SCHIPHOL INTERCHANGE STATION

Integrated design research for the wind and daylight
performance of the building envelope

Name:	Daniel van Kersbergen
Address:	Juniusstraat 157, 2625 WZ, Delft
Telephone number:	+31 64300091
University	Department of Architecture, TU Delft
Master:	Architecture, Urbanism and Building sciences 2011
Specialized in:	Building technology and Architecture
Student number:	1211331
E-mail address:	Danielvankersbergen@gmail.com

STATEMENT

The energy consumption by building accounts for more than a third of the yearly consumed energy in the world. 70% of this energy is used for heating, cooling, ventilation and lighting of the interior spacesof these buildings. This happens often in a very inefficient way, where the fossil energy is used in the wrong way and in the wrong place and time.

I foresee a future, where the on-site renewable energy sources are being used to passively climatise buildings and the build environment. To get there we have to strive for innovative and energy efficient solutions which are going to push the boundaries of the way buildings are climatised in the future.

In this building technology project, I am using my architectural design for the Schiphol Interchange Station as a test case to investigate different ways for using the on-site renewable energy sources in a passive way to climatise the building.
By looking not only at the energy needs/consumption of the building and its inhabitants but also at the architectural design and the way the user wants to perceive/use the interior space, the climatic system and architectural design can be designed into one integral system which not only passively provides the building with the required amount of heating, cooling, ventilation and daylight but also provides a climate, in which the user can work/live/travel in a pleasant, safe and efficient way.

Daniel van Kersbergen

Delft, 16-12-2011

PREFACE

I have undertaken this building technology research as part of a combined architectural engineering (AE) and building technology (BT) graduation thesis. This thesis follows the first year of research and design in which the Schiphol Interchange Station has been designed. The building skin of the train station revealed additional interesting aspects for further research at the building technology graduation lab.
Both architecture and building technology have been of my interest during my Bachelors and Masters Study in which various designs and researches have been building technology based. During my internship at ARUP Amsterdam I've also researched topics such as heat load, daylight, ventilation, evaporative cooling and their performance aspects. That knowledge and experience was used during this building technology thesis.

I would like to extend my gratitude to my teachers Michela Turrin, Florian Heinzelmann and Ype Cuperus for guiding me during my work on this building technology thesis. Their knowledge, experience and criticism have really helped me. Special thanks also to Marko Koops who has supported and helped me during my graduation project.

CONTENTS

	Statement	
	Preface	
1	**Introduction**	**2**
1.1	World energy consumption	2
1.2	Passive strategies	3
1.3	Schiphol Interchange Station	4
2	**Research strategy**	**9**
3	**Wind research**	**10**
3.1	Introduction	10
3.2	Ventilation concept	11
3.3	Wind theory	14
3.4	Benchmarks	18
3.5	Input parameters	19
3.6	Analysis ventilation surface cuts	23
3.7	Analysis original section building	26
3.8	Improving roof wind characteristics	27
3.9	Improved building design	34
3.10	Conclusions	36
4	**Daylight research**	**38**
4.1	Introduction	38
4.2	Daylight theory	40
4.3	Daylight requirements / Demands	43
4.4	References / Inspiration	48
4.5	Solar analysis roof`	54
4.6	Preliminary daylight study: Physical tests (qualitative)	57
4.7	Secondary daylight study: numerical analysis (quantitative)	60
4.8	Digital analysis	82
4.9	Roof system	98
4.10	Materialisation & manufacturing	105
4.11	Conclusions	136
5	**General conclusions**	**138**
	Bibliography	**139**
	Appendices	**142**

1 INTRODUCTION

Prior to this building technology research, a semester of architectural research has been conducted. This research investigated in which way the transportation and infrastructural flows of the Schiphol and Haarlemmerliede location could be used as a basis for the architectural design for the Schiphol Interchange Station: a multi-use utility building which houses a train station, parking spaces and retail functions.

The goal of the Building technology research is to improve the architectural design by making it more energy efficient, sustainable and create a better living environment for the occupants and users in terms of light quality and climatic comfort.
This architectural design will be improved by taking the various building technology aspects of the envelope/building into account. The main aim is to passively use the on-site energy to create passive climate comfort. Out of all passive ways to us on-site energy, wind and daylight are chosen as the main topics for this research in order to improve the architectural design.
The focus for this research is to develop an architectural envelope for the Schiphol Interchange Station. The envelope of the building filters/uses the wind and daylight energy to climatise the building in a passive way.
The wind research will transform the building envelope on a large scale while the daylight research will transform the building envelope on a small/component scale. Both of them will work together in improving the architectural design and the energy performance of the building.

1.1 World energy consumption

The rapidly growing world population and economy is depleting the world's energy resources and having a tremendous environmental impact on the planet. In the last two decades, primary energy has grown by 49% and CO_2 emissions by 43%, with an annual increase of 2%. The latest predictions show that this growing trend will continue in the next decades. The Energy consumption of emerging economies in Southeast Asia and the Middle East are growing even faster. China, for instance, has doubled its energy consumption in the last 20 years, growing 3.7% annually.

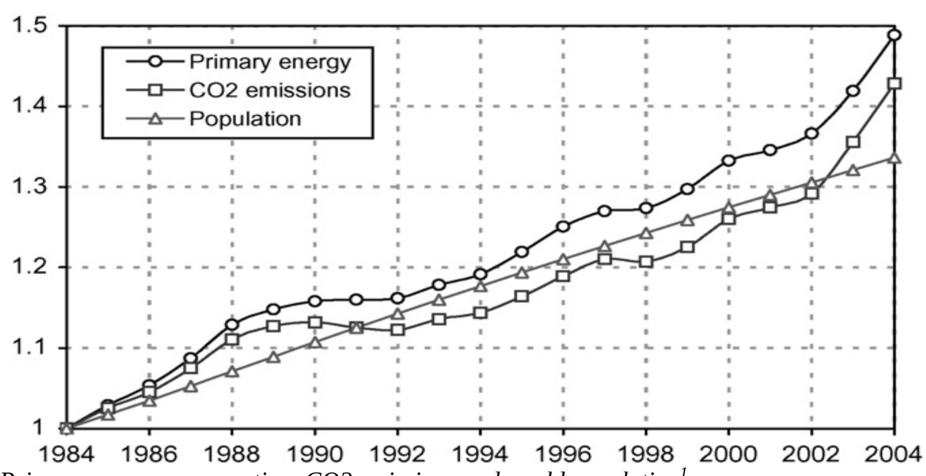


Figure 1: Primary energy consumption, CO2 emissions and world population[1]

[1] *L. Pérez-Lombard, J.Ortiz, and C. Pout, A review on buildings energy consumption information. (UK: Elsevier, 2007), 395*

The energy consumption by buildings rises each year together with the total amount of energy consumed in the world. The energy consumed by buildings is more than a third of the total energy consumed in the world. Due to the growing world population, enhancement of building services and comfort levels, the percentage of the world final energy consumed by buildings has grown from 36% in 1973 to 42% in 2004. It is predicted that this percentage is keeps increasing on a yearly basis in the next decades.

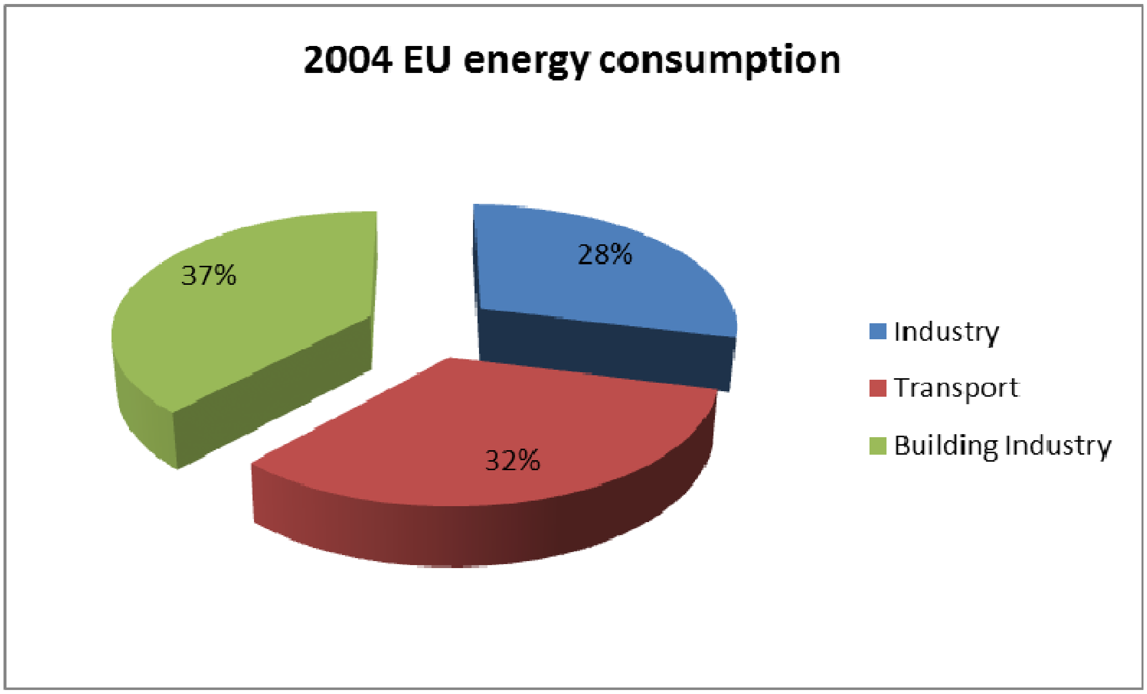


Figure 2: 2004 EU energy consumption

In 2004, building consumption in the EU was 37% of the total energy, which is even bigger than the industry sector (28%) and transport sector (32%).[2] This highlights the importance of increasing the energy efficiency of buildings to decrease the energy consumption of the entire building industry.

1.2 Passive strategies

This section aims at introducing the topic of passive strategies for the use of the on-site renewable energy resources. While both active and passive system can be used in this respect, the main focus has been given to passive systems in this research. Passive systems play a key role in reducing the energy use of the Schiphol Interchange Station. Passive systems can reduce the energy use by minimising the demand, rationalise the use and make the best use of energy from the environment.

Within the realm of passive strategies, thermal and daylight comfort are very significant factors in reducing energy use. HVAC and lighting are the two largest contributors to the

[2] *L. Pérez-Lombard, J.Ortiz, and C. Pout, A review on buildings energy consumption information. (UK: Elsevier, 2007), 396*

buildings energy use, both in the residential and non-residential sector. Together they make up to 70 per cent of the total energy consumed by buildings.

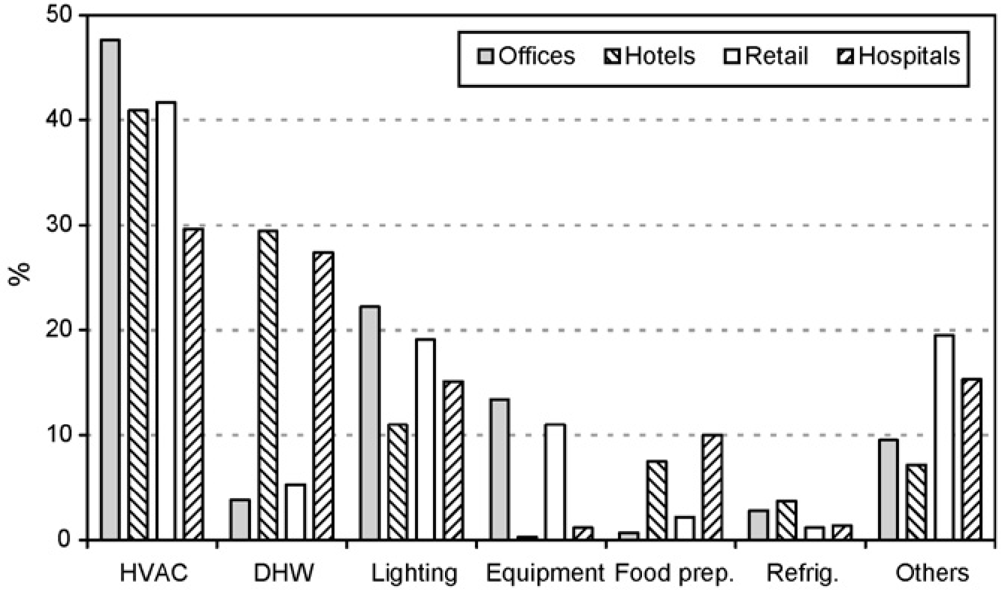


Figure 3: Consumption by end use for different building types[3]

The strategies to achieve thermal and daylight passive comfort are closely related and therefore cannot be seen separate. A solution for achieving thermal comfort may contradict a solution for daylight comfort. While passive ventilation and daylight strategies are the main focus of this building technology research, thermal comfort and architectural quality are therefore kept in mind and considered when making decisions based on the daylight research.

1.3 Schiphol Interchange Station

The Schiphol Interchange Station is part of a masterplan developed for the Haarlemmerliede area near Haarlem, the Netherlands. The masterplan is based on the 'Randstad 2040' vision from the government that foresees an expansion of Haarlem towards the east. Transit oriented development has been chosen as the main driver for the masterplan. In a transit oriented development the aim is to reduce car traffic, noise and pollutions in cities by making the people less dependent on cars. This can be achieved by improving the public transport system in terms of cost and accessibility among others. The chosen site offers great possibilities for a strong public transport system. On the site, the highway from Amsterdam to Haarlem, the highway from Schiphol to the north, and the Train line between Amsterdam and Haarlem are connecting. By connecting Schiphol airport by train to the future Schiphol airport at sea, new transport possibilities arise in which the Haarlemmerliede area will act as a transport/transfer hub in the transport network of the Randstad and the Netherlands as a whole.

[3] *L. Pérez-Lombard, J.Ortiz, and C. Pout, A review on buildings energy consumption information. (UK: Elsevier, 2007), 397*

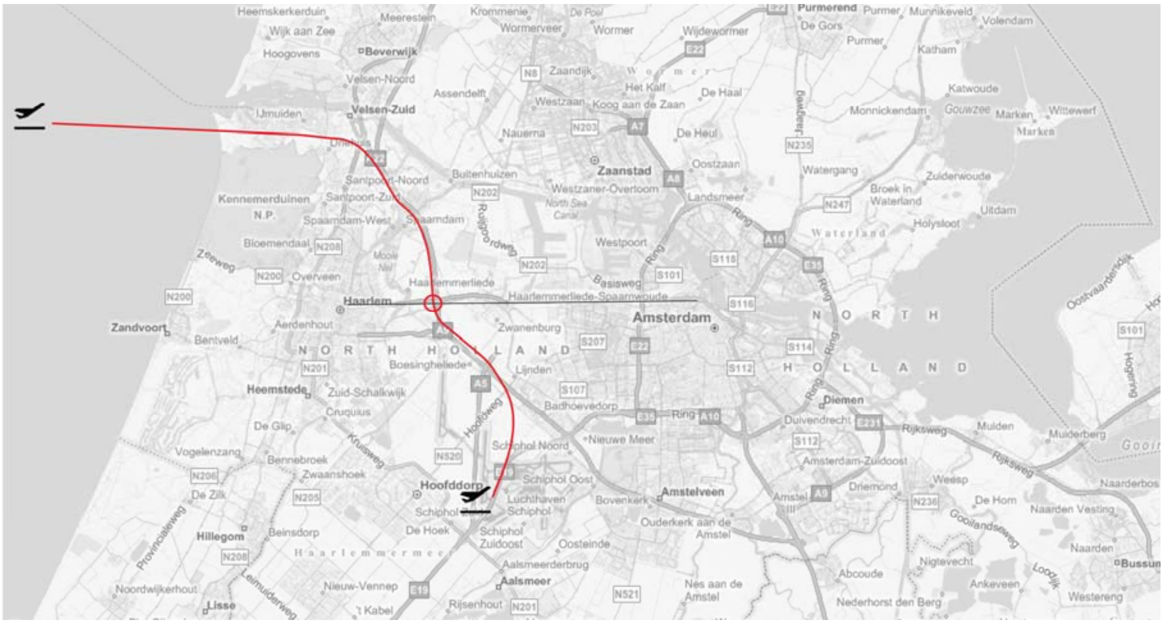


Figure 4: Schiphol at sea

Masterplan

The masterplan is filled with office and commercial related developments. The SIC (Schiphol Interchange Station) facilitates the entrance from the highway into the masterplan and the connection of the two sides of the masterplan. The SIC is an interchange station from the train to the car and vice versa.

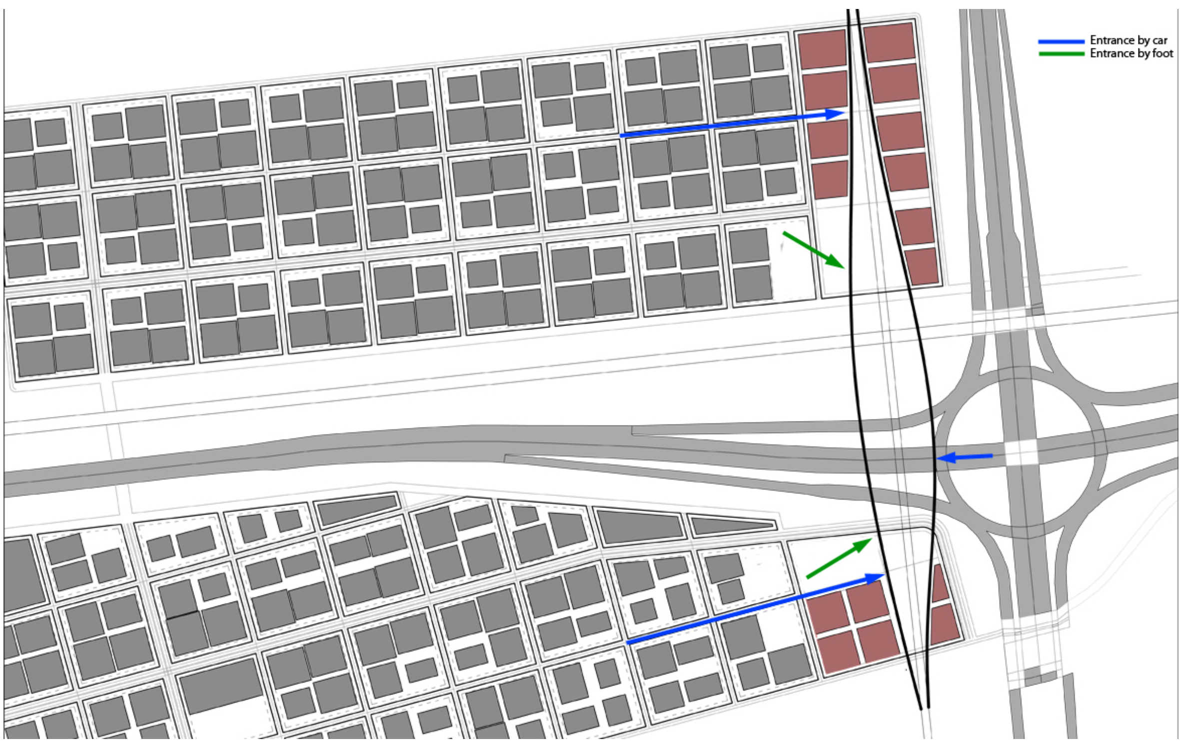


Figure 5: SIC in masterplan

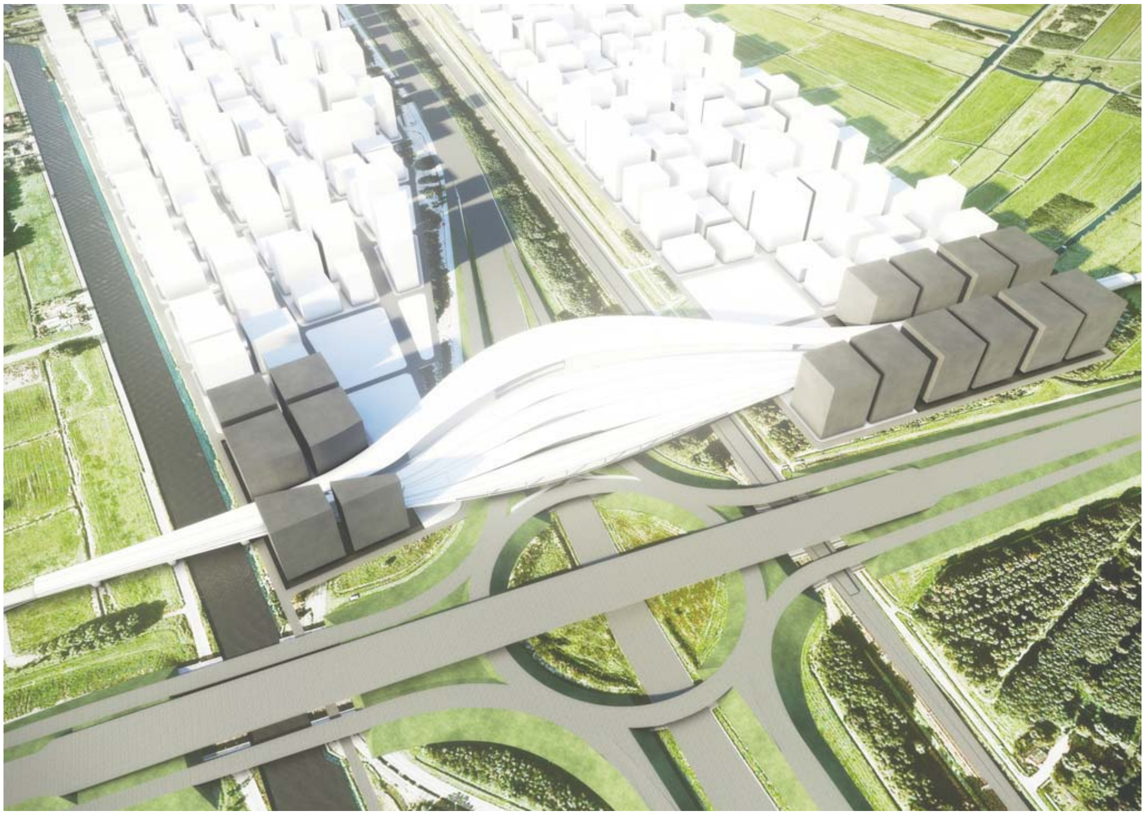


Figure 6: SIC in masterplan

Flows

The architectural layout and design of the building is based on the flows of transport on the site and in the building. It is directly derived from the best integration of the different flows of transport such as cars, trains and people. The functions are placed along these flows to create interesting, open spaces

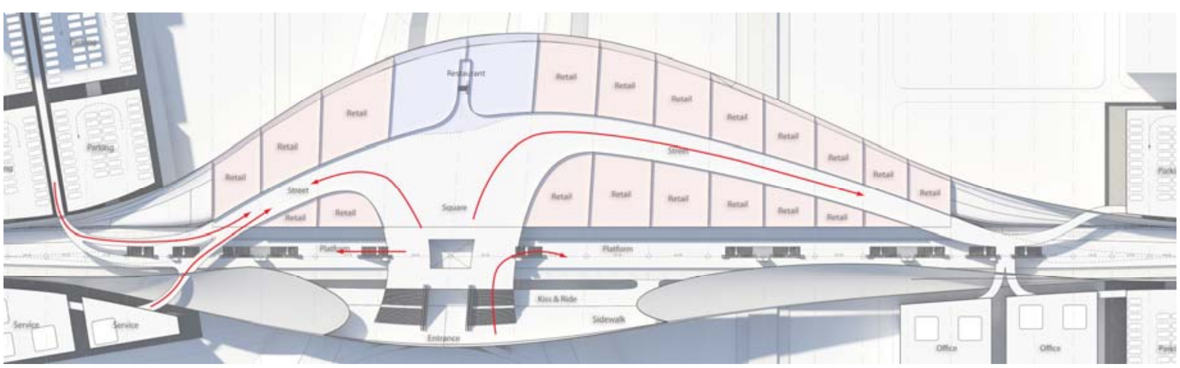
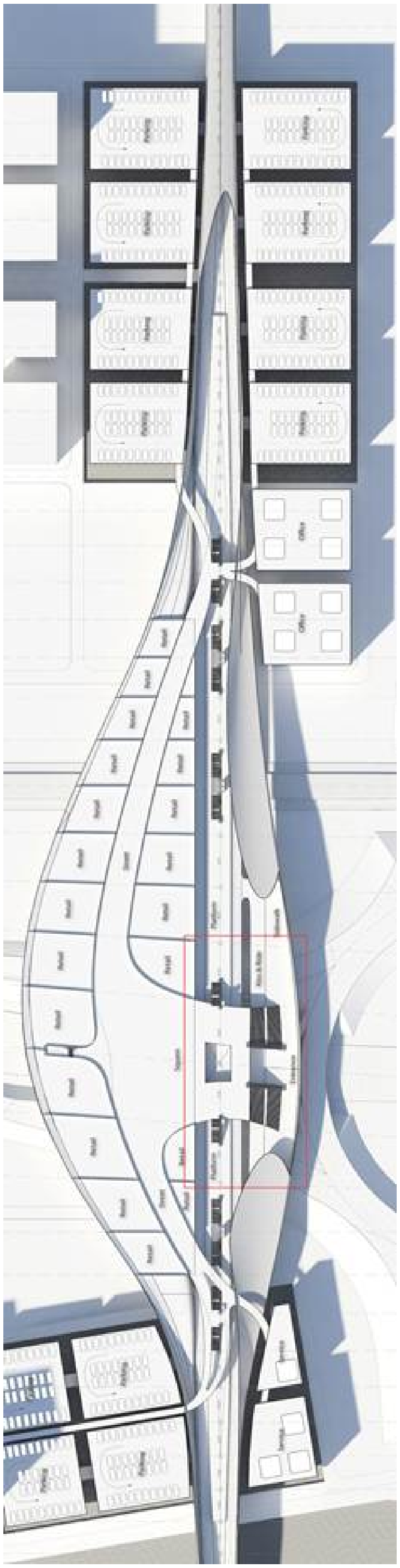
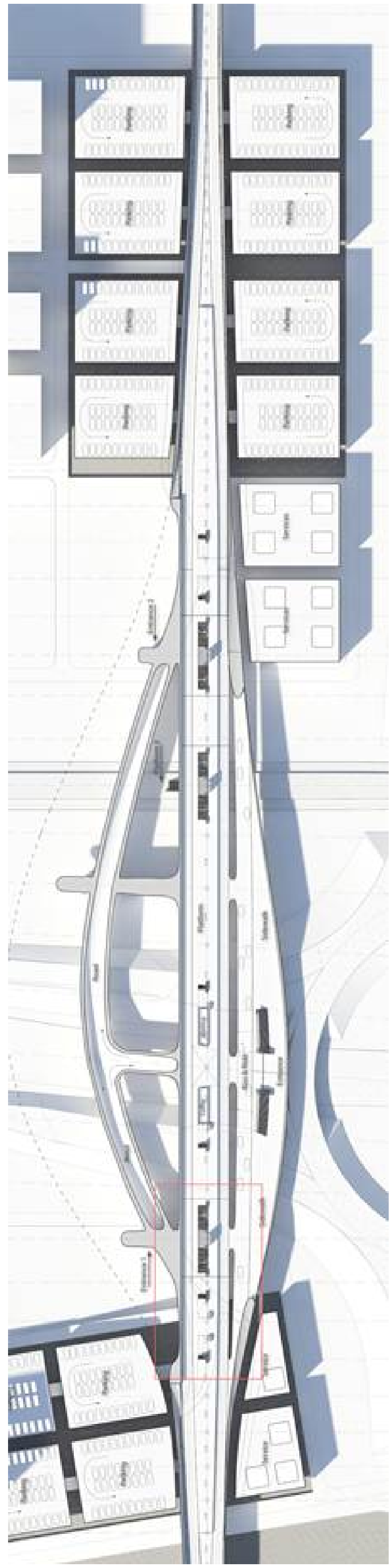


Figure 7: Flows of transport through SIC

The retail functions and transport functions are places on two different floor levels. The transport/transfer functions are placed on the first level. They are easy accessible from the two sides of the masterplan and the building. The retail functions are placed on the second level, with a clear view on the transport zone. In this way the two main functions are adequately separated but are still connected in a visual and transparent way. This helps in the wayfinding process for visitors inside the building.

Floor plans





Perspective views

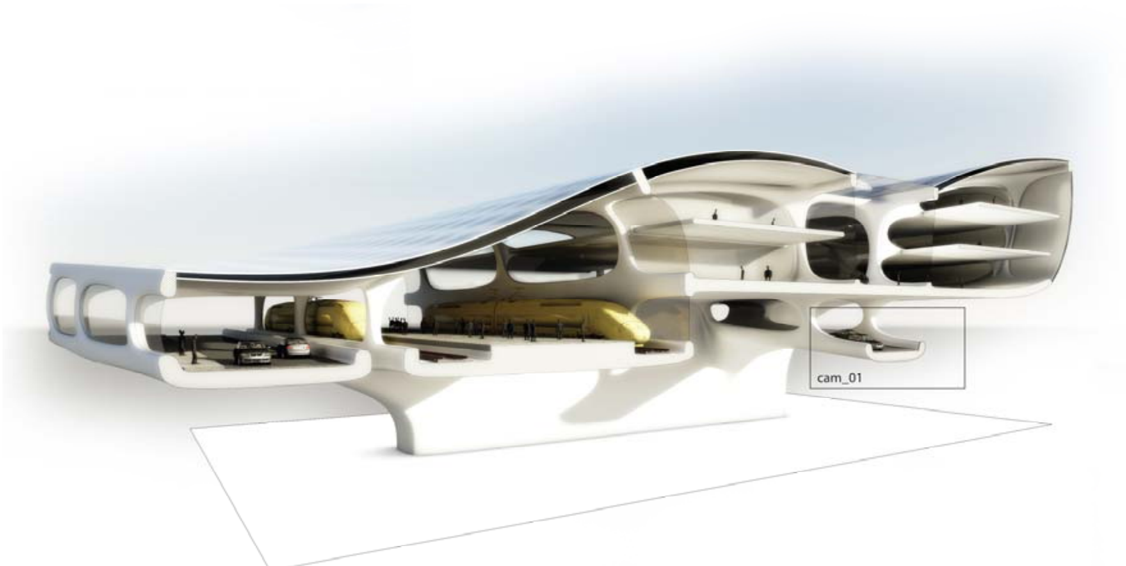


Figure 8: Perspective view 1

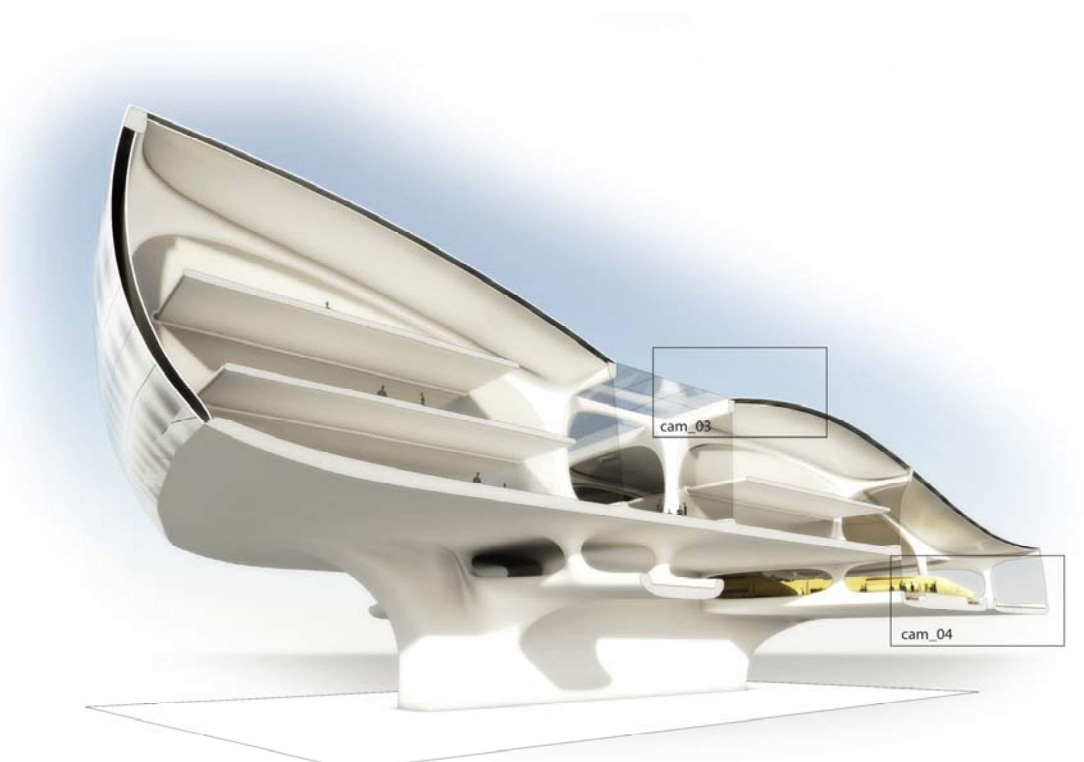


Figure 9: Perspective view 2

2 RESEARCH STRATEGY

This research is a combined research for wind and daylight. These two subjects are interrelated so they cannot be seen separate but have to be conducted simultaneous. For conducting this research, this research strategy is formulated. It shows the steps of the research for both the wind and daylight.

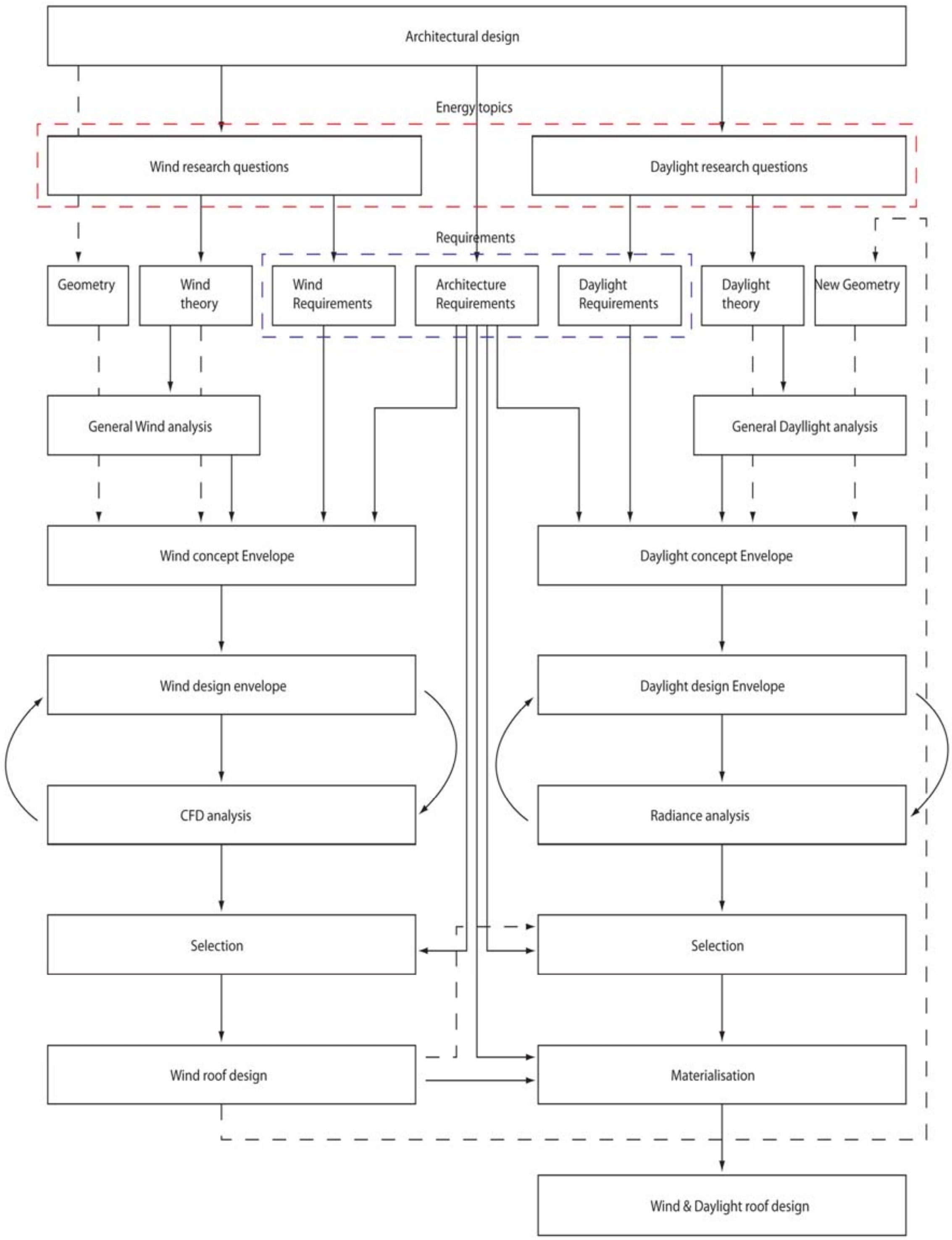


Figure 10: Research strategy chart / workflow chart

3 WIND RESEARCH

3.1 Introduction

The goal for the wind research is to optimise the wind flow over the top of the building in order to maximise the amount of air that is naturally drafted from the building. Over the central atrium, 3 gills in the roof are positioned. The shape, size, direction and position of these gills have to be investigated in order to find the most suitable design for naturally ventilation the building. The airflow over these gills is equally important. For the total roof, the most suitable geometry/shape has to be found to get the highest air movement over the gills as possible and from the best direction possible. These goals are combined in the following research question:

How can the shape/geometry of the building be adapted to improve the wind flow over specific parts of the building so that the entire building can be naturally ventilated?

First the current gills and roof shape have to be analysed. This will probably result in a situation where the wind speed over the gills isn't fast enough for natural ventilation. With these results, 5 design improvements have to be proposed. These improvements have to be analysed. From this analysis, the best improvement/design is selected. This design has to be optimized and then fed back into the design.

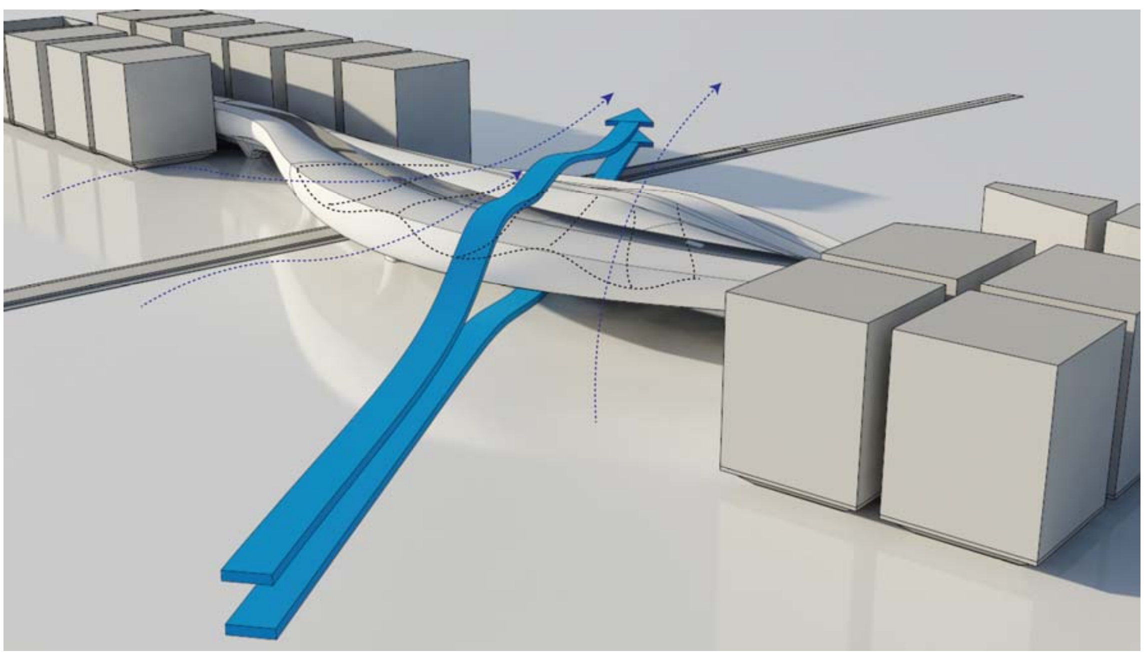


Figure 11: prevailing wind direction over building

The wind analysis will be conducted with Ansys CFX through Ansys Workbench. Ansys Workbench is combination of programs with a workflow that allows the import of geometry, meshing, setup, CFD-calculation and post production of the results.

3.2 Ventilation concept

The ventilation concept explains the way the shops are ventilated and the way the outside wind is used to naturally ventilate the public spaces in the building.

3.2.1 Building layout

The building in this research is a train station that connects two areas of the masterplan by spanning the highway. The building consists of a shopping street with retail functions on both sides. In the centre of the building a central square connects the shopping street to the platforms of the trains and the Kiss & ride area.

Figure 12: area & volume of functions

The retail functions on the outside consist of three floor levels while the shops on the inside consist of two floor levels. The train platform and the kiss & ride area are situated one level lower than the retail area.

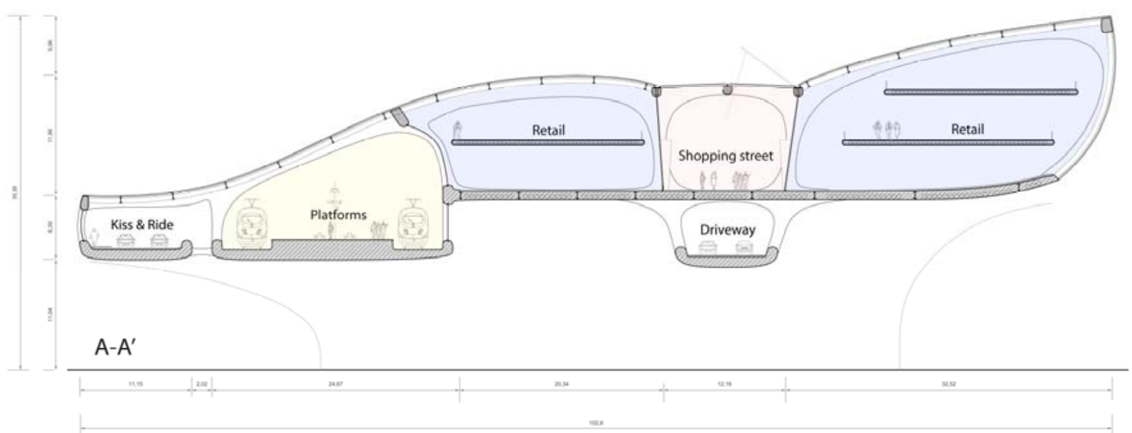


Figure 13: Cross-section of building

The dimensions of these functions are shown in the following table.

function	area [m2]	average hight [m]	volume [m3]
shops outside	7600	15,0	113905
shops inside	3665	10,7	39240
shopping street	6135	15,0	91885
station + kiss & ride	11800	10,3	121885
private spaces	11265	13,6	153145
public spaces	17935	11,9	213770
Total	29200	12,6	366915

Table 1: Area & volume of functions

3.2.2 Ventilation

For ventilation purposes, the building is divided in three zones. These three zones contain different functions, having different climate requirements. These three zones will be treated separately.

- Zone 1: Mechanically ventilated, fully climatised, 8 x air change rate
- Zone 2: Naturally ventilated, semi climatised
- Zone 3: Naturally ventilated, not climatised

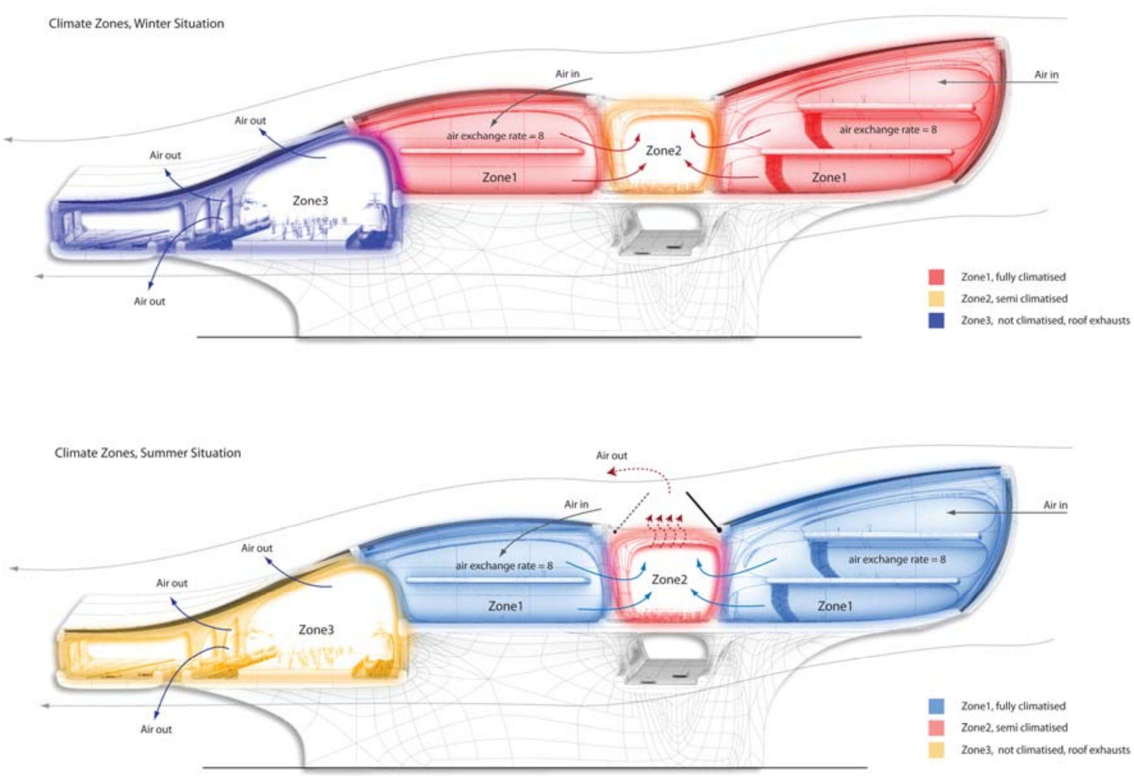


Figure 14: Ventilation scheme

The retail shops are mechanically ventilated with 8 air changes per hour. The exhaust air from the retail shops is automatically forced into the shopping street and is then used to ventilate the shopping street and train station. According to regulations, 50% of the exhaust air from the shops can be considered as fresh air.

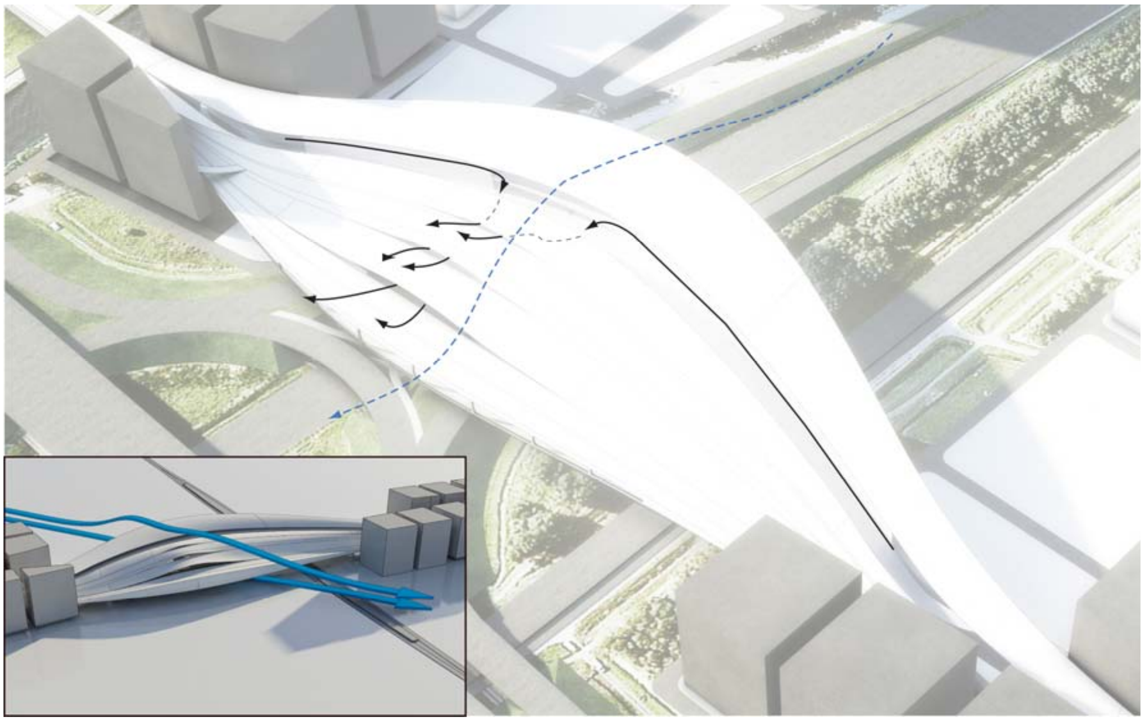


Figure 15: Natural ventilation through cuts

In addition, the public space will be naturally ventilated through the cuts in the roof. The wind over the roof will create a pressure difference between the interior and exterior. This pressure difference will draw the air out of the cuts in the roof situated in the main square (figure 6).

When looking at the general wind theory and the shape of the roof in the default design of the building, the wind speed over the cuts in the roof will probably be very low, zero or even flowing in the wrong direction.
So we can expect that the performance of the ventilation cuts due to the currents shape isn't adequate to naturally ventilate the building. If this expectation will be verified, the overall shape of the building has to be changed and deformed to optimise the wind speed over the cuts in the roof.

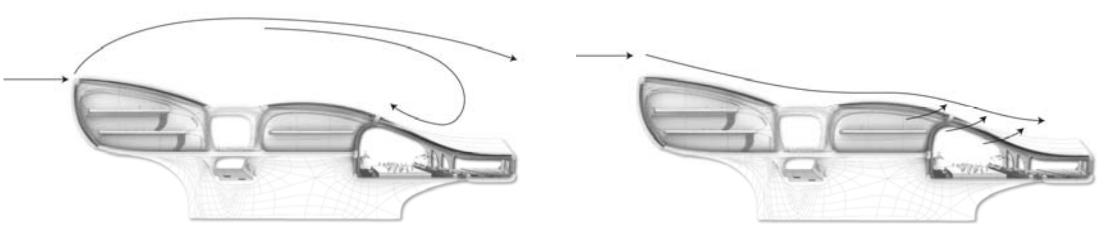


Figure 16: expected wind behaviour & desired wind behaviour

3.3 Wind Theory

This chapter will state the wind theory and formulas used for this wind research. In consists of general information of wind behaviour in and around buildings as well as some specific information and formulas used for various calculations.

3.3.1 Wind around buildings

The air flow around tall, rectangular building from direct linear wind flow is being determined by two pressure systems.

