the results of visual comfort assessment are compared in Fig.57. Visual comfort is equally good in scenario 1 and 2 as their probability of glare occurring were equivalently low compare to the primary design. Scenario 1 is a better choice in terms of construction simplicity, but scenario 2 is better in offering a dynamic look. The most optimal choice for roofing design would be scenario 2 based on the average score. The concept could be enhanced based on the knowledge gained through the comparison. Though the glass ratio of windows of scenario 2 should be reduced to balance out energy loss in the upgrade of Husebybadet. Energy consumption is shown in Fig. 56.

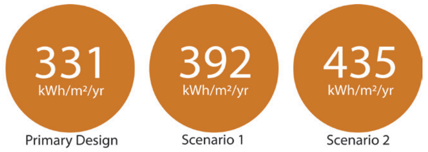


Fig. 56. Energy consumption

PERCEIVABLE GLARE AT THE TIME VIEW / NUMBER OF VIEW

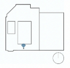
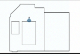
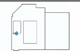
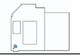
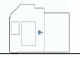
	PRIMARY DESIGN	SCENARIO 1	SCENARIO 2
A View from the ramp 	2/5	2/5	0/5
B View from the lifeguard room 	3/5	2/5	1/5
C View from the therapy pool 	4/5	0/5	0/5
D View from the jacuzzi 	4/5	0/5	3/5
E View from sitting area 	4/5	0/5	0/5

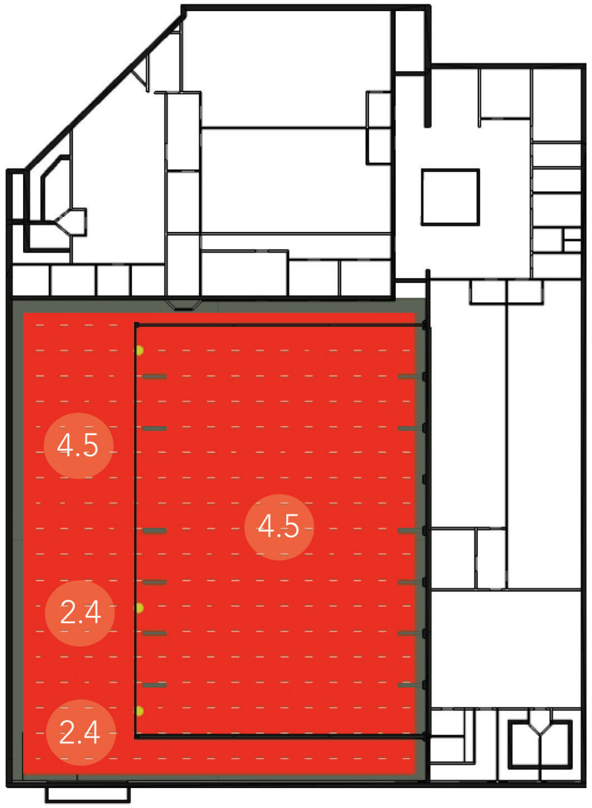
Fig. 57. Comparison of the visual studies results

	PRIMARY DESIGN	SCENARIO 1	SCENARIO 2
DAYLIGHT FACTOR (D)	★☆☆☆	★★★☆	★★★★
VISUAL COMFORT	★☆☆☆	★★★☆	★★★☆
EVEN LIGHT DISTRIBUTION	★★★☆	★★★☆	★★★★
POTENTIAL OF PASSIVE HEATING	★☆☆☆	★★★☆	★★★★
SIMPLICITY OF THE CONSTRUCTION	★★★★	★★★☆	★★☆☆
DYNAMIC LOOK	★☆☆☆	★★★☆	★★★★
ENERGY CONSUMPTION	★★★☆	★★☆☆	★☆☆☆