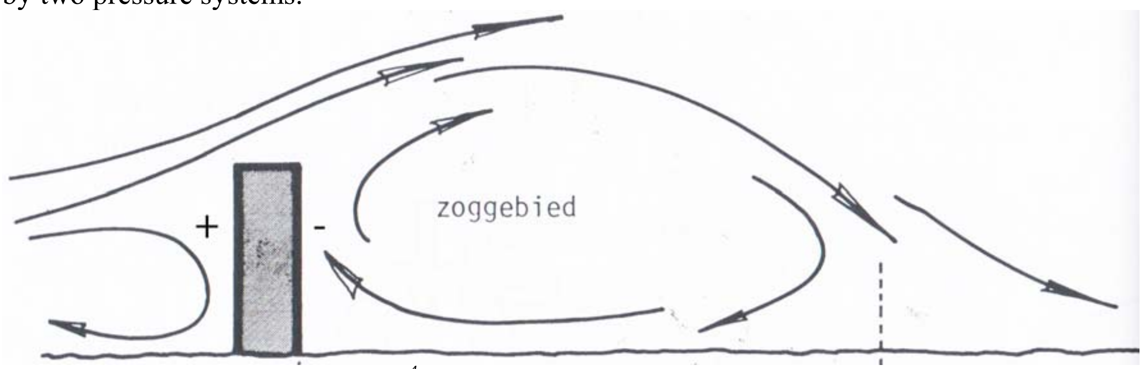


Figure 17: Wind flow over tall buildings[4]

The first pressure system is an overpressure system from direct wind flow on the front face. This overpressure increases from the ground about 70 % of the height of the building, at which the wind speed is maximum. The wind in front of the building is deflected downward and towards the pedestrian area and creates a vortex which flows in opposite direction and creates wind discomfort on the ground. The speed of the wind in this area increases with the height of the building. So in general high buildings give more wind discomfort on the ground.
The second pressure system is an under pressure on the back of the building. This pressure is created by the high speeds of the wind deflecting over and around the building. The pressure difference between the front and the back of the building create areas with very high wind speeds which can have a length of 2-3 times the height of the building. In the wake of the building, there is an area of about 3-5 times the height of the building where the air is flowing back towards the building. The wind speeds in this area are generally high enough to give discomfort to pedestrians.[5] At the entrances to the Schiphol Interchange Station, this discomfort can be expected due to the size and shape of the building.

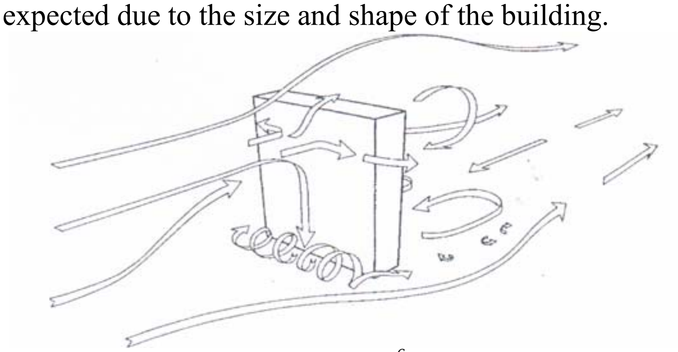


Figure 18: Wind flow around tall orthogonal building shapes[6]

---

[4] *Ir. M. Van den Voorden, Windhinder, Delft: Civiele techniek, 1982.*
[5] *Ir. M. Van den Voorden, Windhinder, Delft: Civiele techniek, 1982.*
[6] *Ir. M. Van den Voorden, Windhinder, Delft: Civiele techniek, 1982.*

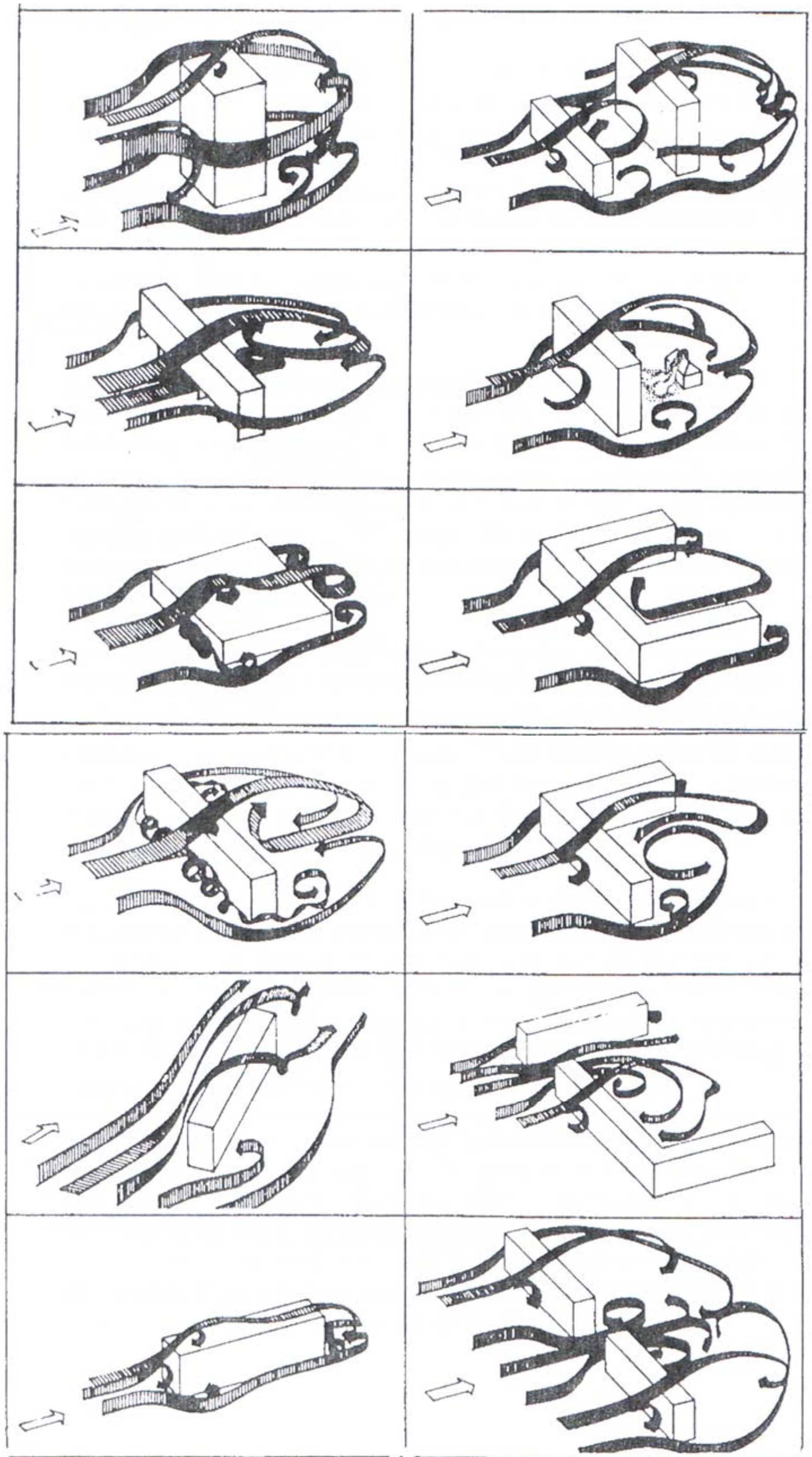


Figure 19: Wind flow around generic building shapes[7]

[7] *Ir. M. Van den Voorden, Windhinder, Delft: Civiele techniek, 1982.*

3.3.2 Wind profile/distribution

Normally, in all wind station the wind is measured in horizontal direction on a height of 10 meters above ground level. With this measured wind speed, the wind speed on every height above ground level can be calculated.
When the wind blows over a terrain with the same overall roughness, the wind speed distribution can be described by a logarithmic function:

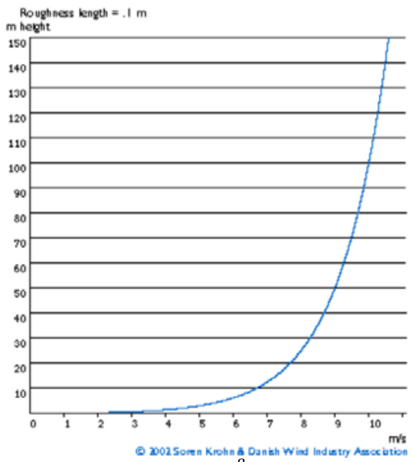


Figure 20: Wind profile[8]

$$\frac{V(z)}{V(10)} = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{10}{z_0}\right)}$$

Figure 21 : Wind speed distribution[9]

Where

V(10) = Wind speed at height z above ground level,
z = height above ground level for the desired velocity, v
Z_0 = roughness length in current wind direction
10 = reference height, i.e. the height where we know the exact wind speed, V(10)[10]

Z_0 is the terrain roughness length. Normally this terrain roughness is estimated by taking 5-10% of the height of the terrain roughness elements.[11]

3.3.3 Drag equation

To calculate the amount of air than can be naturally ventilated through openings in the building with a known air pressure on the openings, the drag equation could be used. The drag equation is a formula used to calculate the force experienced by and object moving through a fluid. The force of a moving object through a fluid is:

$$F_D = \frac{1}{2}\rho u^2 C_D A$$

Where

[8] *http://guidedtour.windpower.org/en/tour/wres/shear.htm*
[9] *F.J. Walker and N. Jenkins. Wind Energy Technology (UK: John Wiley & Sons, 1999),*
[10] *Danish wind industry association, 'Wind speed distribution', http://guidedtour.windpower.org/en/tour/wres/shear.htm*
[11] *Ir. M. Van den Voorden, Windhinder, Delft: Civiele techniek, 1982.*

F_D The force of drag [N]
p The mass density of the fluid [kg/m^3]
u The velocity of the object in the fluid [m/s]
A The referenced area [m^2]
C_D The drag coefficient [-]

The drag coefficient is a dimensionless number which quantifies the resistance of an object in a fluid. The drag coefficient is depends on the surface area and the aerodynamic properties of the object.

3.3.4 Mass flow rate

To calculate the amount of air through an opening with a known air velocity, the mass flow rate could be used. The mass flow rate describes the relationship between the mass flow and speed of air and the surface of the opening which the air flows through.

$$\dot{m} = \rho v A$$

Where

m Mass flow rate [kg/s]
p Mass density of the fluid [kg/m^3]
ʋ Flow velocity [m/s]
A Referenced area [m^2]

If the density is consistent in the whole area, so the air is not compressed, the mass flow rate formula can be simplified.

Q = ʋ A

Where

Q Volumetric flow rate [m3/s]
ʋ Velocity of the object in the fluid [m/s]
A Referenced area [m^2]

3.3.5 Pressure

With a difference in air pressure a fluid can move from one place to another. The Total pressure is a combination of the dynamic pressure and the static pressure.

$$P + \frac{1}{2}\rho v^2 = P_0,$$

Where

P Static pressure [Pa]
½ p ʋ^2 Dynamic pressure [Pa]
p Mass density of the fluid [kg/m^3]
ʋ Flow velocity [m/s]
Po Total pressure

3.4 Benchmarks

In order to simulate and run calculations effectively, it's important to know what time a calculation with a certain level of complexity takes on the computer that will be used. For this research, Ansys CFX will be used for the CFD-calculations. For this test the results from the desktop computer will be compared with the results of the notebook.

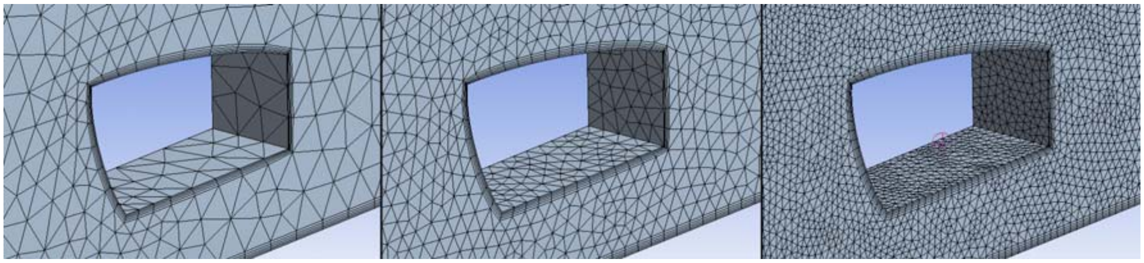


Figure 22: Meshing model for benchmarks; coarse mesh, medium mesh and fine mesh

A default model is made to be used for this test. With that geometry, 3 meshes with different densities are made: a coarse mesh, a medium mesh and a fine mesh.

	nodes [#]	elements[#]	iterations [#]	total time [s]	time per iteration [s]
Notebook					
coarse mesh	17573	71585	200	203	1,015
medium mesh	95760	455284	200	1319	6,595
fine mesh	474751	2396841	200	7997	39,985
Desktop 2 cores					
coarse mesh	17573	71585	200	208	1,04
medium mesh	95760	455284	200	1172	5,86
fine mesh	474751	2396841	200	6811	34,055
Desktop 8 cores					
coarse mesh	17573	71585	200	87	0,435
medium mesh	95760	455284	200	493	2,465
fine mesh	474751	2396841	200	2673	13,365

Table 2: Benchmarks

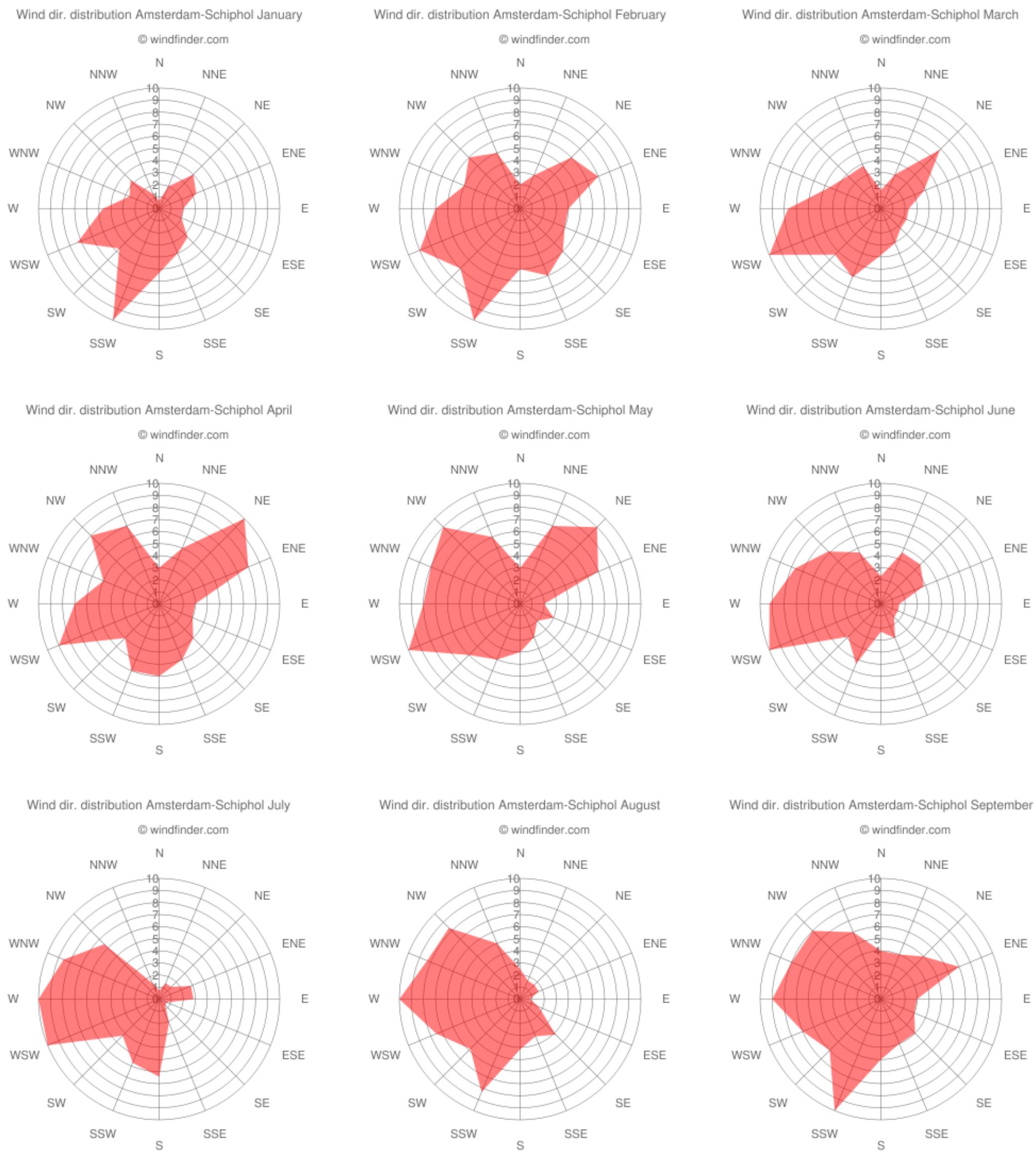
On the notebook it takes about 8000 seconds for the fine mesh to calculate 200 iterations. So the notebook is able to calculate about 15000 nodes per second per iteration. This is about the same as the desktop which runs with two cores. On the desktop with eight cores, the fine mesh takes about 2500 seconds to calculate 200 iterations. So the desktop is able to calculate about 40000 nodes per second per iteration. This means the desktop is about 2.5 times as fast as the notebook and the desktop with 2 cores.

For preliminary testing, running 200 iterations with 500000 nodes is quite adequate. This will take on the desktop computer around 45 minutes. These calculations give a good rough image of the wind behaviour around the building. For the final model, more iterations need to be calculated to get more accurate results. The number of iterations that are needed vary per model and should be determined at the time.

3.5 Input parameters

3.5.1 Wind

When doing a wind analysis for a building, it is vital to know the wind conditions on the site. It is important to know where the wind is coming from throughout the year and what the dominant wind direction is. The site for this building is the highway intersection at Haarlemmerliede. This building is situated over the highway with urban fabric on both sides of the highway. For this specific location, the wind data is not being measured and recorded. The nearest location where wind data is measured on a daily basis is at Amsterdam Schiphol.



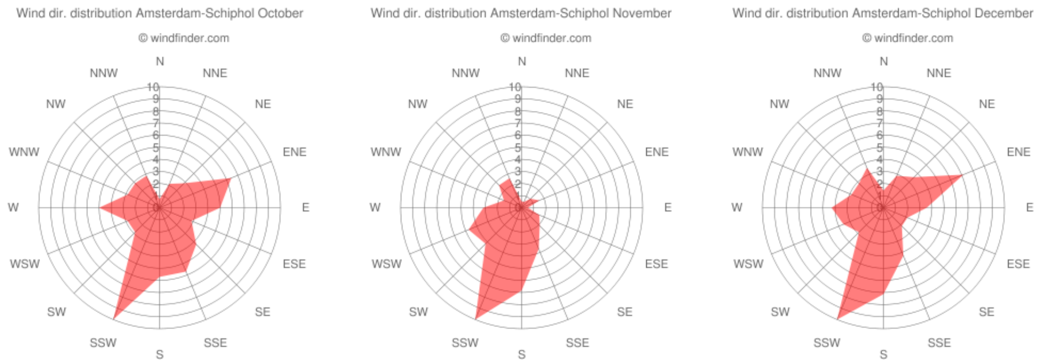


Figure 23: Average monthly Wind speed & direction at Amsterdam-Schiphol[12]

When looking at the average monthly wind speeds and directions, a few things stand out.
In the winter months, the prevailing wind direction is Southsouthwest while in the summer months the prevailing wind direction is Westsouthwest.
The wind speed in the winter months is significantly lower than in the summer months.
This information can be useful when designing and optimising the wind performance of the building.

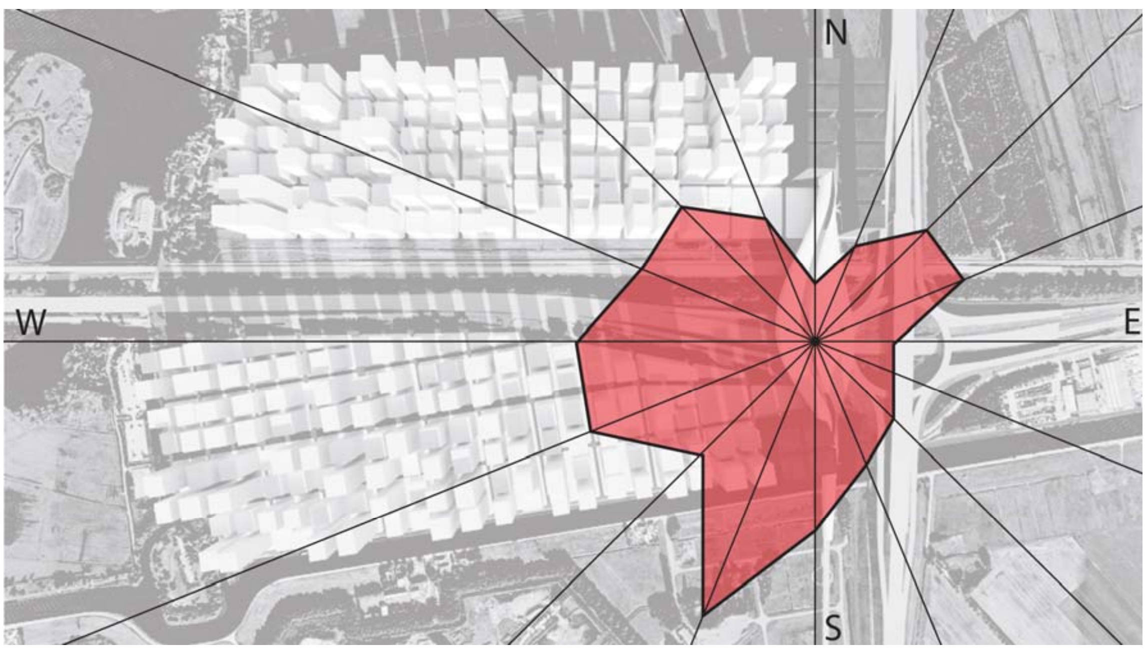


Figure 24: Average yearly Wind speed & direction at Amsterdam-Schiphol

The prevailing wind direction at the Haarlemmerliede area is west. Over 70% of the total wind in the area comes from NNW-SSW direction. For simplification of the research the wind is simulated purely from the west.

For every month of the year, the minimum, maximum and average wind speeds are known. These wind speeds are measured in the open field on a height of 10 meters. For the CFD analysis, the average wind speed will be used as input.

---

[12] *Windfinder, 'Wind en weer statistiek Amsterdam Schiphol', http://www.windfinder.com/windstats/windstatistic_amsterdam-schiphol.htm*

This research is about investigating the possibilities of natural ventilation and cooling. For this purpose, the daily average wind speed is being used. The daily average wind speed at Haarlem varies from 4 to 7 m/s throughout the year. For this research, the average wind speed is set on 5 m/s at a height of 10 m above ground level.

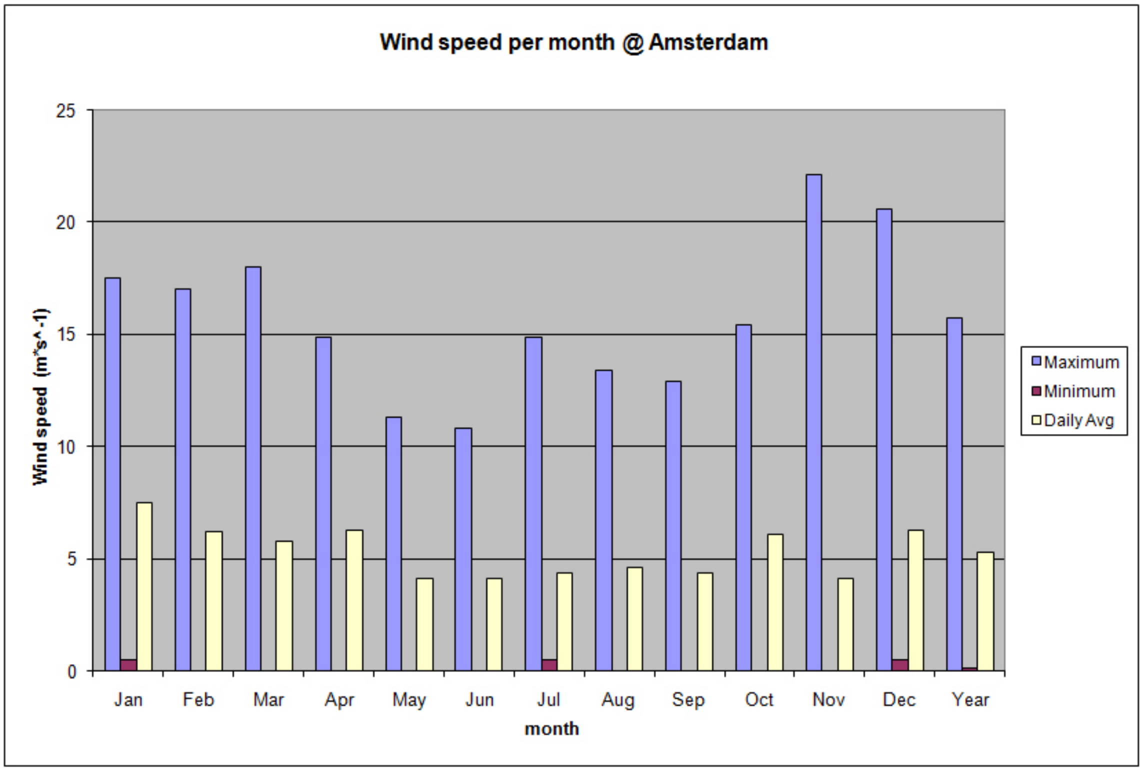


Figure 25: Monthly wind speeds at Haarlem

Context

In this research, the general context around the building in Haarlem is omitted. This is done to simplify the research parameters. This simplification is needed due to limited time and limited computer power. For this research, the building is thus situated in the free field. This means that the results of the wind analysis and the wind behaviour on the building will be significantly inaccurate. Nonetheless, these results are still valid when taking into account the various simplifications of the context.

Building

When doing a CFX calculation, the amount of nodes should be kept to a minimum. When the improvement has a continuous section in the Y-direction, the thickness of the section will be 10 meters. This gives a good view for the wind speed on the building and reduces calculation time.

CFX parameters

In the wind analysis in Ansys CFX the following parameters are used.

Subject	Parameters	Value	unit
general	CFX Modelling scale	1 on 10	[-]
wind	Wind speed	5	[m/s]
	Height of wind speed	10	[m]
	Wind direction	east	[-]
mesh	Curvature normal angle	18	[degrees]
	Min size	default	[m]
	Max face size mesh	2	[m]
	Max size	4	[m]
	Growth rate	default	[m]
inflation	Number of Inflation layers	5	[-]
	Growth rate	1,2	[-]
	Maximum thickness	1	[-]
Inlet	Wall Smoothness building	smooth wall	[-]
	Fractinal intensity inlet	0.05	[-]
	Eddy length scale inlet	20	[m]

Table 2: CFX parameters

3.6 Analysis ventilation surface cuts

In this chapter, the geometry of the surface cuts are analysed and changed to speed up the wind speed over the roof. The pressure on the cuts of these models is calculated. The average pressure on the cuts and the total surface area of the cuts are then used to determine the total amount of air that could be naturally ventilated from the building.

3.6.1 Concept

In order to naturally ventilate the central atrium of the building, the velocity of wind over the top of the building should be as high as possible. If this wind flows over the roof cuts in the correct direction, it could draw the air out of the central atrium which would create a natural draft. This air will move out of the building through the cuts due to a pressure difference. In the atrium and shopping street, normal atmospheric pressure is assumed. Due to the increase of dynamic pressure over the roof, the total pressure will also increase. The difference between the normal atmospheric pressure in the atrium and the total pressure on the roof creates the natural ventilation through the cuts in the roof.

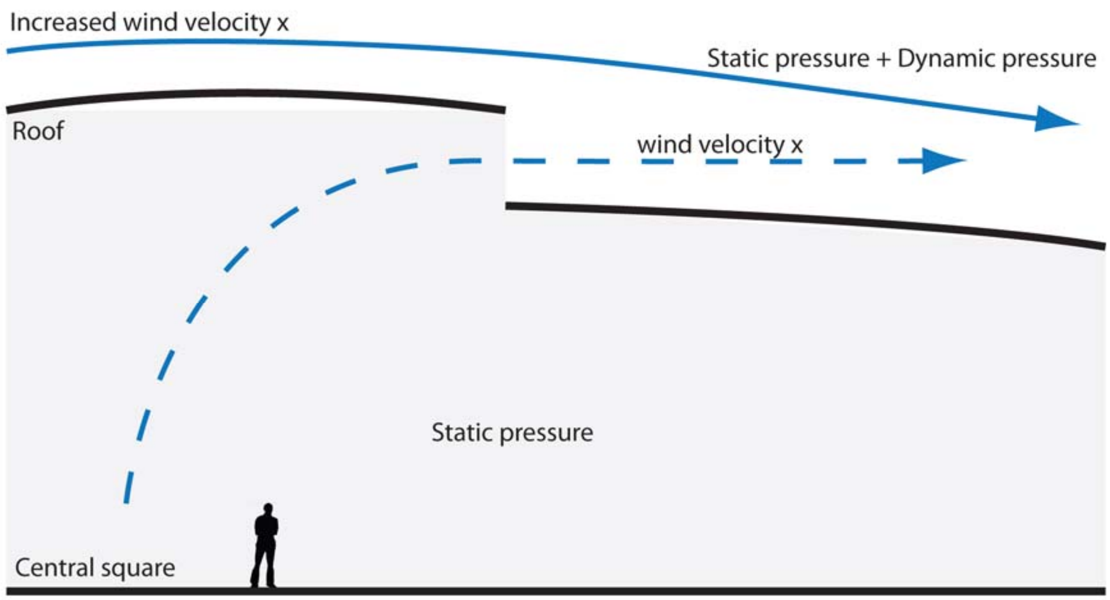


Figure 26: Concept natural ventilation

Due to the dynamic pressure of the wind over the building, it will pull the air out of the building with the same speed as the wind over the building.

3.6.2 Analysing cuts

In order to find the most suitable geometry for the surface cuts, three design alternatives for the surface cuts are proposed and will be analysed. Along with the default cuts from the architectural design, also two changes to the roof geometry around the cuts which might also increase the pressure on the surface cuts.

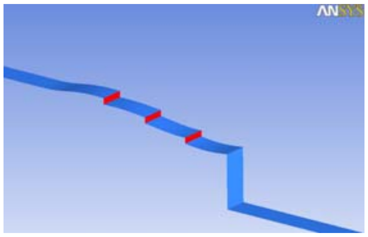
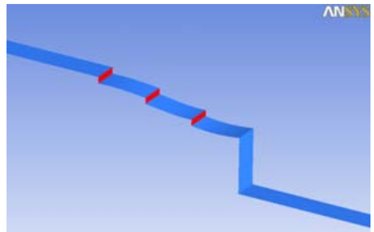
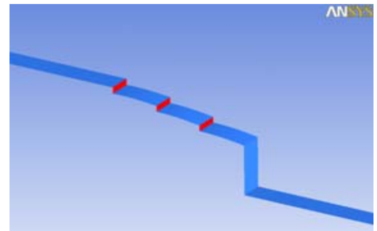


Figure 27: Default surface cuts



Surface cuts 2



Surface cuts 3

These three different designs of the surface cuts have about the same wind properties. The differences in wind behaviour are measured by the pressure on the surfaces (red in picture) in Pascal.

Average	Pressure cut 1 [Pa]	Pressure cut 2 [Pa]	Pressure cut 3 [Pa]
Default surface cuts			
Surface cuts 2			
Surface cuts 3			

Table 3: Pressure on surface cuts

The pressure (suction) on the surfaces of *Surface cuts 3* is slightly higher than the pressure on the surfaces of *Surface cuts 2* which are slightly higher than the pressure on the surfaces of *Default surface cuts*. The reason for this is the improved geometry of *Surface cuts 2 & 3* which allow the wind to flow over the surface more freely. The wind speed over the top surfaces should be as high as possible to get the highest negative pressure on the surface cuts. Figure x shows the pressure on the three surface cuts of *Surface cuts 3.*

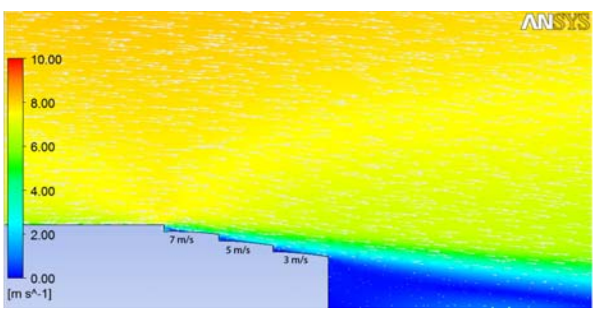


Figure x: Wind speed in x-direction

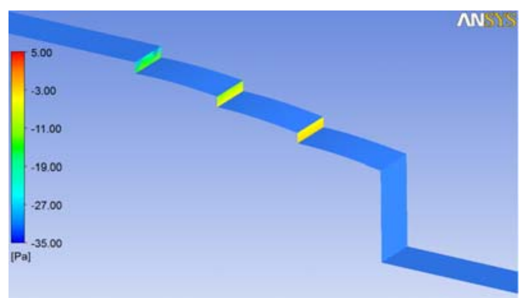


Figure x: Pressure on surface cuts

The chart also shows that the pressure on cut 1 is higher that cut 2 which is higher than cut 3. This is explained by the negative curvature of the roof. The roof bends away from the wind which decreases the airspeed over cuts 2 & 3.

Side note: In this paragraph the cuts in the roof are simulated as closed planes. The planes have different boundary conditions than an opening. The flow of air through the opening will slightly affect the calculated and analysed wind behaviour on the roof. The general principles still apply.

3.6.3 Natural ventilation

The public spaces in the building, such as the shopping street and central square should be naturally ventilated with and air change rate of at least 1.

	surface area [m2]	ventilation air speed [m/s]	Volumetric flow rate [m3/s]	Volumetric flow rate [m3/h]
cut 1	25	7	175	630000
cut 2	20	5	100	360000
cut 3	15	3	45	162000
Total			320	1152000

Table 4: Ventilation through roof cuts

The exhaust air from the mechanically ventilated air from the shops will be drawn to the shopping street. Conforming Dutch regulations, 50% of the exhaust air can be used as fresh air for ventilating the public spaces. However, the same air that is pushed out of the shops will be naturally drawn to the cuts. So the exhaust air cannot be taken into account when calculating the overall air change rate of the shopping street.
The air change rate for retail functions is 8 in the summer and 4 throughout the rest of the year. The critical factor in determining the air change rate is the cooling of the space and not the ventilation for fresh air.

function	volume [m3]	ventilation per hour [m3]	ventilation rate
shops (mechanic)	113905	911240	8
public spaces (mechanic)	213770	455620	2,13135613
public spaces (natural)	213770	1152000	5,388969453
public space (total)	213770	1152000	5,388969453

Table 5: Ventilation rates

3.7 Analysis original section building

The original section of the building is the part that is the basis for all further analysis. The improvement cases will be based on the wind results from this section. This section is located in the middle of the building. In this section, the building is the highest on this points it features a twelve meter high façade where the Café is situated. This façade is situated perpendicular on the main wind direction for the site. This will probably have a big impact on the wind flow on and over the building.

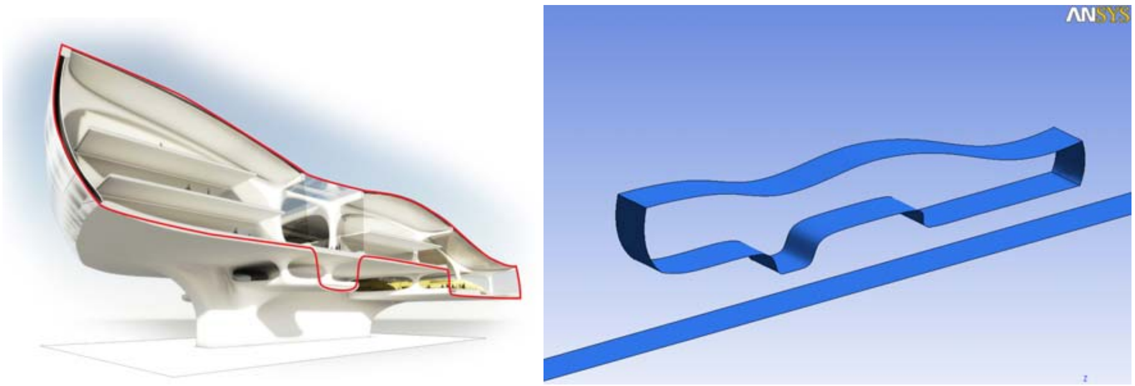


Figure 28: CFX-shape default building

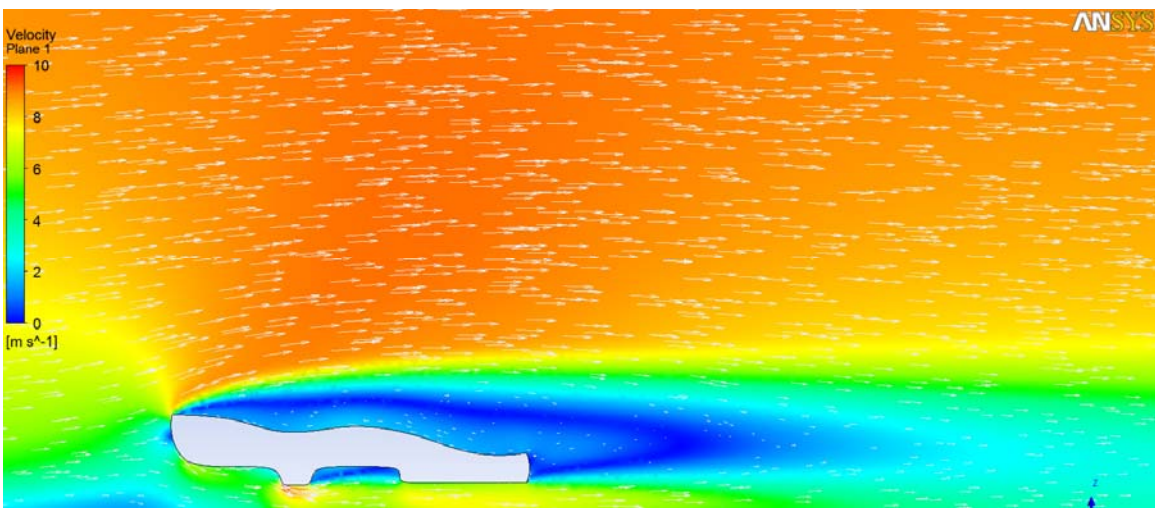


Figure 29: Wind speed in x-direction over roof

This CFX-analysis shows the wind profile being disturbed by the front façade of the building. The building is a major obstruction in the wind flow due to the height of the front façade and the fact that it is a vertical façade. Over the top of the building and behind the building, there is a major vortex with very low winds speeds and some areas where the air is flowing backwards. This vortex area is about three times as long as the building. Underneath the building, the wind speeds up to about 7 m/s due to the funnel like geometry of the bottom of the building.

3.8 Improving roof wind characteristics

To improve the wind characteristics of the building, six geometry changes will be suggested in this paragraph in order to improve the wind flow over the atrium roof. These six improvements are only a selection of many possible design improvements which have been selected due to limitation in time and computer power. These were selected as they are expected to be the most feasible, with the best design possibilities and the best wind behaviour to naturally ventilate the building.
These selected improvements can be categorized in three categories. The first category leaves the original geometry intact and only adds geometry to it. The second category changes the original geometry but stays within the original surface boundaries. The third category changes the original geometry substantially.
The wind speed over the top of the building should be improved from 1 m/s to more than 6 m/s, ideally around 10 m/s. The improvements of the geometry will be tested and evaluated and the best one will be chosen as a basis for an improved roof design.

3.8.1 Improvement 1

For this design improvement, the height of the roof is decreased in 3 areas. These areas are determined by the main wind direction in the area. Locally decreasing the height of the roof will allow the wind to continue over and stick on the roof instead of bouncing away from the roof. These design changes have minor impact on the overall geometry of the building and provide for new possibilities for new building geometry.

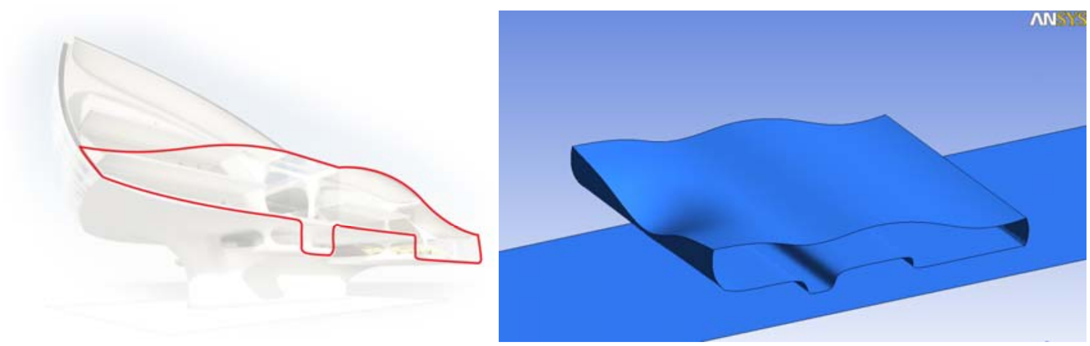


Figure 30: Improvement 1 CFX-shape

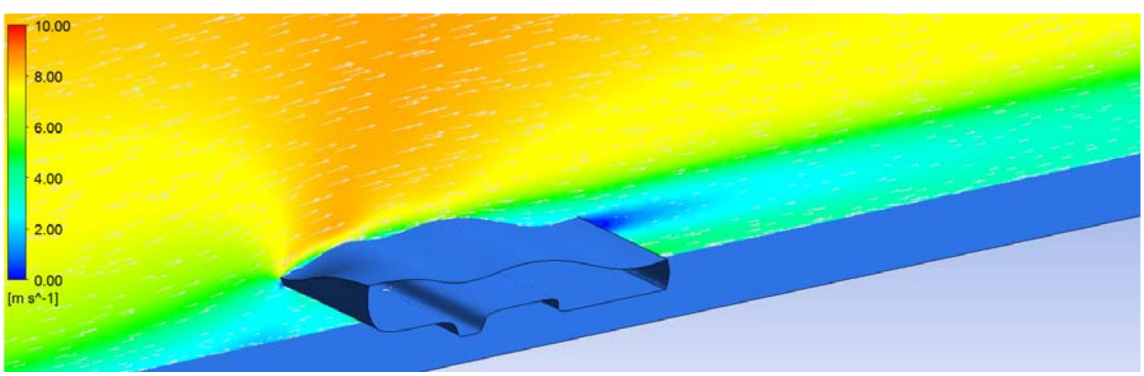


Figure 31: Wind speed in x-direction over roof

Based upon these images, it can be derived that the air speed over the top of the building increases with this improvement to about 6 m/s. With this wind speed flowing over the ventilation cuts on the roof, the building could be naturally ventilated.

3.8.2 Improvement 2

For this design improvement, the façade of the building is fundamentally changed. Where improvement 1 stayed within the original façade boundaries, this improvement extends the façade into a point. This new form is to minimise the façade surface that is situated perpendicular on the wind direction. The new edge of the building should be as sharp as possible. This might allow the wind to flow freely over the top of the building and increase the air speed over the ventilations cuts.

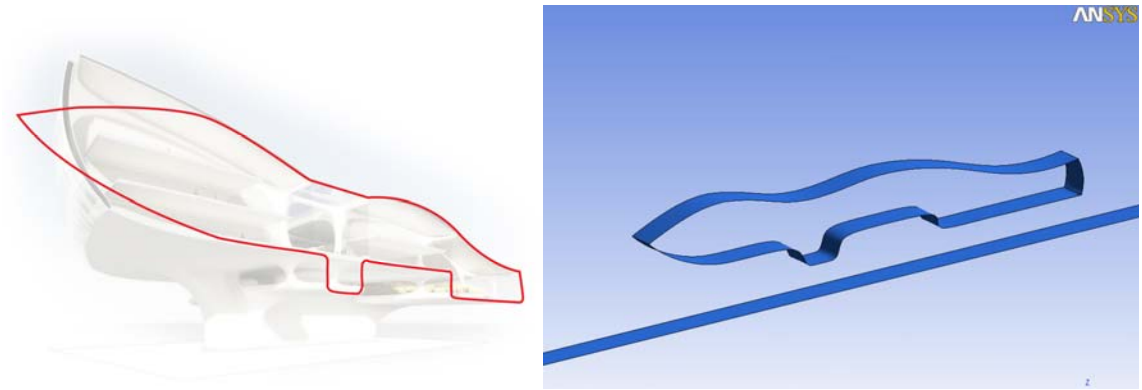


Figure 32: Improvement 2 CFX-shape

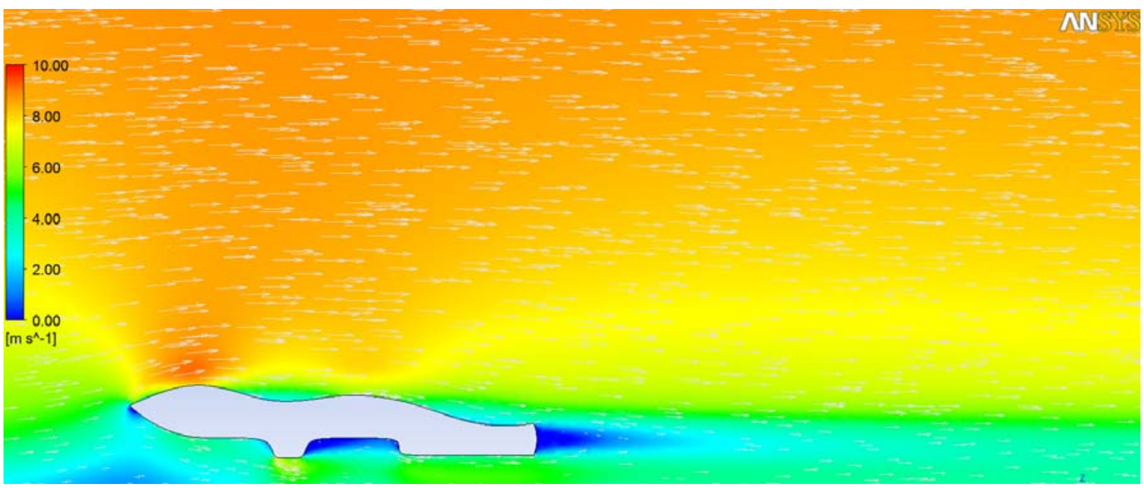


Figure 33: Wind speed in x-direction over roof

Based upon these images, it can be derived that the wind over the air speed is improving with this improvement. In certain areas on the roof, the wind speed has increased to 8 or 9 m/s. This is a significant improvement from the default section of the building. However the increased wind speed doesn't seem to be uniformly distributed over the length of the roof. The highest wind speed is situated on the first part of the roof. The ventilation holes are not situated in this area.

3.8.3 Improvement 3

This improvement is based on improvement 2. Improvement 2 showed great potential to amplify the wind speed over the top of the building. However the amplified wind speed wasn't uniformly distributed over the length of the roof. The high wind speed on the beginning of the roof should be continued to the other side of the roof to maximise the amount of naturally ventilated air from the building.
Improvement 3 features an added aerofoil which should act as a wing to continue the high air speeds on the beginning of the roof towards the other side.

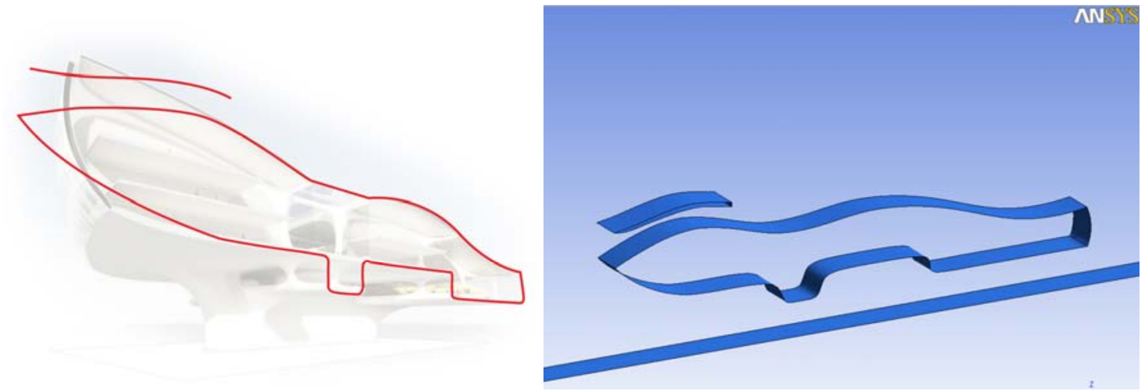


Figure 34: Improvement 3 CFX-shape

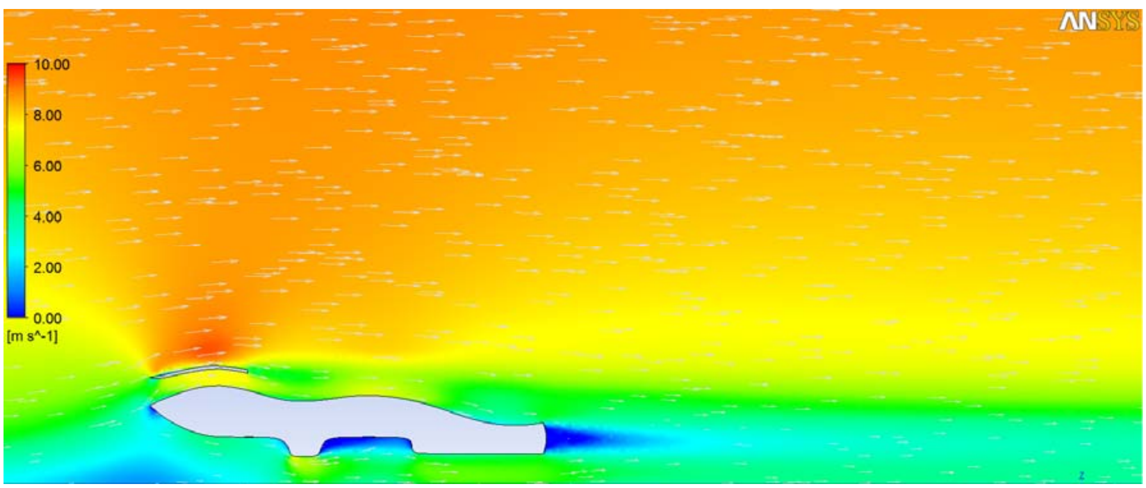


Figure 35: Wind speed in x-direction over roof

Based upon these images, it can be derived that the aerofoil doesn't really improve the wind speed over the roof of the building when compared to Improvement 2 in the way it was expected.
The air directly underneath the aerofoil speeds up to about 7-8 m/s but as soon as the air moves from beneath the aerofoil to the open air, the high air speed can't be maintained and decreases to 5 m/s over the ventilation cuts. The aerofoil only seems to have a local effect on the wind speed.

3.8.4 Improvement 4

This design improvement is based on an aerofoil design combined with a funnel design. This improvement is designed within the geometric boundaries of the original design. The aerofoil design should guide the air into a funnel to increase the air speed over the roof. This increased air speed can then be used for ventilating the building.

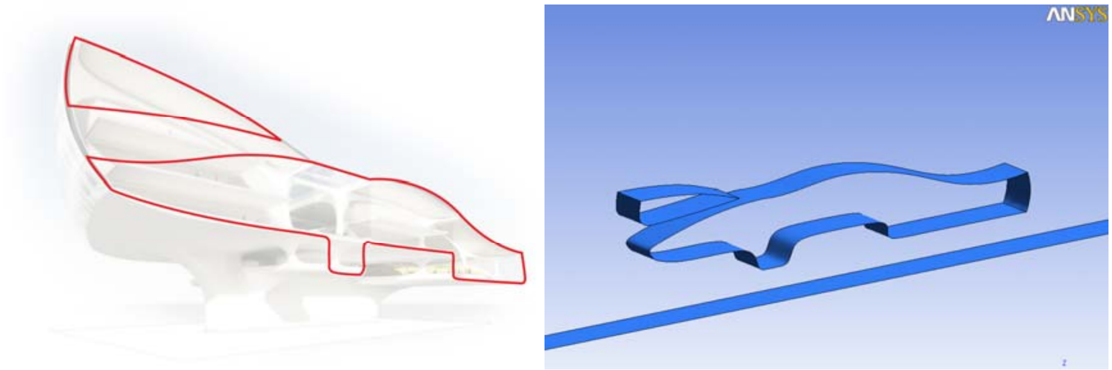


Figure 36: Improvement 4 CFX-shape

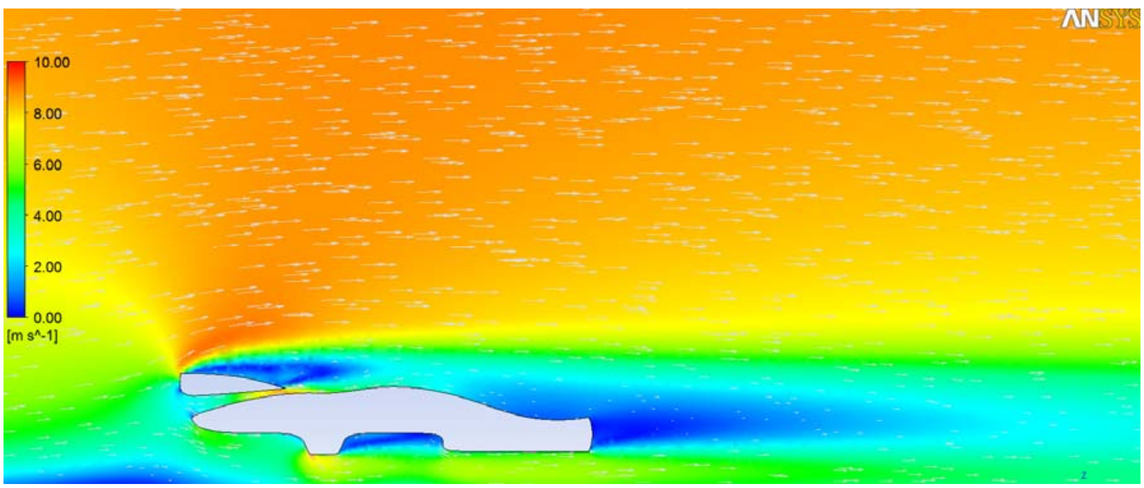


Figure 37: Wind speed in x-direction over roof

Based upon these images, it can be derived that the aerofoil only has a very local effect on the wind speed over the roof. The wind speed directly under the aerofoil at the end of the funnel is increased to 9 m/s but as soon as the wind leaves the funnel the air speed decreases to 2 m/s. The aerofoil only seems to have a very local effect. In addition the shape of the aerofoil seems to be very inefficient to improve the air speed over the roof. The height of the aerofoil creates a low wind speed area/vortex the size of the entire roof that renders the effect of the ventilation cuts down to practically zero.

3.8.5 Improvement 5

Improvement 5 leaves the entire building design intact by adding an aerofoil to the roof. This aerofoil is added to the original roof design to increase the wind speed over the roof. This improvement could prove to be a very easy and inexpensive way to increase the wind speed and naturally ventilate the building.

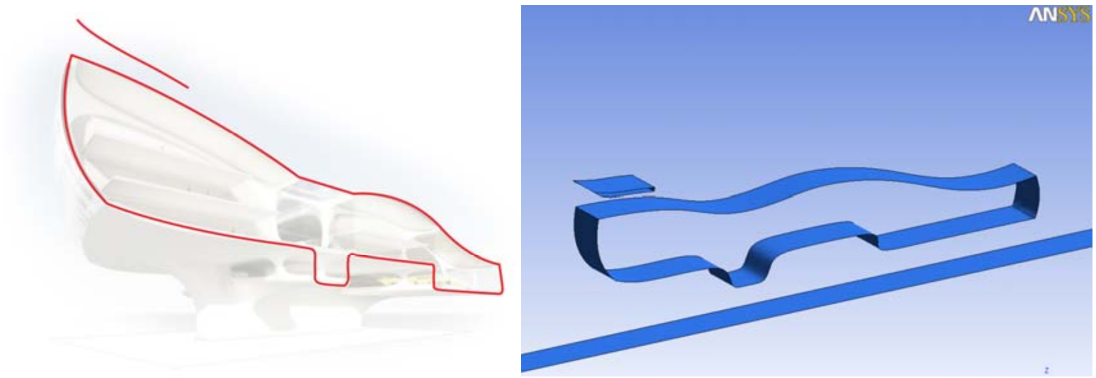


Figure 38: Improvement 5 CFX-shape

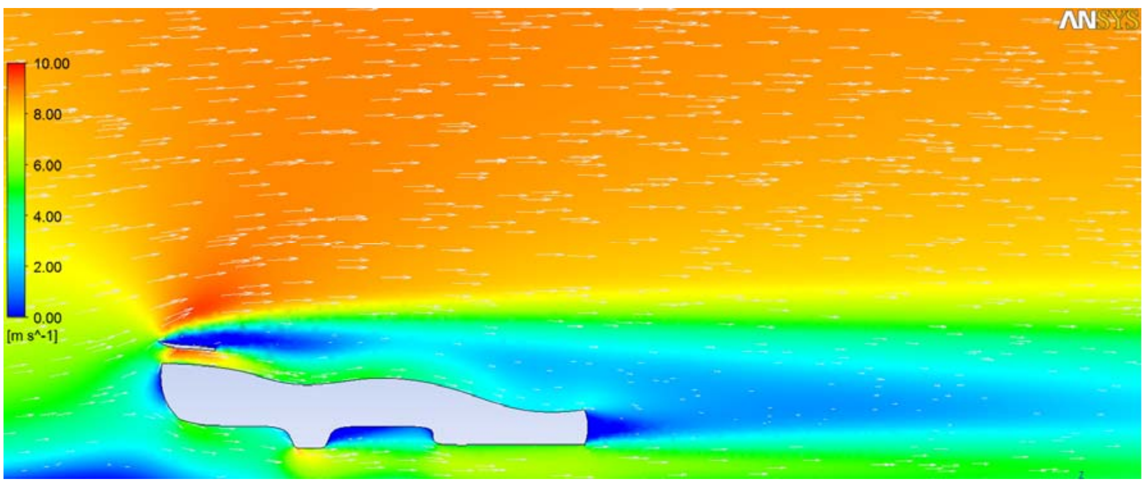


Figure 39: Wind speed in x-direction over roof

Based upon these images, it can be derived that the wind speed is increased to 10 m/s underneath the aerofoil. The wind speed then slowly decreases to about 4 m/s over the area with the ventilation cuts. The aerofoil seems to have a very local effect, just as in improvement 4. Due to the standing edge in the frontal profile, the aerofoil creates a big vortex over the top of the building.

3.8.6 Improvement 6

Improvement 6 is directly based on Improvement 5. Improvement 5 shows promising improvements in air speeds over the roof but the vortex created by the aerofoil is still too large and decreases the wind speed. Improvement 6 features an improved aerofoil design which extends over the roof edge to gather the wind that travels upwards from hitting the vertical façade. The tip of the aerofoil is also slightly pointed downwards to minimise the vortex behind it.

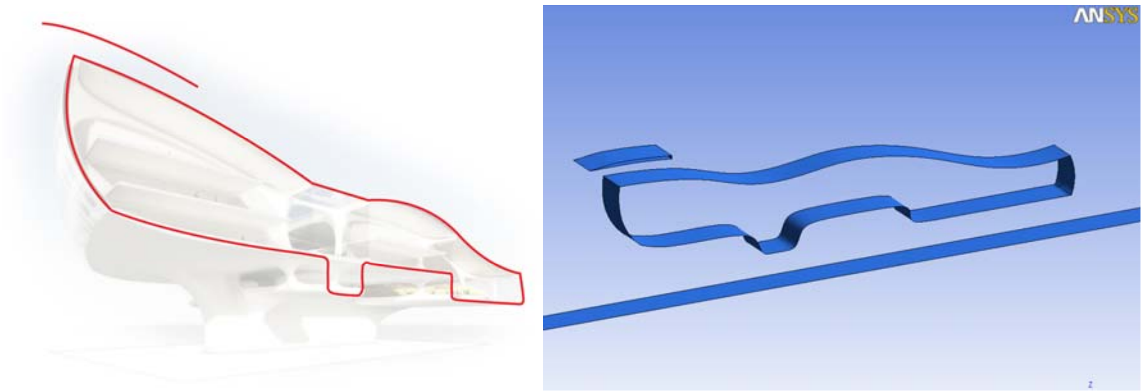


Figure 40: Improvement 6 CFX-shape

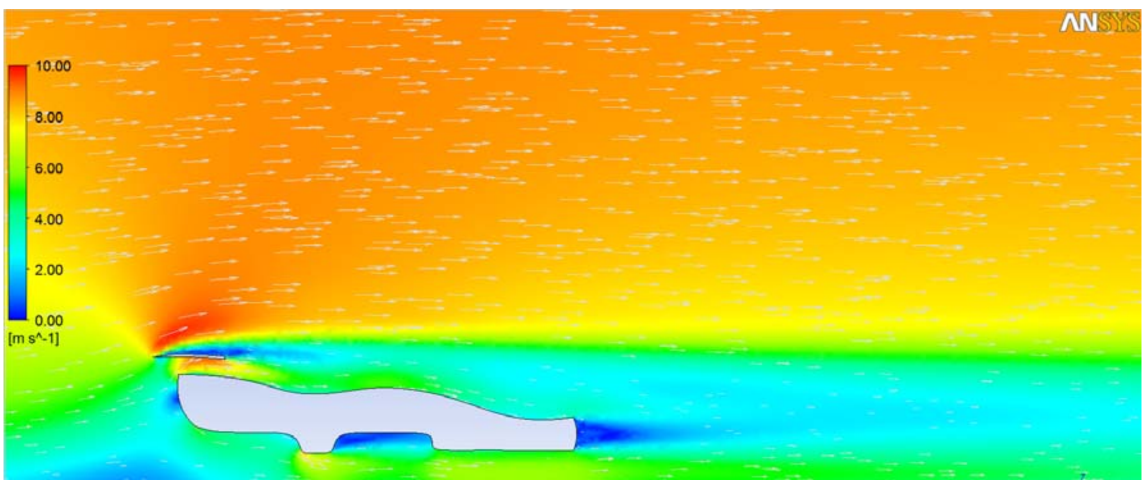


Figure 41: Wind speed in x-direction over roof

Based upon these images, it can be derived that the vortex created by the aerofoil is much smaller than in improvement 5. However, the aerofoil still seems to have a very local effect. The average wind speed over the building is not high enough to naturally ventilate the building.

3.8.7 Evaluation of improvements

Now that the wind characteristics of the six building improvements are analysed and calculated, they can be evaluated. One improvement or a combination of multiple improvements will be selected as a basis for the roof development/design.

The improvements will be selected on the following primary criteria:

- Design possibilities
- Design changes
- Wind speed over roof in x-direction
- Wind distribution

Some criteria are only assumed and play a small role in the decision making process. These secondary criteria are:

- Structural consequences
- Costs

improvement	Design	Changes	Wind speed	Wind distribution	Structural	Costs
1	XXX	XX	XX	X	XXX	XX
2	X	XX	X	X	XXX	XX
3	-	XX	XX	XX	X	XX
4	XX	X	-	-	XX	X
5	X	XXX	X	X	X	XXX
6	X	XXX	X	XX	X	XXX

Table 6: Combined evaluation chart improvements

As a basis for the new building skin, improvement 1 is selected. This improvement is the most flexible. An improvement is achieved through changing overall building skin without added elements. Improvement 1 increases the wind speed to 6 m/s on the roof while maintaining an almost uniform distribution across the roof.
This architectural design could be more interesting due to the changing height of the façade. It also focuses the attention to the central atrium which now will be highlighted as the highest point of the building, directly above the highway. Also different wind directions can be taken into account for maximum natural ventilation.

3.9 Improved building design

Improvement 1 is selected as the improvement on the existing geometry with the highest potential. With improvement 1 as a basis for the new design and the general knowledge gained in the previous chapter, two new designs have been made. These two designs will be analysed in CFX to select the best improvement.

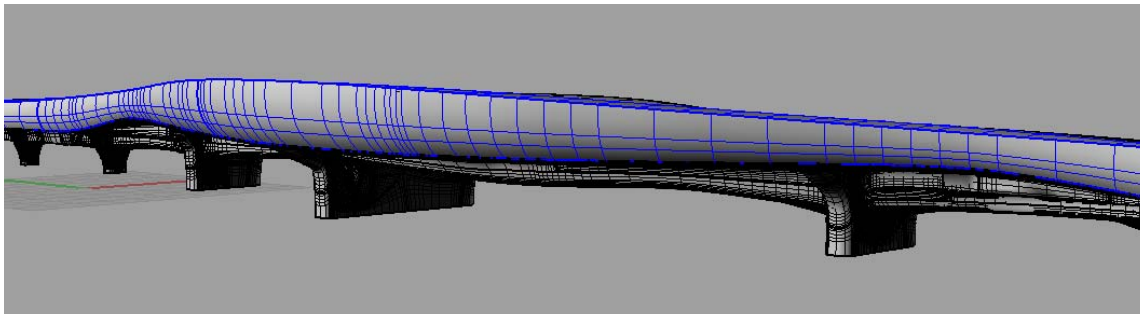


Figure 42: Original design

3.10.1 Wind designs

This wind design is a translation from Improvement 1 from the wind analysis part. The wind design features one central low point where the wind will flow easily over the roof towards the roof cuts. The design is optimised for the wind from the WZW to WNW direction.

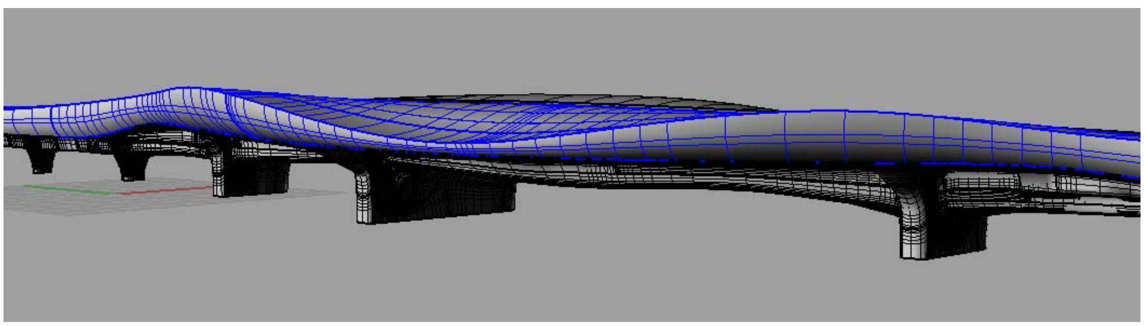


Figure 43: New wind design 1

From an architectural standpoint, this wind design has one high point and two low points. The high point is located in the middle of the building at the central atrium. The low points are located on both sides of the high point. The two dips in the building make sure the wind from the WZW to WNW direction is directed to the roof cuts.

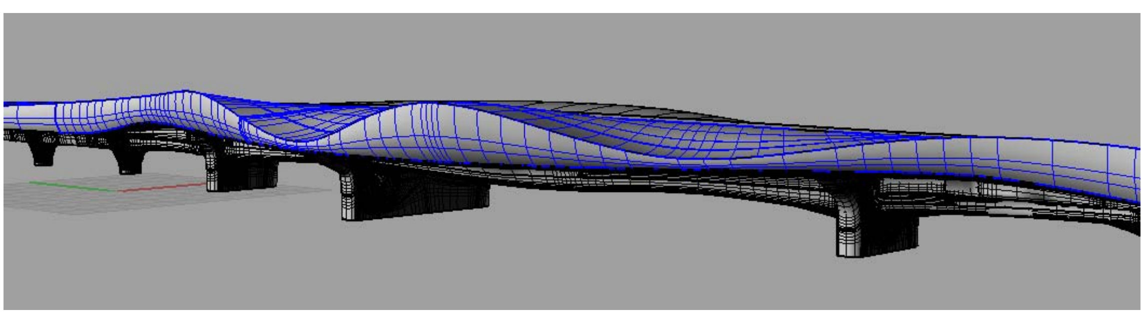


Figure 44: New wind design 2

With these two wind design, the velocity of the wind over the top off the building is increased from 1 to 7 m/s. From a performance standpoint, both wind designs are equally effective. However, when looking at the design in relation to the architectural design, wind design 2 clearly offers more possibilities for the architectural design. The wind is able to flow over the roof surface of the building due to the two low points in the façade. The high point highlights the centre of the building, which is situated directly above the highway. In this area of the building, the main square, lounge and bar are situated, thus making it the centre of the building in a functional and visual way.

3.10 Conclusions

These conclusions begin with answering the research questions stated in chapter 3.1. The performance of the roof system will be evaluated and the main goals are checked if they have been achieved. The conclusion ends with exterior images which show the new roof geometry of the Schiphol Interchange Station.

The CFD-analysis have provided a good understanding of the way wind flows on and around buildings as well as the potential to naturally ventilate the building using the available wind at the Haarlemmerliede area. From these wind CFD-analyses a few things can be concluded:

When the wind hits a vertical object, it is deflected in a direction perpendicular to the impact surface. The wind velocity on top of the surface is almost zero. By increasing the aerodynamics of the impact surface of the building, the wind can be guided over the building. Compared with a non-aerodynamic shape, the performance can be increased with a factor 5-8.

1. The shape/geometry of the building can be changed to improve the wind flow over the central part of the roof. In order to achieve this improvement, the rear side of the roof is lowered at two points. These low points make that the wind follows the roof surface of the building and speeds up on top of the building. This is a great improvement compared to the original roof design where the wind was vertically deflected due to the shape of the roof. This resulted in a wind velocity of almost zero on top of the building. The wind velocity over the roof is increased from 1 m/s in the original design to 7 m/s in the final roof design.

   The wind speed over the roof surface combined with the area of the roof opening makes that the Schiphol Interchange Station can be naturally ventilated based on the input variables that have been used. However, these input variables, such as wind speed, wind direction and wind turbulence are dynamic factors. These will change throughout the year, which means that the simulated/measured wind performance is an estimation of the real wind performance.

Final roof shape

The final results of the wind research is the new geometry for the Schiphol Interchange Station. These images show the final roof geometry.

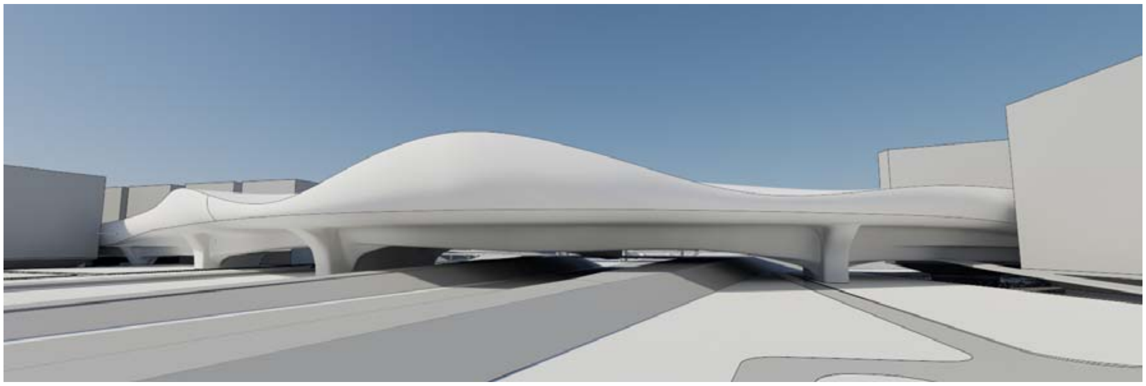


Figure 45: Perspective view 1

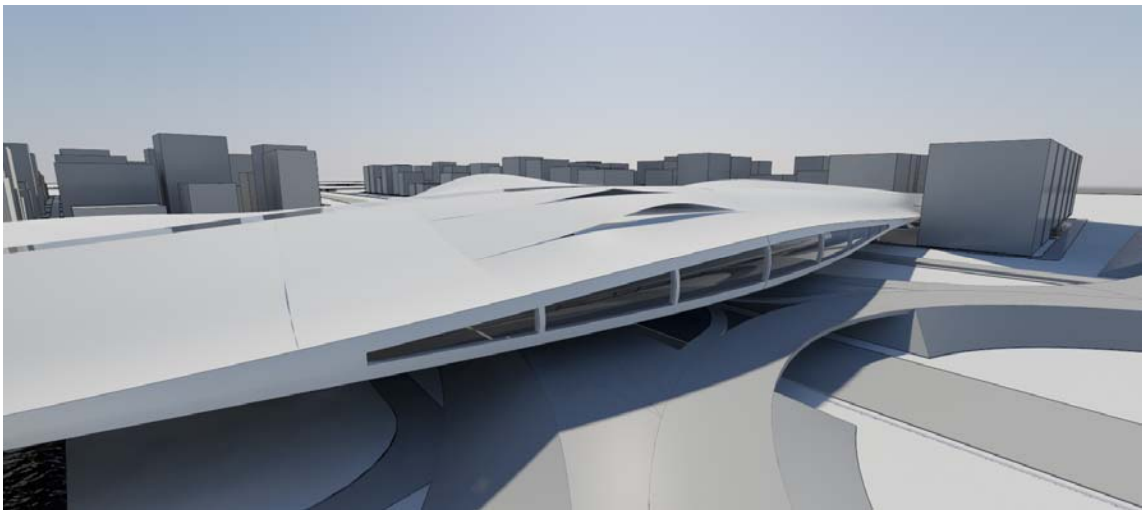


Figure 46: Perspective view 2

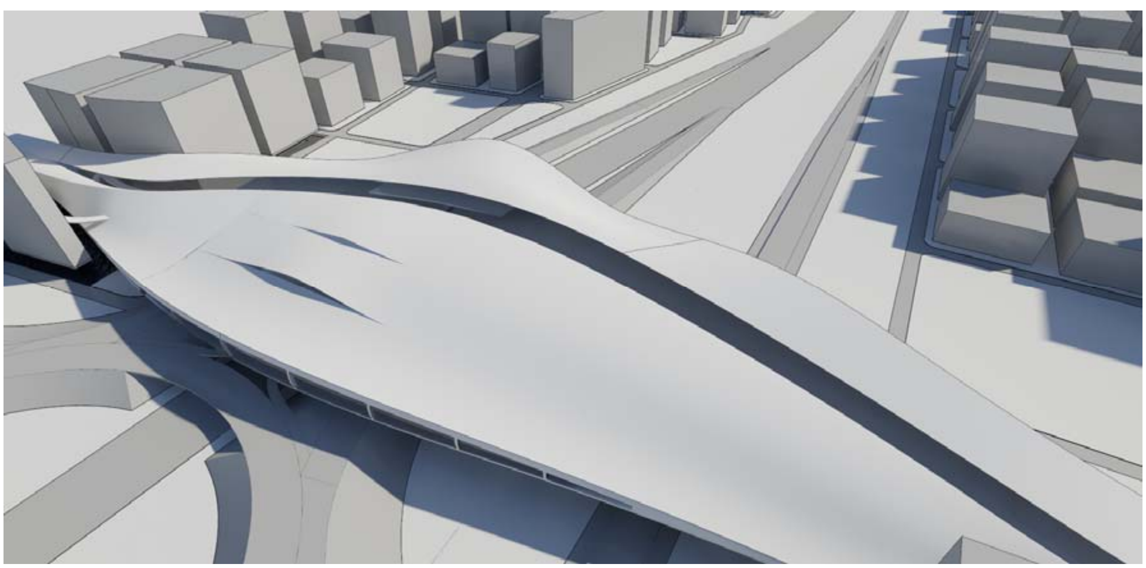


Figure 47: Perspective view 2

4 DAYLIGHT RESEARCH

4.1 Introduction

4.1.1 Research questions

1. How can a skin component be designed to allow for different amounts of daylight, direct or diffuse, into the functions to reduce the use of electric, additional lighting as much as possible?

2. How can a non-orthogonal skin with a parametrically designed roof system provide the required amount of daylight into the specific functions so that the architectural concept with regards to light and daylight is achieved?

Sidenote: Because this is a double graduation track, other aspects of the roof, such as view, heat load, cost and atmosphere, are being taken into account when selecting the most suitable roof design. This way the building technology research is merged with the architectural design where the end result is based both on the building technology research and the various design choices.

4.1.2 Goals

The goal for this research is to develop a component which provides for enough daylight to the functions inside the building. The outer skin of the building has been designed for the natural ventilation of the building. This skin will be used as a basis for designing the component. The roof system will be designed to meet the architectural concept and daylight requirements of the different functions of the building. For each function, all architectural and daylight requirements will be formulated to outline the performance aspect of the research.

After formulating the daylight requirements for different functions, some first shape studies have to be made in order to find a form/shape for the geometry of the roof system. These different studies, drawings and models have to be analysed. This analysis will lead to a final design of the roof system. This design will first be tested in daylight software. The roof system will then be parametrically modelled and used to populate the entire surface of the building.

In this research, two types of parameters are being used on two different scale levels. On the overall scale of the building, parameters are used to populate the building’s roof surface. On the local scale, design parameters, such as shape, inclination, reflectivity and other, are used for design exploration and daylight research.

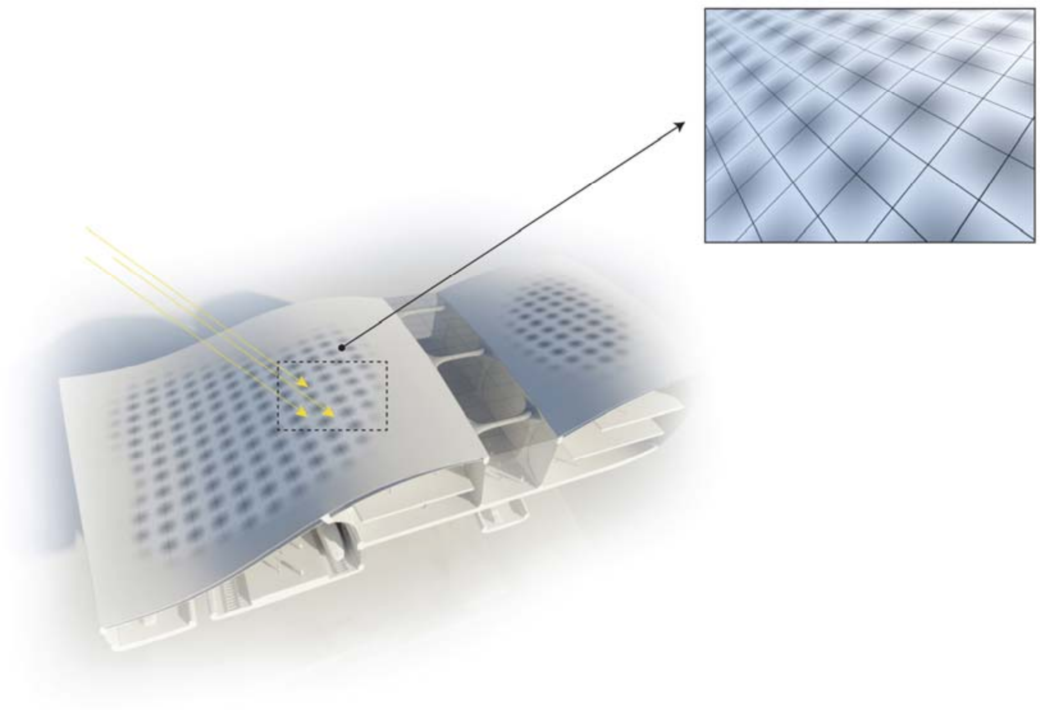


Figure 48: Designing roof daylight component

4.2 Daylight theory

The daylight theory is used as a basic understanding of daylight and materials properties in order to use these properties in the design and research process. The first paragraph of the daylight theory covers the material and geometrical properties. These properties are used to design the roof system, both in geometry and material. The second paragraph covers the performance properties. These properties are used to measure and quantify the effect of the design of the roof system.

4.3.1 Material and geometrical properties

The way light waves interact with objects and materials are determined by a combination of reflection, transmittance, absorption and refraction. The influence on these phenomena on the interior lighting conditions will be tested in this paragraph.

Reflection

Reflection is the change in direction of the light when its hits a surface/material in such a way that is returned into the medium where it originated. Reflected light always keeps the same amount of energy. Light can be reflected specular or scattered diffuse. When it comes to specular reflection the direction of the ingoing light and outgoing light make the same angle with respect to the surface normal. When light encounters a material with a different refractive index a part of the light will be reflected. A normal single-layered glass pane reflects about 10% of the light.

Surface inclination

The inclination of object and surfaces can determine how light is reflected into the building. The inclination can directly control the direction in which the light is reflected.

Transmittance and absorption

Transmittance is the fraction of light that, at a specified wavelength, can pass through a material. The absorption is the fraction of the light that is absorbed by the material. Both are properties of the material itself.

Refraction

Refraction is the bending of the light when it passes from one transparent medium to another at an oblique angle. The amount of light stays the same, while the speed and direction in which the light travels changes. The refraction depends on the physical properties of the material. Generally when a ray of light moves through a glass pane with 2 parallel faces the total deviation is 0. Refraction is described by the Snell's law, which explains the relation between the angles and the velocities of waves.

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

Where $\theta 1$ and $\theta 1$ respectively are the angle of incidence and refraction, $\upsilon 1$ and $\upsilon 2$ are the velocity of the light in the material and n1 and n2 the refractive indices.

Transparency, translucency and opacity

Transparency, translucency and opacity are all physical properties which influence how light passes through a material. The amount of light and the way the light moves through the material depends on the wavelength of the light and material itself. Transparent materials allow the light to transmit through the material where translucent materials only allows light to pass through diffusely. Opaque materials do not allow any transmittance of light.

4.3.2 Performance properties

Luminance & Illuminance

Luminance is the luminous intensity of light travelling in a certain direction, per unit area. Luminance is based on the amount of light reflected off surfaces or objects. Luminance indicates how much luminous power will be perceived by a person's eye; therefor luminance is an indicator of the brightness of surface. Luminance pictures display the colour and reflectance of each diffuse visible surface. In SI derived units, luminance values are displayed in candela per square meter (cd/m^2).

Illuminance is the total luminous flux on a surface, per unit area. Illuminance is based on the amount of light falling on objects and therefore doesn't represent surface colours and reflectances. For a designer, the illuminance values are often more important than the luminance values as almost all building regulations specify minimal illumination levels for functions and environments. In SI derived units, illuminance values are displayed in lux or lumens per square meter. [13]

- 1 lux = 1 lumen/m^2 = 1candela/m^2

Visual comfort & glare

Visual comfort is achieved by eliminating any causes of visual discomfort. Lights that are too bright can cause discomfort to their surroundings. This kind of discomfort is called discomfort glare. This discomfort can be caused by natural lighting or artificial lighting.
Discomfort can be caused by material properties such as high gloss materials, which can, in the right viewing angle, be seen as a light source on their own. High contrasts between the luminance of the light source and the luminance of the background against which it is seen can be another reason for discomfort.
Disability glare occurs when the brightness of the light source is such that contrast of the visions is so reduced that the vision is impaired. This kind of glare should be avoided, especially in travelling areas and places such as train stations and roads.[14]

Daylight factor

The daylight factor expresses the ratio of illuminance at a specific point in a space as a percentage of the total illuminance from the whole, unobstructed, overcast sky.

---

[13] *Natural frequency. 'Radiance and Daylight Factors'. 2007. http://naturalfrequency.com/articles/radiancedf*
[14] *Robert Bean, Lighting Interior and Exterior,(Elsevier, 2004), 33*

- *Daylight factor = (indoor illuminance / outdoor illuminance) * 100%*

The daylight factor is important when trying to minimise the need for electric lighting. If the daylight in an office is around 5%, the occupants will feel this as adequate lighting. If the daylight factor falls below 2%, then the occupants are very likely to switch on the electrical lighting. Daylight factors are measured in this research within the CIE overcast sky.[15]

Emissivity

The emissivity of a material is its relative ability to emit energy through radiation. The value is related to the emissivity of a true black body which has an emissivity value of 1. Any real object would always have an emissivity value less than 1. The duller and blacker a material is, the closer the emissivity is to 1.
A list of Emissivity values can be found at: *http://snap.fnal.gov/crshield/crs-mech/emissivity-eoi.htm.*[16]

For instance, a general white paint will have an emissivity value of around 0.9.

Specularity

The specularity of a material controls the size and brightness of the specular highlights it reflects. Smooth and reflective objects have specular hightlights that are small and bright while rough surfaces have hightlights that are large and diffuse. The brightness of the highlights is directly related to the reflection value of the surface/object.[17]

Roughness

The roughness of a material is its ability to scatter the reflected light in a diffuse way. A value of 0 will scatter the light in a direct way while a value of 1 will scatter the light in a fully diffuse way.

[15] *Robert Bean, Lighting Interior and Exterior,(Elsevier, 2004), 115*
[16] *Lawrence Berkeley Laboratory. Material Emissivity Properties. http://snap.fnal.gov/crshield/crs-mech/emissivity-eoi.html*
[17] *Artifice, Inc. Specularity. http://www.artifice.com/support/user_guide/documents/tips/specularity.html*

4.3 Daylight requirements

To develop a building envelope by using daylight as the main driver, the daylight requirements must be assessed first. The daylight requirements can be divided in three categories.

- Architectural effect / getting the user involved through lighting conditions
  Quality of light / perception of space / light i.r.t. function / Atmosphere

- Lighting regulations such as preventing Glare / homogenous distribution / Minimum daylight factor for functions / avoiding dark areas

- Heat / temperature gain due to incoming light

The daylight requirements have to be determined for each function. These requirements are the basis for further daylight research/design.

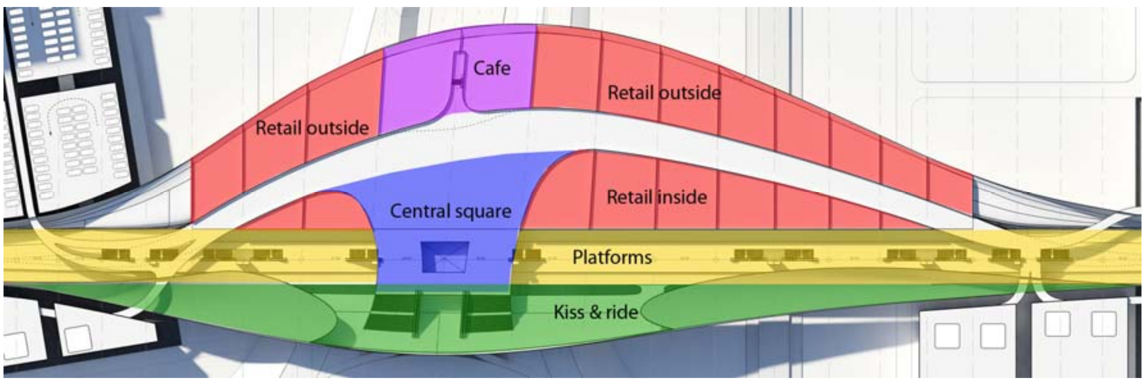


Figure 49: functions in building

4.3.1 Requirements functions

Retail

For shops, the main purpose it to sell their merchandise. Since the main purpose is to sell goods, an exterior view is not necessary. The shops need a high level of general illuminance throughout the store, in the range of 750-1000 lux. This level of luminance is mainly achieved by luminaires which don't cause glare. The daylight coming into the retail function through the front façade party helps in illuminating the store.
Light-coloured, diffuse surface materials should be used throughout the stores to provide a good diffuse lighting component.[18]

- Only diffuse daylight
- 750-1000 lux (partly luminaires)
- Direct view to the outside not necessary

[18] *Robert Bean, Lighting Interior and Exterior,(Elsevier, 2004), 33*

Central Square

When entering a public building, the two main elements are impression and direction. The materials and light play a vital role in these two elements. The central square in the station should have the impression of a meeting place. The second element should inform people where the information they require can be found and how to get there. The central squire should have a high illumination to inform people that it is the centre of the building. Also an unobstructed view to the outside is helps in this aim. Additional luminaires should optimise the way-finding process.

- Direct & diffuse light allowed
- Even distribution of daylight during the day
- 500-700 lux
- High luminance level. Special light effect which shows the central aspect of the square
- Component could show the direction of the movement of the people
- Direct view to the outside necessary to a wide direction

Platforms

The main function of the platforms is for entering and exiting the trains. Due to the fact that trains are moving at these platforms, safety is key factor to consider when designing light conditions for the platforms. Glare has to be avoided and illuminance levels should be in the range of 100-200 lux. For the platforms, wind and temperature can range more freely than in the retail spaces. Openings to the outside are possible.

- Diffuse light allowed
- Even distribution of daylight during the day
- 100-200 lux
- No glare allowed due to safety issues
- Component can be partly open to the outside

Kiss & ride

The kiss & ride area is where the people arriving by car are entering the building. Due to safety issues, glare should be avoided. Enough light should be admitted to the area to give a sense of centrality to the kiss & ride area. The area should have a clear view to the outside to have a connection with the surrounding highway and roundabout.

- Diffuse light allowed
- 200-300 lux
- Roof should provide visual means for entering the building. More light should enter the building when getting closer to the entrance
- No glare allowed due to safety issues

Train track skin

The train track skin doesn't have many requirements in terms of illuminance levels and views.

- Component could give a sense of speed in the longitudinal directing
- Direct and diffuse light allowed
- Views to the outside are not necessary
- Component can be open to the outside

Cafe

The Café is located in the centre of the building, right over the highway. This cafe is a place for having drinks and small informal meals. The Café should have a big view to the outside, of the highway as well as the other surroundings.

- Diffuse light & partially direct light allowed
- 200-300 lux
- Big views to the outside are vital. View to the highway to enforce mobility / transportation feeling.

Daylight requirements chart

The daylight requirements are combined in a chart. This chart is the basis for the design of a parametric roof component. This chart with daylight requirements gives qualitative and quantitative requirements for the use of daylight.

- Light intensity (lux)

The illuminance requirements of the building are quantitative requirements for the amount of light entering the building and falling upon objects in the buildings. A maximum amount of natural light should enter the building where possible in order to avoid additional electric lighting as much as possible.

- Daylight quality

The qualitative daylight requirements of the spaces in the building are being determined by the type of activity in that space. The quality of the light should be informing people about the function of the space and make their activity in the space as safe, efficient and pleasant as possible.

Functions	Direction facade	View	Infrastructure / habitation	Daylight quality	Safety	Light intensity [lux]	Daylight factor
Central square	-	XX	Infrastructure	Direct/diffuse	XX	500-700	7%
Retail outside	Vertical/Horizontal	X	Habitation	Direct/diffuse	X	750-1000	2%
Retail inside	Horizontal	-	Habitation	Diffuse	X	750-1000	2%
Cafe	Vertical	XXX	Habitation	Direct/diffuse	X	200-300	2%
Shopping street	Horizontal	-	Infrastructure	Direct/diffuse	XX	2500	50%
Kiss & ride	Vertical	X	Infrastructure	Diffuse	XXX	200-300	2%
Platforms	Horizontal	-	Infrastructure	Diffuse	XXXX	100-200	1%

Table 7: Daylight requirements chart

recommended lighting levels for working areas

table of nominal levels of illuminance: standard values for working areas

general rooms:	(lx)
circulation zones in storage buildings	50
storerooms	50
storerooms with access requirements	100
storerooms with reading requirements	200
gangways in storage racking systems	20
operating platforms	200
dispatch areas	200
canteens	200
break rooms	100
gymnasiums	300
changing rooms	100
washrooms	100
toilet areas	100
first-aid areas	500
machinery rooms	100
power supply installations	100
postrooms	500
telephone exchanges	300

circulation zones in buildings:	(lx)
for persons	50
for vehicles	100
stairs	100
loading ramps	100

offices, administration rooms:	(lx)
offices with workstations near windows	300
offices	500
open-plan offices	
– high reflection	750
– moderate reflection	1000
technical drawing	750
conference rooms	300
reception rooms	100
rooms for public use	200
data processing	500

chemical industry:	(lx)
facilities with remote controls	50
facilities with manual operations	100
continuously occupied technical processing facilities	200
maintenance facilities	300
laboratories	300
work requiring a high degree of visual acuity	500
colour testing	1000

cement industry, ceramics, glass works:	(lx)
working positions or areas at furnaces, mixers, pulverising plant	200
rollers, presses, forming operations	300
glass blowing, grinding, etching, glass polishing, glass instrumentation manufacture	500
decorative work	500
hand grinding and engraving	750
fine work	1000

iron and steel works, rolling mills, large foundries:	(lx)
automated production facilities	50
production facilities, manual work	100
continuously occupied work positions in production facilities	200
maintenance	300
control stations	500

metal processing/working:	(lx)
forging of small components	200
welding	300
large/medium machining operations	300
fine machining work	500
control stations	750
cold rolling mills	200
wire drawing	300
heavy sheet working	200
light sheet working	300
tool manufacture	500
large assembly work	200
medium assembly work	300
fine assembly work	500
drop forging	200
foundries, cellars, etc.	50
scaffolding, trestling	100
sanding	200
cleaning castings	200
work positions at mixers	200
casting houses	200
emptying positions	200
machine forming operations	200
manual forming operations	300
core making	300
model construction	500
galvanising	300
painting	300
control stations	750
tool assembly, fine mechanics	1000
motor body operations	500
lacquering	750
night-shift lacquering	1000
upholstery	500
inspection	750

power stations:	(lx)
charging equipment	50
boiler house	100
pressure equalising chambers	200
machine rooms	100
adjoining rooms	50
switchgear in buildings	100
external switchgear	20
control rooms	300
inspection work	500

electrical industry:	(lx)
manufacture of wire and cable, assembly work, winding thick wire	300
assembly of telephone equipment, winding medium-thick wire	500
assembly of fine components, adjustment and testing	1000
assembly of fine electronic components	1500
repair work	1500

jewellery and watchmaking:	(lx)
manufacture of jewellery	1000
preparation of precious stones	1500
optical and watchmaking workshops	1500

wood preparation and woodworking:	(lx)
steam treatment	100
saw mills	200
assembly	200
selection of veneers, lacquers, model woodworking	500
woodworking machinery	500
wood finishing	500
defect control	750

paper manufacture and processing, printing:	(lx)
pulp factory	200
paper- and boardmaking machinery	300
book-binding, wallpaper printing	300
cutting, gilding, embossing, plate etching, work on blocks and plates, printing machines, stencil manufacture	500
hand printing, paper sorting	750
retouching, lithographics, hand and machine composition, finishing	1000
colour proofing in multicolour printing	1500
steel- and copper-plate engraving	2000

leather industry:	(lx)
vat operations	200
skin preparation	300
saddle making	500
leather dyeing	750
quality control, moderate demands	750
quality control, high demands	1000
quality control, extreme demands	1500
colour inspection	1000

textile manufacture and processing:	(lx)
work in dyeing vats	200
spinning	300
dyeing	300
spinning, knitting, weaving	500
sewing, material printing	750
millinery	750
trimming	1000
quality control, colour check	1000

foodstuffs industry:	(lx)
general work positions	200
mixing, unpacking	300
butchery, dairy work, milling	300
cutting and sorting	300
delicatessen, cigarette manufacture	500
quality control, decoration, sorting	500
laboratories	1000

wholesale and retail trades:	(lx)
salerooms, continuously occupied work positions	300
cashier's positions	500

trades (general examples):	(lx)
paint shops	200
pre-assembly of heating and ventilation equipment	200
locksmiths	300
garages	300
joinery	300
repair workshops	500
radio and television workshops	500

service operations:	(lx)
hotel and restaurant receptions	200
kitchens	500
dining rooms	200
buffet	300
lounges	300
self-service restaurants	300
laundries, washrooms	300
ironing machines	300
hand ironing	300
sorting	300
inspection	1000
hairdressers	500
beauty salons	750

Figure 50: Lighting levels for working areas[19]

[19] *Ernst Neufert, Architects' Data Third Edition, (Oxfort: Blackwell Science Ltd, 2000), 149*

4.3.2 Requirements building skin

The conceptual roof skin describes the local component on the roof. This roof skin has to perform a specific task in order to provide for and contribute to the desired lighting conditions of the inside functions. The requirements form the guideline for the design of the roof skin in order to meet the daylight requirements of the interior functions/spaces. The geometry of the roof describes the lay out and the build-up of the component.

Requirements:

- The roof system should provide for natural daylight on areas where it is needed.
- The roof system should be able to block direct sunlight and let diffuse light into the building.
- The roof system should amplify the direction of the building. The main direction should be longitudinal to amplify the infrastructural direction of the building.
- The roof system should provide an overall smoothness / homogenous effect of the roof so the wind performance for natural ventilation is ensured.
- The roof system should not interfere with the roof cuts for ventilation. If possible, the roof system should be amplifying the effect of the ventilation cuts.
- The roof system and the ventilation cuts should be designed by the same system.
- The design system from be parametrically based, build and optimised.
- The roof should be light in order to be able to span the spaces of the train station. The roof could be self-carrying.
- The roof system should consists of as little number of elements as possible due to the size of the roof and

4.4 References / Inspiration

These references are used for inspiration on how to deal with light in buildings with big roof spans. The references are grouped in three categories: Recent buildings, 20th century building and PhD-researches.

4.4.1 Recent buildings

- Zaragoza Bridge pavilion - Zaha Hadid

Figure 51: Zaragoza Bridge pavilion[20]

Figure 52: Zaragoza Bridge pavilion[21]

The Bridge pavilion is organized around four main sections (pods) that act as structural elements and spatial enclosures for expositions. The design on the bridge is based on a diamond shaped section which offers structural and programmatic properties. The diamond section is extruded along a slightly curved path to generate the four pods. This way, the loads are distributed across the four trusses instead of a single element, therefor reducing the size of the load-bearing elements.
Building is enveloped by a skin that not only encloses the exhibition spaces but also acts as a permeable membrane which allows air and light inside thus minimising the required cooling and heating.[22]

- Heydar Aliyev cultural centre – Zaha Hadid

Figure 53: Heydar Aliyev cultural centre[23]

[20] *Design LAB workshop, Bridge Pavilion in Zaragoza, Spain by Zaha Hadid, http://designlabworkshop.blogspot.com/2009/12/bridge-pavlilion-in-zaragoza-spain-by.html*
[21] *Gabe Bridwell, Show and Tell – Zaha Hadid, http://gabebridwell.com/index.php/tag/zaha-hadid/*
[22] *Marcus Fairs, Zaragoza Bridge Pavilion by Zaha Hadid. Dezeen magazine (2008), http://www.dezeen.com/2008/06/16/zaragoza-bridge-pavilion-by-zaha-hadid*

The Heydar Aliyev Centre is currently being built in Azerbaijan, in the city of Baku. The Centre will house a conference hall with three auditoriums, a museum and a library. The key feature of this project is the skin which emerges from the landscape's natural topography and wrapping all the functions inside. The landscape emerges from the ground to merge with the building and blurring the boundary between the building and the grounds. The continuous surface breaks up to bring light into the functions and give each function its own identity and piece of the outer skin.[24]

- Shenzhen airport – Reiser Umemoto

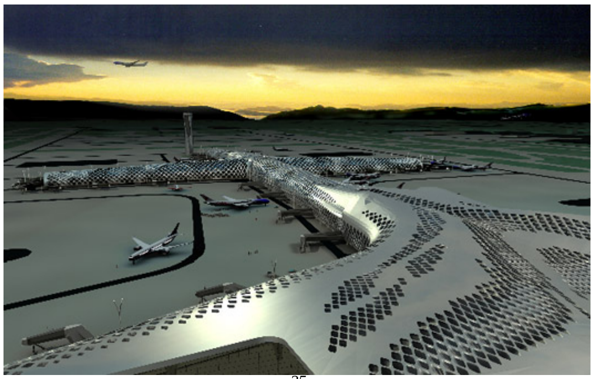



Figure 54: Shenzhen airport[25]

The roof in the Reiser + Umemoto design for the Shenzhen Bao'an International Airport competition features a diamond shaped patters. This pattern on the roof allows opening for view and daylight where necessary. The thickness and orientation of the openings are used to create shade and admit direct light into the building in such a way that the daylight requirements can be met. The roof of the building is one solid slap that looks like it has been fabricated from one solid material and contains all the functions inside it, opening up to the outside when needed.

- Shenzhen airport – Fuksas

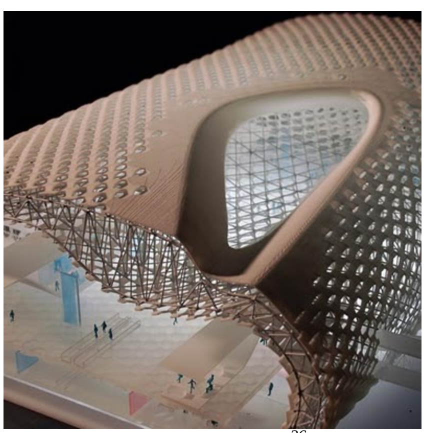



Figure 55: Shenzhen airport[26]

---

[23] *Zaha Hadid Architects. Heydar Aliyev Centre. http://www.zaha-hadid.com/cultural/heydar-aliyev-cultural-centre*
[24] *Zaha Hadid Architects. Heydar Aliyev Centre. http://www.zaha-hadid.com/cultural/heydar-aliyev-cultural-centre*
[25] *http://www.reiser-umemoto.com*

The skin of the Fuksas Design for the Shenzhen Bao'an International Airport competition features an outer and an inner skin with the structural elements in between. The structure of the skin is designed to allow for different lighting experiences needed for the various functions inside the airport while being in constant communication with the outside world. The skin is built based on a honeycomb component. Each panel varies in glass size and angle of opening to meet the requirements.

- Amsterdam Bijlmer Arena train station - Grimshaw

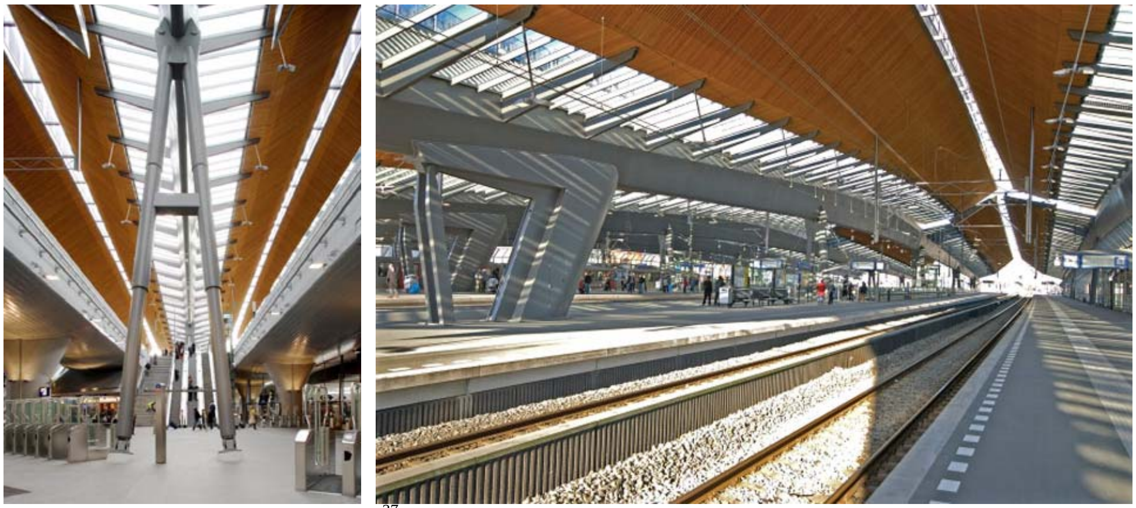


Figure 56: Amsterdam Bijlmer Arena[27]

The Amsterdam Bijlmer Arena train station is one of the newest train stations in the Netherlands. The station is laid-out in the north-south direction. The roof of the station is a sort of shed roof like the old factory building. However the openings in the roof are made in this sense. The glass covered openings in the roof are also situated in the north-south direction. In the summer there is a lot of direct sunlight entering the station and falling on the platforms due to this orientation of the glass surfaces. Because of the altitude of the sun in these situations, the direct sunlight on the platforms will not produce much glare.