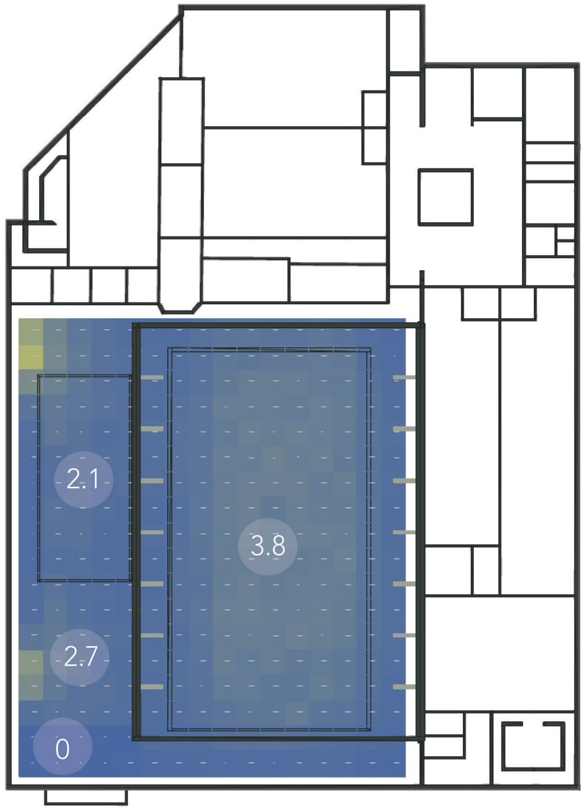
Fig. 59. Final comparison of proposal´s evaluation

SPACE	Target values	Primary Design	Scenario 1	Scenario 2
Main pool	4.5%	3.8%	16%	65%
Therapy pool	4.5%	2.1%	14%	6.4%
Children pool	2.4%	2.7%	15%	6.6
Massage pool (jacuzzi)	2.4%	0%	0%	7%