---

[26] *http://www.fuksas.it*

[27] *Grimshaw Architects, Amsterdam Bijlmer Arena Station, http://www.grimshaw-architects.com/base.php?in_projectid=*

4.4.2 20th century buildings

- Insitute du Monde Arabe - Jean Nouvel

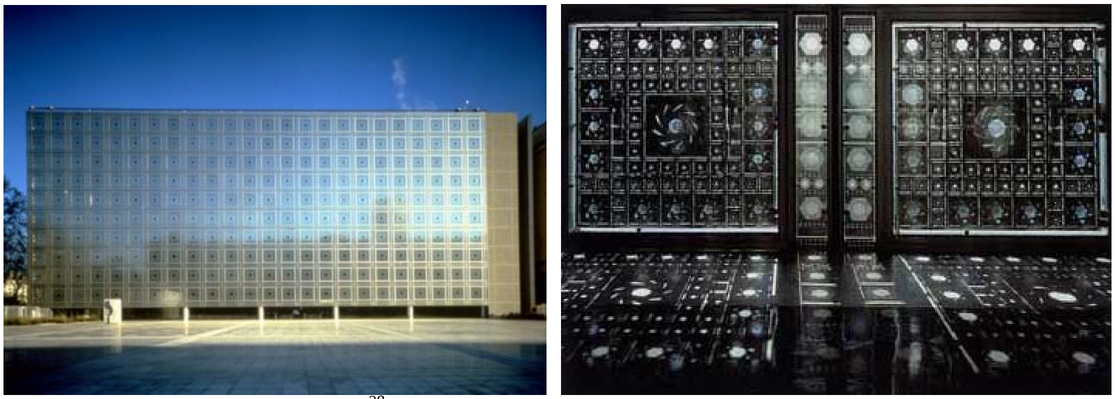


Figure 57: Insitute du Monde Arabe[28]

The Institute du Monde-arabe which is designed by Jean Nouvel and completed in 1987 in Paris. For the time it featured one of the most high tech facades of the world. Electronically controlled sun-shading diaphragms like mechanical versions of traditional Arabic screens were used to control the amount of direct sunlight entering the building. It seemed like a good idea, but time has learned that the mechanic sun-shading devices will stop working after a while. This is the same with other dynamic sun-shading devices and roofs.[29]

- Pinakothek der Moderne Munich – Stephan Braunfels Architekten

Figure 58: Pinakothek Munich[30]

De Pinakothek der Moderne is a museum complex that houses four different collections, art, architecture, design and works on paper. It is designed by Stephan Braunfels and was completed in September 2002. The entrance and centre of building is the three-story rotunda.

[28] *www.jeannouvel.com*

[29] *William j.r. Curtis, Modern Architecture since 1900, (London: Phaidon Press Limited, 2005), 672-673*

[30] *Stephan Braunfels Architekten, Pinakothek der Moderne, http://www.braunfels-architekten.de/pd_pinakothek.html?en,3,2,1,2,0px*

From this atrium, all the galleries are branching off. The Pinakothek features a very effective way of lighting the exhibitions spaces. The exhibitions spaces are covered by big translucent sky lights which, together with the white walls, bring a very even distributed, diffuse light into the building that is very suitable for the exhibitions.[31]

- Bauhaus Archives Berlin – Walter Gropius

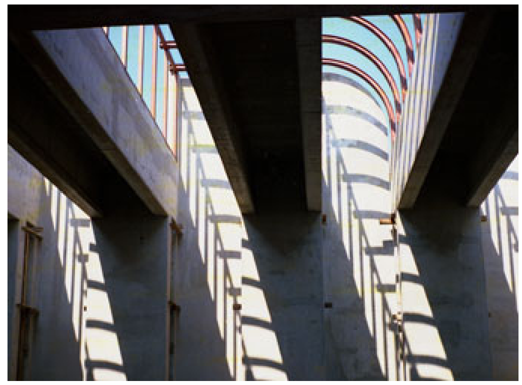



Figure 59: Bauhaus Archives Berlin[32]

The Bauhaus archives were commissioned to house the growing collection of the Bauhaus movement in Berlin. The building is designed by Walter Gropius in 1964 and completed in 1979. The most interesting aspect of the building is the shed roof system. The glass openings of the sheds are facing north to prevent direct sunlight from entering the building. The shapes of the sheds are designed to bring double reflected light diffusely into the building.

4.4.3 PhD-researches

- Yoshimura Fold - Florian Heinzelmann

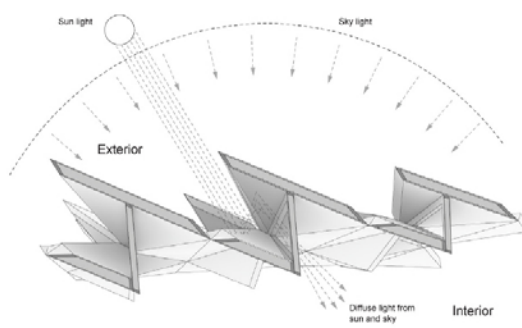



Figure 60: Yoshimura Fold[33]

This research from Florian Heinzelmann investigates a performance based parametric design principle for tessellating roof shapes based on the Yoshimura Origami fold. The folding of the skin creates openings with various apertures in order to regulate the amount and type of

[31] *Stephan Braunfels Architekten, Pinakothek der Moderne, http://www.braunfels-architekten.de/pd_pinakothek.html?en,3,2,1,2,0px*
[32] *www.bauhaus.de*
[33] *Florian Heinzelmann, 'Lightweight Origami structure & daylighting modulation,' (Paper presented at the annual IASS Symposium, Valencia, Spain, September 2009)*

daylight entering the building. This system also adds structural height to the roof, enabling it to span large areas.[34]

[34] *Florian Heinzelmann, 'Lightweight Origami structure & daylighting modulation,' (Paper presented at the annual IASS Symposium, Valencia, Spain, September 2009)*

4.5 Solar analysis roof

As a basis for the component design, first the daylight conditions in the building with a closed roof must be analysed. The roof and floors of the building are imported in Ecotect. On these surfaces, the following daylight conditions will be analysed in radiance:

- Daylight factor values
- Illumination of functions inside the building
- Sun & shade

4.5.1 Input parameters

When doing a solar analysis for a building, it is vital to know the orientation of the building and the solar conditions on the site. The site for this building is the highway intersection at Haarlemmerliede. This building is situated over the highway with urban fabric on both sides of the highway.

Figure 61: Orientation building

4.5.2 Geometry of the test model

The geometry of the Schiphol Interchange Station has to be prepared before it is suitable for radiance analysis in Ecotect. The 3D-model is stripped of all unnecessary objects and surfaces in order to make it as light as possible for daylight analysis in Ecotect. For this mode,l the doubly curved bottom of the building is omitted. This doesn't affect any results and greatly improves the calculation time.

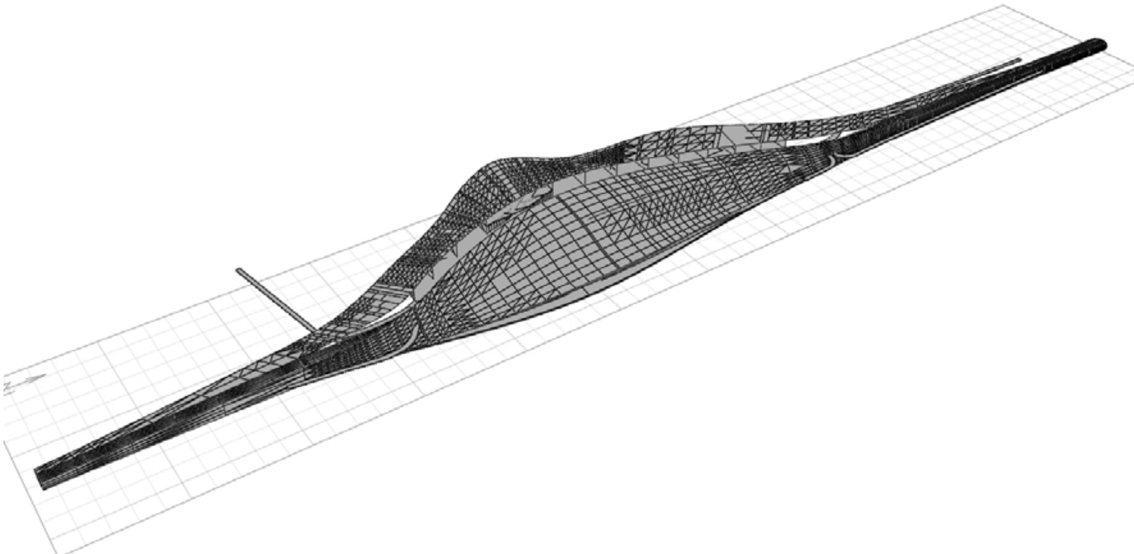


Figure 62: Ecotect geometry for Daylight testing

The surfaces of the glass facades in the front of the building and in the shopping street are omitted for calculation purposes. By omitting the surfaces, the facades are simulated as 100% transparent glass facades.

4.5.3 Daylight factors

The daylight factor expresses the percentage of light in that point in the building of the total CIE overcast sky. The daylight factors show the possible need for electrical lighting in the different functions of the train station.

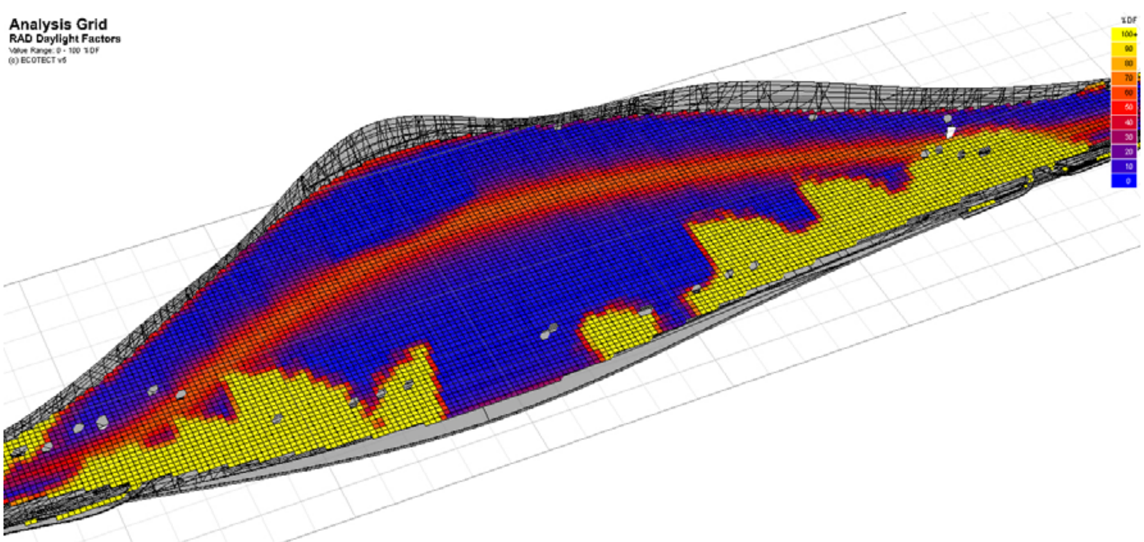


Figure 63: Daylight factors Shopping street/Retail (+19m)

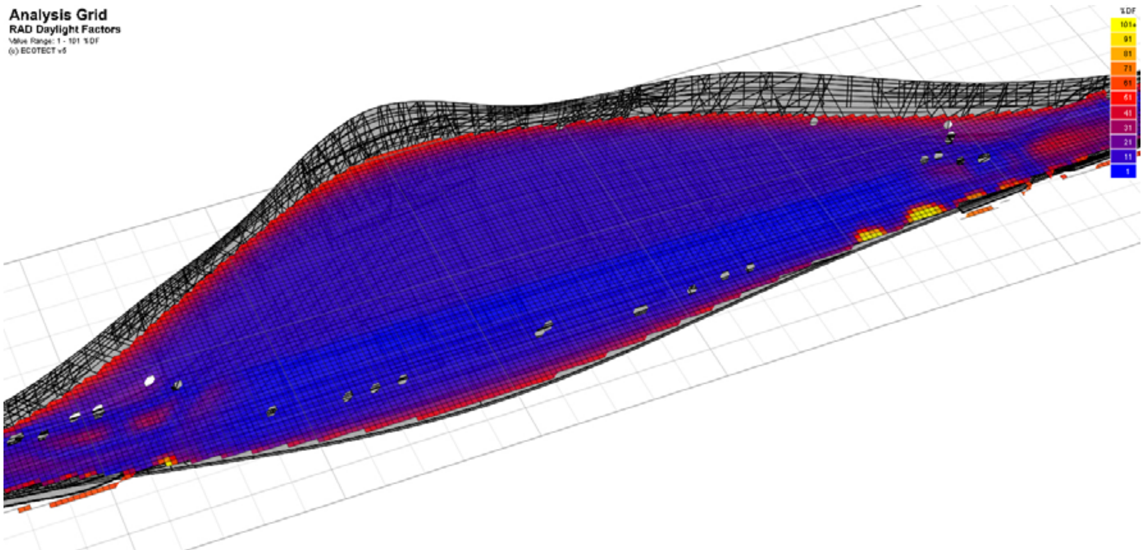


Figure 64: Daylight factors Kiss & ride/Platforms (+13m)

Functions	Mean daylight factor [%]
Central square	2
Retail outside	3
Retail inside	3
Cafe	2
Shopping street	65
Kiss & ride	2
Platforms	4

Table 8: Daylight factors from radiance

The mean daylight factors for the functions show that only the shopping street has adequate daylight levels, the other function don't have sufficient lighting and need additional daylight or electrical lighting.The design of a surface component / roof system should allow more light into the building through the roof. This could improve the illuminance levels and daylight factors in the building.

4.6 Preliminary daylight study: Physical tests (qualitative)

In the general information section of this chapter, some aspects regarding light and daylight were introduced and explained. To get a better understanding of the effect on the light quality of these previously introduced aspects, 34 physical tests were conducted. Each test contains a physical model with a new type of geometry or material property that is being tested. These 34 tests will be compared in the comparative chart.

4.6.1 Set up

These tests have been conducted in a square shoe box. The shoebox is inlaid with white paper in order to get a good image of the light and casted shadows. The top of the shoebox can be replaced with different roof systems, geometries and materials to test their influences on the previous introduced light aspects. The short sides of the box are oriented in the north-south direction. The camera is attached to the short south-facing side of the box. In this way, the light is never shining directly into the lens. A standard desk lamp is used for simulating the direct and diffuse sunlight in these tests.

Figure 65: Test set up

4.6.2 Test settings

These physical tests are all simulated in summer time, on the 21st of July, when the sunlight is the most intense and is likely to cause discomfort. For each set up, three images are taken.

Test	date	time	azimuth	altitude
1	21 July	9:00	90	27
2	21 July	14:00	180	60
3	21 July	19:00	270	23

Table 9: Test settings

The photos are taken in a dark room without additional daylight. The camera is shooting with an aperture of F10 and a shutter speed of 1,6 seconds. These settings have proven to give the best results where the lightest pictures are not completely white and the darkest picture not completely black.

4.6.3 Test results

These test results are a selection from the comparative lighting chart in the appendix to show a few key results of the tests.


Figure 66: Translucent material


Figure 67: Thickness to avoid glare


Figure 68: Inward inclined plane


Figure 69: Outward inclined plane


Figure 70: High reflective material


Figure 71: Double reflection

Figure 72: Inclined solar shading slabs

Figure 73: Diamond pattern, no glare

Conclusions

The thickness of a horizontal roof can be used to prevent direct sunlight from entering the building in the morning and evening. The width of a north-south oriented opening shouldn't exceed more than twice the high of the opening if glare is to be avoided.

Translucent materials can be used very effectively to bring light into the building in places where direct solar radiation should be avoided. Translucent materials also provide for a more even light distribution in the building. Although direct solar radiation is not entering the building, solar heat is entering the building and heating it up.

In plane roof and façade opening are a good way to bring light into the whole building. Openings in the roof into specific directions by using roof cuts are less effective and don't give an even light distribution.

By opening the roof to the eastern direction, a large amount of direct solar radiation enters the building in the morning. In the afternoon and the evening no direct radiation is entering the building. Also, glare can cause problems in the morning hours.

The use of double reflections of sunlight through the geometry is a very effective way to bring light diffusely into the building. However it only works during some parts of the day and doesn't provide for an evenly distribution of the light inside the building.

Curved planes can be used in a roof or façade to make the best use of the double reflection to bring as much diffuse light into the building.

The material and finishing of the material of the reflecting surfaces has a big impact on the way the light is being reflected in the building and the amount that is admitted to the building. High reflecting materials bring much more light into the building when inclined at a specific angle.

When using a north-south oriented glass strip in the roof of a building, south-west oriented inclined sun shading strips can be used to reduce the direct radiation and heat load during summer afternoons.

4.7 Secondary daylight study: numerical analysis (quantitative)

With the conclusions from the qualitative daylight study and the reference projects, four different roof designs will be proposed to meet the requited lighting conditions inside the building. These four roof designs will be tested and analysed both physically and digitally. By comparing the physical and digital numeric results, they can be validated._With the results of the physical tests and digital tests along with the architectural possibilities, the best roof design will be selected for further research and development.

4.7.1 Roof designs

These designs are all based on the daylight requirements, results from the qualitative light study and the architectural concepts for the roof of the building and spaces inside the building.

Cuts design

The Cuts design is based on the idea of creating a system of openings that will allow for daylight to enter the building and also allows the natural ventilation of the central atrium. The cuts in the centre of building will allow for natural ventilation while the other cuts allow for light to enter the building.

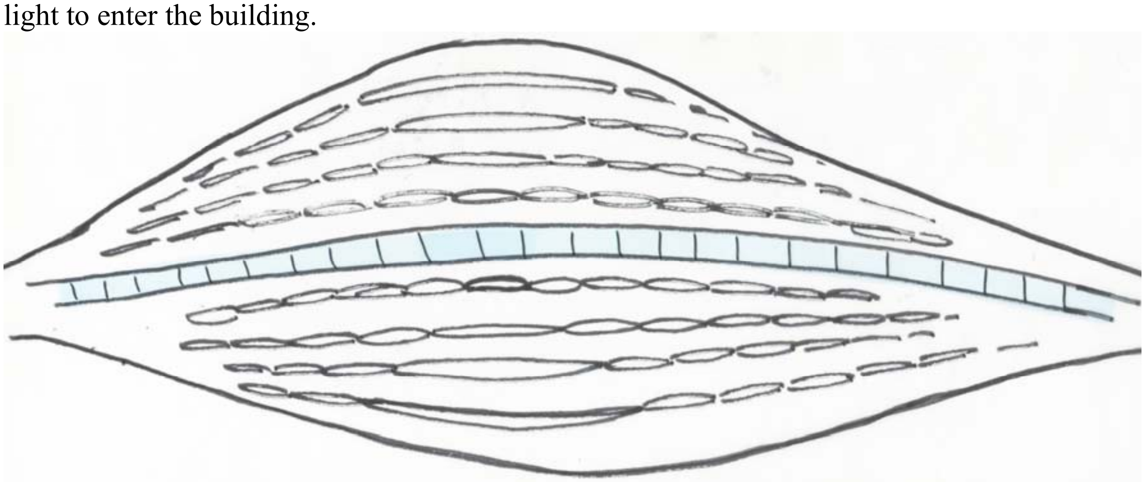


Figure 74: cuts design

Each cut has its own X,Y and Z vector for transformation. This XYZ-vector is specific for this component. A high amount of variations for the opening of the component can be made by controlling both vectors and curves that create the opening. This way the cuts can be set up for viewing, ventilation or daylight purposes. The X, Y and Z-vector will be individually controlled by a specific daylight/viewing aspect. The X-vector is controlled by the required amount of daylight inside, the Y-vector by the need for shading inside and the Z-vector is controlled by required view from inside to outside.

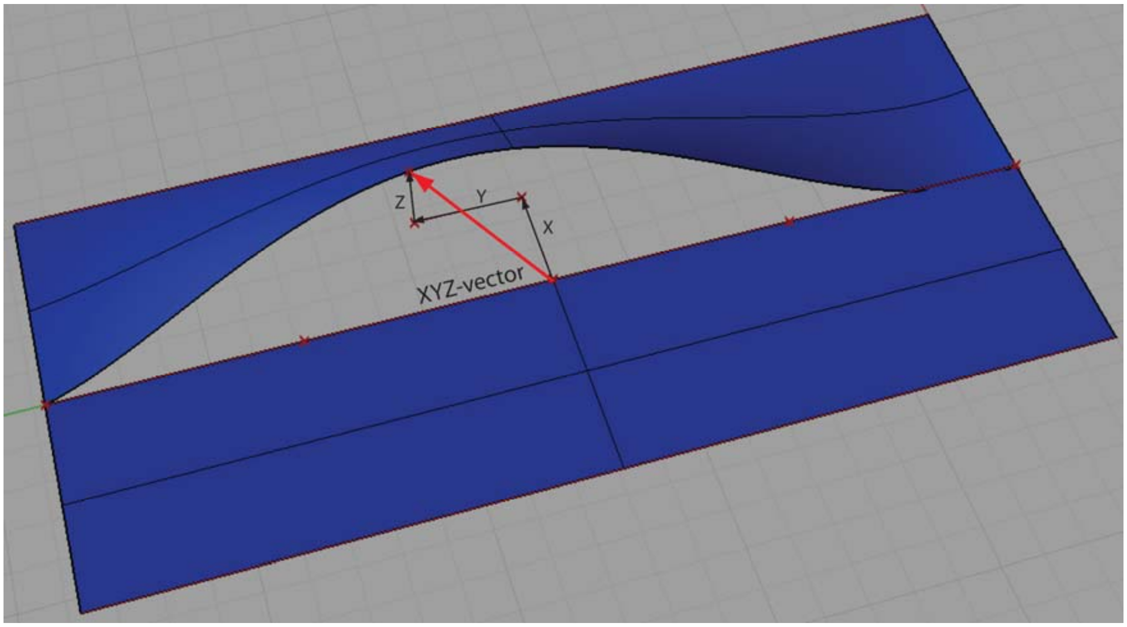


Figure 75: XYZ-vector displacement

Slab design

The Slab design is based on the idea of preventing glare inside the station in the morning and the afternoon when the sun altitude is low enough to cause glare. The thickness of the roof and the width of the glass strips are important. If the width of the glass strip is not more than twice the height of the thickness of the roof, all direct light in the morning and evening is prevented from getting inside and reflected in a diffuse way.

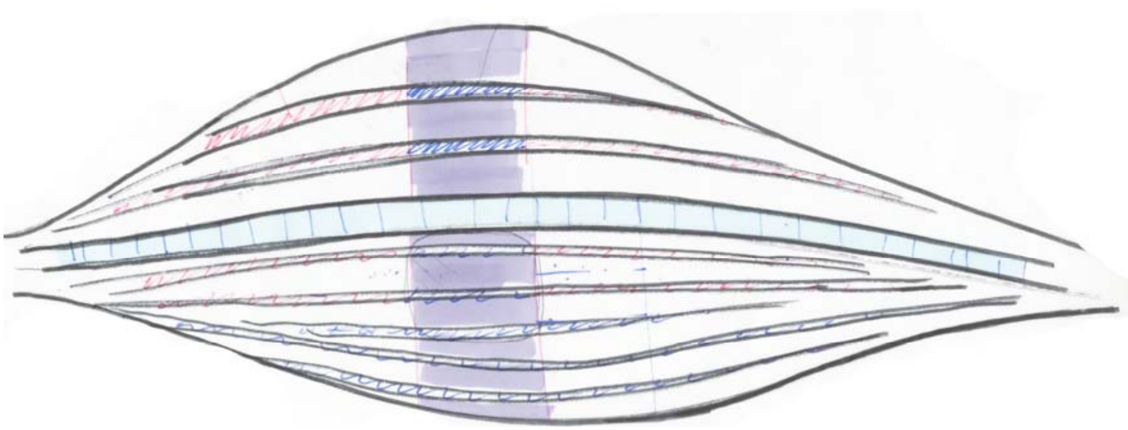


Figure 76: slab design

The slab design integrates the need for daylight in certain parts of the building and the possibility to naturally ventilate the building through the glass areas covering the central square. Just like in the Heydar Aliyev cultural centre from Zaha Hadid, the slabs are able to converge and diverge, to move up and down. With this design, the required daylight and ventilation levels could be achieved.

Scoop design

The Scoop design is based on the idea of locally allowing more daylight into the building while preventing glare in the morning and afternoon from entering the building. The scoop design doesn't have one main direction such as the cuts design or slab design. The scoop design is bases on an omni-directional, single roof slab without orientation.

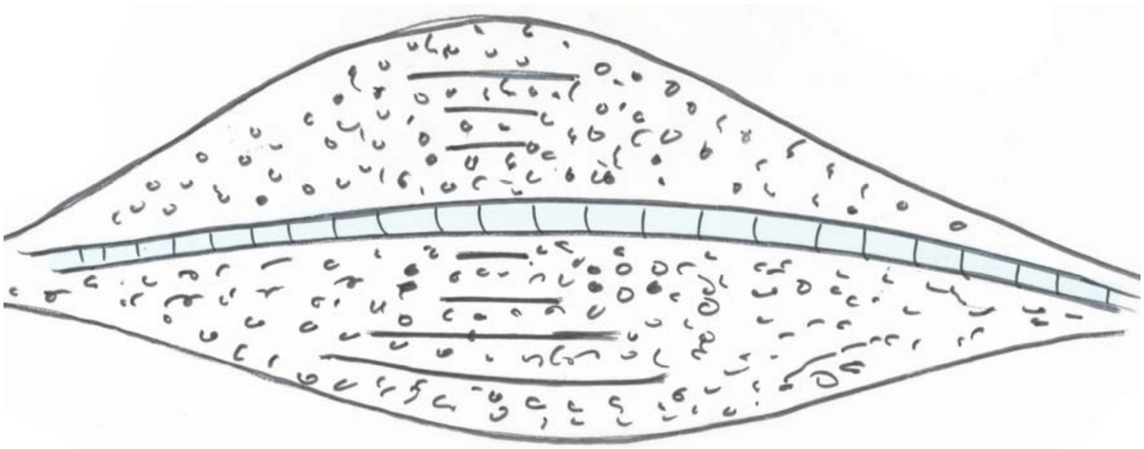


Figure 77: scoop design

The size of the scoops and the density of the scoops could change when there is a change in lighting requirements. Just like in the Shenzhen Airport designed by Fuksas, the lights scoops would have to be omitted around the ventilation cuts in order to secure the structural integrity of the roof and the visual aspect of the ventilation cut. Fresnel lenses could be used to redirect the light that hits the roof of the building downwards into the train station. Fresnel lenses have the advantage that they are cheap to fabricate, have a have a relatively small thickness and can be fabricated with diameters up to a few meters, which is far larger than normal lenses or mirrors. [35]

Grid design

The Grid design is based on a diamond shaped pattern which is draped over the roof geometry. With the diamond shaped grid is it possible to realise the doubly curved roof that was envisioned in the architectural design and wind research. The thickness of the material and the aperture of the openings could prevent glare in the morning and afternoon. The aperture of the diamond cells should be individually connected to the light requirements of functions in the building. Transparent as well as translucent materials could be used to get the desired lighting effect in certain spaces.

[35] *3Dlens.com. Fresnel Lens Polarizer. http://www.3dlens.com/*

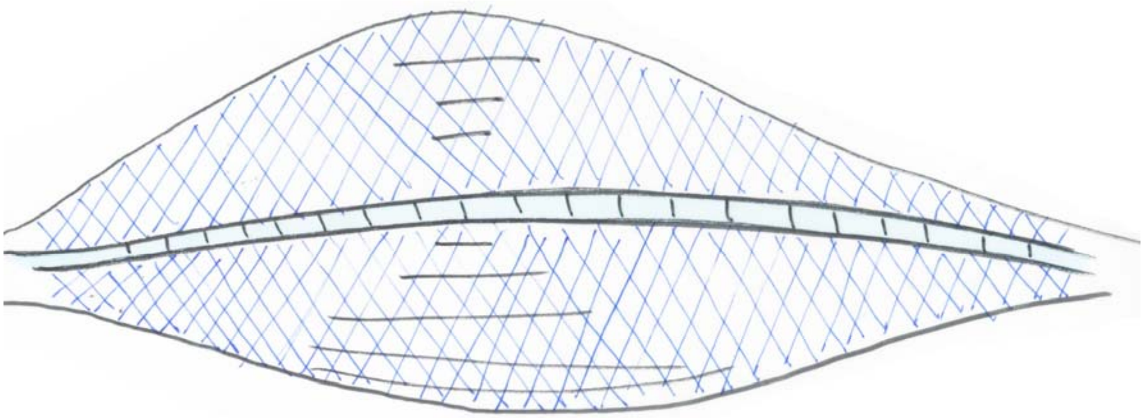


Figure 78: grid design

Just like in the Reiser + Umemoto design for the Shenzen airport, the top and bottom layer of the diamond shaped grid could be displaced to prevent direct radiation in certain moments during the day from entering. A possible problem could arise when trying to integrate the diamond grid with the openings for the natural ventilation. The ventilation openings have to be positioned on the centre lines of the diamond grid. Also, the size of the grid is important to adjust to the ventilation openings.

4.7.2 Work flow and set up

To be able to conduct physical and digital numerical tests, the roof designs have to be simplified. This makes it possible to accurately produce the physical models. The simplified models have been precisely modelled physically and digitally. If the test models are exactly the same, the results can be compared later between physical and digital simulation. The results and conclusions from these tests then have to be compared based on the lighting and architectural requirements. One of the concepts can then be selected as a basis for the new roof design.

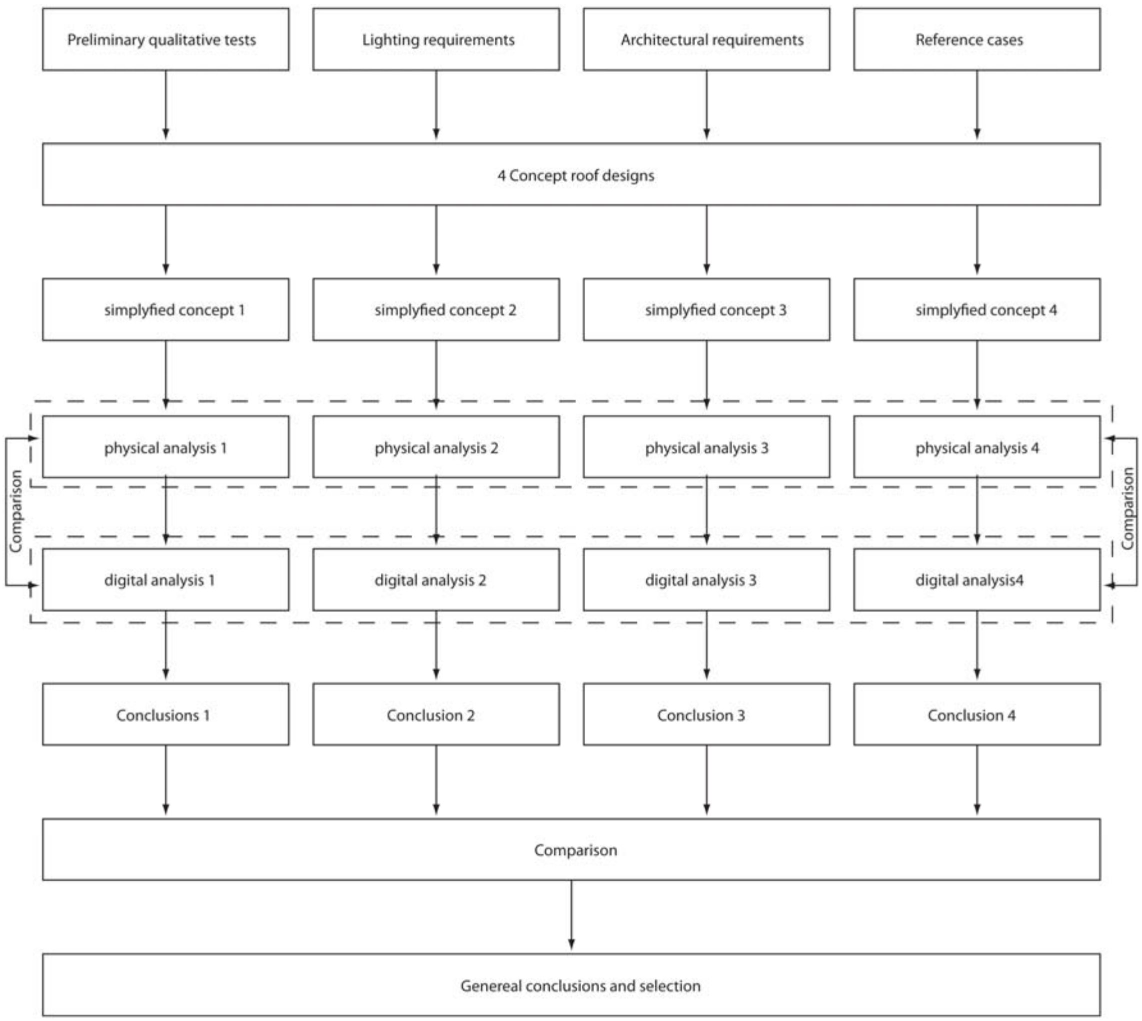


Figure 79: Work flow numerical tests

4.7.3 Physical tests

These physical tests are conducted in order to set a baseline for the digital tests. These physical tests will investigate the influence of four types of roof systems/geometries on the qualitative and quantitative daylight inside the building.

Designs

For fabrication purposes, the four roof designs are simplified to their essentials. The four designs are simplified to single curved designs measuring 30 by 15 cm in size. The roof designs will be manufactured by using the lasercutting machine of the camlab from the Architecture faculty. Using the lasercutter is the only way to precisely fabricate the roof designs. This precision is necessary to get accurate results and a meaningful comparison between the physical and digital results.

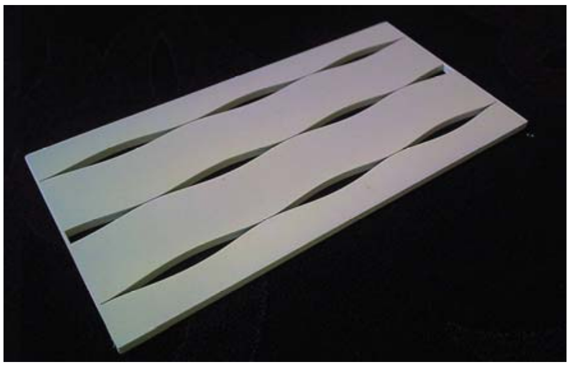


Figure 80: Cuts design model

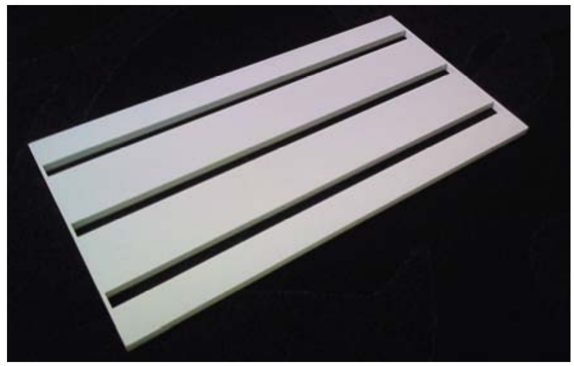


Figure 81: Slab design model

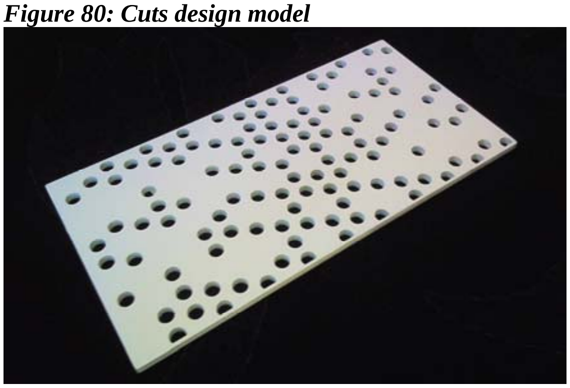


Figure 82: Scoop design model

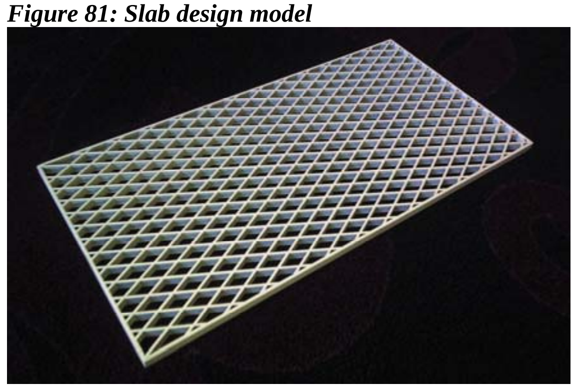


Figure 83: Grid design model

In order to make a valid comparison between the design concepts, the area of the roof openings have to be measured and compared.

#	Design	Area Closed [m2]	Area openings [m2]	Opening percentage [%]
1	Closed roof	472,75	0	0
2	Cuts	424,93	47,82	10,1
3	Slab	382,75	90	19,0
4	Scoop	382,4	90,35	19,1
5	Grid	165,42	307,33	65,0

Table 10: Openings of roof designs

Illumination values

Climate conditions: Overcast sky
Date: 15 June, 2011
Time: 15:00 – 17:00
Outside illuminance: 35 000-37 000 lux

These values are measured within the test box with the four different roof designs as described before.

- *Set up*

These tests are conducted on a big empty parking place close to the Delft train station. In Delft, this is the best place to conduct these measurements. The ground is level and the surrounding buildings aren't very tall and they are far away. The influence of the direct environment on the daylight measurements is therefore minimal. In this way the results of these physical tests can be compared to the digital tests.

The illuminance meters which are used for this test are from Konica Minolta's T-10 series. The T-10 and T10M are used to measure the illumination strength in the tests. The T-10 is used for standard illuminance measurements (exterior) and the T-10M for small-surface illuminance measurements (interior). [36]

Figure 84: Interior and exterior illumination meters

The measuring points inside the box are conducted on two lines, the front and middle lines. The front line is located 3 cm from the south side of the box and the middle line is located 15 cm from the south side of the box. These two lines will give enough information about the illumination values and distribution on the floor of the test box. The two lines start 2.5 cm from the long side of the box and feature 21 measuring points each with 5 mm spacing between the points.

[36] *Konica Minolta. T-10 Series. http://www.konicaminolta.eu/measuring-instruments/products/light-display-measurement/illuminance-meters/t-10-series/introduction.html*

When executing the tests, the T-10M illuminace meters is used to measure the illuminance on the designated interior measuring points. The T-10 illuminace meter is used to verify a stable exterior illumination when gathering data from the interior sensor.

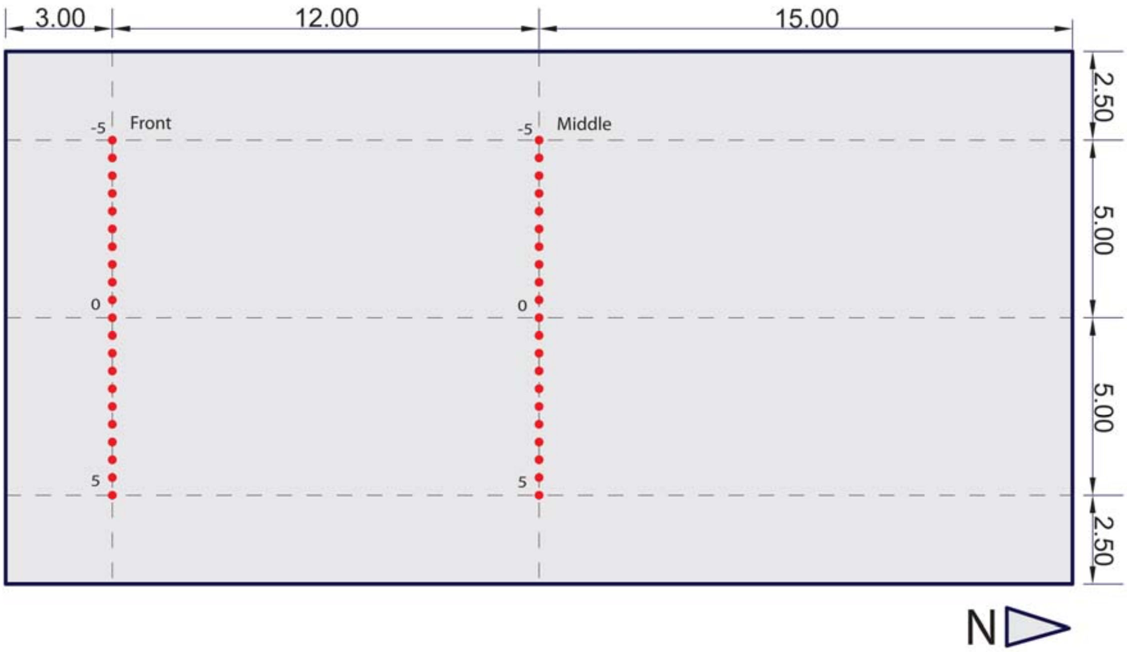


Figure 85: Measuring points for illumination

The illumination sensor is placed within the grove in the bottom of the test box. The slider features a scale with the 21 measuring points and is manually controlled into the correct position. The middle grove is covered to minimise the measuring error.

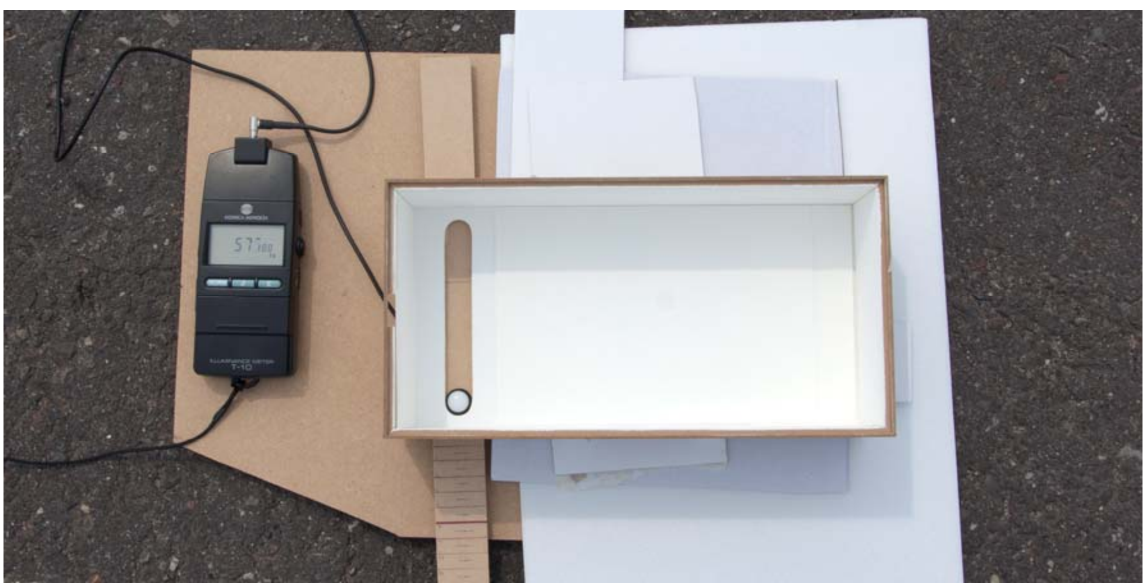


Figure 86: Set up illumination test

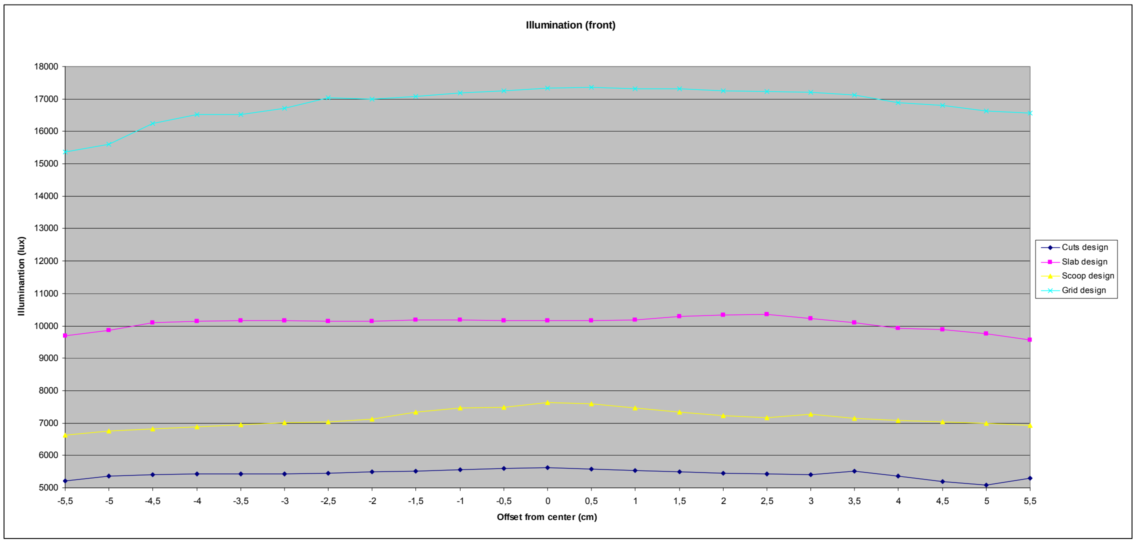


Figure 87: Illuminance values front

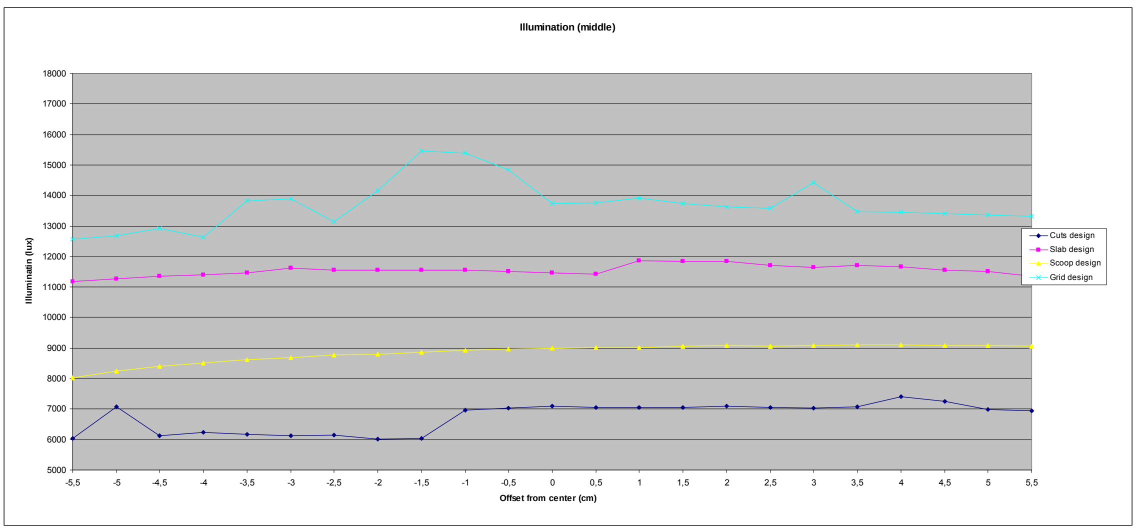


Figure 88: Illuminance values middle

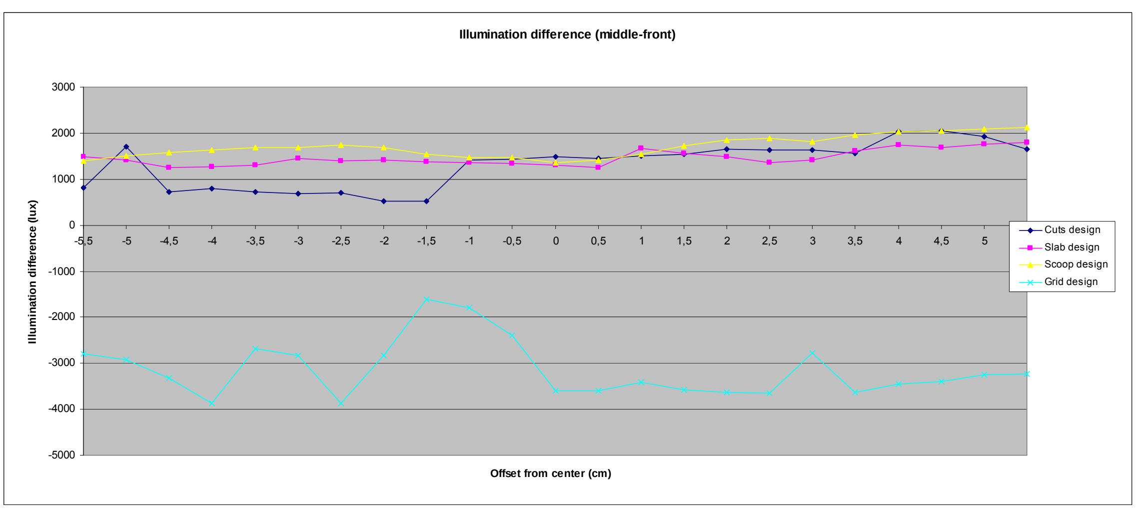


Figure 89: Illuminance differences between middle and front measurement

Findings illumination values physical tests

#	Design	Opening percentage [%]	Average illumination [lux]	Effectiveness per % [Lux]
1	Closed roof	0	0	0
2	Cuts	10,12	6083,26	601,4
3	Slab	19,04	10815,92	568,1
4	Scoop	19,11	7996,71	418,4
5	Grid	65,01	15280,90	235,1

Table 11: Effectiveness physical roof designs

- All designs achieve an average illumination value on the floor of the room of at least 5000 lux.
- All designs show a small parabolic distribution from -5.5 to 5.5 as was expected since the diffuse sky component close to the walls is smaller.
- The cuts design has an average illumination at the front measurements of 5427 lux and 6740 lux at the middle measurements.
- The slab design has an average illumination at the front measurements of 10082 lux and 11550 lux at the middle measurements.
- The scoop design has an average illumination at the front measurements of 7143 lux and 8850 lux at the middle measurements.
- The grid design has an average illumination at the front measurements of 16849 lux and 13713 lux at the middle measurements.
- The grid design has from the four designs the highest illuminance values on the bottom surface or the box followed by the slab design, then the scoop design and the cuts design has the lowest illuminance values.
- The illumination values of the middle nodes are on average about 1500 lux higher that the illumination values of the front nodes. An exception is the grid design.
- The middle illuminance values with the grid design are on average 3000 lux lower than the front illuminance values. This seems highly possible from a theoretical point of view since the middle measuring points have a bigger diffuse sky component. Therefore, the middle illumination values are for now regarded as measurement errors.
- The cuts design is from the four designs the most effective to bring light into the building followed by the slab design, then the scoop design and the grid design is the least effective.
- The cuts and slab design are both more than twice as effective as the grid design.

Luminance images

- Set up

The test set up to obtain the luminance images is essentially almost the same as the set up for the illuminance values. The hole for the luminance meter is covered since the illuminance meter is not necessary for taking the lumination pictures. To take the pictures, a calibrated DSLR Canon camera with a 18-50 mm lens is attached to the box. This provides a good view of all the inside walls of the box.

Figure 90: Set up for Luminance images

The camera settings need to be adjusted before making the pictures. The camera makes 3 pictures in a row with different exposure levels (0, -2.5, and 2.5). Since the body and lens of the camera are calibrated, special software (Techno Team LMK 2000) is able to merge these three photos in a lumination image. These lumination images show a false colour rendering of the lumination (cd/m2) values on the surfaces inside the box.[37]

---

[37] *TechnoTeam Bildverabeitung GmbH. http://www.technoteam.de*

Test 1

Climate conditions: Overcast sky
Date: 15 June, 2011
Time: 16:25
Outside illuminance: 30 000 lux

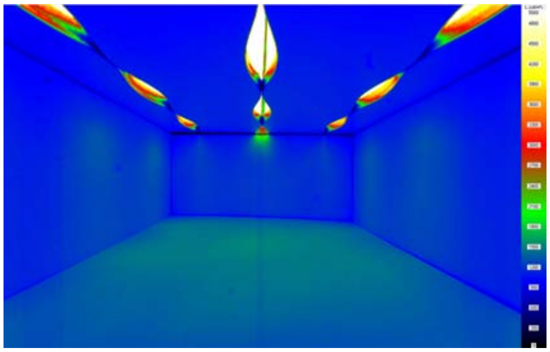


Figure 91: Luminance values cuts design

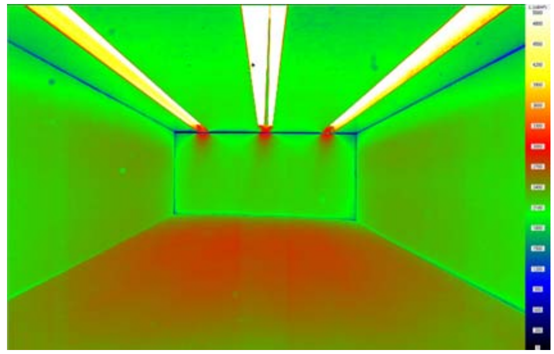


Figure 92: Luminance values slab design

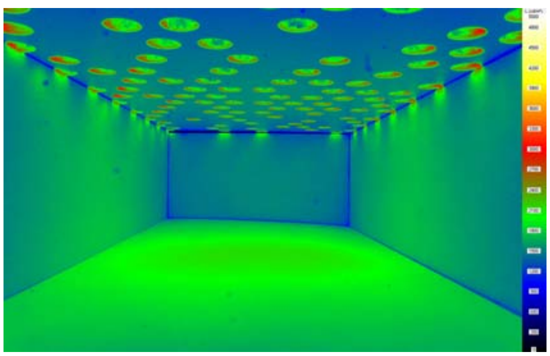


Figure 93: Luminance values scoop design

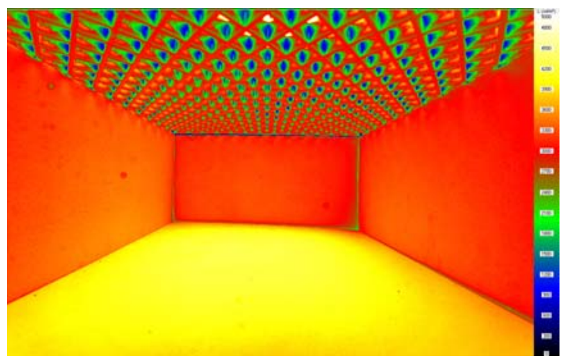


Figure 94: Luminance values grid design

Test 2

Climate conditions: Overcast sky with direct sunlight
Date: 15 June, 2011
Time: 15:05
Outside illuminance: 63 000 lux

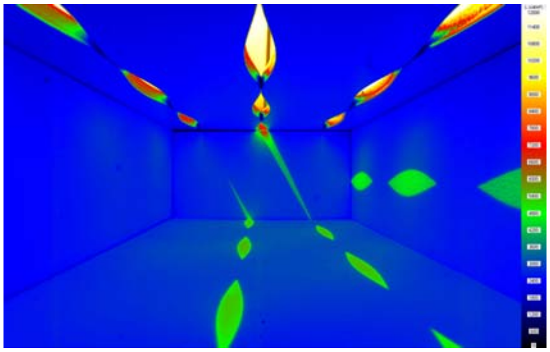


Figure 95: Luminance values cuts design

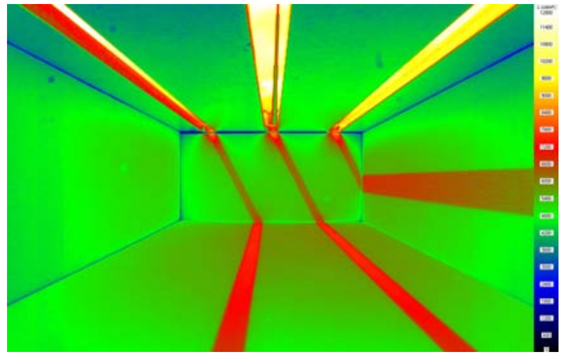


Figure 96: Luminance values slab design

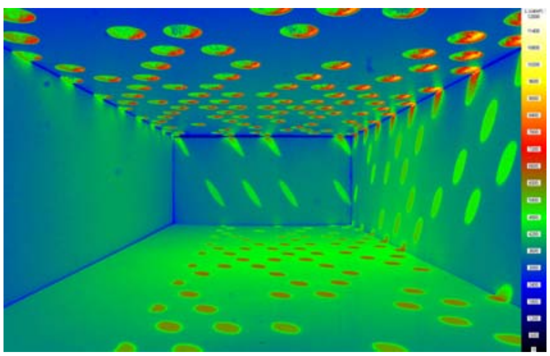


Figure 97: Luminance values scoop design

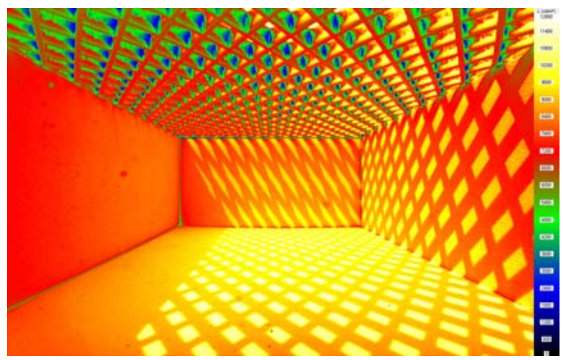


Figure 98: Luminance values grid design

Findings lumination values physical tests

	overcast sky			overcast + direct sunlight	
	diffuse1 [cd/m2]	diffuse through direct [cd/m2]	diffuse 2 [cd/m2]	direct + diffuse [cd/m2]	direct [cd/m2]
cuts	1400	1450	**2850**	**5000**	**2150**
slab	2600	2800	**5400**	**7250**	**1850**
scoop	1850	2300	**4150**	**6150**	**2000**
grid	4000	5000	**9000**	**11200**	**2200**

Table 12: Lamination values physical test

- The calculated direct lumination is ~2000 cd/m2 for each roof design. This verifies the almost constant lighting conditions during the tests.
- The direct sunlight also adds diffuse radiation to the test box due to reflection inside the test box.
- The diffuse lumination in the test box doubles when direct sunlight enters the test box.
- The floor of the test box in the overcast sky calculation is evenly lit with every roof design. The cuts and slab design appear to be less evenly lit as the scoop and the grid design due to the constraints of the test box.
- Discomfort from high contrasts between direct lit areas and diffuse lit areas can be a problem. The perceived contrast is ~2000 cd/m2 with each roof design.
- The total brightness of the test box can lead to visual discomfort. The grid design has the highest average luminance values with direct sunlight. However, the total brightness is related to the openings in the roof so it doesn't necessarily mean that the grid design will lead to more visual discomfort from high brightness.

	Overcast sky		
	Opening percentage [%]	average diffuse lumination [cd/m2]	Effectiveness per % [cd/m2]
cuts	10,12	1414	139,8
slab	19,04	2580	135,5
scoop	19,11	1863	97,5
grid	65,01	4002	61,6

Table 13: Effectiveness roof openings

- All designs achieve an average lumination value on the floor of the room of at least 1402 cd/m2.
- The cuts design is from the four designs the most effective to bring light into the building followed by the slab design, then the scoop design and the grid design is the least effective.
- The cuts and slab design are both more than twice as effective as the grid design.

4.7.4 Digital tests

These digital tests are conducted in order to verify the results from the physical test and investigate the levels of precision of the digital test. In order to be able to compare the results from the physical and digital test, the digital model has to be as accurate as possible, both in modelled geometry and set up values such as date, time sky illumination and materials.

Designs

These are the digital models of the four designs which have been physically tested. The scale, geometry and dimensions are identical to the physical models.

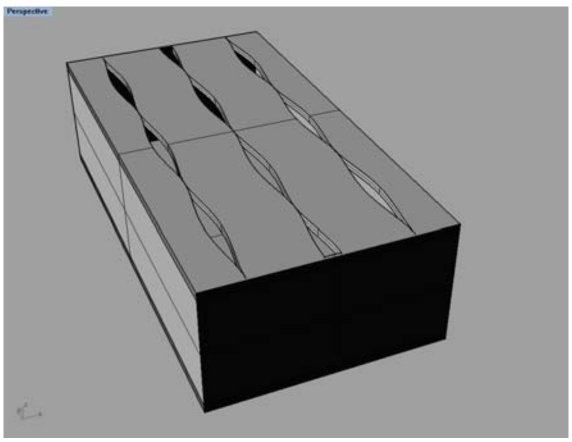


Figure 99: Cuts design model

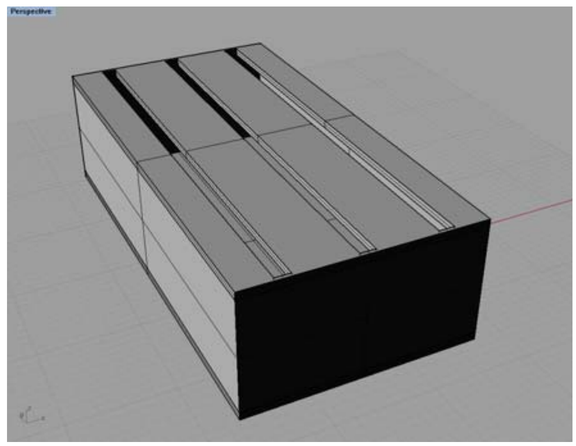


Figure 100: Slab design model

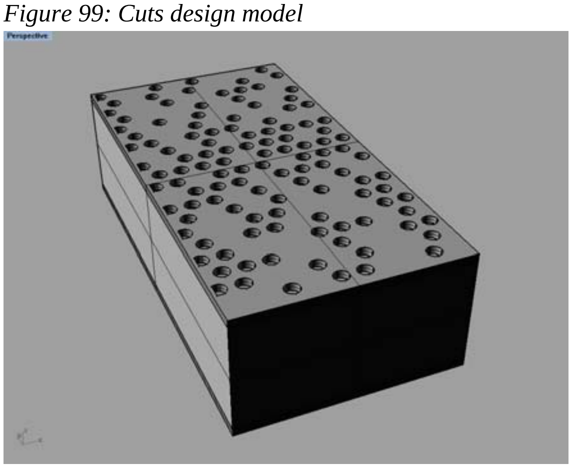


Figure 101: Scoop design model

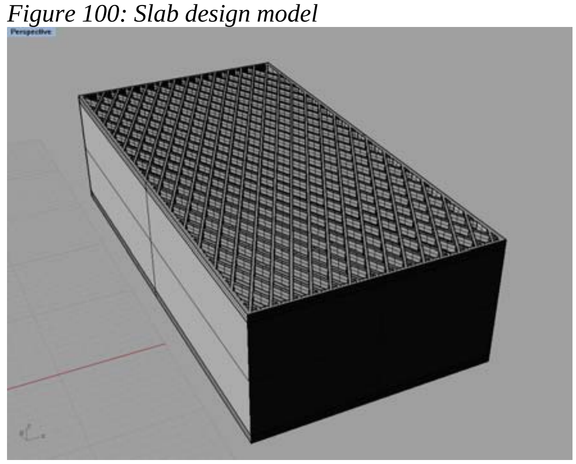


Figure 102: Grid design model

Set up

Parameters digitals test:

The outside illuminance in the physical test of 35 000-37 000 lux is measured on a horinzontal plane with an overcast sky between 15:00 and 17:00. To test the digital model in Ecotect with the same sky illuminance as the physical models, the design sky illuminace has to be determined which gives an illumination on the horizontal plane of 35 000 lux.
The illumination of a given horizontal plane is a combination of the diffuse radiation and the direct radiation.

Total radiation (W/m2) = Diffuse radiation (W/m2) + Direct radiation (W/m2)

Since the sky illumination at the physical tests is assumed CIE overcast, the sky conditions are set to Cloudy Sky (CIE overcast) in Ecotect. The design sky illumination is set to 32 767 lux since that is the maximum value in Ecotect.

Sky Conditions:	Cloudy Sky
Date:	15 June, 2011
Time:	15:00
Design Sky illuminance:	32 767 lux

Grid

The grid inside the digital test box has to be set up in such a way that for every measuring point in the physical test (figure x) there is grid point in the digital grid with the same x,y-value. This means that the grid for the digital model has 10 divisions in X-direction and 30 divisions in Y-direction.

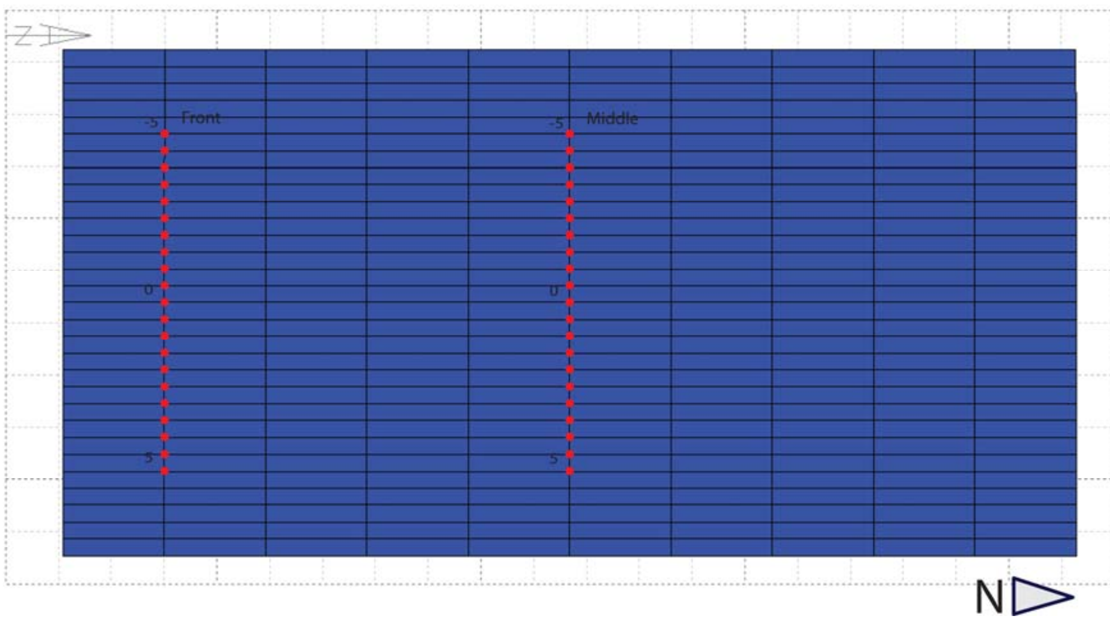


Figure 103: Grid division for digital model

Radiance ambient values

The results from radiance rely heavily on the correct numerical 'rtrace' parameters. Radiance features a large number of parameters to change and adjust. To get meaningful qualitative output from radiance, these parameters have to be set correctly. The 'rtrace' parameters which are documented on the radiance website can be split into six groups.

Explanation all parameters: *http://radsite.lbl.gov/radiance/man_html/rtrace.1.html*

From these six groups, the ambient parameters are the most important. There are seven ambient parameters which control the calculation. These parameters control the way radiance uses indirect calculation for the diffuse inter-reflection between surfaces. These parameters

determine, for instance, the amount of times the light bounces between surfaces and the accuracy of the radiance calculations.
The values for the ambient parameters in table 14 have been selected as they have proven to produce accurate results within acceptable calculation times. The other ‘rtrace’ parameters stay on the programs default values.[38]

	ambient parameters	value
1	ambient value (-av)	0.01 0.01 0.01
2	ambient weight (-aw)	-
3	ambient divisions (-ad)	2048
4	ambient supersample (-as)	512
5	ambient bounces (-ab)	7
6	ambient accuracy (-aa)	0.1
7	ambient resolution (-ar)	128

Table 14: Radiance ambient values

Reflection coefficient

As a start to the physical test, the physical properties of the test box have to be measured in order to use these values in the digital tests. This way, the results from the physical and digital tests can be compared. The reflection coefficient of the material in the test box has to be calculated. In order to do thi,s a Luminance photograph is taken of a wall in the test box with a reference plate on top. The luminance values of the test box and reference plate can be measured from this photo. Also, the reflection coefficient of the reference plate is known. The reflection coefficient of the test box can be calculated with this data.

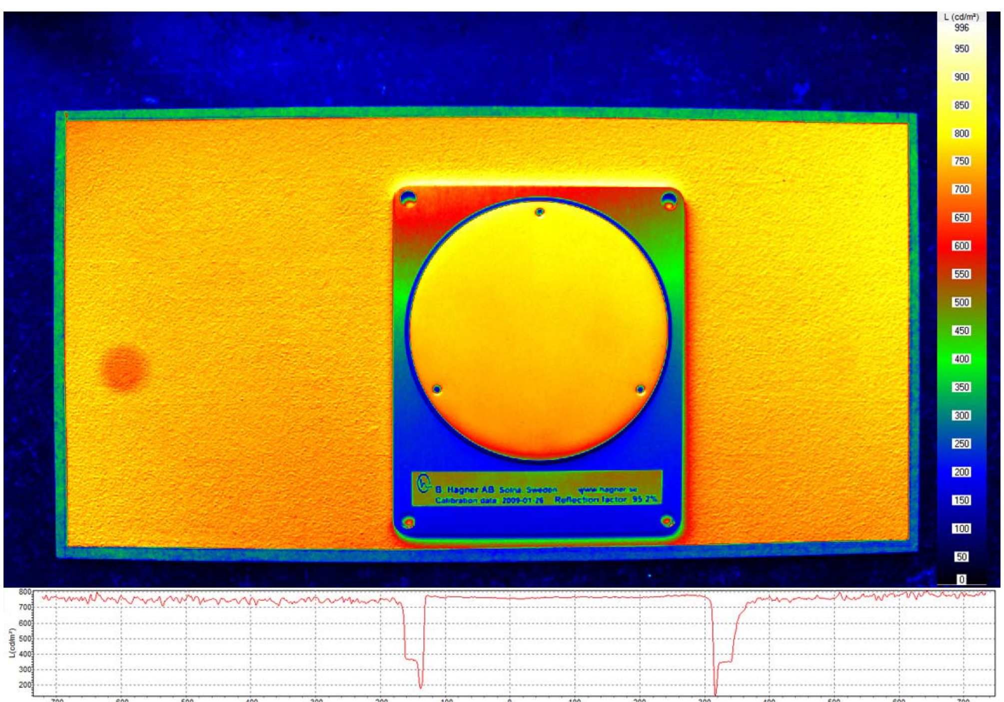


Figure 104: Luminance values of test box & reference plate

[38] *D. Lash, ‘Assessing the daylight transmittance of atria roofs in real buildings’, (PhD diss., Sheffield Hallam University, United Kingdom, 2004)*

Sidenote: The dark orange spot on the base plate of the box shows a significantly higher luminance compared to the surrounding areas of the base plate. This is a result of either dust on the lens of the camera or dust on the window. The image also shows a small gradient in the luminance of the base plate. This has occurred due to the fact that the top part of the base plate is closer to the window that the bottom part of the base plate.

The reflection coefficient of a particular surface or material can be calculated. The relation between the illuminance, luminance and reflection is described by the following formula:

Luminance = Illuminance x (Reflectance / π)   or:
Reflectance = (Luminance * π) / Illuminance

This formula shows that there is a linear relationship between the Reflectance and the Luminance.[39]

Measurements:

Reflection coefficient reference plate	=	0.952	
Mean luminance reference plate	=	760	lux
Mean luminance test box	=	745	lux
Calculated Reflection coefficient test box	**=**	**0.95**	

Ecotect values

The material properties determine the amount of light and how the light bounces and scatters off the materials. The reflectivity of the surfaces has been determined on 0.95 by the lumination test with the reference plate.

	ecotect parameters	Internal	External
1	Colour (reflectivity)	0.953	0.953
2	Emissivity	0.9	0.9
3	Specularity	0	0
4	Roughness	0	0

Figure x: Ecotect material properties

[39] *Cornell University Ergonomics Web. DEA3500: Ambient Environment: Lighting and Color. http://ergo.human.cornell.edu/studentdownloads/DEA3500notes/Lighting/lightingnotes1.html*

Illumination values

These images show the amount of light falling on the ground surface of the digital box. The illumination values are shown in 3d to get a better picture of the light distribution on the surface.

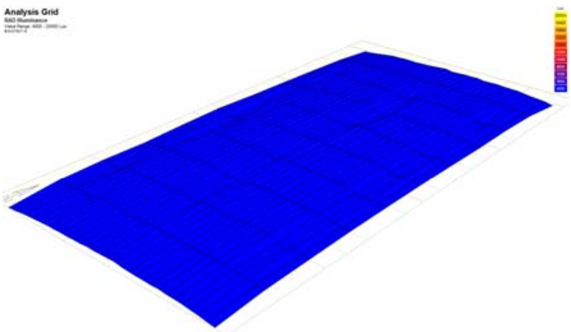


Figure 105: 3D Illumination values cuts

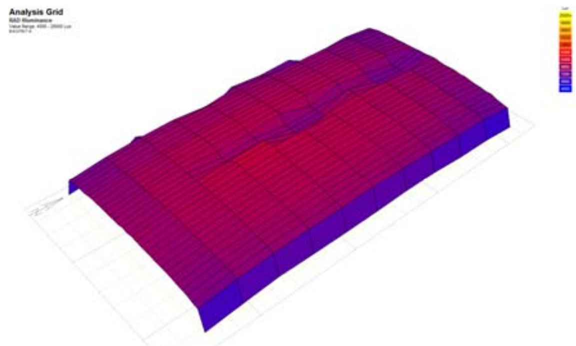


Figure 106: 3D Illumination values slab

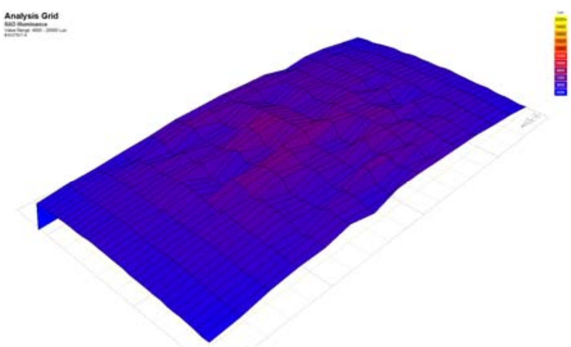


Figure 107: 3D Illumination values scoop

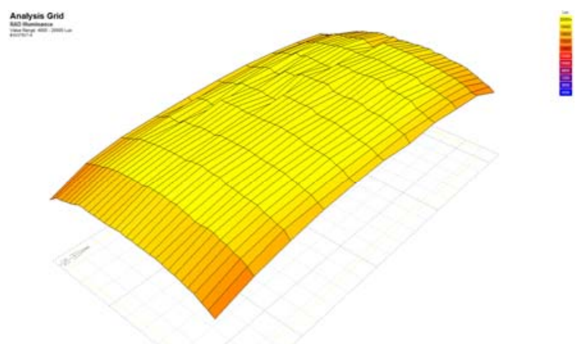


Figure 108: 3D Illumination values grid

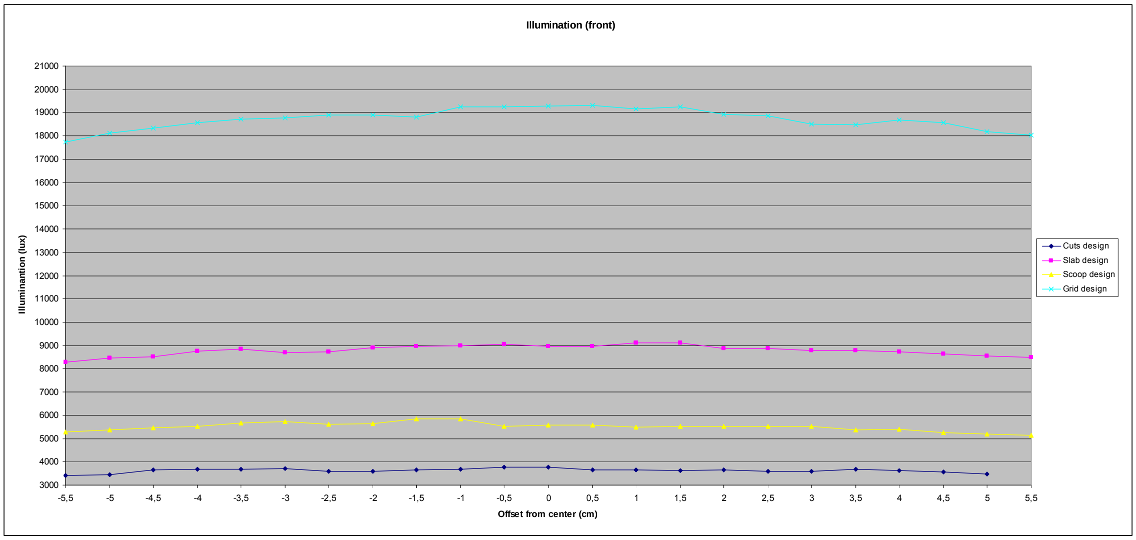


Figure 109: Illuminance values front

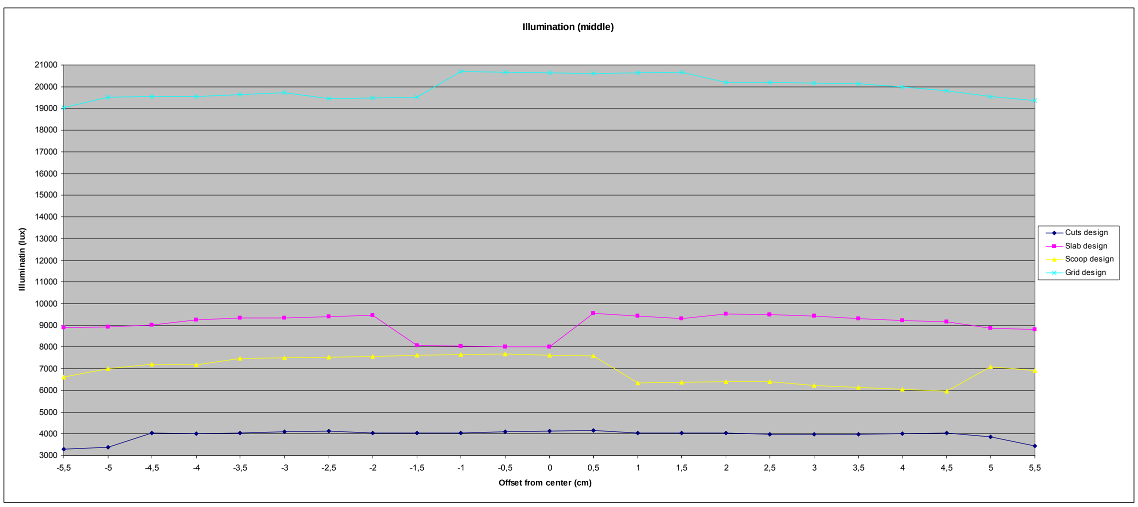


Figure 110: Illuminance values middle

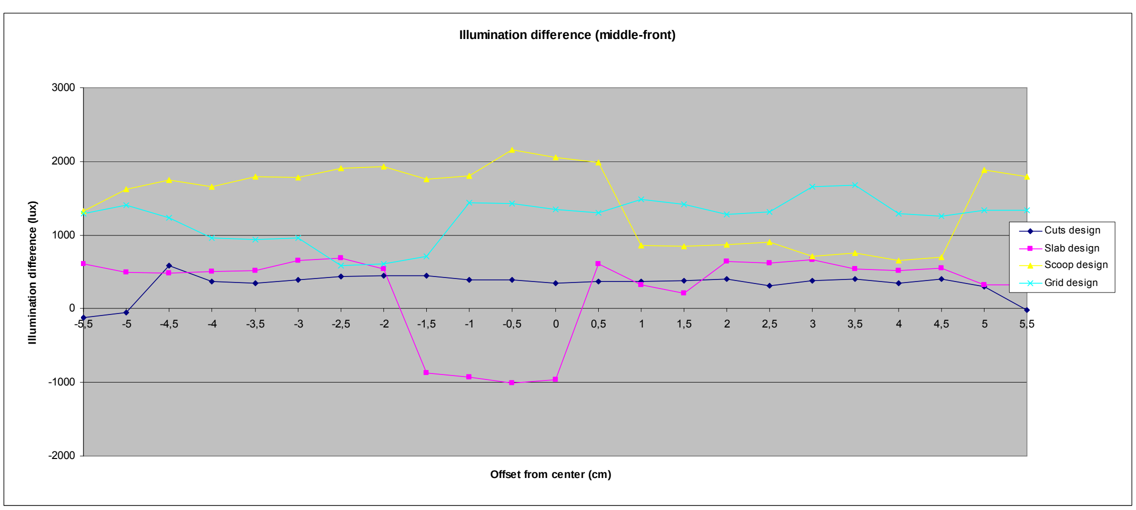


Figure 111: Illuminance differences between middle and front measurement

Findings illumination values digital tests

#	Design	Opening percentage [%]	Average illumination [lux]	Effectiveness per % [Lux]
1	Closed roof	0	0	0
2	Cuts	10,12	3580,33	354,0
3	Slab	19,04	8386,76	440,5
4	Scoop	19,11	5807,92	303,9
5	Grid	65,01	18716,14	287,9

Table 15: Effectiveness digital roof designs

- All designs achieve an average illumination value on the floor of the room of at least 3000 lux.

- All designs show a small parabolic distribution from -5.5 to 5.5 as was expected since the diffuse sky component close to the walls is smaller.

- The cuts design has an average illumination at the front measurements of 3617 lux and 3949 lux at the middle measurements.

- The slab design has an average illumination at the front measurements of 8780 lux and 9041 lux at the middle measurements.

- The scoop design has an average illumination at the front measurements of 5508 lux and 6965 lux at the middle measurements.

- The grid design has an average illumination at the front measurements of 18722 lux and 19952 lux at the middle measurements.

- The grid design has from the four designs the highest illuminance values on the bottom surface or the box followed by the slab design, then the scoop design and the cuts design has the lowest illuminance values.

- The illumination values of the middle nodes are on average about 500-1500 lux higher that the illumination values of the front nodes.

- The middle illumination values from the slab design show a decrease from the -2 to the 0.5 parameters. The values are even lower than the front illumination values. These values aren’t making any sense yet. They could be occurring due to calculation errors in the radiance program.

- The slab design is from the four designs the most effective to bring light into the building followed by the cuts design, then the scoop design and the grid design is the least effective.

4.7.5 Comparison Physical vs. Digital

In order to use the values from the digital test, the results from the digital tests first have to be validated by comparing the values with the values from the physical tests.

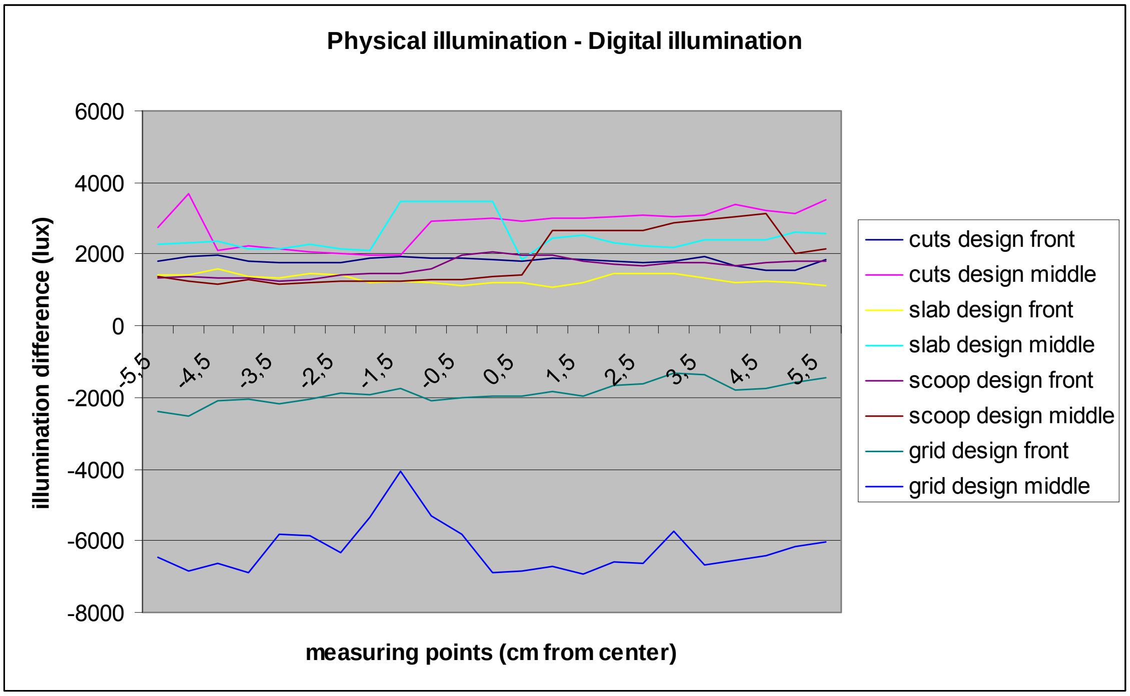


Figure 112: Illuminance differences between physical and digital analysis

- There is a significant difference between the results from the digital tests and the results from the physical tests.
- The Illuminace values from the digital tests are on average around 2000 lux lower than the values from the physical tests.
- The Illuminace values from the digital tests on the grid design are higher than the values from the physical tests. The front measurements are ~2000 lux higher and the middle measurements ~6000 lux higher. There is no direct explanation for these anomalies.
- This discrepancy between the physical and digitals result could be a result of the used software and the input variables in that software.
- These results show the validity of the digital tests. Only the 2000 lux difference has to be kept in mind.

4.8 Digital analysis

The four roof design will be used for further qualitative digital lighting analysis. False colour rendering will be used to compare the four roof designs in different lighting conditions throughout the year. The equinoxes and solstices are the best dates for testing the roof designs.

Equinox	*20 March*
Solstice	*21 June*
Equinox	*23 September*
Solstice	*22 December*

On these dates the four roof designs will be tested at 09:00, 12:00 and 16:00.
First the four roof designs will be tested throughout the year with sunny and overcast sky conditions. The roof designs can then be evaluated and changed for additional digital analysis.

Date	Time	Solar azimuth [deg.]	Solar altitude [deg.]
20-march	9:00	117,1	19,1
	12:00	164,7	36,4
	16:00	234,1	24,1
21-june	9:00	89,8	30,1
	12:00	136	55,2
	16:00	235,5	51,1
23-sep	9:00	107,5	13,3
	12:00	151,5	34,4
	16:00	223,5	29,5
22-dec	9:00	131,4	0,4
	12:00	170,7	13,7
	16:00	224,8	2,6

Table 16: Solar azimuth and altitude during equinox and solstice

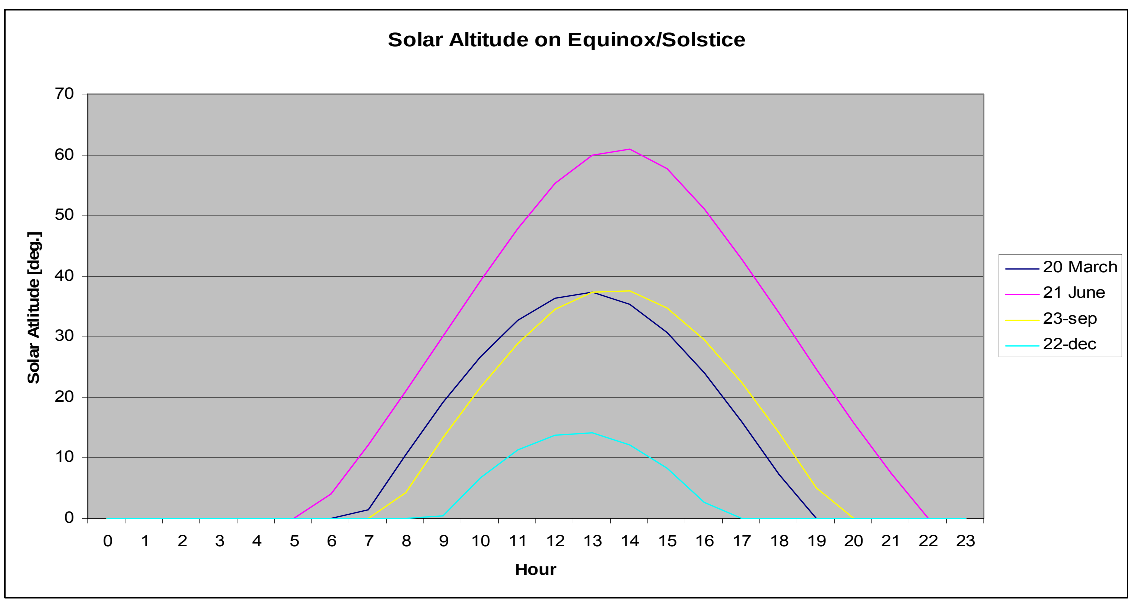


Figure 113: Solar azimuth and altitude during equinox and solstice

4.8.1 Sunny Sky

First, the four designs will be tested with a sunny sky throughout the year. This way, the roof designs can be tested for glare and other lighting discomforts.

20 March 09:00 Sunny sky

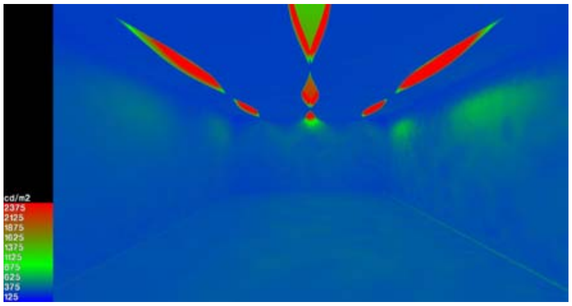


Figure 114: Cuts design

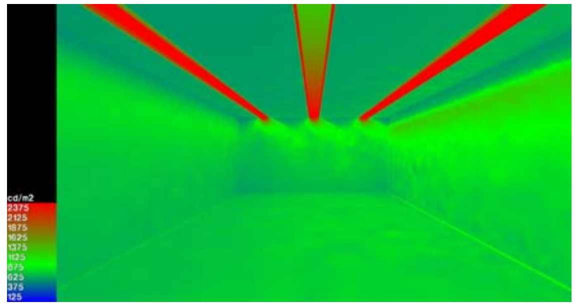


Figure 115: Slab design

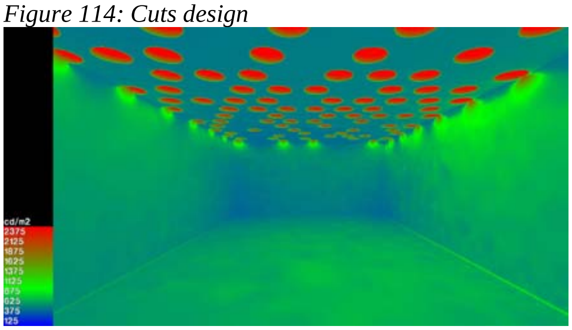


Figure 116: Scoop design

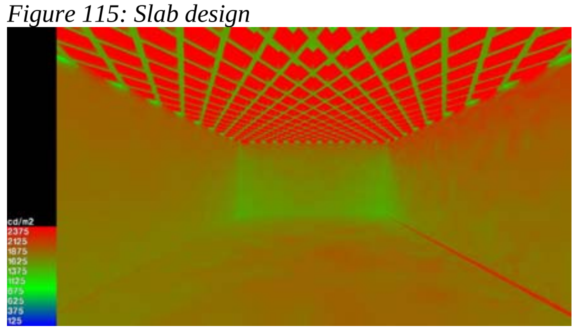


Figure 117: Grid design

20 March 12:00 Sunny sky

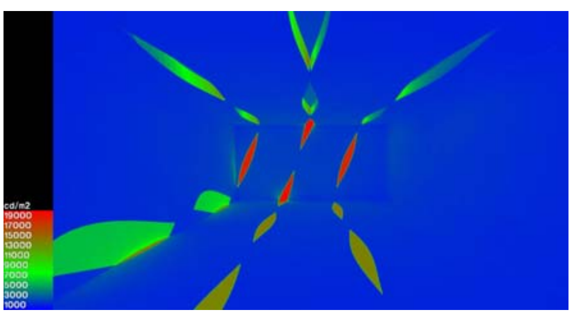


Figure 118: Cuts design

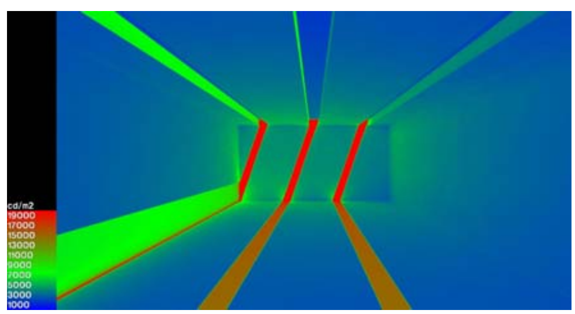


Figure 119: Slab design

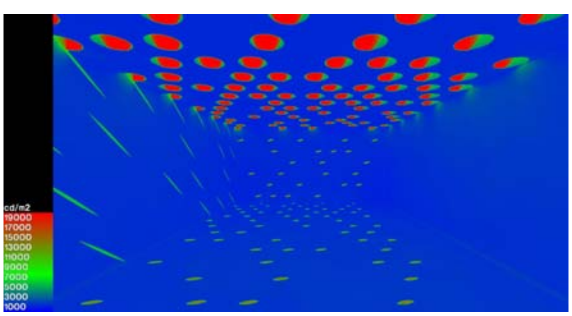


Figure 120: Scoop design

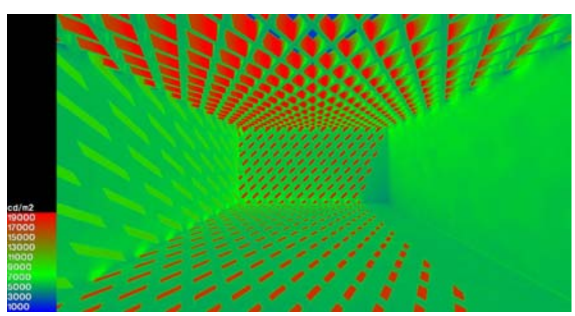


Figure 121: Grid design

20 March 16:00 Sunny sky

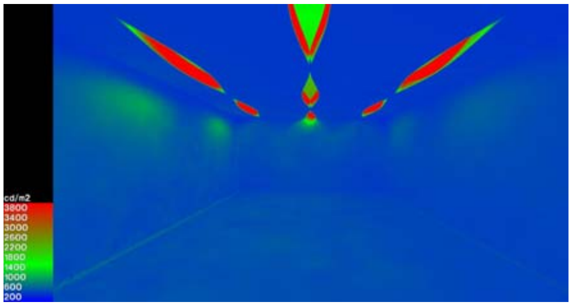


Figure 122: Cuts design

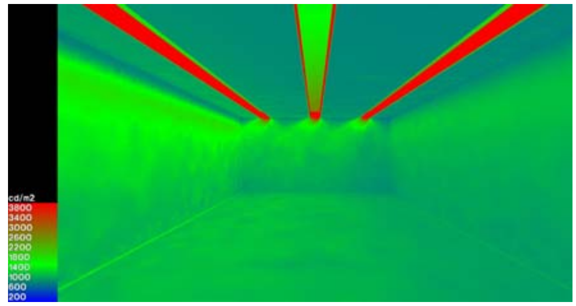


Figure 123: Slab design

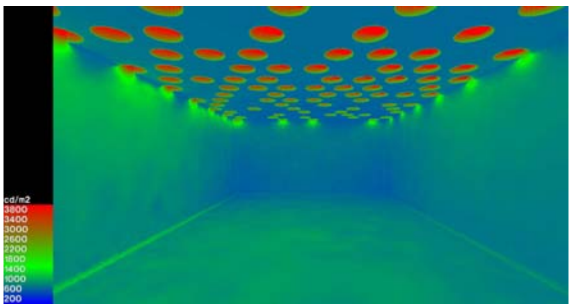


Figure 124: Scoop design

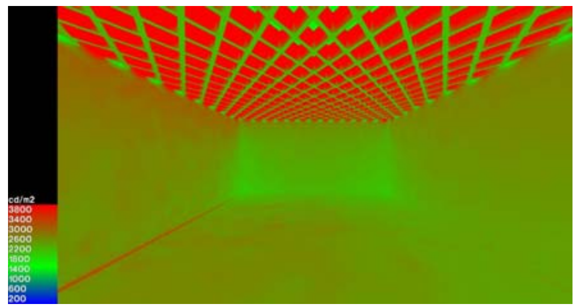


Figure 125: Grid design

20 June 09:00 Sunny sky

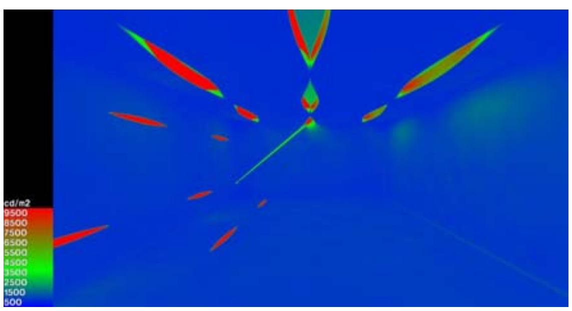


Figure 126: Cuts design

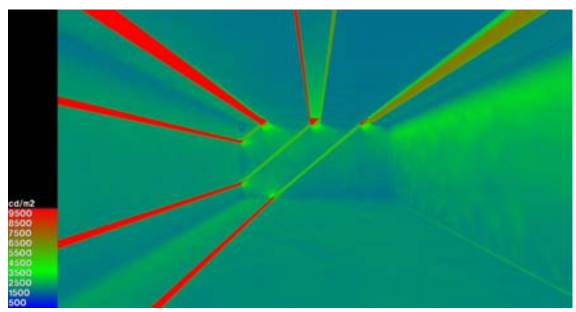


Figure 127: Slab design

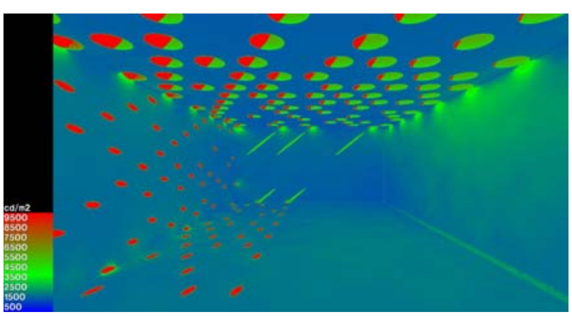


Figure 128: Scoop design

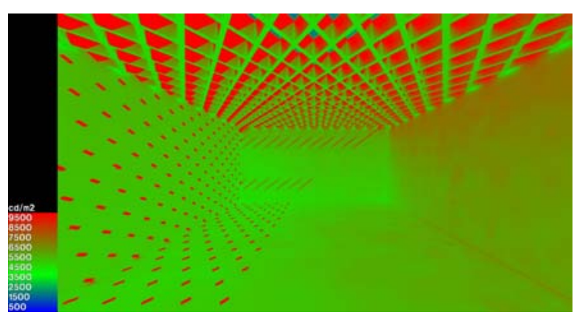


Figure 129: Grid design

- Due to the solar altitude of 19.1 degrees, small amounts of direct sunlight are entering the building. This direct light can cause direct glare and has to be avoided.

20 June 12:00 Sunny sky

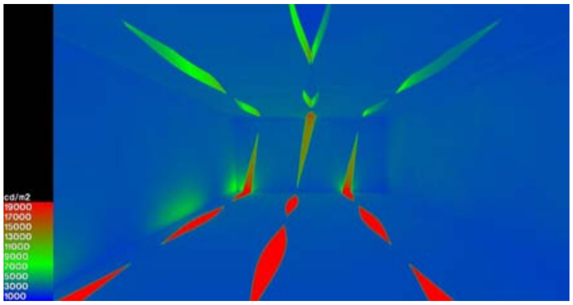


Figure 130: Cuts design

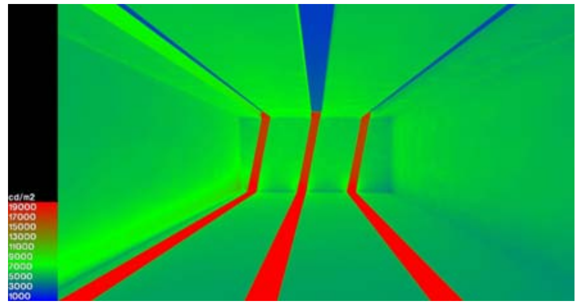


Figure 131: Slab design

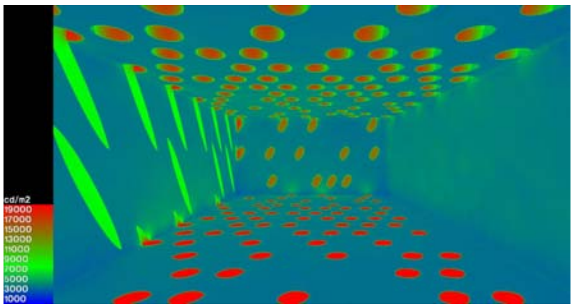


Figure 132: Scoop design

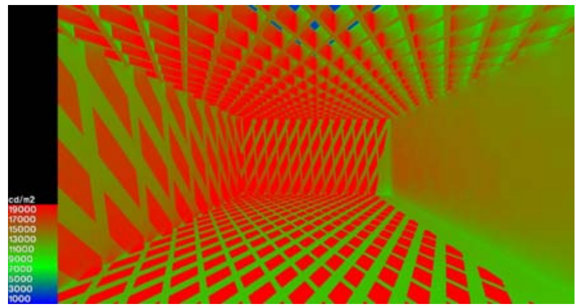


Figure 133: Grid design

- The brightness in the grid design is over 12000 cd/m2. This can cause discomfort due to brightness. The shading pattern can also cause confusion and safety issues.