Fig.58. Daylight factor values comparison

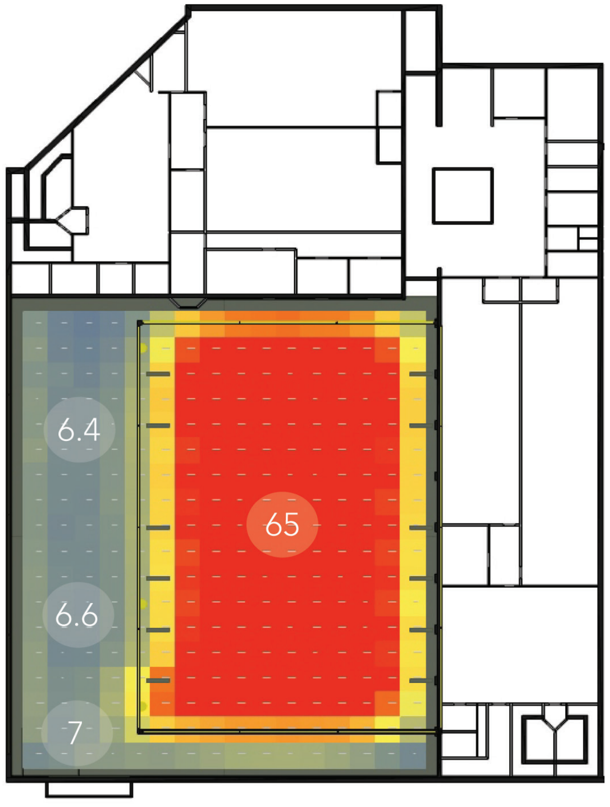


TARGET

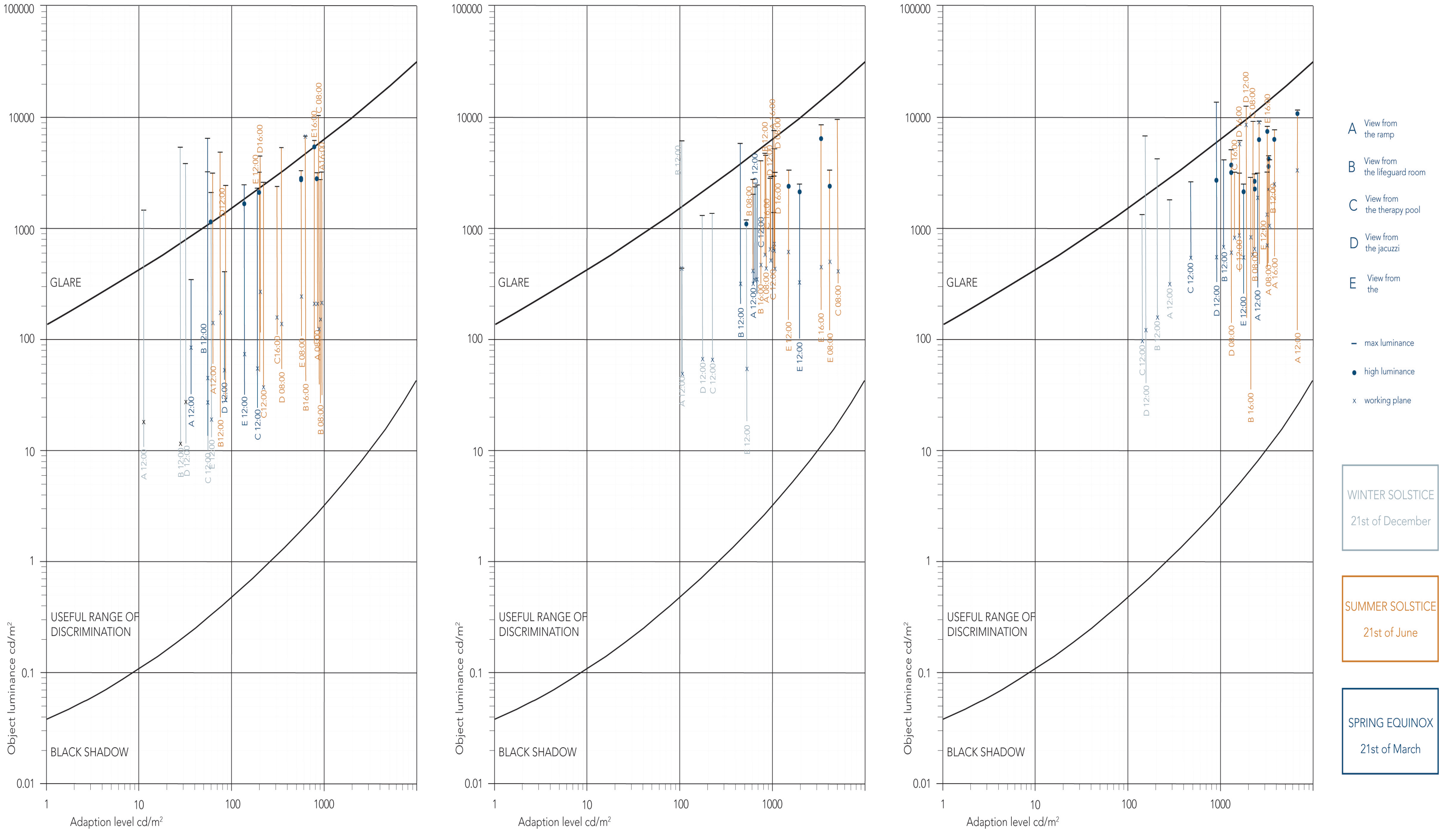


PRIMARY DESIGN

SCENARIO 1



SCENARIO 2



Primary Design

Scenario 1

Scenario 2

Fig. 60. Luminance dynamic comparison. Assessment of the most perceived

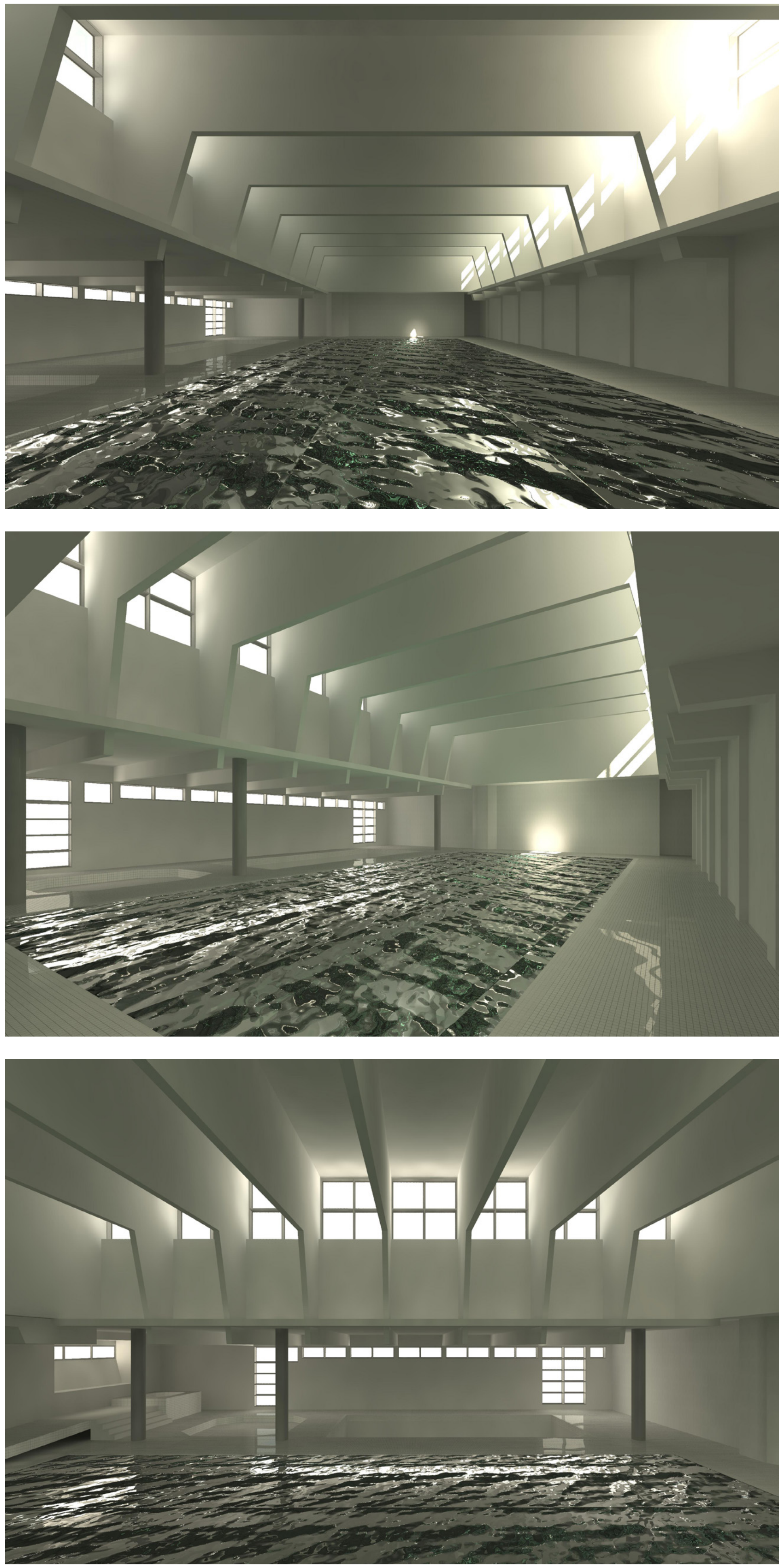


Fig. 61 . Primary Design

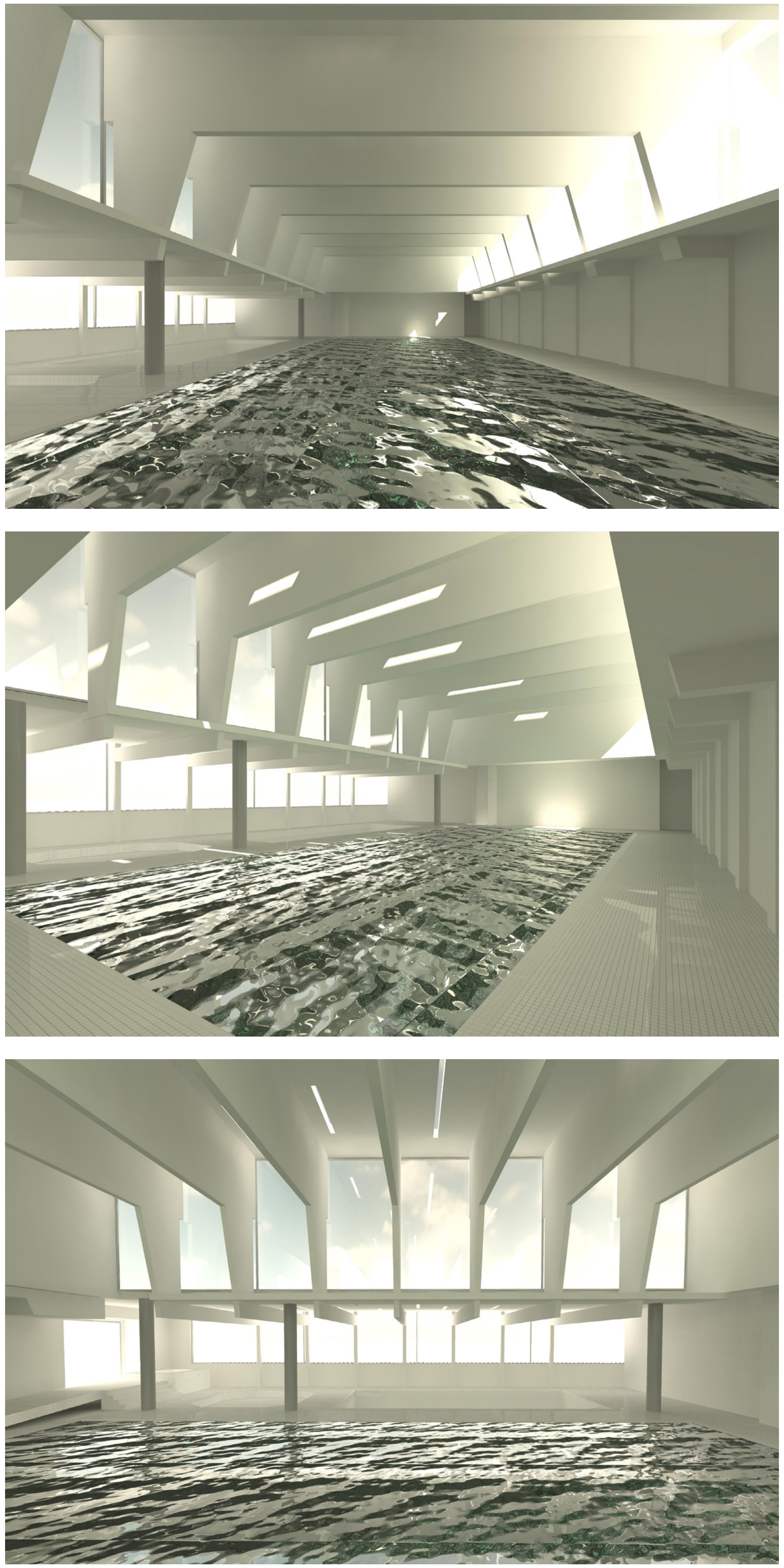


Fig. 62. Scenario 1

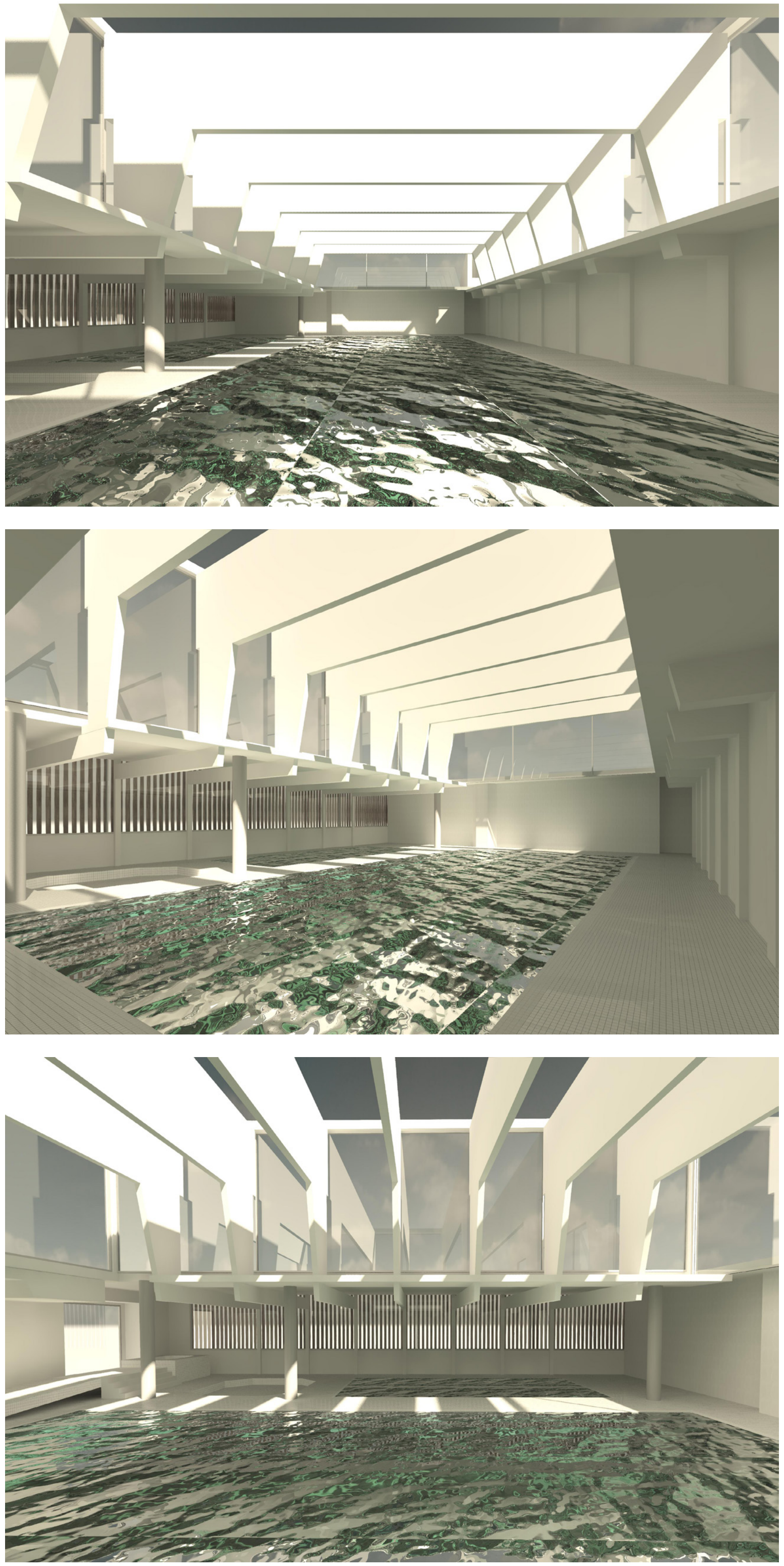


Fig. 63. Scenario 2

6. CONCLUSIONS

SUMMARY

This thesis proposes a retrofitting solution for roofing design in public swimming hall, Husebybadet in Trøndelag, Norway. It includes optimisation of the existing west and east facing windows and skylights in the swimming hall. Primary design and proposed concepts of roofing design were analysed in terms of light provision and visual comfort. Together with literature review, it forms a base for further design. Design Criteria Matrix was conducted and used as a pre-design tool to record architectural condition, lighting demands and target light levels. Daylight factor analysis of the primary design illustrated light levels and distribution problems. Target values are based on European Standard daylight provision recommendations.

Two lighting scenarios were developed based on 3D modelling in Revit. Design responds to the specific climate conditions such as low sun inclination, overcast sky and snow. Both scenarios intend to optimise daylight provision, offer good visual condition for pool users, ensure glare free environment and enable passive solar heating. Both scenarios aim to achieve a dynamic and vibrant look. They have different glazing area but same U-values of windows.