20 June 16:00 Sunny sky

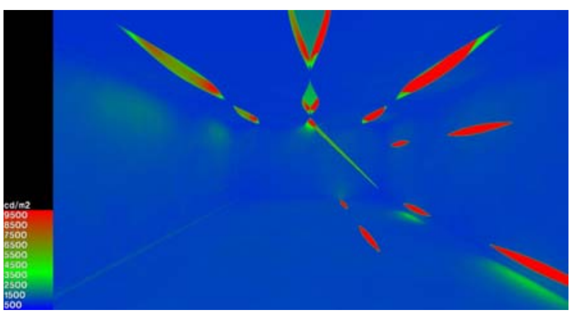


Figure 134: Cuts design

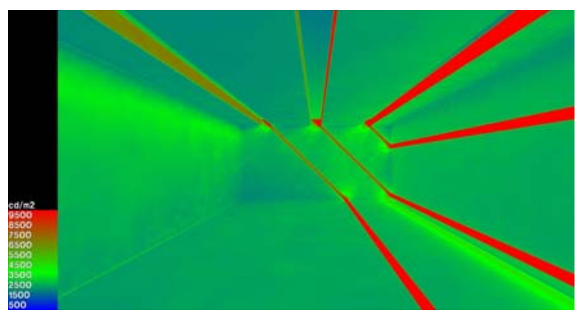


Figure 135: Slab design

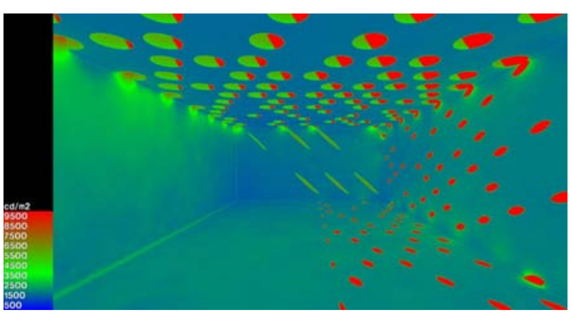


Figure 136: Scoop design

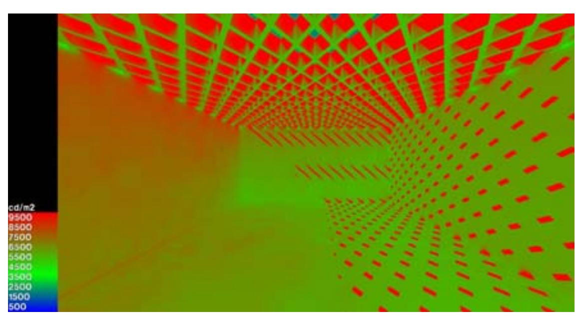


Figure 137: Grid design

22 December 09:00 Sunny sky

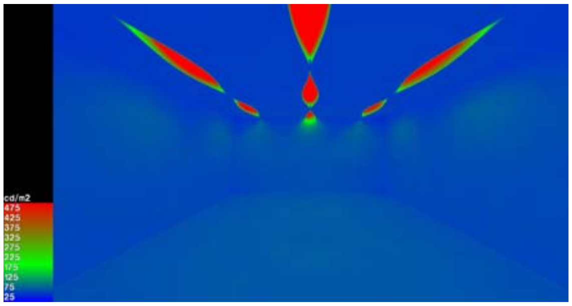


Figure 138: Cuts design

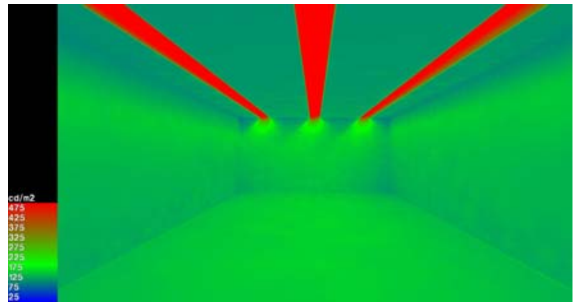


Figure 139: Slab design

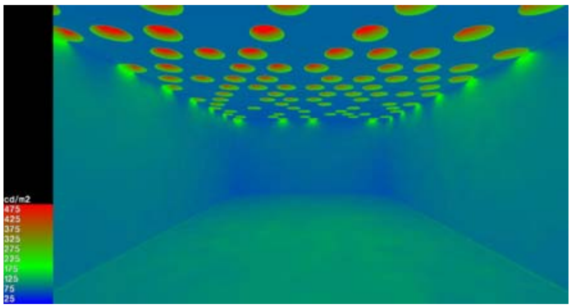


Figure 140: Scoop design

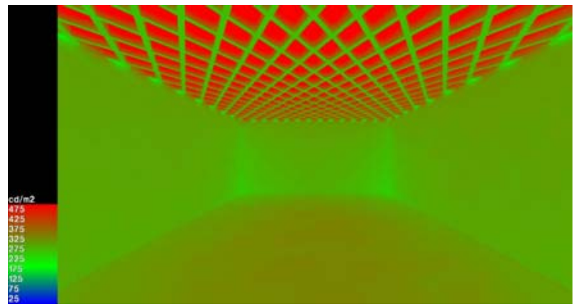


Figure 141: Grid design

22 December 12:00 Sunny sky

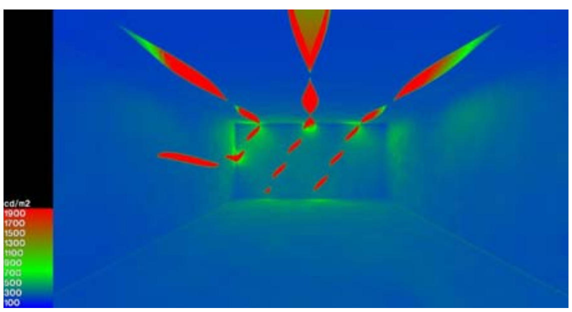


Figure 142: Cuts design

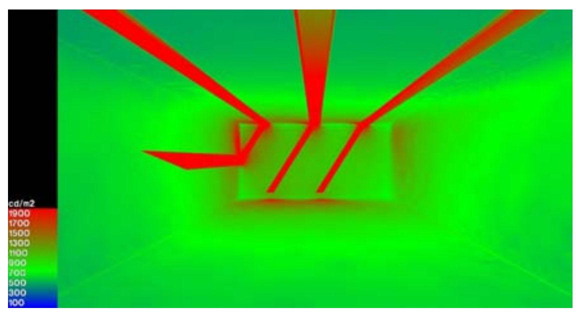


Figure 143: Slab design

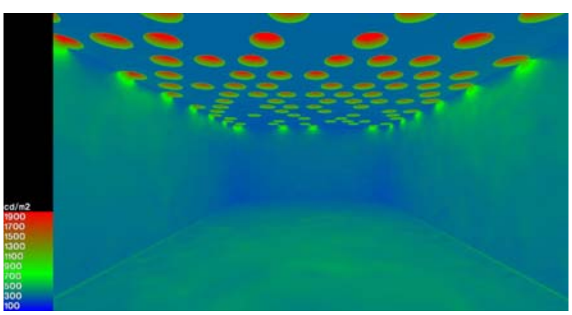


Figure 144: Scoop design

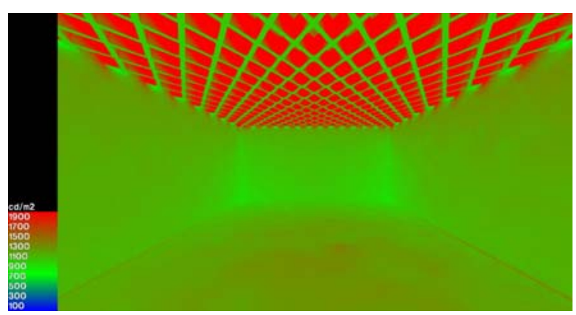


Figure 145: Grid design

- Due to the longitudinal direction of the cuts and slab design, some direct light is entering the room. The scoop and grid design are only allowing diffuse light into the room.

22 December 16:00 Sunny sky

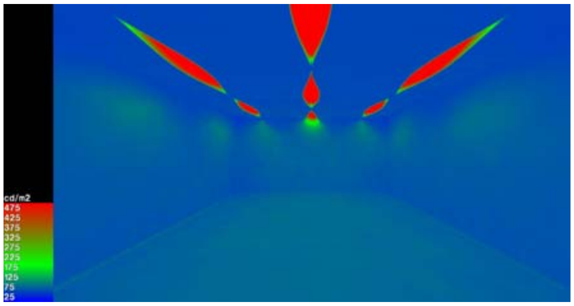


Figure 146: Cuts design

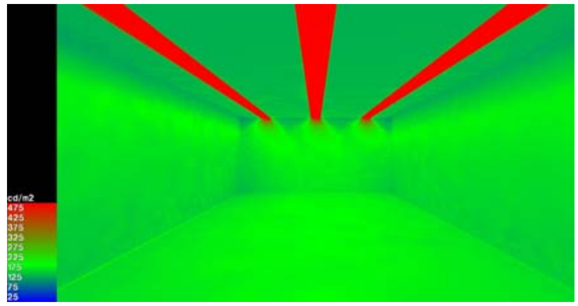


Figure 147: Slab design

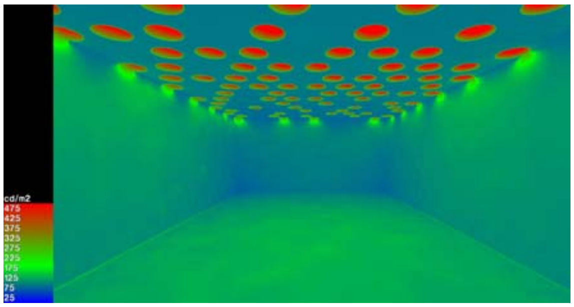


Figure 148: Scoop design

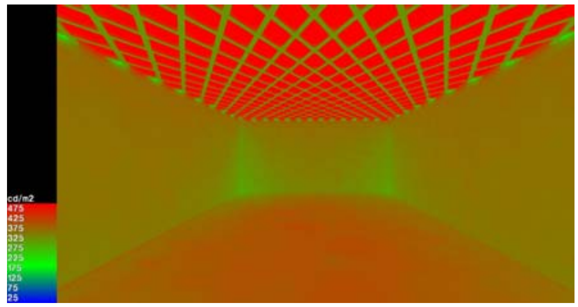


Figure 149: Grid design

Summary

- The pattern of direct light on the floor of the room made by the scoop and grid design could be potentially confusing and dangerous to pedestrians on the train tracks and the kiss and ride area.

- Due to the solar altitude and the construction height of the roof, small amounts of direct sunlight enter the room in the mornings and afternoons in March and June. This could cause direct glare and has to be avoided. The construction height or geometry could be adjusted in order to avoid this.

- The grid design allows the most (direct) sunlight to enter the building. Because of this, the total brightness of the room could lead to discomfort. Further investigation/analysis is necessary when discomfort brightness exactly occurs.

- Due to the longitudinal direction of the cuts and slab design, some direct sunlight is entering the room in December. With the scoop and grid design, no sunlight is entering the room throughout the day.

4.8.2 Overcast sky

The four roof designs will be tested with overcast sky conditions in December. December is the indicating month for the lowest natural light levels and needed electrical lighting.

22 December 09:00 Overcast sky

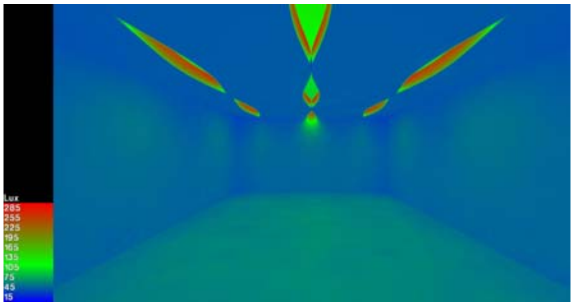


Figure 150: Cuts design

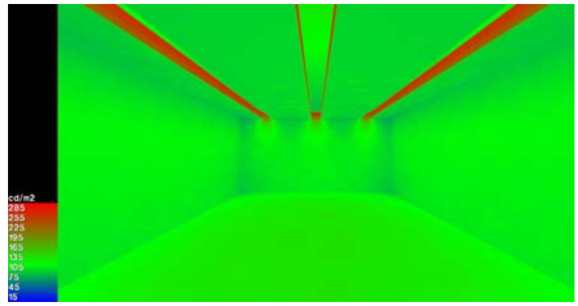


Figure 151: Slab design

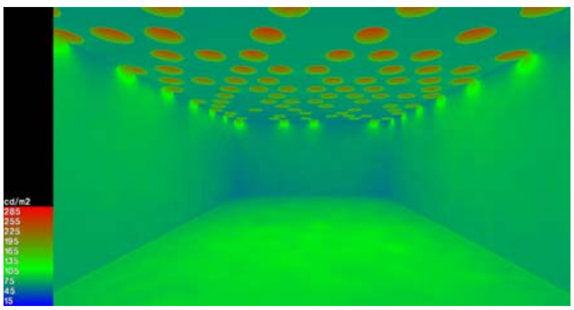


Figure 152: Scoop design

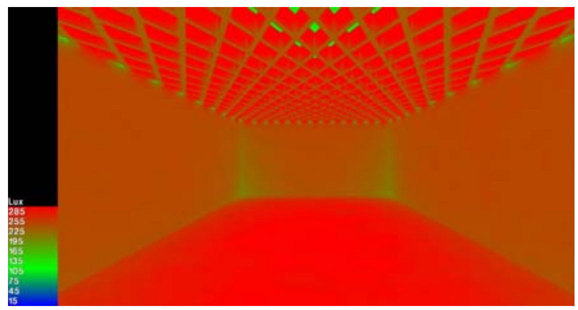


Figure 153: Grid design

22 December 12:00 Overcast sky

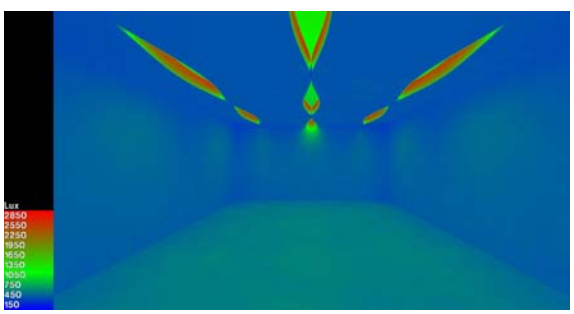


Figure 154: Cuts design

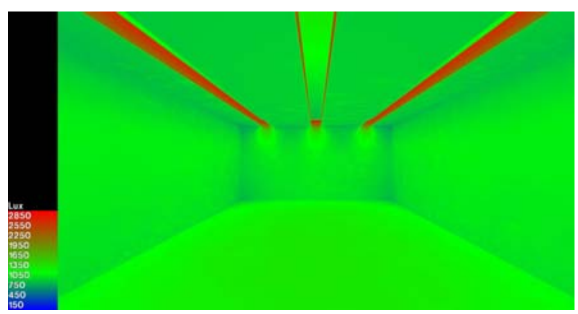


Figure 155: Slab design

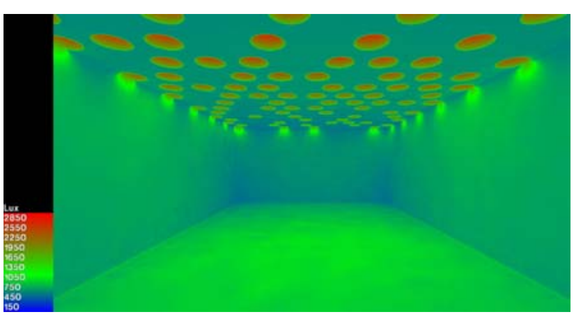


Figure 156: Scoop design

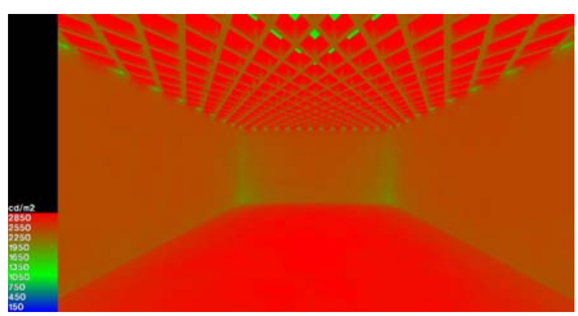


Figure 157: Grid design

22 December 16:00 Overcast sky

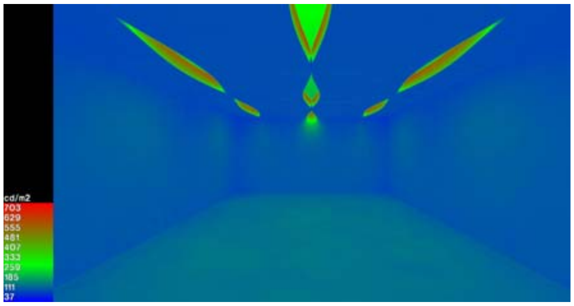


Figure 158: Cuts design

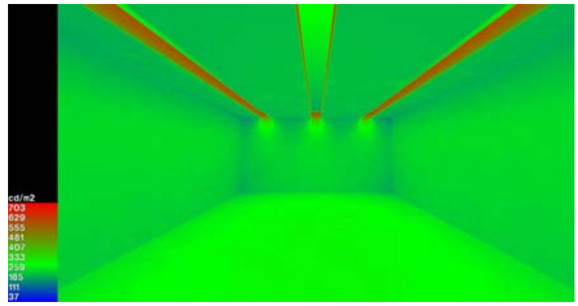


Figure 159: Slab design

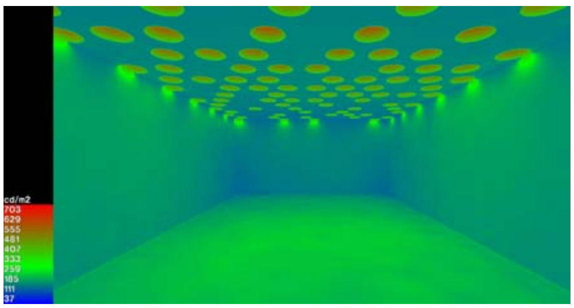


Figure 160: Scoop design

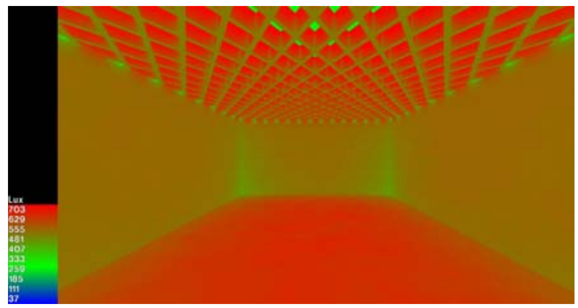


Figure 161: Grid design

Findings

The images show the illumination of the inside space with the four roof designs. The illumination shows the amount of light falling on the surfaces inside. The illumination of a room should always exceed the minimum illumination required for that function.

Illuminance		22 december overcast sky			
		9 uur	12 uur	16 uur	Average 22 december
	Opening percentage [%]	illumination [lux]	illumination [lux]	illumination [lux]	Effectiveness per % [lux/%]
cuts	10,12	55	535	120	23,40
slab	19,04	123	1210	270	28,07
scoop	19,11	92	885	202	20,56
grid	65,01	280	2825	625	19,13

Table 17: Effectiveness digital roof designs

- The inside illumination at 09:00 is about 10 times as little as the inside illumination at 12:00. The inside illumination at 16:00 is about 5 times as little as the inside illumination at 12:00.

- All fours designs meet the lighting requirements of the functions at 12:00, on December 22nd, the darkest day of the year. In the morning and afternoon, additional lighting is needed to comply with the minimal illumination requirements for the functions.[40]

[40] *Ernst Neufert, Architects' Data Third Edition, (Oxfort: Blackwell Science Ltd, 2000), 149*

- The grid design needs the least amount of additional electrical lighting, followed by the slab, scoop and cuts design. Reason for this is the amount of openings and the total area of the openings opening in the grid design.

- The slab design is from the four designs the most effective to bring light into the building followed by the cuts design, then the scoop design and the grid design is the least effective.

4.8.3 Inclination

The geometry of the scoop and grid design allows the designer to prevent direct sunlight from entering the building, even at 12:00 at June 21st. The directions of the openings can be angular directed to the north. This way, the light cannot directly enter the building. The light will then enter the building diffusely. The entire roof could act as a diffuse lighter for the interior.

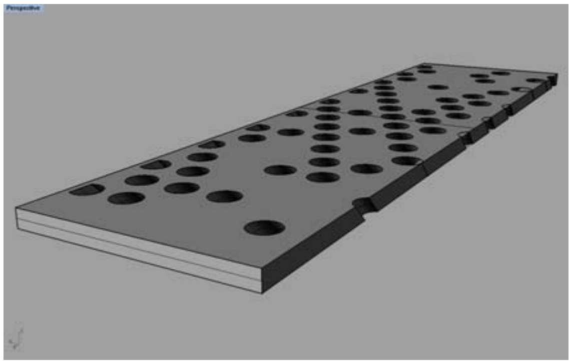


Figure 162: Cross-section inclined scoop design

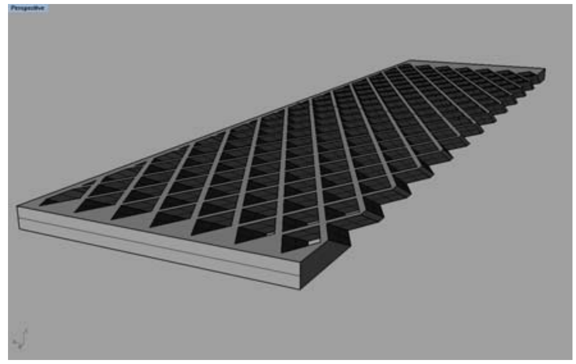


Figure 163: Cross-section inclined grid design

The angle for the openings is determined by using the dimensions of the opening together with the azimuth and altitude on June 21st at 14:00, when the altitude is at its highest. The angles of the openings have been calculated in such ways that no direct sunlight will enter the building. This new geometry for the scoop and grid design is tested on June 21st and December 22nd.

21 June 09:00 Sunny sky

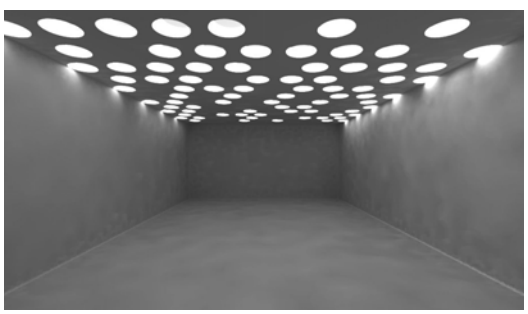


Figure 164: Scoop design, render

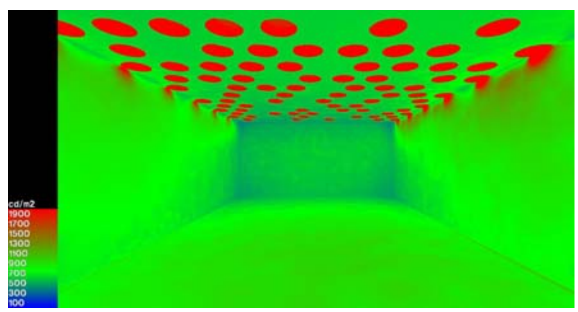


Figure 165: Scoop design, false color render

Figure 166: Grid design, render

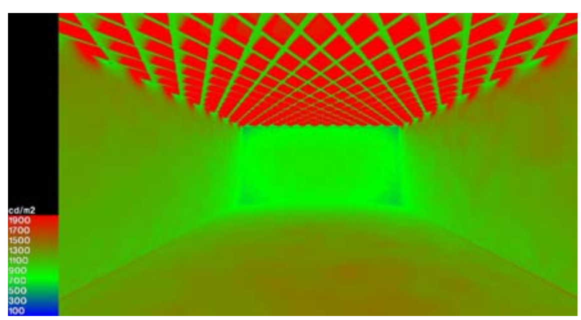


Figure 167: Grid design, false color render

21 June 12:00 Sunny sky

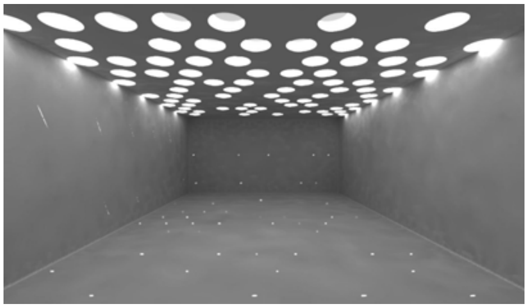


Figure 168: Scoop design, render

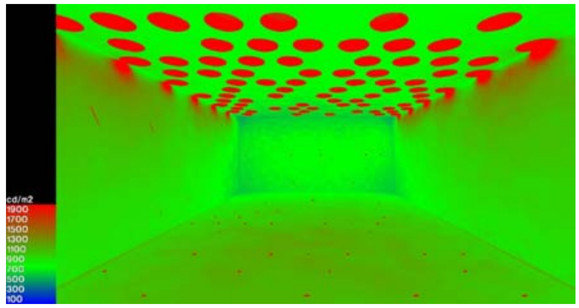


Figure 169: Scoop design, false color render

Figure 170: Grid design, render

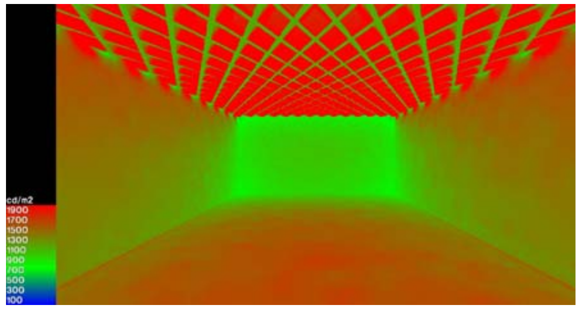


Figure 171: Grid design, false color render

21 June 16:00 Sunny sky

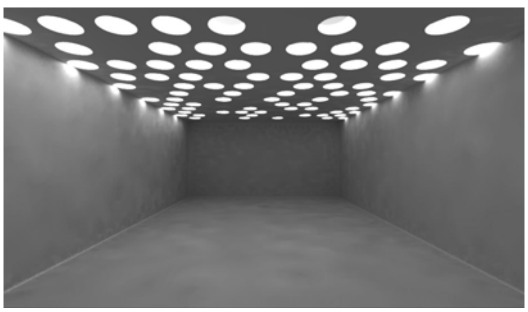


Figure 172: Figure 111: Scoop design, render

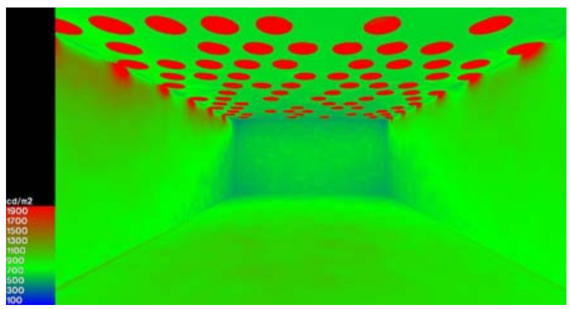


Figure 173: Scoop design, false color render

Figure 174: Grid design, render

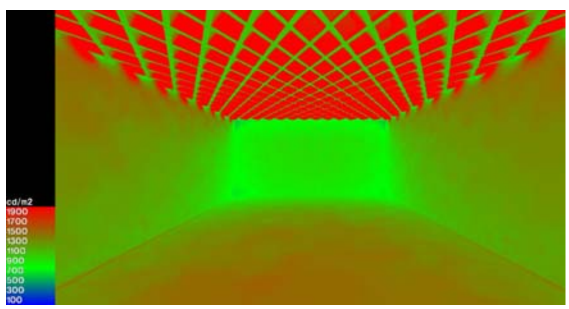


Figure 175: Grid design, false color render

22 December 09:00 Sunny sky

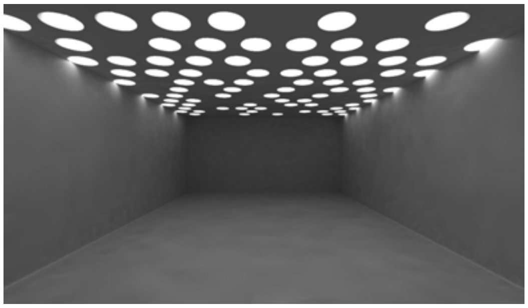


Figure 176: Figure 111: Scoop design, render

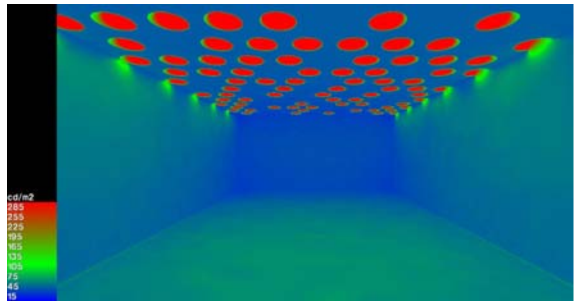


Figure 177: Scoop design, false color render

Figure 178: Grid design, render

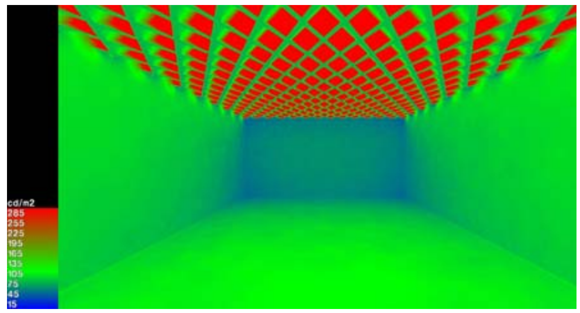


Figure 179: Grid design, false color render

22 December 12:00 Sunny sky

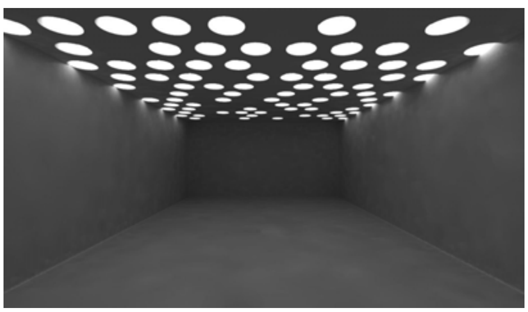


Figure 180: Figure 111: Scoop design, render

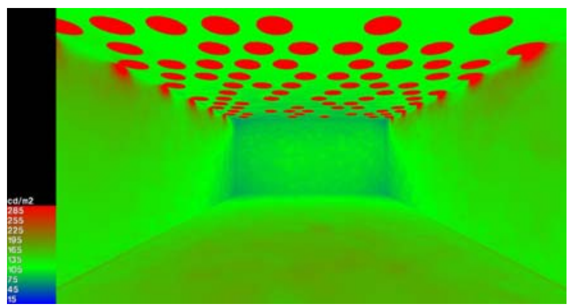


Figure 181: Scoop design, false color render

Figure 182: Grid design, render

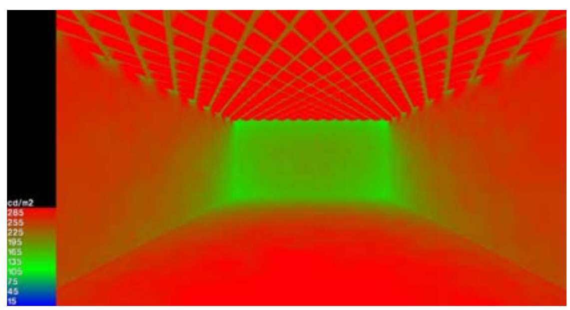


Figure 183: Grid design, false color render

22 December 16:00 Sunny sky

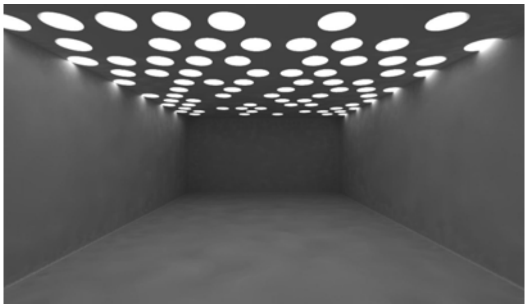


Figure 184: Figure 111: Scoop design, render

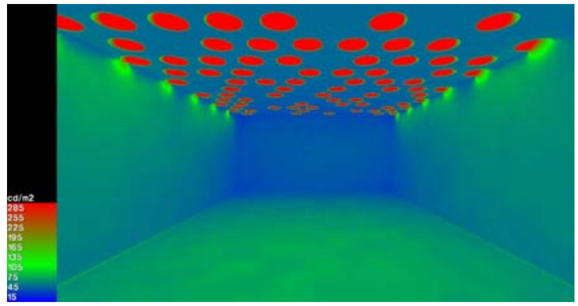


Figure 185: Scoop design, false color render

Figure 186: Grid design, render

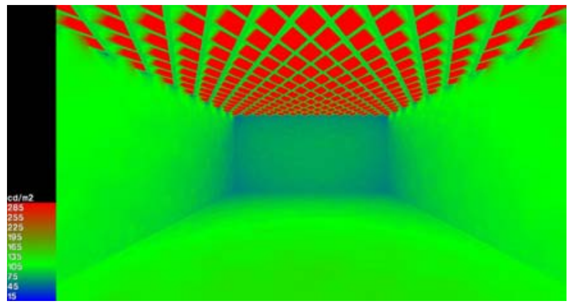


Figure 187: Grid design, false color render

Findings

- The angular openings prevent direct sunlight from entering the building
- The roof brings light diffusely into the building and works as a big bright object/light.

		9 uur lumination [cd/m2]	12 uur lumination [cd/m2]	16 uur lumination [cd/m2]
Scoop	21 june sunny	1800	3500	2100
Scoop angle		950	1150	1125
Grid		5500	11000	6100
Grid angle		1325	1650	1450
Scoop	22 december sunny	110	440	140
Scoop angle		60	170	75
Grid		335	1300	400
Grid angle		110	290	125
Scoop	22 december overcast	31	300	66
Grid		90	915	200

Table 18: Lumination values normal and angular directions

- The lumination values of the angular grid design are 4-7 times lower than the regular grid design. Both on June 21st as December 22nd.
- The lumination values of the angular scoop design are 2-3 times lower than the regular scoop design. Both on June 21st as December 22nd.

- The lumination values of the scoop angle and grid angle design on June 21st are more evenly distributed then the normal scoop and angle design because no direct sunlight is entering the room. The reason indoor lumination at 09:00 and 16:00 are almost as high as on 12:00 is because of the sun altitude on June 21st which allows the direct sunlight to bring extra diffuse light into the building.

- On December 22nd the angle design show a less evenly distribution throughout the day then on June 21st because of the low altitude of the sun in the morning and afternoon.

- The scoop and grid design have a higher indoor lumination with an overcast sky than the scoop angle and grid angle design with a sunny sky on December 22nd at 12:00 because no direct sunlight is entering the room and the diffuse sky component of the angle designs is smaller.

4.8.4 Conclusions and selection

The four roof designs have been tested and analysed throughout the year with sunny and overcast skies. The designs have to be compared and judged if they can meet the quantitative and qualitative lighting demands as described in chapter 4.4. The following chart compares the four roof designs on all meaningful subjects. The first series of subjects are daylight aspects which have been analysed and quantified. The second series of subject are design aspects, which have been estimated, but are also used in the decision making process.

	Subject	Slab	Cut	Scoop	Grid
Daylight	Discomfort constrast	+	+	++	++
	Discomfort glare	++	++	++	++
	Discomfort brightness	+++	+++	++	+
	Diffuse light through geometry	+	+	++	+++
	Quantitative daylight demands	+	-	++	++
	Qualitative daylight demands	++	+	+++	+++
	Effectiveness brightness	+++	++	+	
	Equal light distributing diffuse	++	++	+++	+++
Design	Design	+++	+	++	++
	Design direction	+++	+++	+	+++
	Design freedom	++	++	+++	++
	Costs	+++	++	+	+
	Total	**26**	**20**	**23**	**24**

Table 19: Comparative chart roof designs

The slab design has the highest overall ration when looking at the chart while the cuts design has the lowest overall ration. However, not all subjects on the chart are of equal importance when deciding which roof design to select for further development.

- The slab design features the best integration with the original building design because it integrates different parts of the building together and strengthens the overall direction of the building.

- The grid design features the best possibility of meeting the required lighting demands only through the geometry. The slab design can only meet all daylight requirements by using special materials such as milky glass in order to bring only diffuse light into the building.

- The slab design is the most straightforward and easy to construct design. It will be the cheapest roof design, both in terms of material costs and labour costs.

When designing the roof geometry, the best properties of the slab and grid roof design could be combined to design a roof which suits the original design and can also meet the daylight requirements throughout the building.

The grid design is the starting point for the roof design. The grid design follows the shape of the envelope of the building created by the architectural design and wind research. The diamond shape of the grid design creates a diamond tessellation for the entire building. The diamond shapes can be open or close where it is needed. These diamond-shaped openings provide the required light quality and bring the light into the building, directly or diffusely.

Concept renderings

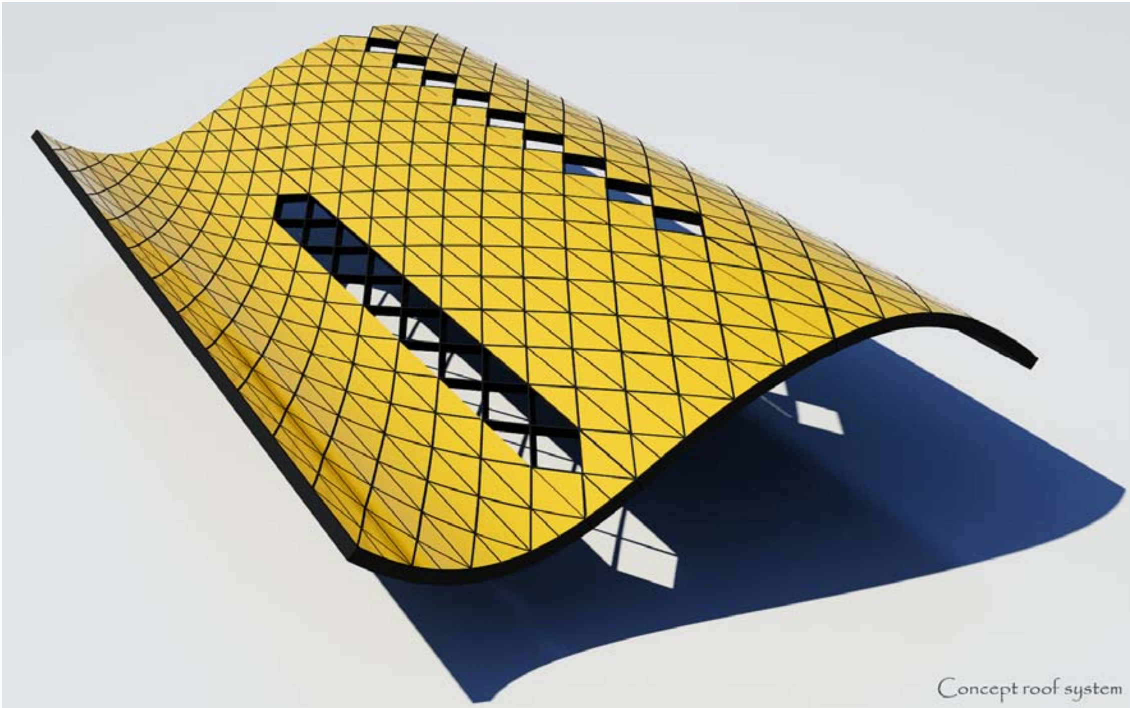


Figure 188: Rendering design concept – diamond & triangles

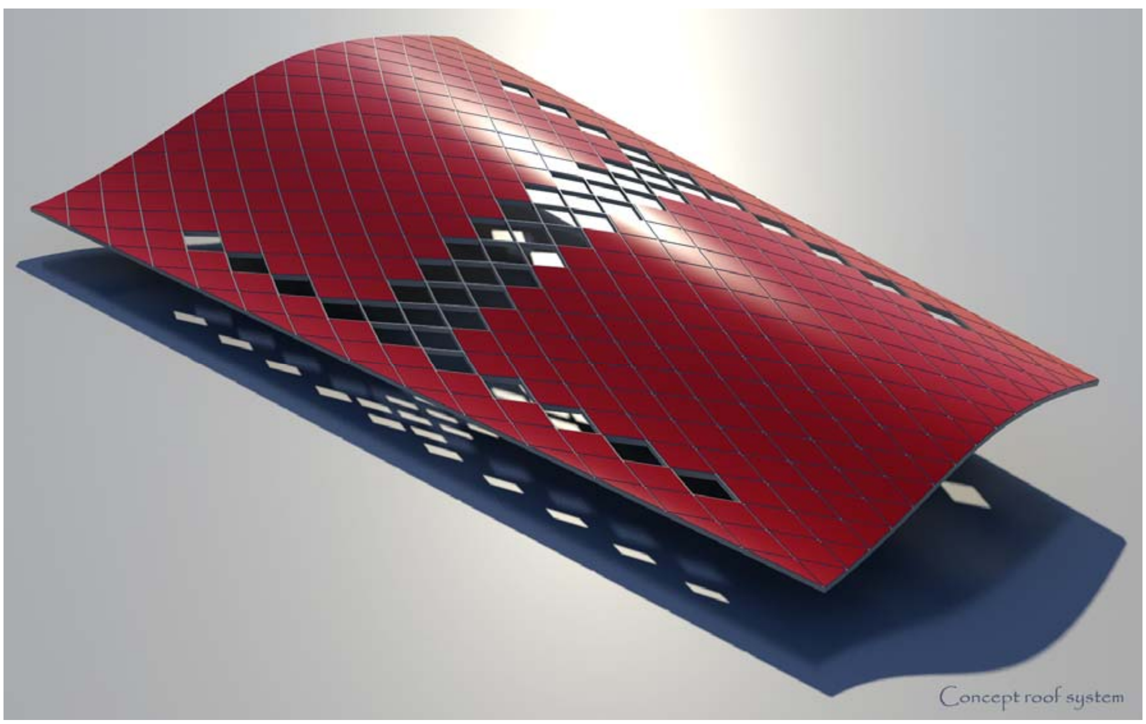


Figure 189: Rendering design concept – diamonds

These renders show the slab design and grid design coming together. However, the directionality of the diagrid does not allow for straight/square openings. The only way to achieve square openings is use a triangle tessellation instead of a diamond tessellation

4.9 Materialisation & manufacturing

Because of the general roof envelopes that will have already been shaped by the daylight performance, the component on the roof should be optimised for realising the envelope shape. The effect of various geometrical shapes on the appearance of the roof envelope will be considered. Also the design possibilities of each shape will be discussed.
The main issue is finding a component/panel type which can be used to tessellate the daylight optimised roof envelope.

4.9.1 Panelling shapes

The tessellation of a surface can be based on various basic component/panel shapes:

- Triangle-shaped
- Diamond-shaped
- Honeycomb-shaped
- Curved panels

Triangle-shaped

Figure 190: Chek Lap Kok airport, Foster + Partners[41]

Figure 191: Stansted,airport, Foster + Partners[42]

Diamond-shaped

Figure 192: Marrakesh Menara airport[43]

[41] *http://www.fosterandpartners.com/Projects/0639/Default.aspx*
[42] *http://www.fosterandpartners.com/Projects/0300/Default.aspx*
[43] *http://en.wikiarquitectura.com/index.php/Marrakech-Menara_Airport_Extension*

Honeycomb-shaped

Figure 193: MAD architects Honeycomb skyscraper[44]

Curved panels

Figure 194: Zaha Hadid Nordpark railway stations[45]

[44] *http://inhabitat.com/mad-sinosteel-plaza/*
[45] *http://www.zaha-hadid.com/category/built-works*

Figure 195: Chanel Pavilion, Zaha Hadid[46]

These examples of panelling shapes are only a small selection from the vast possibilities of panelling and materialising for a building skin. The diamond and honeycomb-shaped components/panels offer great possibilities but are limited to rectangular and single curved building shapes. When designing a doubly curved roof or façade, a triangular panelling system is the most common, easiest and cheapest way to achieve the desired shape. A series of flat triangular panels are then used to construct the doubly curved shape.
To get the smoothest doubly curved shapes, curved panels can be used to create the shape. This is a very labour intensive and expensive way of materialising a skin because of the great number of different doubly curved panels which have to be manufactured individually.
If surface curvatures are small, flat metal panels can be bend into (doubly-) curved shape. This reduced manufacturing costs greatly.

4.9.2 Manufacturing

The way the roof and façade panels are manufactured, transported and assembled are also of great influence on the design of the roof. There multiple ways to manufacture and assemble a double curved roof or façade:

- Assembling of flat/curved panels on site

All the traditional façade elements such as beam, girders and panels are delivered on the build site. Assembling of the façade elements is manually carried out on site. This is a very labour intensive way of realising a doubly curved skin. This build method is more prone to build error because of the manual labour and installation. This is a method normally used for

[46] *http://www.zaha-hadid.com/built-works/chanel-mobile-art*

smaller building and façade systems where the building is too small for justifying the cost of a mass production process.

- Assembling of large pre-assembled facade elements on site

When the desired architectural image is that of a free form roof without any panelling, edges and seams, large doubly curved roof elements could be delivered to the site by ship or helicopter and installed on the building. These roof elements could also include the construction of the roof. This was the original plan for the roof of the Rabin Center in Tel Aviv, Israel. However, due to the expected high costs of shipping the panels from the Netherlands to Israel and the low budget of the project, the roofs wings were decomposed into transportable components which could be manufactured in Israel and assembled on-site. The top layer of the shells is applied after the individual components were connected to create a smooth roof with 30m spans. [47]

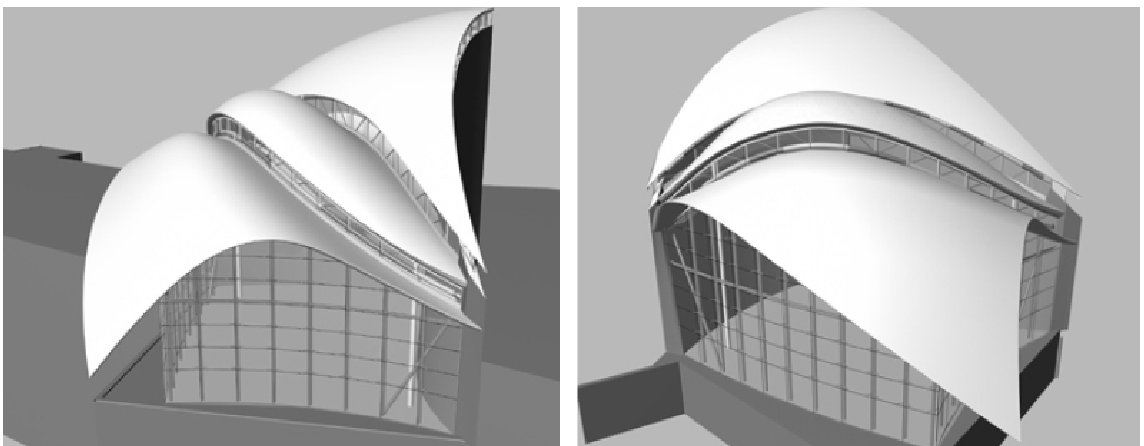


Figure 196: Roof wings of the Rabin Center[48]

Figure 197: Assembling of the roof parts[49]

[47] *Mick Eekhout, "Composite Stressed Skin Roofs for Liquid Design Architecture".*
[48] *Mick Eekhout, "Composite Stressed Skin Roofs for Liquid Design Architecture", 12*
[49] *Mick Eekhout, "Composite Stressed Skin Roofs for Liquid Design Architecture", 19*

4.9.3 Materials

The type of material that makes up the roof is of importance for the structural system and architectural image of the building. Selecting the best material for the roof and façade is important. Various properties of the selected materials have to be taken into account:

- Strength & stiffness
- Manufacturing size & thickness
- Possible shapes
- Resistant against water, wind and sunlight
- Colours & finish
- Opaque/Translucent/Transparent
- Costs
- Transport

The most important property of the materials for the architectural image is the ability to follow the architectural design as close as possible. The architectural design features a doubly curved roof which is the most challenging of shapes. The size of the panels and the way to transport them are also very important. The site for the Schiphol Interchange Station is situated at a shipping channel. This opens possibilities for transporting large roof panels by ship to the site.

Materials for roof panelling

- Metal panelling

Metal panelling can be used to cover flat, single curved or doubly curved surfaces. Many different metals can be used for panelling. The selection of the type of metal depends on the desired architectural quality, size and shape of the panels, the budget for the façade/building and the climatic environment of the site. In case of the Guggenheim museum in Bilbao, the deciding factor has been the architectural quality and reflected light colour of titanium panels, despite the high material costs of titanium. In most cases, aluminium is used because of the low weight, shape versatility and non-corrosive nature of the material. Aluminium roof panels can be painted and receive any kind of finish.

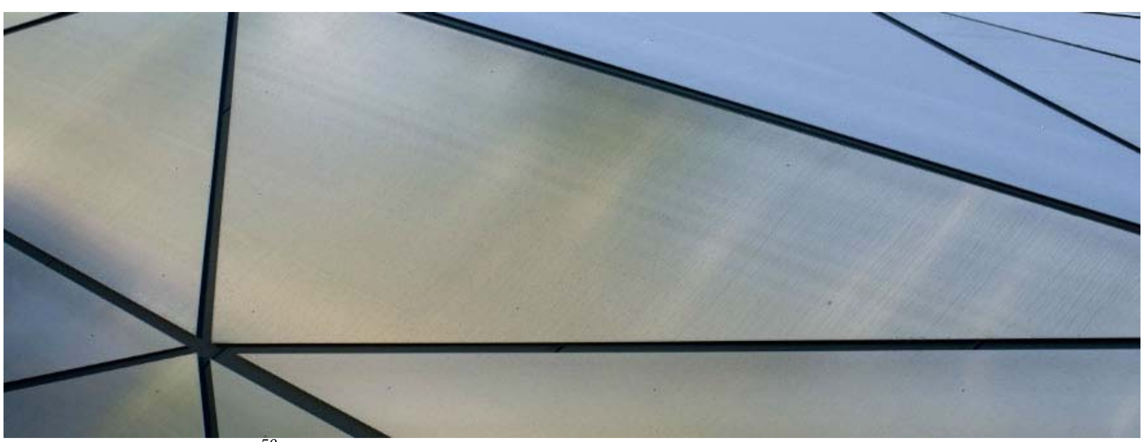


Figure 198: Metal panels[50]

[50] *http://www.kingspanbenchmark.nl/case-studies*

- Fibre Re-inforced Plastic panelling / Glass fibre reinforced polyester (GFRP)

Composite panelling like Fibre reinforced plastic is made of a fibre reinforced polymer. A plastic matrix is combined with fibres to create the composite. The plastic matrix can be epoxy, a thermosetting plastic (polyester/vinylester) or a thermoplastic. The result is a lightweight, very strong material. Though it is less strong and stiff than carbon fibre, it is also far less brittle and much cheaper than carbon fibre. This makes it very interesting as a façade material in the building industry.
Building with a fibre reinforced plastics are one of the best ways to realise doubly curved roofs and facades. A custom mould has to be made to create each panel which makes this system quite labour intensive and very expensive. The costs for a façade/roof system with doubly curved composite panels up to ten times as expensive as a standard curtain wall façade. The Chanel Art Pavilion, designed by Zaha Hadid is a very good example of this system. It is one of the first buildings in the world which features perfectly smooth composite panels made at Dutch composites. The cost of the panels got so out of hand that halfway through the production process of the panels the material for the roof was changed to a PVC fabric which is much cheaper.
The size for the panels is only limited to the manufacturing of the mould and the possibilities for transport. Large size panels could be transported by ship or helicopter to the build site.[51]

Manufacturing *http://www hollandcomposites.nl*
http://www.npsp.nl/

Figure 199: Composite panels[52]

- PVC fabric

Polyvinyl chloride (PVC) is a chlorinated hydrocarbon polymer. It is made from chlorine, carbon and hydrogen. PVC roofing membranes are easy to install, highly waterproof and are very low maintenance. The fabric is fire retardant and retardant against chemicals. Specials coatings can enhance these properties.

[51] Zaha Hadid Architects, Mobile Art Chanel Contemporary Art Container, http://www.zaha-hadid.com/architecture/chanel-art-pavilion/
[52] *http://www.hollandcomposites.nl/over-hci/12/Gevelbeplating/*

Figure 200: Chanel Pavilion, Zaha Hadid[53]

Using PVC-fabric is a very cost effective way to clad large surface areas. Especially when working with large doubly curved roof and façade surfaces. The pvc fabric has to be stretched over a substructure in order to achieve the doubly curved shape. A PVC fabric was used as the roof material for Zaha Hadid's Chanel pavilion in order to achieve the desired doubly curved surfaces but at the same time keep the costs down.[54]

[53] *http://www.zaha-hadid.com/architecture/chanel-art-pavilion/#]*
[54] *Vinyl Council Australia, Cladding and roofing membranes. http://www.vinyl.org.au/Claddingandroofingmembranes*

4.10 Roof system/roof design

The grid design will be used as a basis for the new roof design. The grid design can be applied in different ways. The diamond tessellation/pattern can have different orientations and sizes.
The diamond tessellation follows the main direction of the building since it amplifies the directionality of the building and works best in admitting the right quantity and quality of daylight into the building (as described in chapter 4.10).

4.10.1 Diagrid orientation

The first type of orientation is the default orientation of a diagrid. It uses two diagonal directions to create a diamond tessellation on the surface. This diagrid provides a smooth overall curvature but conflicts with the main direction of the building in certain areas.

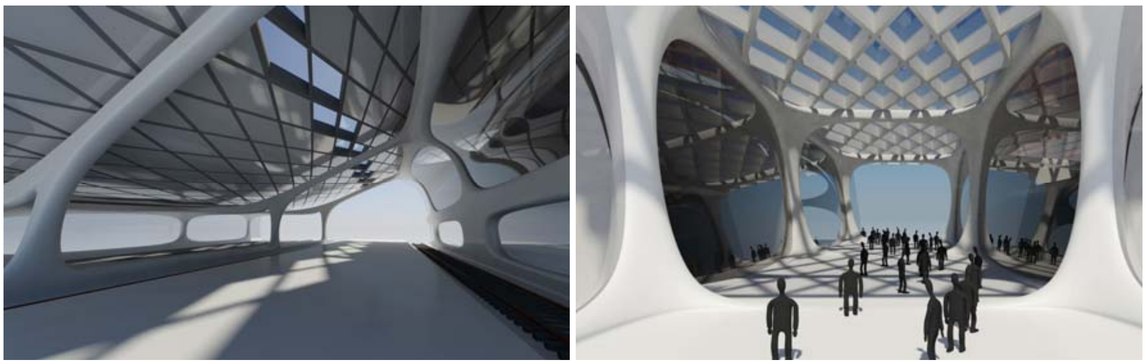


Figure 201: Interior views diagonal orientation

The second type or orientation uses one diagonal direction and one longitudinal direction. This diagrid provides a tessellation of parallelograms where the longitudinal direction of the tessellation follows the longitudinal direction of the building. The secondary diagonal direction is rotated ~45 degrees.

Figure 202: Interior views parallel orientation

This diagrid doesn't conflict as much with the construction and building directionality as the previous one. It still has about the same light properties as the tested grid design.
However, the angle of rotation of the diagonal direction must be chosen according to the lighting needs of the functions with construction and materials costs kept in mind.

4.10.2 Roof tessellation

The roof of the Schiphol Interchange Station has to be tessellated with a diagrid system. This can be realised in three different ways with various amounts, shapes and sizes of the panels in the diagrid.

1. Constant U-divisions throughout the roof / panels varying in size and shape
2. Changing U divisions throughout the roof / same size panels / panels cut off at the edges of the roof
3. Changing U divisions throughout the roof / panels varying in shape (strange panel shapes) / panels end perfectly at edges.

Tessellation 1: Constant U-divisions

The entire surface is divided with in a constant number of panels in the U direction. This allows for perfect panels at the edges which gives a smooth boundary on the edges of the building.
The divisions in the V direction of the surface change according to the width and the height of the building in that particular area. When the width of the surface is bigger, then that piece of roof surface is divided in more pieces in the V-direction to maintain a consistent width/height ratio and shape of the panels.
This type of tessellation creates panels with a consistent shape but with different sizes.

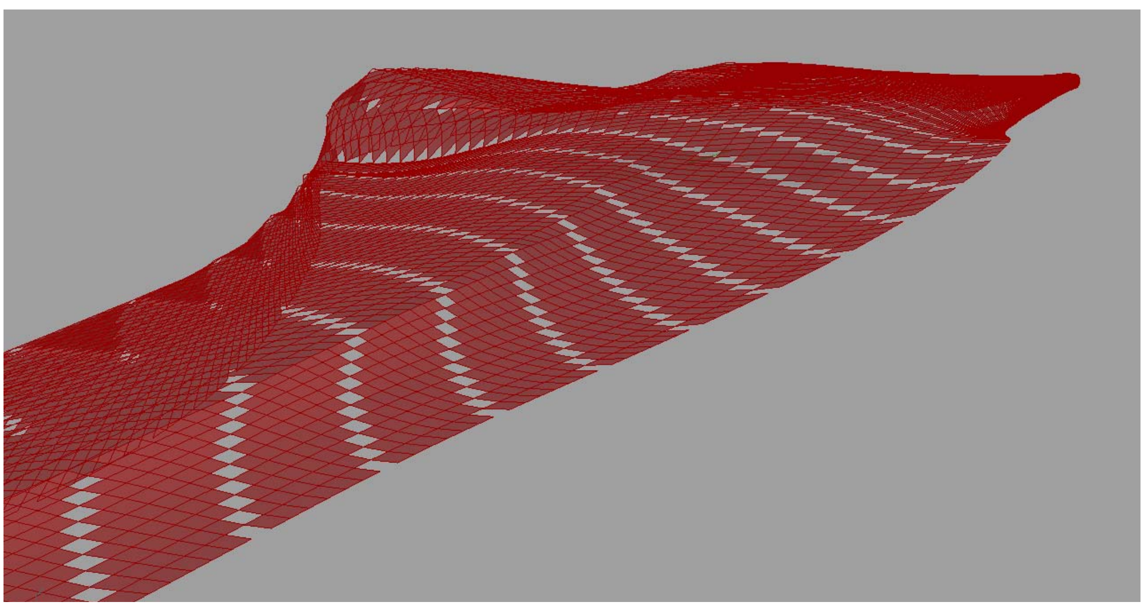


Figure 203: Constant U-divisions

Tessellation 2: Wrapping with constant panel size

The entire surface is wrapped with a tessellation which features panels from about the same size. The amount of panels in the U-direction changes according to the width of the surface, ensuring a fixed panel size. Where the surface is wider, there are more U-divisions.
Since the surface is divided in the U-direction by a fixed panel size, the panels aren't perfectly connected to the edges of the surface. The panels at the end of the surface are cut off by the

surface edge which produces smaller panels of all shapes and sizes. This type of tessellation doesn’t connect very well to the surface edge.
This type of tessellation creates panels with a consistent shape and a consistent size. This minimises material and fabrication costs.

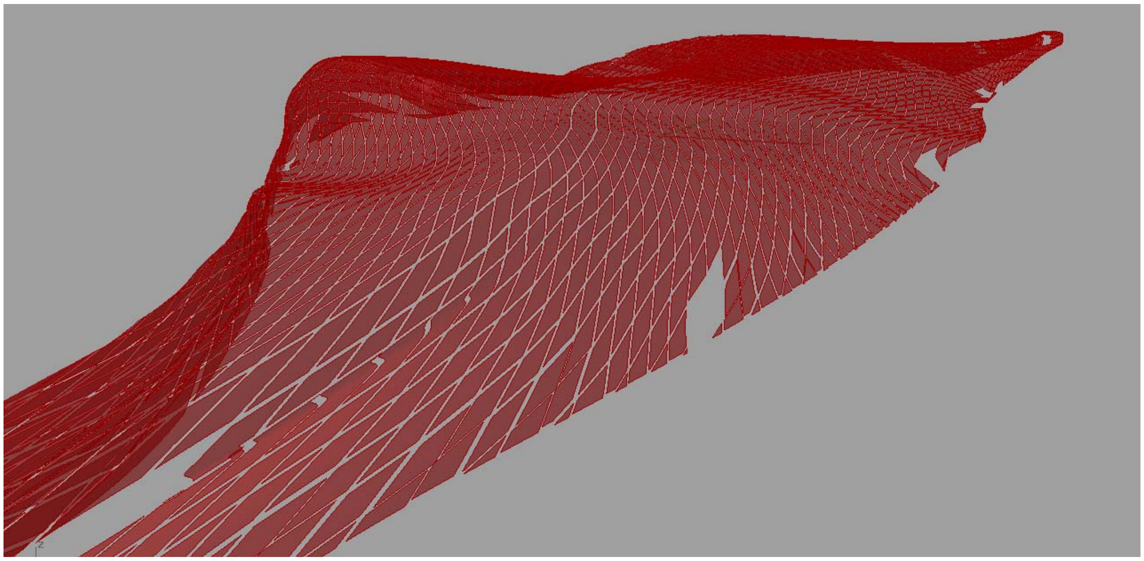


Figure 204: Changing U-divisions

Tessellation 3: Wrapping with varying panel size

The entire surface is wrapped with a tessellation which features panels from about the same size. The amount of panels in the U-direction changes according to the width of the surface, making the panels more or less the same width size. To gain full edge control, a braiding system has been used in the centre to account for the varying width of the surface.

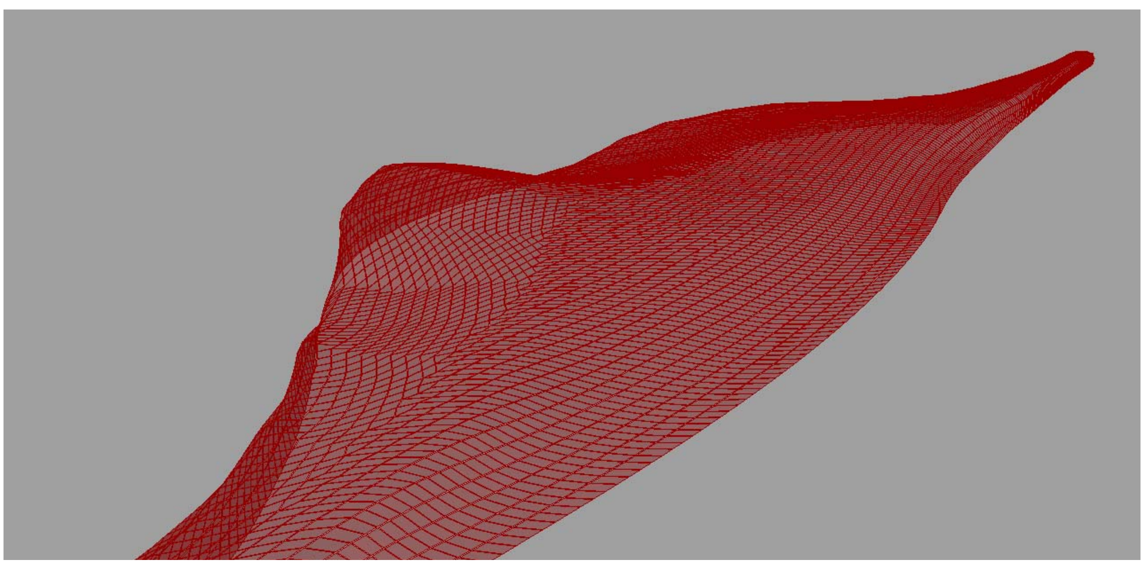


Figure 205: Changing U-divisions

This system creates a surface tessellation with full edge control, omitting the need for any cut of panels. The total amount of panels is as low as possible so the construction cost, both in terms of material and labour, would be lower than the other tessellations.

Comparing tessellations

	smoothness	# panels / material	constant shape	constant size	edge control
Tesselation 1	++	+	yes	no	yes
Tesselation 2	+++	++	yes	yes	no
Tesselation 3	+++	+++	yes	no	yes

Table 20: Comparing tessellations

A tessellation with changing U-divisions along the longitudinal direction of the building provides for a low amount of panels with the same size. However the panels at the edges are cut off and are of different shape and size.
The tessellation with a constant U-division has more panels in total. The panels have the same shape but are different in size. The biggest advantage of this tessellation is that the tessellation ends perfectly at the surfaces edge and connects better to other surfaces. Different surfaces can be tessellated separately and still be connected. Tessellation 3 combines the best properties from tessellation 1 and 2. The panels are about the same size throughout the building with perfect edge control. This way the number of panels is minimal and the panels are all of constant shape but not of constant size.

Braiding system

The way the size of the centre panels is determined in relation to the size of the other panels is vital to create smooth lines in the longitudinal direction of the surface. The braiding system determines how the panels are attached / braided together in the centre of the surface.
The first braiding system has panels of all the same size, but it makes very small panels in the centre of the surface, which are not practical.
The second braiding system divides the width of the surfaces in an exact amount of panels with the same width. This way, the panel width will be constant per length divisions but be changing throughout the length of the building.
The third braiding system divided the width of the surfaces into panels with a gradually smaller width from the outside to the centre. This way, the longitudinal lines are continuing in a smoother way across the surface. This gives the smoothest tessellations of all three braiding systems.

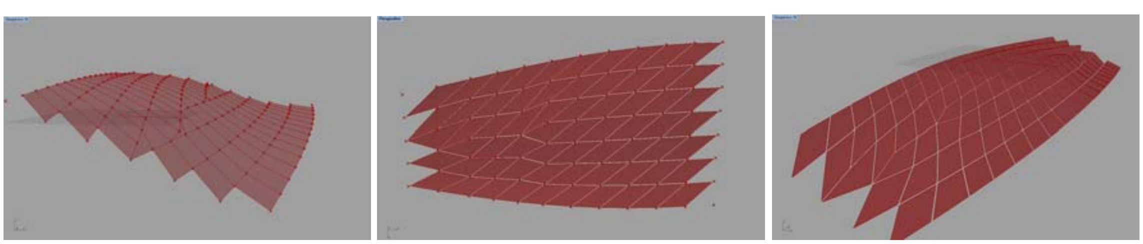


Figure 206: Braiding system 1, 2 & 3

Roof tessellation design

The final roof tessellation is based on Tessellation 3. This tessellation allows for full edge control and a constant panel shape throughout the roof. The surface is as smooth as possible and the number of panels is kept to a minimum. Braiding system 3 binds the surfaces together in the middle of each tessellation band.

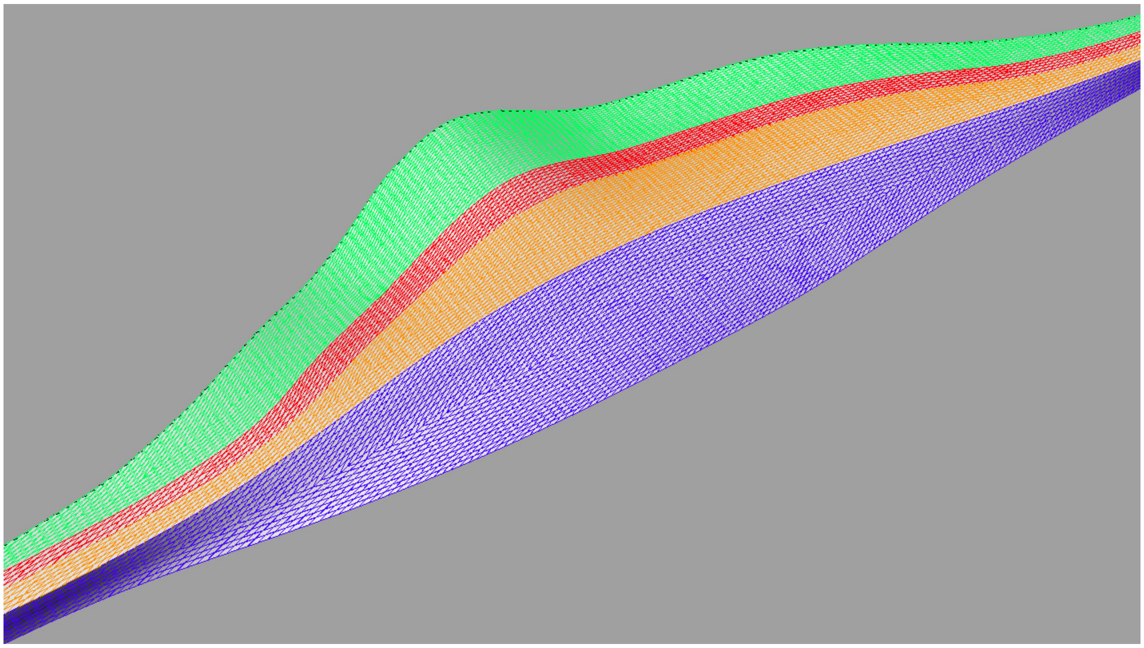


Figure 207: Tessellation bands

The roof surface is divided in four tessellation bands in order to create a direct relation between the function in the building and the roof surfaces (opaque/transparent). This way, the panels on top of a function are directly connected to and in line with the façade of the function.

- *Green:* *Outer retail shops*
- *Red:* *Shopping Street*
- *Orange:* *Inner retail shops*
- *Blue:* *Train tracks*

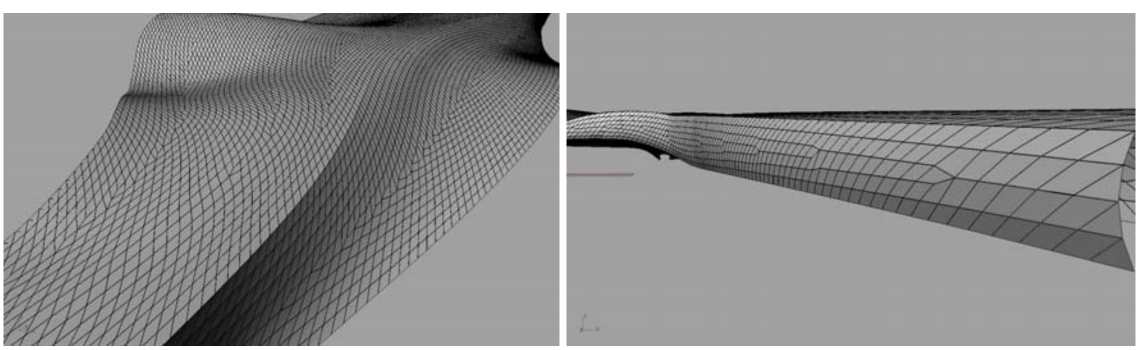


Figure 208: Close up tessellation and braiding system

Further research

Further research is needed to achieve the most suitable tessellation for the Schiphol Interchange Station. The surface is now tessellated based on a basic point relaxation in the diagonal direction of the building.
With a parametric point relaxation in two directions between the structural supports, the overall tessellation of the building could potentially be smoother than it is now.

The design of the steel and glass British Museum Great Court Roof is a very good example of an internal relaxed surface. Forsters and Parners worked together with Buro Happold to span the rectangular courtyard that spans 70 by 100 meters with a triangulated structural grid.[55]

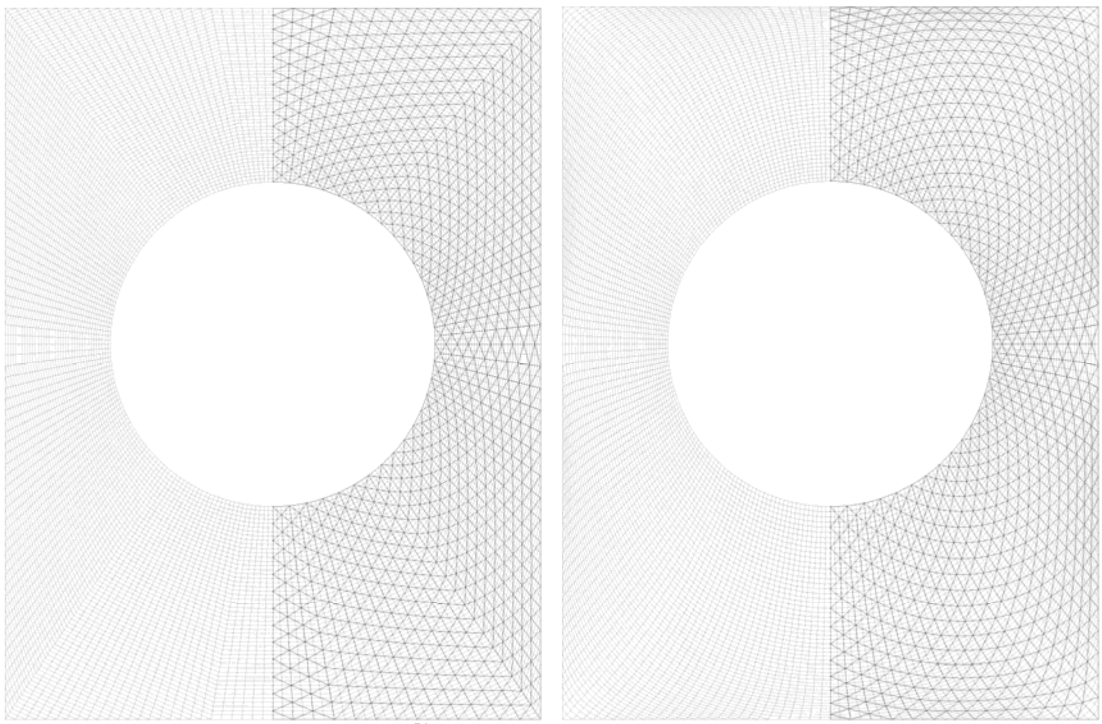


Figure 209: Starting grid & relaxed grid[56]

With a similar internal surface relaxation, the roof of the Schiphol Interchange Station could be relaxed to a much smoother state.

[55] *Chris J.K. Williams, 'The analytic and numerical definition of the geometry of the British museum great court roof', (UK: University of Bath)*
[56] *Chris J.K. Williams, 'The analytic and numerical definition of the geometry of the British museum great court roof', (UK: University of Bath)*

4.10.3 Curvature analysis

The skin of the Schiphol Interchange station is divided in panels. These parallelogram panels are based on four points. A surface made from four individual points can never be a planar surface when applied on a double curved surface.
The final roof tessellation will have an immense amount of panels, of which none are completely planar/ flat. The planarity of the panels depends on the tessellation of the surfaces. If the individual panels are small enough, the panel curvature could remain very small.

In order to a select a suitable material for the panelling of the building skin, in terms of appearance, light properties and visual appearance, the curvature of the individual panels must be analysed.

Curvature analysis

In the Rhino software there is a curvature analysis available. This curvature analysis analyses the Gaussian or Mean curvature of a surface.

"Gaussian and Mean curvature analysis can show if and where there may be anomalies in the curvature of a surface. Unacceptably sudden changes like bumps, dents, flat areas or ripples, or in general areas of curvature that are higher or lower than the surrounding surface can be located and corrected if needed. Gaussian curvature display is helpful in deciding whether or not a surface can be developed into a flat pattern. A smooth surface has two principal curvatures. The Gaussian curvature is a product of the principal curvatures. The mean curvature is the average of the two principal curvatures."[57]

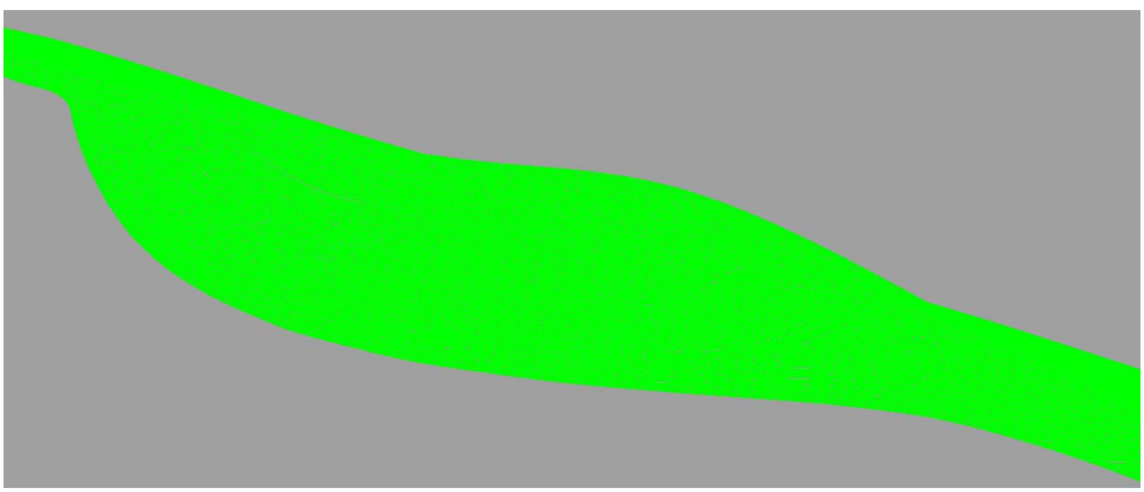


Figure 210: Gaussian curvature

This image shows all panels of the roof surface being green, which means a zero Gaussian curvature. A zero value means that the surface is flat in at least one direction (planes, cylinders and cones). The tessellation of the roof surface, with a high amount of panels in the diagonal direction, together with the relative low curvature of the roof surface, makes that the panels are single curved.

[57] *Curvature analysis, http://www.rhino3d.com/5/help/commands/curvatureanalysis.htm*

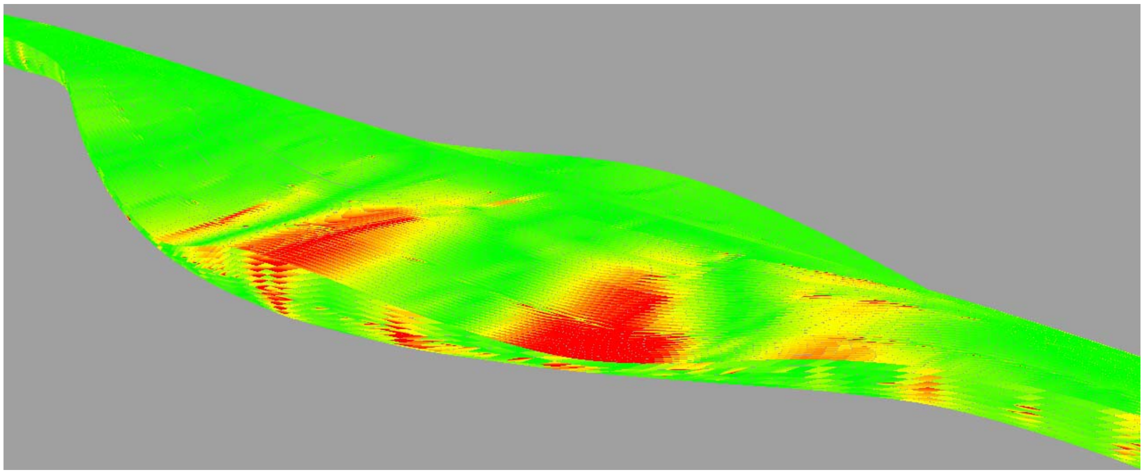


Figure 211: Mean curvature

This image shows panels of the roof surface with different colouring, ranging from green (zero mean curvature) to red (positive mean curvature). The mean curvature is the average of the two principal curvatures. A zero value means that the surface is flat in both directions. A positive value, in this case, means that the surface is curved in one direction. The highest curvature is 0.2.

On site cold bending

The panels with a very small mean curvature could be cold bended / folded on site by hand without the need for machines. The panels could be cold bended on the mounting supports by fixing the panels on one support at the time. This method relies on a very small thickness of the panels in relation to the width and length of the surface.
The panels are left with residual stresses after the cold bending. These residual stresses depend on the thickness, size, material and curvature of the panels. The stresses have to be kept to a minimum when looking at the durability of the building.

Figure 212: iWEB pavilion Kas Oosterhuis[58]

[58] *http://www.oosterhuis.nl/quickstart/index.php?id=web*

The iWEB pavilion from Kas Oosterhuis features 2mm thin Hylite aluminum panels. This material is a very elastic composite capable of absorbing the residual internal forces in the surfaces from the bending.[59]

Cold bending / Panel triangulation

When the curvature of a panel is too high for on-site bending, then a solution is to triangulate the panel by cold bending it in the factory. A triangulation of the surfaces will results in only flat panels. These flat panels can make the same type of roof system as the doubly curved panels. These panels could be fabricated from diamond-shaped panels, which would be centre-folded in the longitudinal direction.

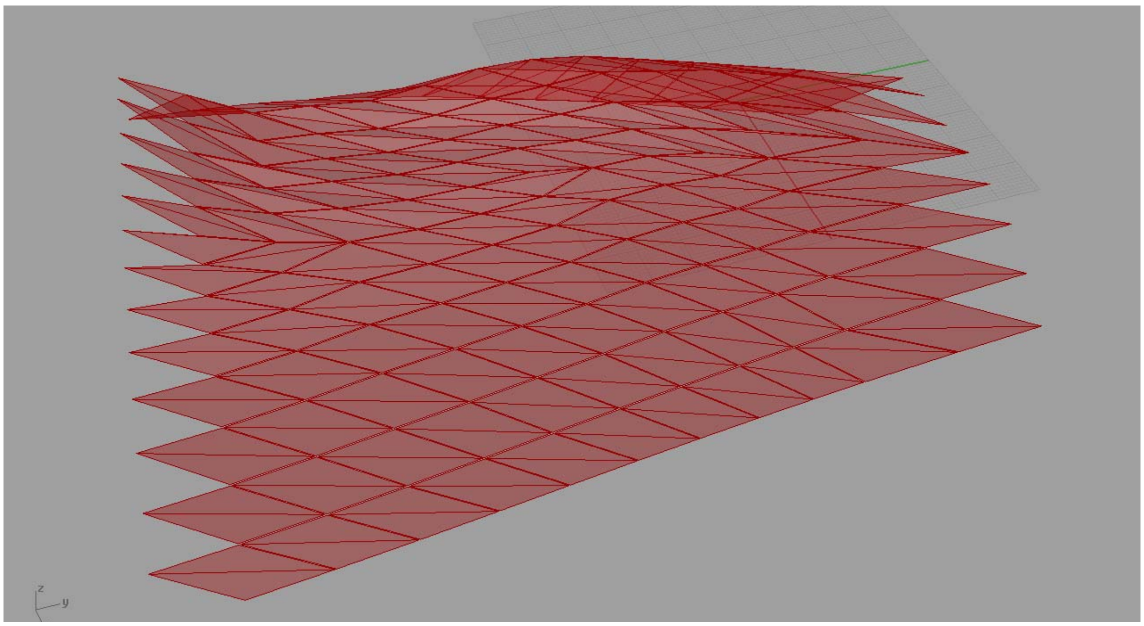


Figure 213: Triangulated surface

There are various types of cold bending metal sheets such as air bending, bottoming, coining, V bending, U bending and other types of bending. Air bending is the best option for this roof design due to the high amount of different panels.
Air bending is a bending process where the punch bends the material between two dies without bottoming in a lower cavity. This method eliminated the need for a special die for each panel. With this bending process, there is a small spring back after the punch is released. This affects the precision of the bending process and has to be kept in mind when bending.

[59] *http://www.oosterhuis.nl/quickstart/index.php?id=web*

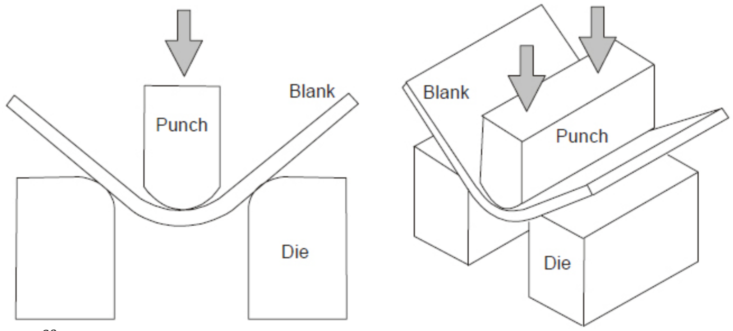


Figure 214: Air bending[60]

4.10.4 Section design

The total roof system of the Schiphol Interchange Station is too big for a comprehensive daylight analysis and daylight design. A small section is selected for further research and development. This section features all the different functions in the building. In this way the research and design of the section is representative for the entire Schiphol Interchange Station.

The design of the section is the final step in the daylight research process. The things that have been learned and the lighting principles that have been deduced from the lighting research will be used to technically design the section of the Schiphol Interchange Station.

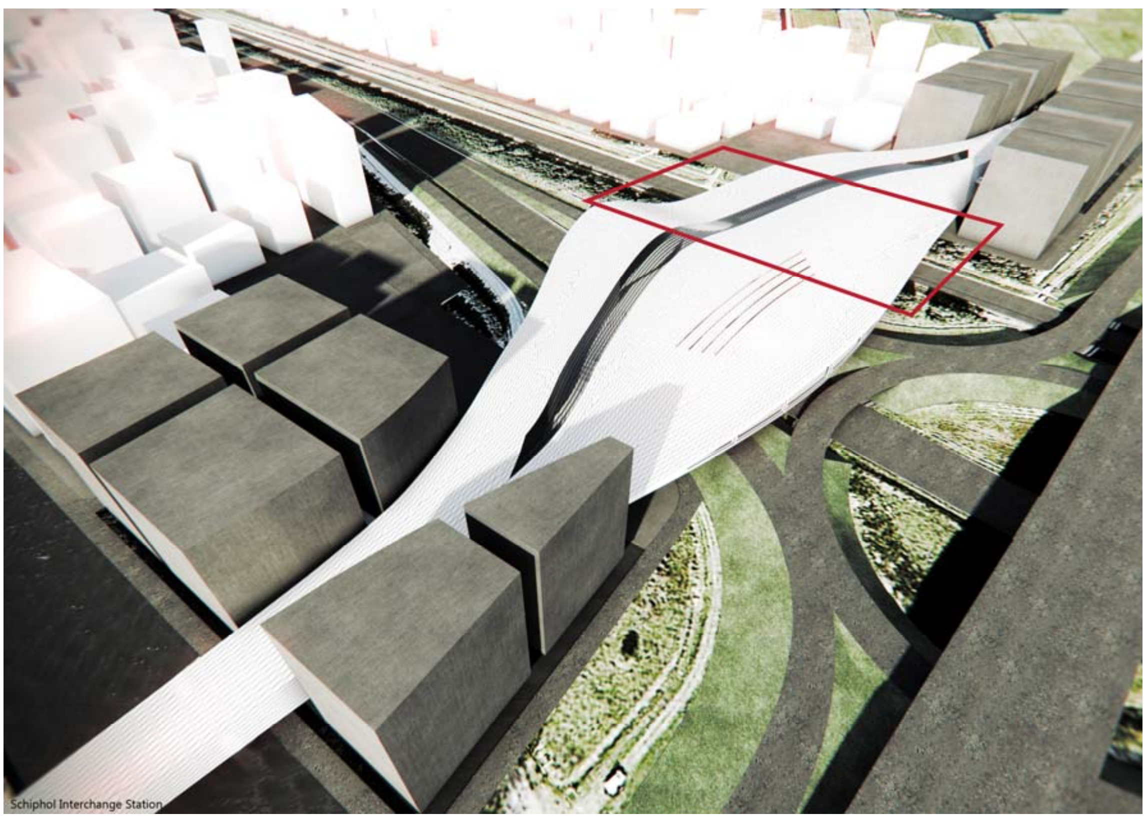


Figure 215: Position of the section in the Schiphol Interchange Station

[60] *http://www.ciri.org.nz/bendworks/bending.pdf*

Workflow roof design

The lighting requirements have been described for all the functions inside the Schiphol Interchange Station. The conducted physical and digital light research and experiments have led to certain geometrical principles (such as inclination, materials, opening and shapes).

From these geometrical principles, a first roof design can be proposed. This proposed design will then be tested in Ecotect to calculate the light quantity and quality inside the functions of the building. These light values have to be checked with the required values.
If these values are not within acceptable range of the required values, then the roof design has to be adjusted and tested again. This feedback loop iterates itself until acceptable values are found through adjusting the geometric principles and material properties. This all leads to a final roof design for the building with a specified geometry and materials.

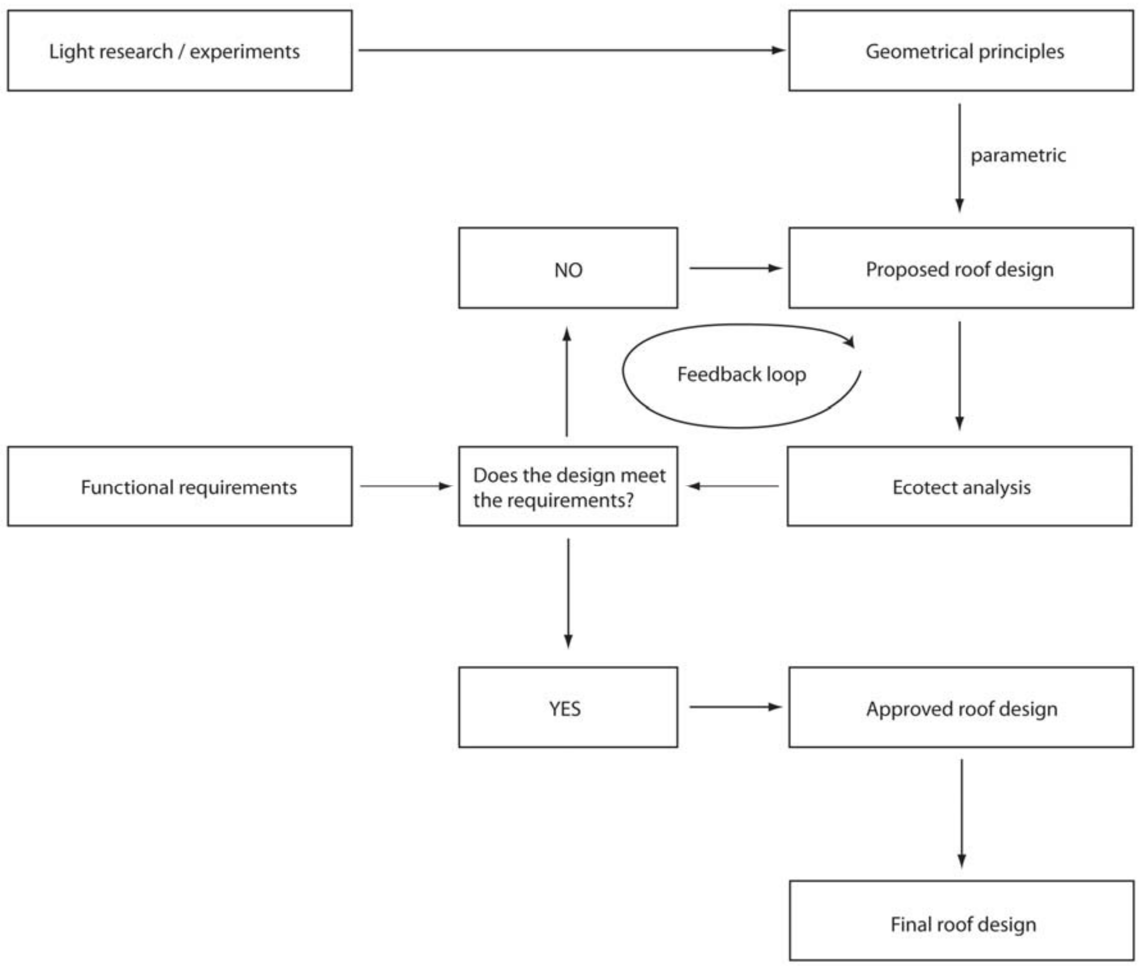


Figure 216: workflow roof design

Decisions making for panelling

The parallel diagrid covers the entire roof of the building. Within this tessellation, different types of geometries and panels should be considered. This chart structures the decision making process when deciding which type of panels to use based on the required light quantity and quality.

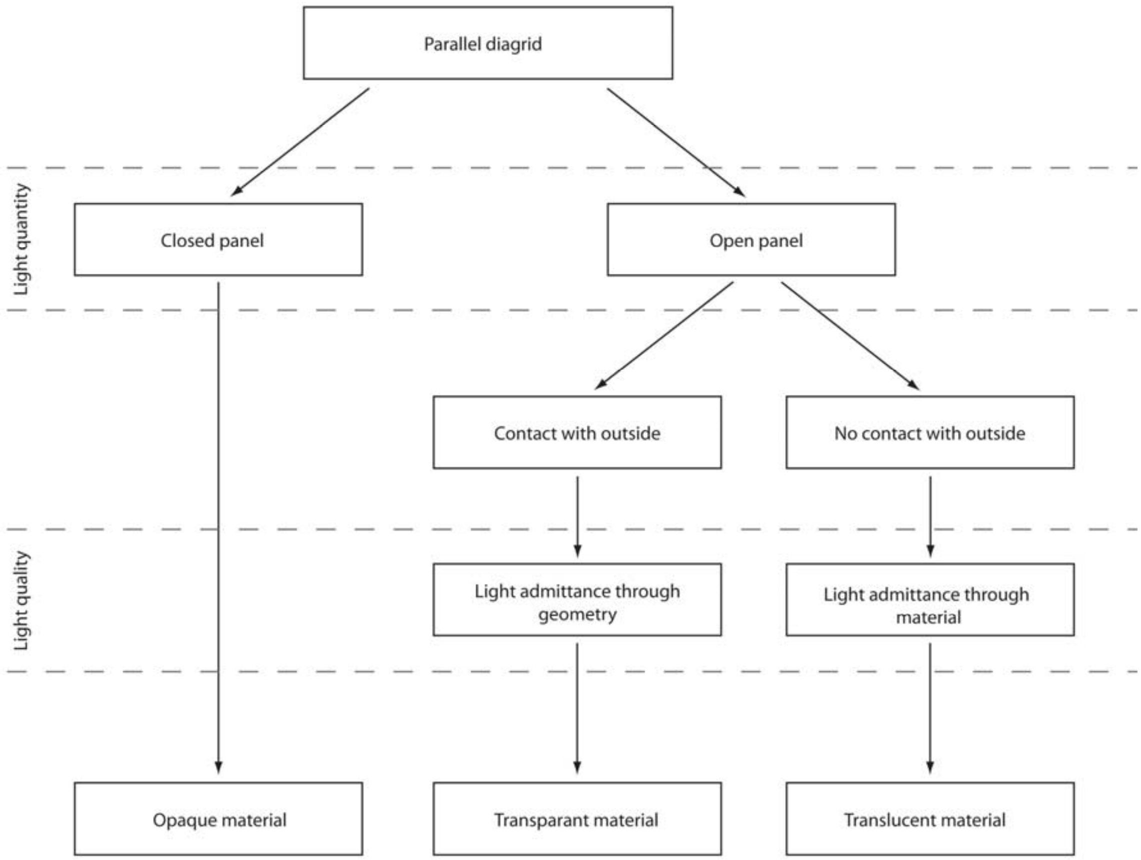


Figure 217: decision making chart paneling

The next table shows for each function of the building, how that part of the surface will be treated and which kind of geometry and panels will be used.

Function	open/closed	View to outside	geometry/material	panel
Retail inside	open	no	material	translucent
Retail outside top	open	no	material	translucent
Retail outside side	open	yes	geometry	transparant
Central square	open	no	material	translucent
Shopping street	open	yes	geometry	transparant
Platforms	open	no	material	translucent
Kiss & ride	open	no	material	translucent
Train track skin	closed			opaque
Café	open	yes	geometry	transparant

Table 21: Decisions panelling

Proposed roof design

Geometrical and material principles have been applied to the section of the Schiphol Interchange Station to create the first proposed roof design. This roof design will be used for daylight testing in Ecotect. The roof design can then be adjusted and tested again until it meets the interior daylight requirements.

Figure 218: Proposed roof design perspective 1

Figure 219: Proposed roof design perspective 2

4.10.5 Ecotect analysis

The section from the proposed roof design has to be prepared for the Ecotect light analysis. The sides of the section are closed to ensure the only light entering the building is through the building skin. The geometry of the building is simplified and stripped down as much as possible in order get a working model in Ecotect and acceptable calculations times.

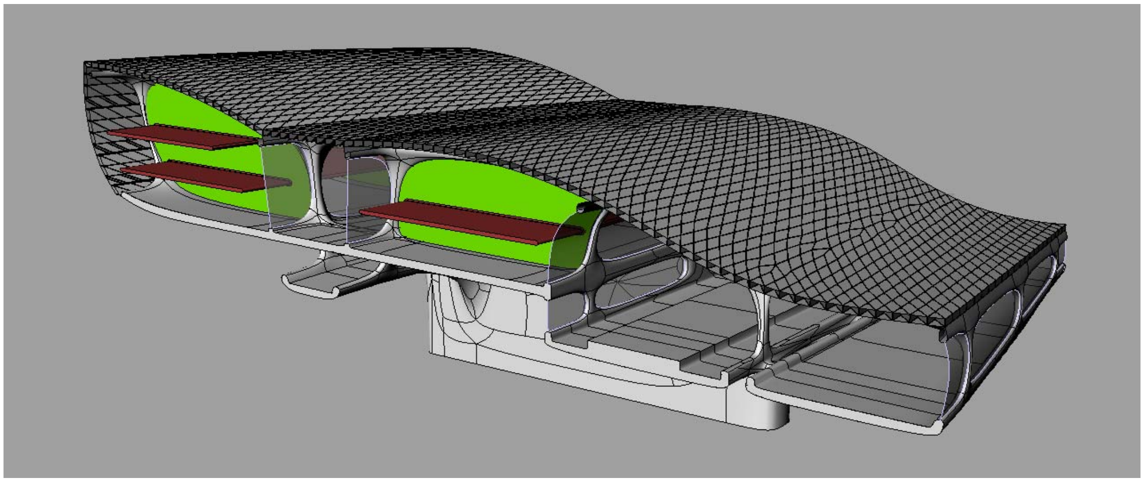


Figure 220: Ecotect model proposed roof design

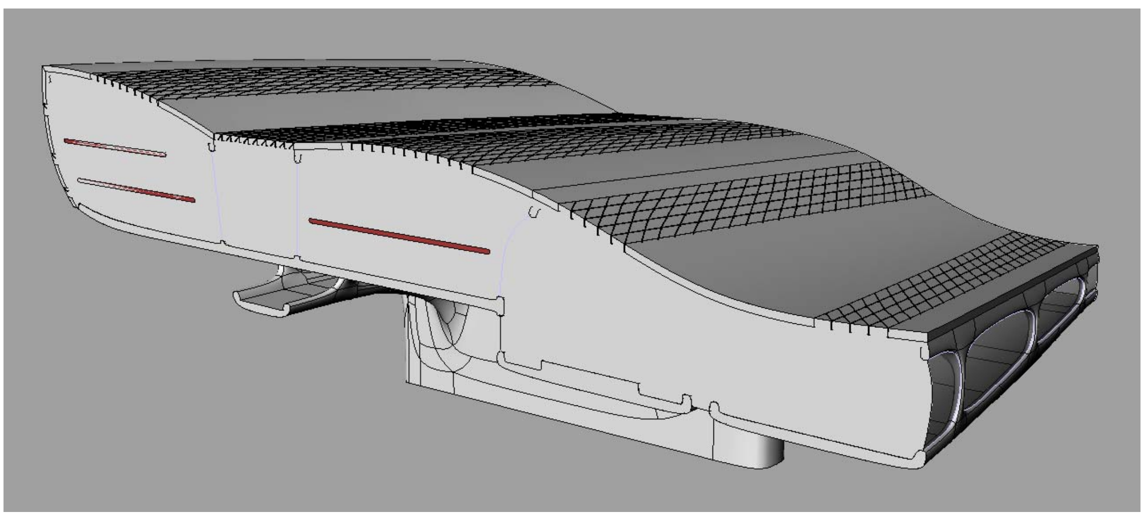


Figure 221: Stripped down design

Set up

The proposed roof design is now ready to be analysed with the Radiance solver in Ecotect.
False colour rendering will be used to view the illumination results and to compare them to the stated daylight requirements.
The daylight performance of the proposed roof design will be tested on March 20, June 21 and December 22. On these dates the proposed will be analysed at 09:00, 12:00 and 16:00.

Parameters

All parameters which influence the amount of diffuse and direct daylight that enter the building are described in the daylight theory of chapter 4.3. There are certain parameters in the proposed roof design which can be adjusted in order to meet the lighting requirements for the functions. The vertical and the horizontal inclination of the diagrid, as well as the visible transmittance of the upper and lower panels, are the primary parameters which are used meet the daylight requirements.

- Parameter A: Vertical inclination (beam)
- Parameter B: Horizontal inclination (beam)
- Parameter C: Visible transmittance (panel)

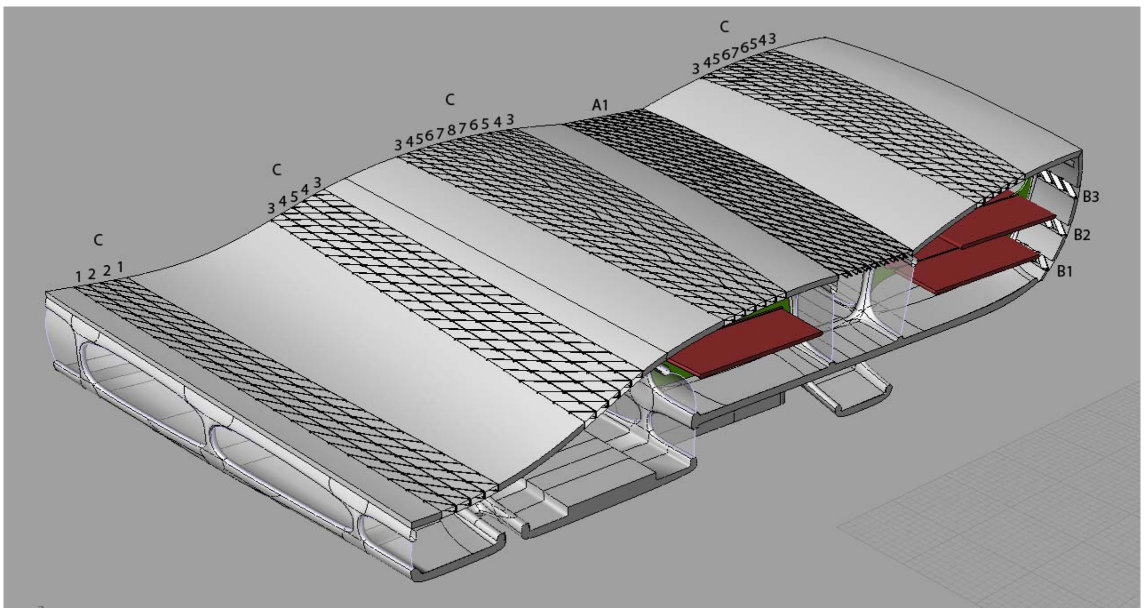


Figure 222: Daylight parameters on section

For the primary daylight analysis of the proposed roof designs, the parameters are set as shown in the table below. The visible transmittance is the transmitted radiation through any surface. This is affected by the transparency of the material (Ftrans) as well as, for windows, their shading coefficient (SC) and the effects of refraction (Frefract). The Visible transmittance is described by the following formula:[61]

$$G_{transmitted} = G_{incident} \times F_{trans} \times SC \times F_{refract}$$[62]

A visible transmittance of 0.25 is used for almost opaque panels, where a visible transmittance of 0.7 is used for low-E clear glass. For this first test, the visible transmittance of the translucent panels will range from 0.3 to 0.5. This can be compared with a normal transparency from 0 to 50%.