Scenario 1 and 2 were developed and analysed in terms of daylight factors. European Standard was followed in the simulation settings. Camera views in different part of the swimming hall were used as a base for visual comfort assessment. These views were converted into luminance false colour maps in spring equinox, summer and winter solstice. Useful range of discrimination for each view was discovered based on their average luminance. Evaluation of perceivable glare was then conducted. Results were converted to a brightness dynamic graph. Realistic renders were created to measure aesthetic of the scenarios.

To compare the scenarios, seven categories were listed. These include daylight factor, visual comfort, even light distribution, potential of passive heating, simplicity of the construction, dynamic look and energy consumption. Result of the comparison shows that scenario 1 has an even grading among most criteria, whereas scenario 2 is more outstanding in four out of seven criteria.

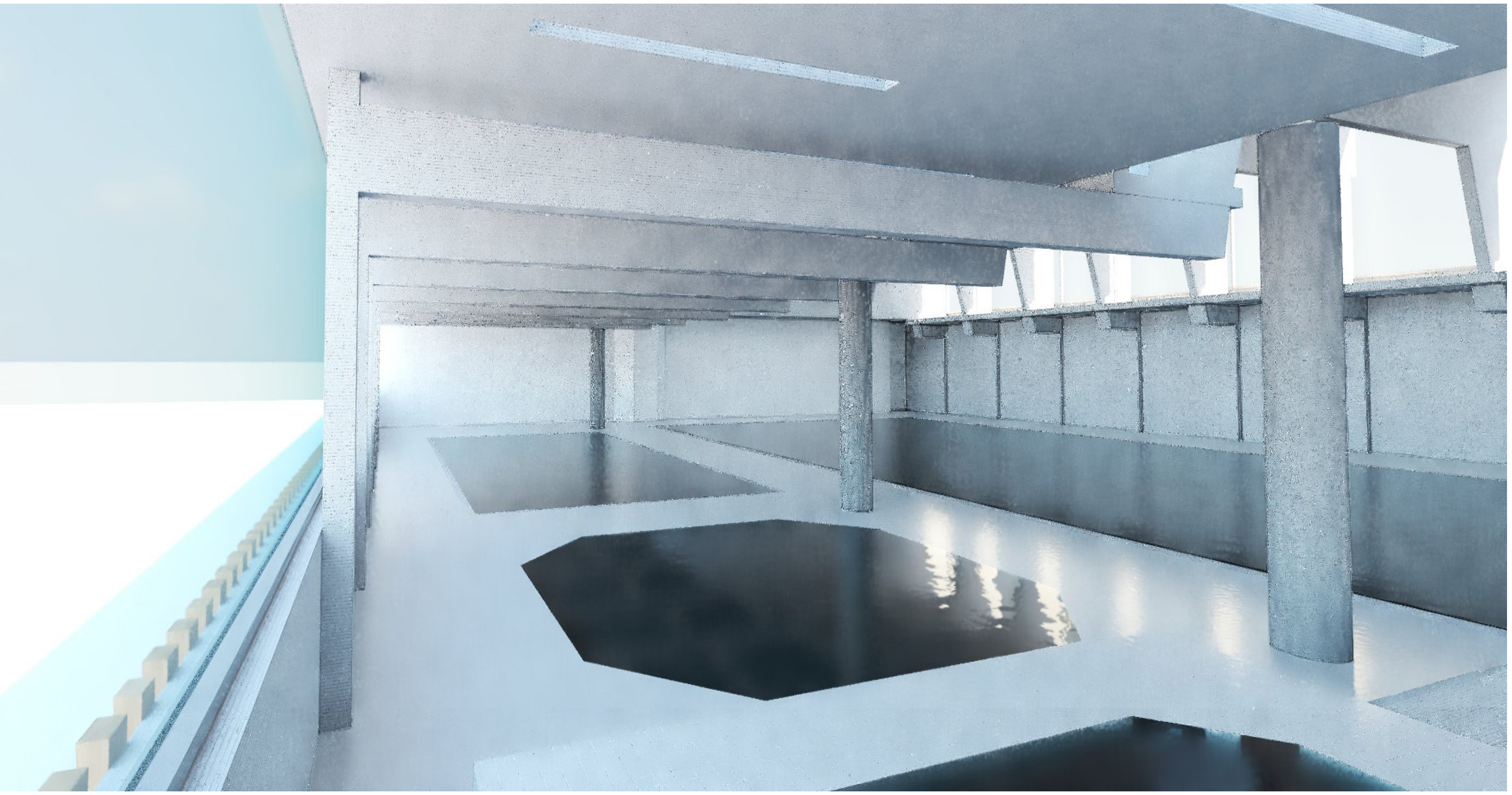
FURTHER STUDIES

To honour the chosen design scenario, electrical lighting should be integrated, including both task and ambient lighting. Analysis of the same view used in the study under artificial light should then be conducted. With emphasis on the long dark winters when daylight is insufficient, artificial lighting is necessary. A comparison of visual performance of spaces could then be carried out in daylight condition, artificial light and a mixture of both. These would lead to a complete lighting design analysis of the swimming hall.

FINAL CONCLUSIONS

Visual comfort evaluation utilised is one of the wider perspectives of this study, which could be applied in future architectural design processes. The visual comfort analysis base on luminance maps and useful range of discrimination should be applied in the early phase of daylighting design.

The process used in this thesis was demanding, which is one of the drawbacks of utilising such a method in the architectural practice. Besides, there are prerequisites in terms of skills in 3D modelling in both Revit and Rhino. Furthermore, understanding of radiance materials is compulsory to achieve accurate results.
The best analytical tool should be able to measure visual comfort in the space automatically, this include the generation of different views at certain times. There should also be a well-documented material library integrated into the software. The analysis result should be automatically plotted on a log-log graph indicating perceptible useful range of discrimination related to adaptation level. The idea described above should be further developed either as a plug-in or integrated into an existing BIM software. This could be an efficient way to measure visual comfort in space lit by both side-lit and sky lighting.



7. REFERENCES

M. Guzowski (2018). The Art of Architectural Daylighting. Laurence King Publishing Ltd.

S. V. Szokolay (2014). Introduction to Architectural Science – The Basis of Sustainable Design (third edition). Routledge.

N. Baker, K. Steemers (2013). Daylight Design of Building). Earthscan.

Byggkvalitet, D. f. (2011). TEK 10 chapter 13-12: Byggteknisk forskrift. Retrieved from https://dibk.no/byggeregler/tek/

C. Cajochen (2007). Alterting Effects of Light. Retrieved from https://pubmed.ncbi.nlm.nih.gov/17936041/

Reinhart, C. F., & Wienold, J. (2011). The daylighting dashboard–A simulation-based design analysis for daylit spaces. Building and Environment, 46(2), 386-396.

NS-EN-12464-1. (2012). Light and lighting - Lighting of work places - part 1: indoor workplaces. Standard Norge.

Dubois, M.-C., Gentile, N., Amorim, C. N. D., Geisler-Moroder, D., Jakobiak, R., Matusiak, B., . . . Stoffer, S. (2016). Monitoring Protocol for Lighting and Daylighting Retrofits A Technical Report of IEA Shc Task 50: Fraunhofer-Institut für Bauphysik.

Wienold, J., & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and buildings, 38(7), 743-757.

Isoardi, G., Garcia-Hansen, V. R., & Hirning, M. (2012). Evaluation of the luminous environment in open-plan offices with skylights. Proceedings of WREF 2012, 1-8.

Osterhaus, W. (2002). Recommended luminance ratios and their application in the design of daylighting systems for offices. Paper presented at the 35th Annual ANZAScA Conference.

Standard Norges komité SN/K 034. Criteria for passive houses and low energy buildings - Non-residential buildings. Norsk Standard NS 3701: 2012. October 1, 2012

Technical Committee CEN/TC 169 "Light and Lighting", European Standard CEN/TC 169/WG 11 - Daylight. September 12, 2017.

Norwegian Green Building Council. (2016). BREEAM-NOR. Retrieved from https://ngbc.no/wp-content/uploads/2015/09/BREEAM-NOR-Engl-ver-1_1_0.pdf

SINTEF, NTNU. DIVA4Rhino. (October 11, 2016) Integrated Energy Design Course.