[61] *Wiki.naturalfrequency.com. Shading: solar incidence. http://wiki.naturalfrequency.com/wiki/solar_incidence*
[62] *Wiki.naturalfrequency.com. Shading: solar incidence. http://wiki.naturalfrequency.com/wiki/solar_incidence*

Based on the results from this first daylight analysis, the parameters can be further refined to meet the daylight requirements if necessary.

A	vertical Inclination [degrees]	B	horizontal Inclination [degrees]	C	Visible transmittance
A1	45	B1	45	C1	0.3
		B2	45	C2	0.35
		B3	45	C3	0.3
				C4	0.35
				C5	0.4
				C6	0.45
				C7	0.5
				C8	0.5

Table 22: Parameters first analysis

Results

- *20 March 09:00 Intermediate sky*

Figure 223: Platform, render

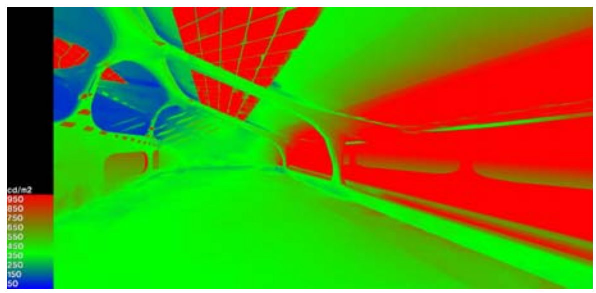


Figure 224: Platform, false color render

Figure 225: Shopping street, render

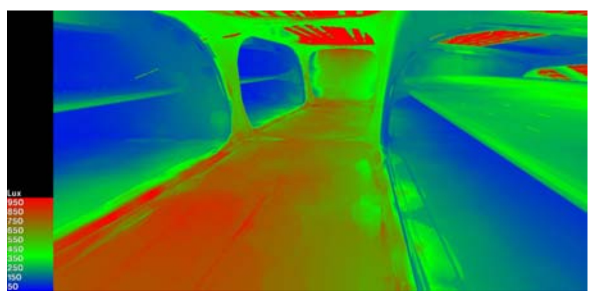


Figure 226: Shopping street, false color render

Figure 227: Retail, render

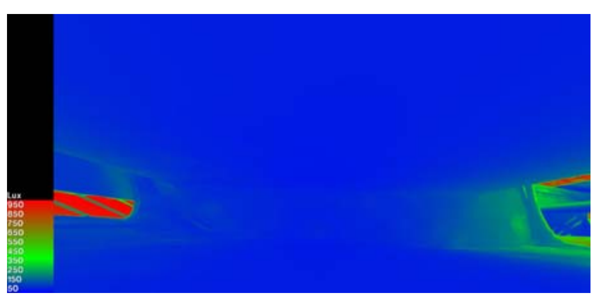


Figure 228: Retail, false color render

- *20 March 12:00 Intermediate sky*

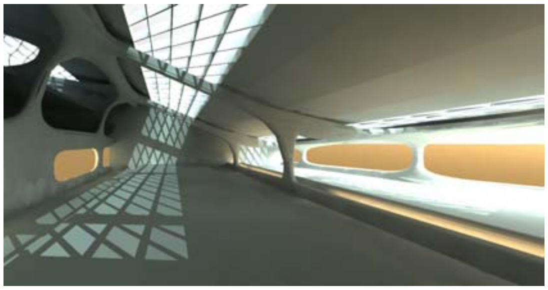


Figure 229: Platform, render

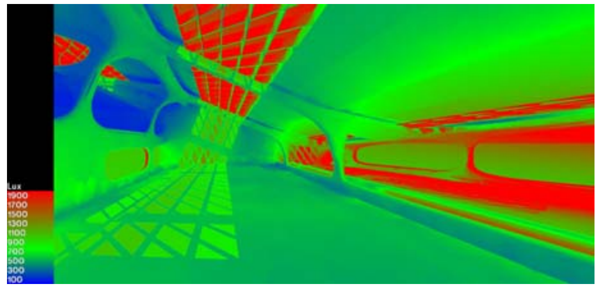


Figure 230: Platform, false color render

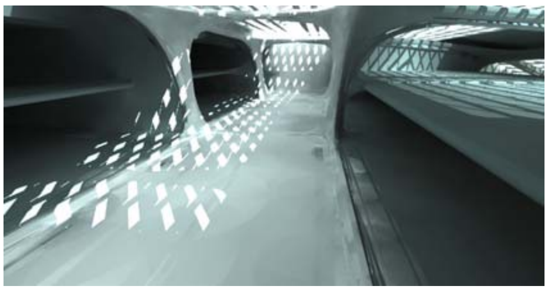


Figure 231: Shopping street, render

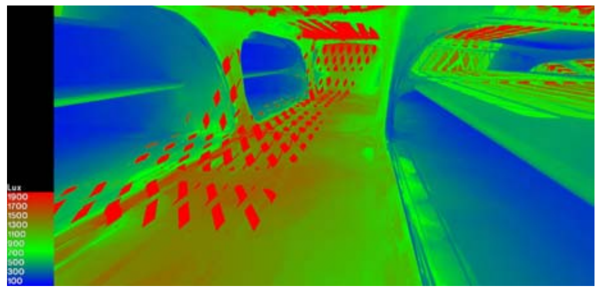


Figure 232: Shopping street, false color render

Figure 233: Retail, render

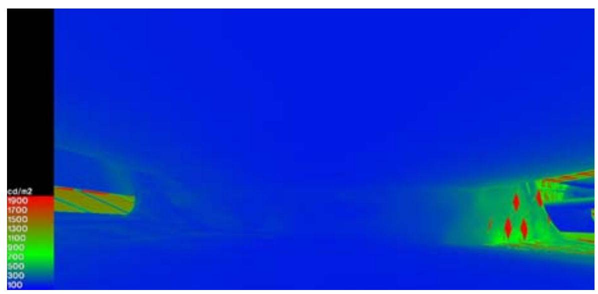


Figure 234: Retail, false color render

- *20 March 16:00 Intermediate sky*

Figure 235: Platform, render

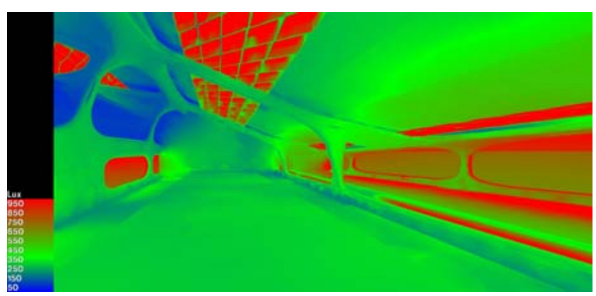


Figure 236: Platform, false color render

Figure 237: Shopping street, render

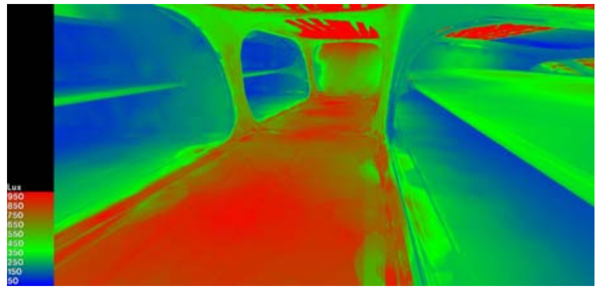


Figure 238: Shopping street, false color render

Figure 239: Retail, render

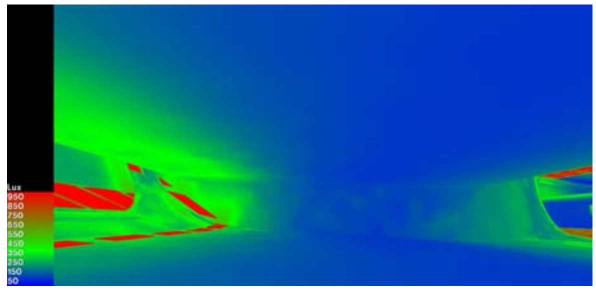


Figure 240: Retail, false color render

- *21 June 09:00 Sunny sky*

Figure 241: Platform, render

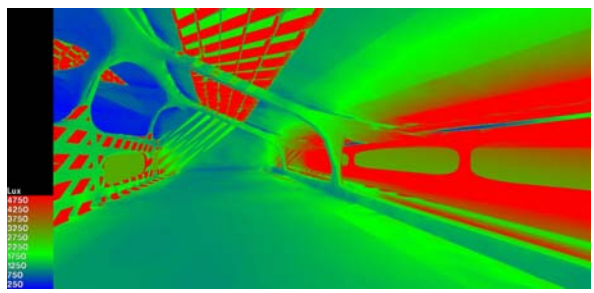


Figure 242: Platform, false color render

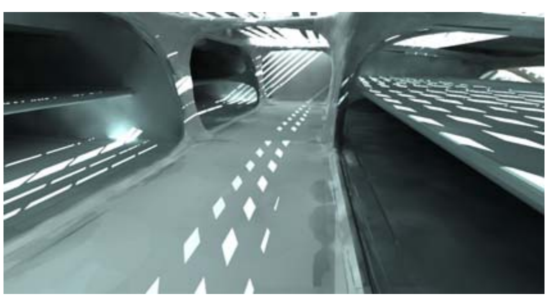


Figure 243: Shopping street, render

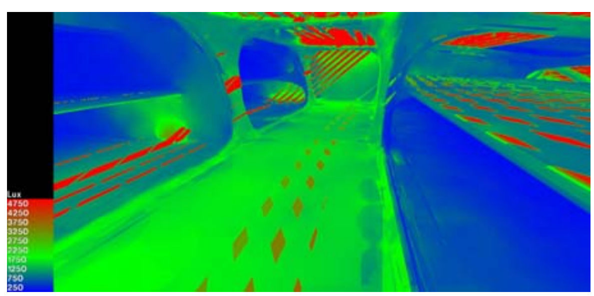


Figure 244: Shopping street, false color render

Figure 245: Retail, render

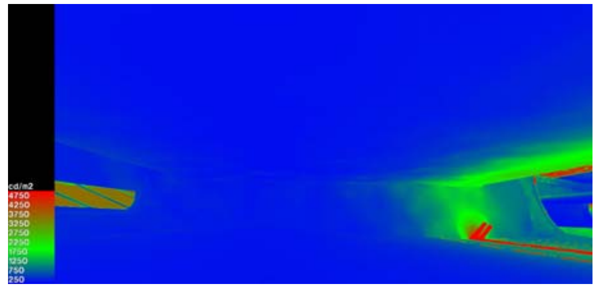


Figure 246: Retail, false color render

- *21 June 12:00 Sunny sky*

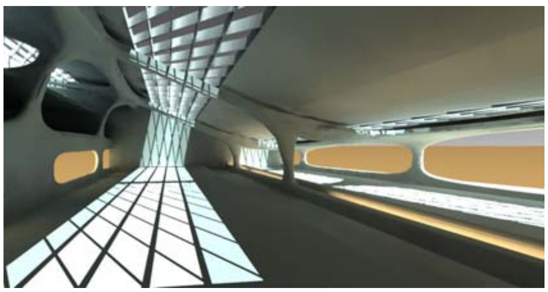


Figure 247: Platform, render

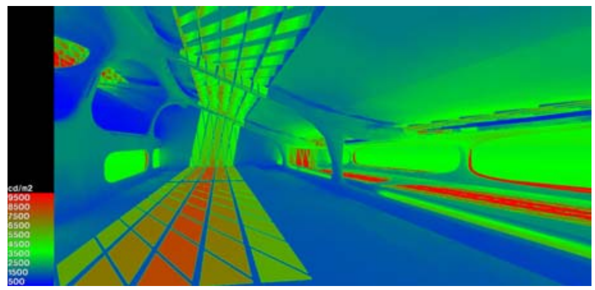


Figure 248: Platform, false color render

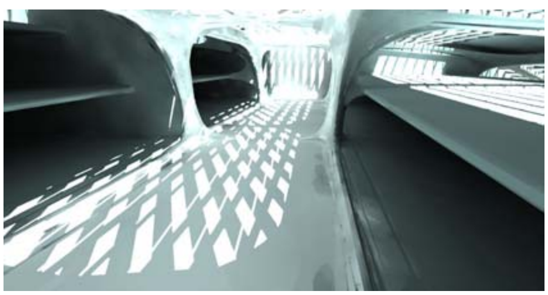


Figure 249: Shopping street, render

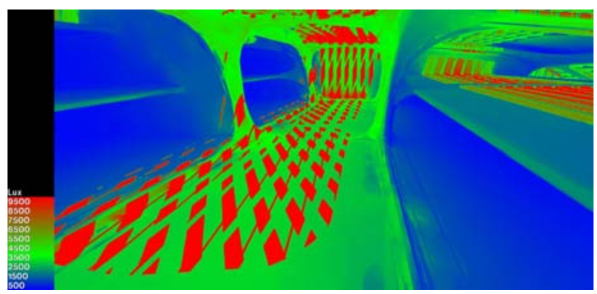


Figure 250: Shopping street, false color render

Figure 251: Retail, render

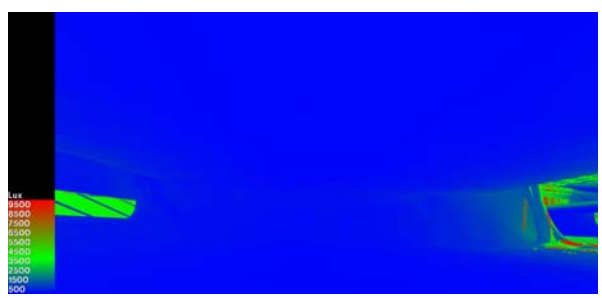


Figure 252: Retail, false color render

- *21 June 16:00 Sunny sky*

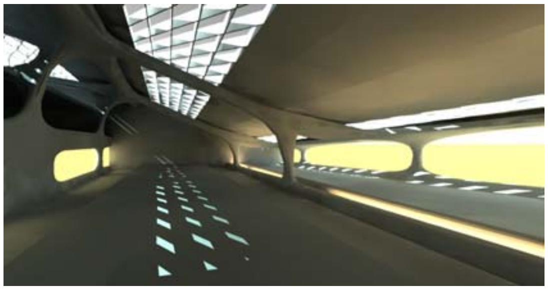


Figure 253: Platform, render

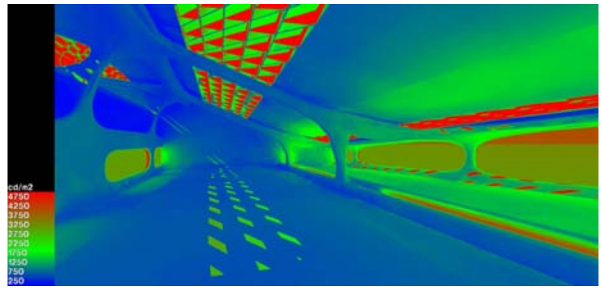


Figure 254: Platform, false color render

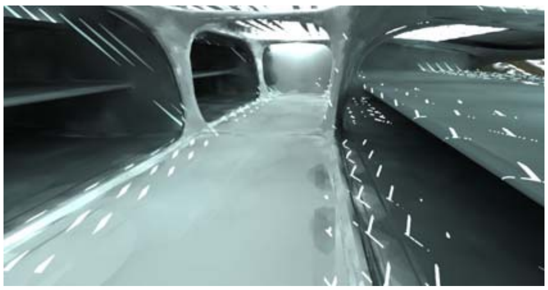


Figure 255: Shopping street, render

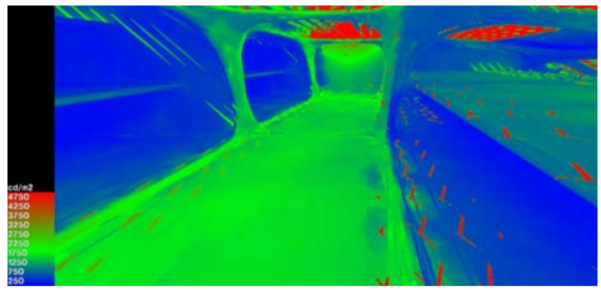


Figure 256: Shopping street, false color render


Figure 257: Retail, render

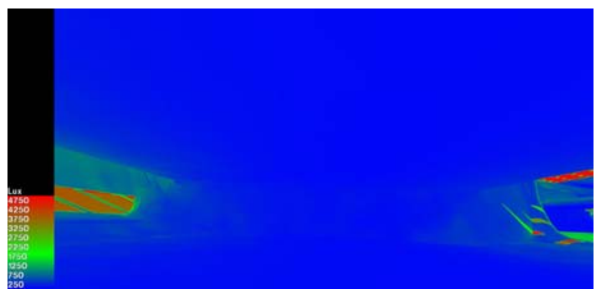


Figure 258: Retail, false color render

- *22 December 09:00 Cloudy sky*


Figure 259: Platform, render

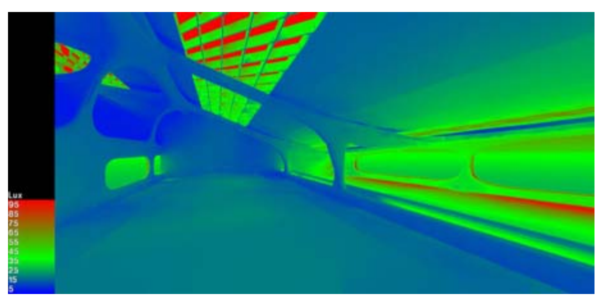


Figure 260: Platform, false color render

Figure 261: Shopping street, render

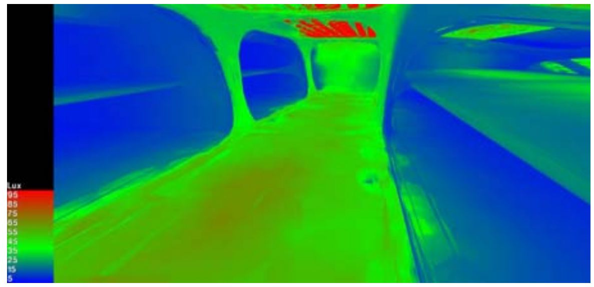


Figure 262: Shopping street, false color render

Figure 263: Retail, render

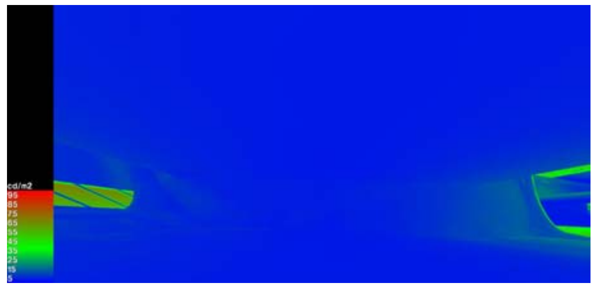


Figure 264: Retail, false color render

- *22 December 12:00 Cloudy sky*

Figure 265: Platform, render

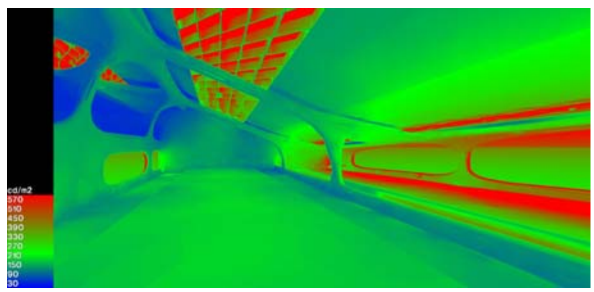


Figure 266: Platform, false color render

Figure 267: Shopping street, render

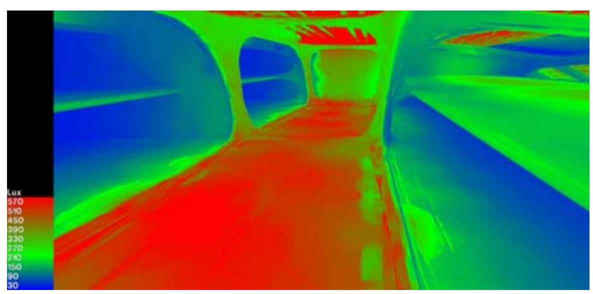


Figure 268: Shopping street, false color render

Figure 269: Retail, render

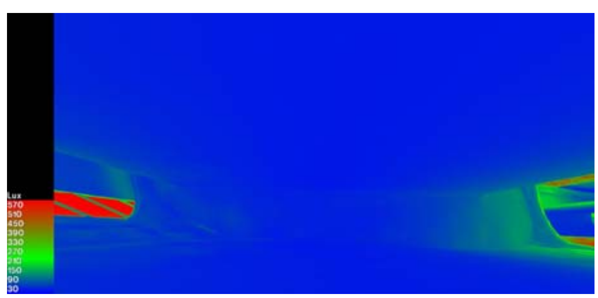


Figure 270: Retail, false color render

- *22 December 16:00 Cloudy sky*

Figure 271: Platform, render

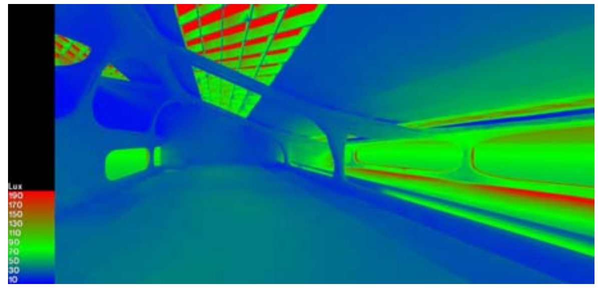


Figure 272: Platform, false color render

Figure 273: Shopping street, render

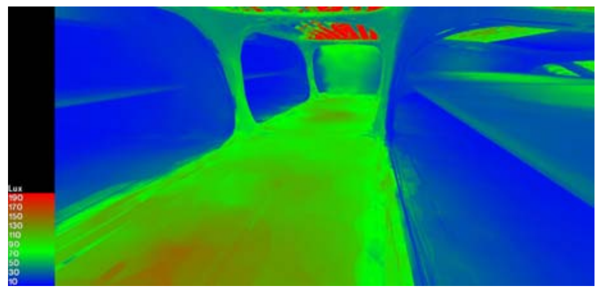


Figure 274: Shopping street, false color render

Figure 275: Retail, render

Figure 276: Retail, false color render

Findings

The findings from the daylight analysis on the proposed section design for the Schiphol Interchange Station is summarized in the following table.

Function	date	time	Daylight quality	Light intensity [lux]	Glare
Retail	20 march	9:00	diffuse	60	no
	20 march	12:00	diffuse	200	no
	20 march	16:00	diffuse/direct	150/1900	no
	21 June	9:00	diffuse	175	no
	21 June	12:00	diffuse	250	no
	21 June	16:00	diffuse	150	no
	22-dec	9:00	diffuse	6	no
	22-dec	12:00	diffuse	25	no
	22-dec	16:00	diffuse	7	no
S. street	20 march	9:00	diffuse	750	no
	20 march	12:00	diffuse/direct	1250/5000	contrast
	20 march	16:00	diffuse	900	no
	21 June	9:00	diffuse/direct	1750/3200	contrast
	21 June	12:00	diffuse/direct	3200/42000	contrast/brightness
	21 June	16:00	diffuse	1700	no
	22-dec	9:00	diffuse	65	no
	22-dec	12:00	diffuse	550	no
	22-dec	16:00	diffuse	125	no
Platforms	20 march	9:00	diffuse	400	no
	20 march	12:00	diffuse	650	no
	20 march	16:00	diffuse	300	no
	21 June	9:00	diffuse	1150	no
	21 June	12:00	diffuse	1250/7000	no
	21 June	16:00	diffuse	650	no
	22-dec	9:00	diffuse	20	no
	22-dec	12:00	diffuse	185	no
	22-dec	16:00	diffuse	35	no
Kiss & ride	20 march	9:00	direct	3400	direct
	20 march	12:00	direct	2200	no
	20 march	16:00	diffuse	800	no
	21 June	9:00	diffuse/direct	5000/30000	contrast/brightness/direct
	21 June	12:00	diffuse	3500/7500	no
	21 June	16:00	diffuse	1380	no
	22-dec	9:00	diffuse	65	no
	22-dec	12:00	diffuse	600	no
	22-dec	16:00	diffuse	125	no

Table 23: Findings daylight analysis proposed roof design

- The retail stores, especially the lower levels, don't receive enough daylight to meet the requirements for retail functions. The maximum natural daylight throughout the year is 250 lux which isn't enough for a retail function which need a constant light level of 750-1000 lux.
  Due to the shape and size of the retail functions, changing the daylight parameters in order to improve the lighting conditions is not possible. Additional electric lighting is needed to provide for an adequate and constant light intensity throughout the year.
  The inclination of the beam (B1, B2 and B3 parameters) on the back side of the building succeeds in preventing direct light from entering the building in the afternoon.

- The shopping street is adequately lit from daylight during the mid-season months and summer. The shopping street always more illuminated then the surrounding shops so it can as a shopping street and a transport area. The average illuminance is about 1000 lux.
  The inclinations of the beams prevent most of the direct sunlight from entering the building during the day. However, in the middle of the day some direct light is entering the building. This is only a problem during the summer when the direct light could lead to glare due to the overall brightness of the area and contrast between the lighted and shaded areas. The heat gain from this direct radiation could also cause overheating in the building.
  Adjusting the inclination of the beam (A1 parameter) in the shopping street could prevent more light from entering the shopping street. As a downside, the light intensity during the winter month would decrease.

- The platforms receive sufficient daylight during the midseason to meet the daylight minimum illumination of 200 lux. In the winter, the natural light levels are too low to meet the requirements. Increasing the visible transmittance of the panels over the train platforms could increase the amount of daylight entering the building in the winter. Electrical lighting could also be used to provide additional light when and where necessary.

- Due to the open façade, instead of the diagrid façade, the Kiss & Ride area receives a very high amount of daylight during the morning hours. The high amount of direct radiation combined with the low altitude could cause direct glare problems for traffic entering the Kiss & Ride area. Additional sun shading devices could be used to reduce the direct sunlight that enters the building through the front façade.

Sidenote: Translucent materials can't be used in Ecotect. Therefore, only the visible transmittance determines the amount of radiation transmitting through the panels and entering the building. The direct light that is entering through the panels is not taken into account and regarded as diffuse.

Further research

Further Ecotect research is needed to parametrically connect the A,B and C-parameters from the rhino model to the Radiance solver. By parametrically connecting the input parameters to the results from the Radiance solver, the most suitable parameters can be found to achieve the most suitable roof design. The Geco plug-in for grasshopper (*http://utos.blogspot.com*) can be used to connect Rhino to Radiance.

4.10.6 Materialisation

The section of the Schiphol Interchange Station is now designed in such a way that it meets the daylight requirements. The materialisation of the building is the key step to connect the daylight research to the architectural design. The daylight research provided for a conceptual geometry and materials that have to be translated to a geometry and materials which can be fabricated, shipped and assembled in such a way that it fits within the architectural design.

Insulation

The diagrid that covers the roof of the Schiphol Interchange Station needs to be partially insulated. Various parts of the roof covers stored and shops which need a constant indoor temperature. The roof surface can be insulated in two different ways.

- Insulation layers separate from panels
- Insulation integrated in panels (sandwich panels)

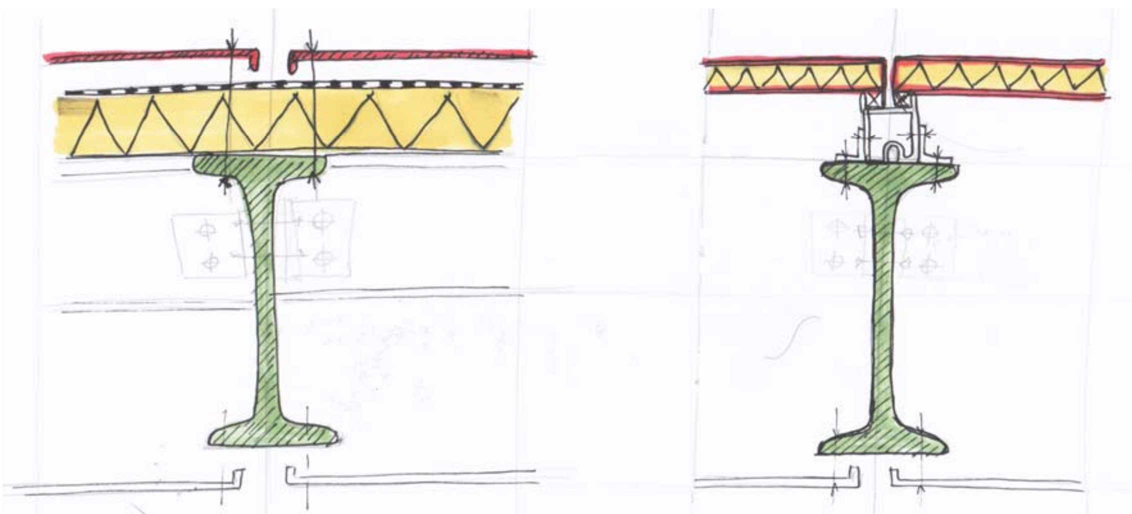


Figure 277: Sketch insulation options

	Thermal bridges	Flexibility	Manufacturing costs	Labour costs
Layering	+	++	+++	+
Ingrating	+++	-	+	++

Table 24: Comparison chart

Integrating the insulation into the panels is the most advanced option. The sandwich panels are clamped into thermal profiles which are fixed to the secondary construction. This option is very well insulated and thermal bridges don't occur.

Separating the panelling and the insulation in two different layers allows for more flexibility in the fabrication process of the panels. The panels are bolted on the secondary beams and don't need to be fixed in thermal profiles. This option is much cheaper in manufacturing costs while it takes more time to bolt the panel to the frame on the job site. The downside to this solution is that the panels have to be fixed through the insulation. Thermal bridges can occur in these places. With detailing, these thermal bridges can be reduced to a minimum.

Reference project façade build-up

This build-up of the primary façade detail will be illustrated by images from the main reference building, the Kunsthaus in Graz, Austria. This building is selected because the structure and façade are doubly curved in a similar way as on the Schiphol Interchange Station. The fact that the panels are fixed on top of the insulation layer is also of similarity to my design.

The building is a museum for the multimedia art and that is why the buildings architects Peter Cook and Colin Fournier tried to make art with this building itself. The building connects to an existing building on site, and in this way acts as a landmark marking the beginning of the old city.

Figure 278: Kunsthaus Graz (Peter Cook/Colin Fournier[63]

The façade of the Kunsthaus consists of 1300 unique panels of acrylic glass which are different in shape and size. A custom mold was fabricated for each of the panels, which were then heat formed over the mold.
A construction consisting of steel beams is connected to the concrete core of the building.
In between the steel beams, steel sandwich panels are connected as a roof element on which to lay the insulation. The steel sandwich panels are taped airtight and received a bitumen layer to make the building temporary watertight during construction.

The insulation goes on top of the layer of steel sandwich panels. Due to the curvature of the building and fire prevention, the insulation is made from cellular glass insulation. The properties of this material allow for an easy connection to a sloping surface. The insulation panels are adhering to the steel sandwich panels. In areas were the slope of the façade / roof is too big for adhesion, the insulation is fixed with z-shaped anchors to the steel sandwich panels. The glass insulation panels are connected and covered with bitumen filler. The insulation surface will then be sanded smooth before installing the top layer. The final layer is a watertight, self-adhering synthetic fabric. On steep parts of the building skin, this layer is connected to the insulation with steel plates which prevent it from sliding down.

[63] *www.free-d.nl*

The connection rods for the roof panels are sticking through the insulation layer and watertight layer. The insulation is applied very carefully around the connection rods so that the thermal bridges through the steel connection rods are minimized. The synthetic roof membrane creates a watertight seal around the connection rods.
The synthetic roof membrane under the roof paneling drains the water from the surface of the building.

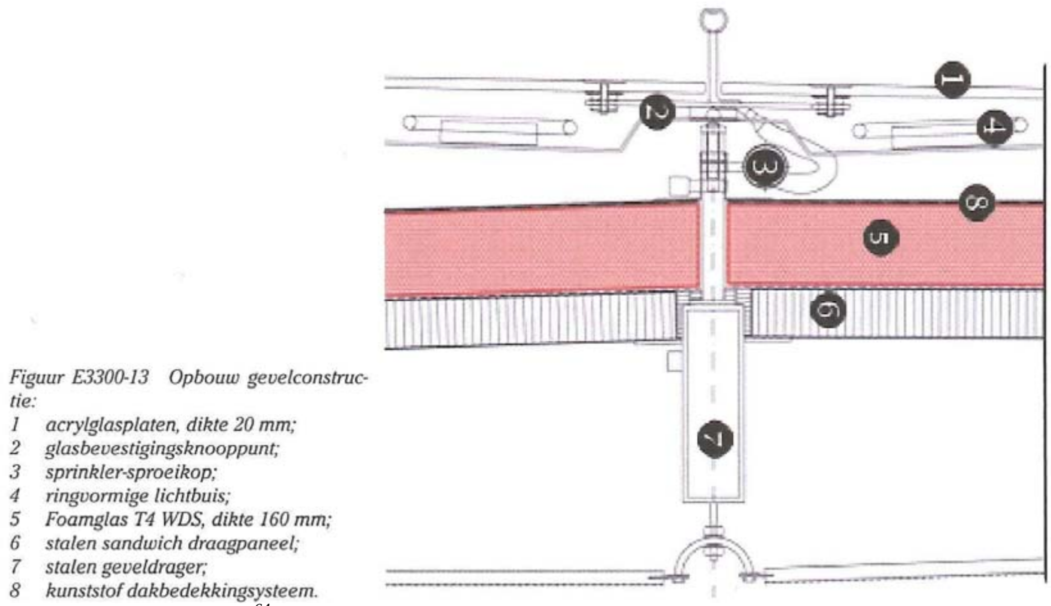


Figure 279: Façade detail[64]


Figure 280: Façade build-up[65]

This first picture shows how the steel sandwich panels are connected to the steel beams. The second picture shows the cellular glass insulation being adhered to the façade of the building and how the connection plates are used to prevent the insulation from sliding down.

---

[64] *Handboek gevels. (D6000 Gevelvullingen van kunststof). Den Hague, 2011: E3300-11 Voorbeeldproject 'Kunsthaus te Graz*
[65] *Handboek gevels. (D6000 Gevelvullingen van kunststof). Den Hague, 2011: E3300-11 Voorbeeldproject 'Kunsthaus te Graz*

Figure 281: Facade build-up[66]

These two pictures show how the insulation panels are sanded down to a continuing insulation layer and the way the synthetic membranes are connected around the rods in order to create a fully watertight seal.[67]

Detailing

The points that have been selected from the section for further detailing are the most important details in the building and are directly related to the daylight research and architectural design. The six details that have been selected show the layering and detailing of the roof system. The materials that will be selected are being determined by the desired architectural effect of the roof system and interior spaces.

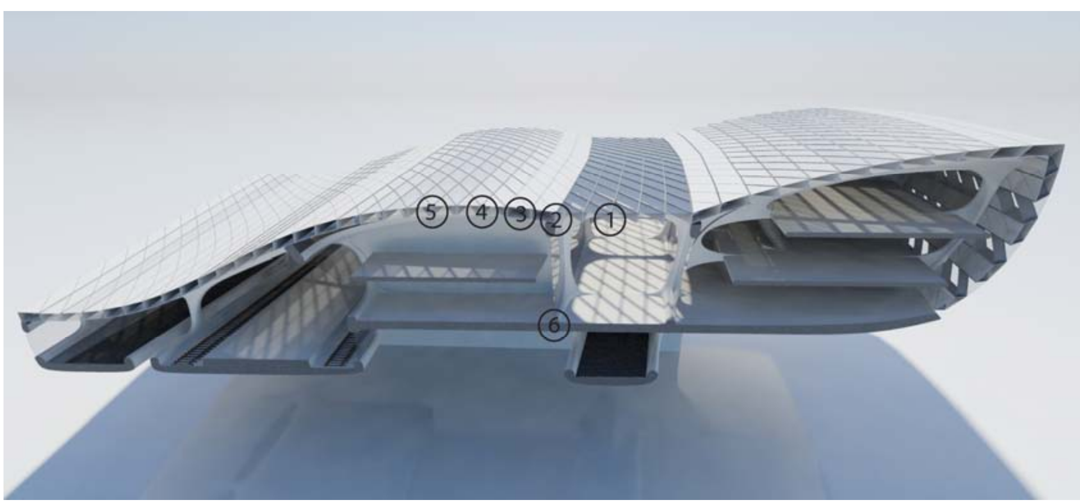


Figure 282: Selected points for 1:5 detailing

[66] *Handboek gevels. (D6000 Gevelvullingen van kunststof). Den Hague, 2011: E3300-11 Voorbeeldproject 'Kunsthaus te Graz*

[67] *Handboek gevels. (D6000 Gevelvullingen van kunststof). Den Hague, 2011: E3300-11 Voorbeeldproject 'Kunsthaus te Graz*

The challenge was in the materials for the exterior and interior paneling. Two different materials are used for the exterior of the building skin, aluminum panels and translucent glass panes with different translucency values. The aluminum panels must be finished and painted in such a way to closely match the appearance of the translucent glass panes. This way, the two parts of the roof surfaces on either side of the shopping street will remain single entities instead of falling apart into multiple parts. The same goes for the interior roof paneling where opaque aluminum panels and translucent plastic panels must form one entity.

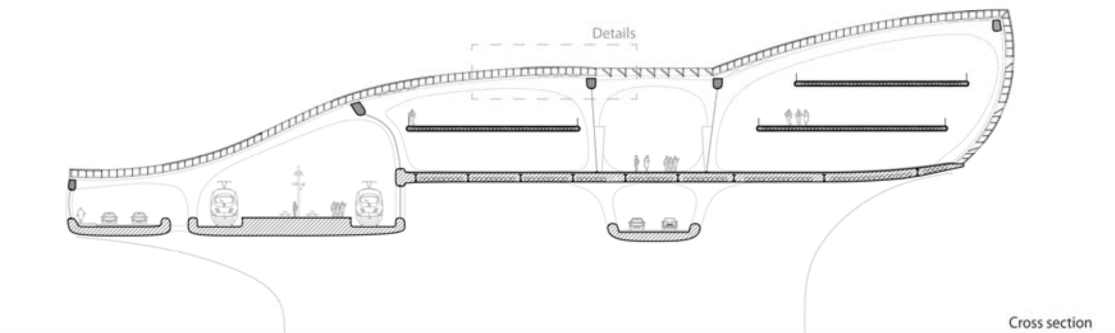


Figure 283: Cross section

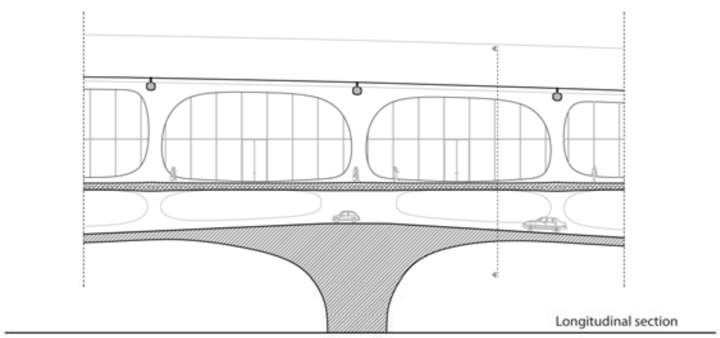


Figure 284: Longitudinal section

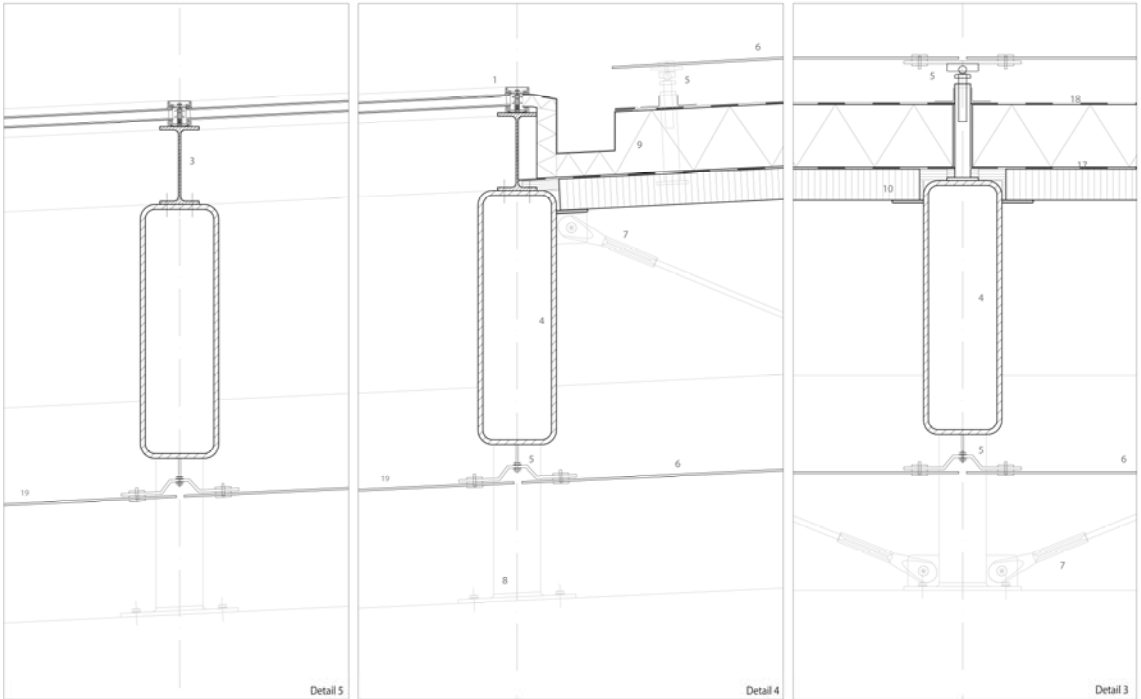


Figure 285: Details 3, 4 and 5

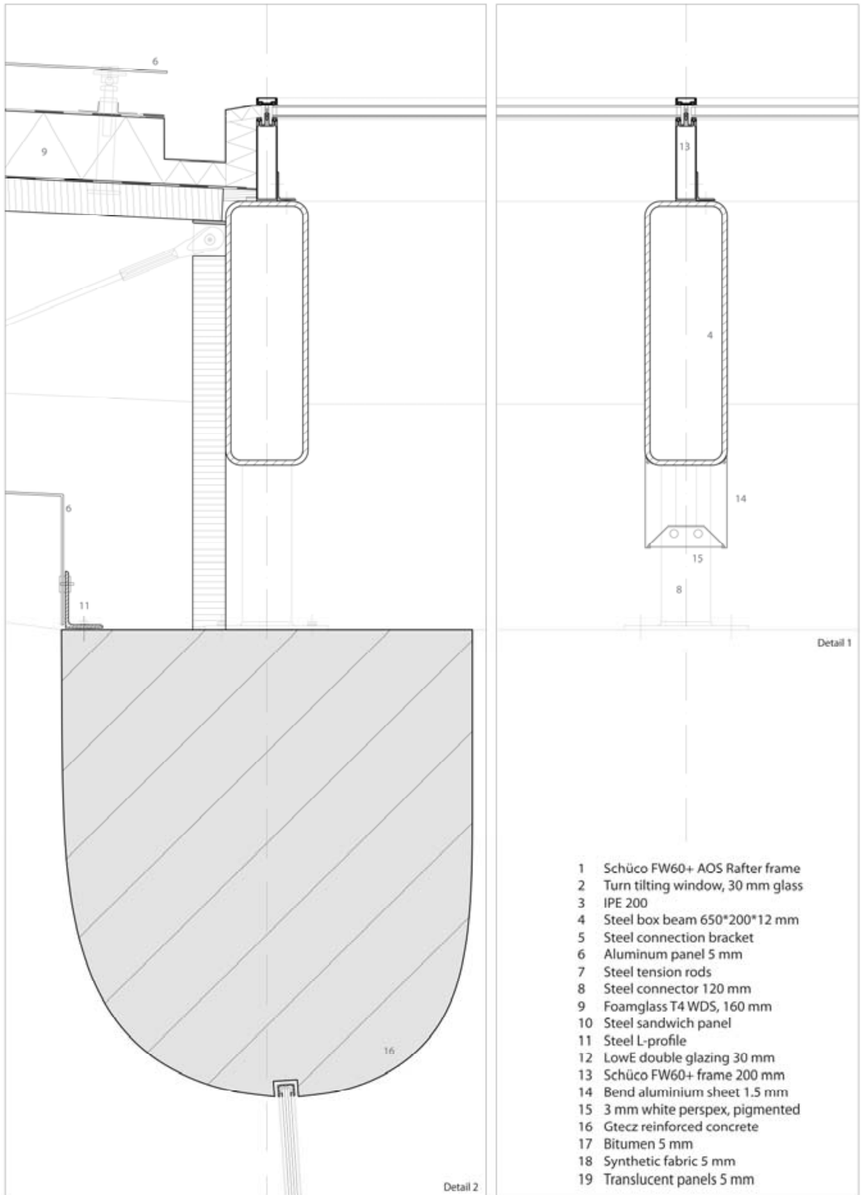


Figure 286: Details 1 and 2

Rectangular steel sections make up the structural diagrid on top of the main concrete structure. Rectangular elements are easily connected to other elements, straight or angular. Because of the many different angular connections in the roof system, rectangular elements are preferred over I-beams. The panels are connected with steel connector to the rectangular beams. The rectangular steel beams are laying on the primary concrete structure on steel risers. To prevent the roof from sliding off the building, the secondary steel structure is connected to the primary concrete structure with steel tension rods.
Aluminum lighting boxes are connected to the longitudinal beams in the shopping street. The height of the box itself will increase the height of the beam. This added height and the emitted light will amplify the main longitudinal direction of the building and helps in the way finding process through the building.

4.11 Conclusions

These conclusions begin with answering the research questions stated in chapter 4.1. The performance of the roof system will be evaluated and the main goals are checked if they have been achieved. The conclusion ends with interior images which show the light quality of the interior spaces.

The daylight testing and analysing has provided a general idea of the geometrical and material properties that influence the amount of daylight entering the building through the roof system. From these various daylight tests and analyses a few things can be concluded:

The Slab design is the most effective design in bringing daylight into the building. The direction of the slab also amplifies the longitudinal direction of the building.
The Grid and Scoop design are the most flexible in bringing a certain quantity and quality of daylight into various interior spaces/functions of the building. The Grid and Scoop design can use the inclination of the geometry to block the mid-day sun and bring it diffusely into the building, whereas the Slab and Cuts design always allows direct light into the building during those hours.

1. The roof design will be based on a combination of the directionality of the Slab design and the daylight properties and flexibility of the Grid design. The combination of these two provided the most suitable solution for bringing different amount of direct and/or diffuse daylight inside.

2. The roof design is populated with a diagrid system. The main direction of this diagrid is in the longitudinal direction of the building, where the secondary direction creates the parallelogram components in the roof system. Each of these components can be open or close depending on the required light intensity inside. If the light intensity is not sufficient, then the component will be open. The required lighting demands, quantitative and qualitative, can then be achieved through the geometry or the material; depending on the required daylight quality and if an outside view is necessary (chapter 4.12.5). The final component can have straight or inclined sections with an opaque, transparent or translucent panel.

The proposed roof design is analysed and tested in Ecotect as described in chapter 4.12.5. The results from this first analysis aren't fully meeting the daylight requirements for the functions. In further research, the first proposed roof design and the analysis results are used as feedback for a new proposed roof design. This is a process (feedback loop) of designing, analysing, comparing and feeding it back into the design continues until the proposed roof design meets the daylight requirements. The most suitable roof design will then be refined to create the final roof design.

Light quality

The final results of the daylight research are the rendered images of the public interior spaces in the Schiphol Interchange Station. These images show the final quality of the daylight in the design.
The first image shows the light quality in the kiss & ride area. Within the diagrid system, different types of materials for the panels are used to create the desired daylight effect. Parts of the roof act a luminaires to light interior spaces while the roof still remains a single entity.

The translucent panels in the ceiling bring light diffusely into the building and create a very subtle shading pattern on the floor.

Figure 287: Light quality Kiss & ride area

The second image shows the interior light quality in the shopping street. The secondary beams of the diagrid over the shopping street are inclined to block direct sunlight from entering the building during the middle hours of the day and bringing the light diffusely into the building. The double reflection of daylight provides diffuse light for the shopping street and still maintains a view to the outside (from one direction).

Figure 288: Light quality Shopping Street

5 GENERAL CONCLUSIONS

This building technology research has been a combination between a wind research and a daylight research. These two components are part of the overall notion of saving energy through the use of passive strategies. These two researches, wind and daylight, have not been separate researches but are combined on the roof system of the Schiphol Interchange Station. Where the wind research focussed on the big scale, the daylight researched on the small scale. The wind research has changed the original shape of the building skin in such a way that a wind over the top of the building could potentially naturally ventilate the entire building. The final product of the wind research, a new shape of the skin of the building, acted as the starting point for the daylight research. The daylight research investigated ways in which to bring the required amount of direct and diffuse light into the building by using geometry and material properties. The final result of the daylight research is a diagrid-based roof system, which brings light into the building where it is needed. Diffuse light is provided into the interior of the building, either through the inclined geometry of the roof beams or through translucent materials for the roof panels.

This research has provided new insight and good results and conclusions both for the wind and daylight research. However this building technology research is not totally conclusive and improvements can be made. The parts that would be improved could be suitable for further research in the future.

Further research could be conducted into the wind part of the building technology research. The shape of the new wind design should be analysed in the Ansys CFD software. This way, the wind performance of the new roof geometry can be investigated and the choice for that particular wind design can be validated.

Further research could be conducted into a more suitable/fluent tessellation for the building skin of the Schiphol Interchange Station. The diagrid tessellation is currently relaxed in only the diagonal direction. Further point relaxation in both directions between the structural supports, could lead to a smoother and more suitable overall tessellation for the Schiphol Interchange station.
Another point for further research is the final Ecotect analysis on the section of the train station. The findings from the Radiance analysis of the proposed roof design indicate a few areas in the Schiphol Interchange Station which exceed the maximum allowed illumination and could encounter glare problems during certain times of the year. Ideally, a parametric feedback loop between the Radiance solver in Ecotect and Rhino is used to find the values for the geometrical and material parameters which results in the required amount of daylight inside the Schiphol Interchange Station. That way, the most suitable roof design is for the train station.

The wind and daylight research results, conclusions and options for further research show the validity of this building technology research for the Schiphol Interchange Station. This building technology research has introduced me to new ways of doing research and design. During this research, I have familiarized myself with new software packages and research strategies. It has not only been a process of applying knowledge that I already had but also about learning and applying new insights while going along. This building technology research has expanded my knowledge and skill level and has resulted in a satisfying roof system based on wind and daylight research.

BIBLIOGRAPHY

- Pérez-Lombard, L., Ortiz, J. and Pout, C. *A review on buildings energy consumption information.* UK: Elsevier, 2007.

- Walker, F.J. and N. Jenkins. *Wind Energy Technology*. UK: John Wiley & Sons, 1997.

- Danish wind industry association. 'Wind speed distribution'. http://guidedtour.windpower.org/en/tour/wres/shear.htm

- Voorden, van den, ir. M. *Windhinder*. Delft: TH Delft, 1982.

- Windfinder. 'Wind en weer statistiek Amsterdam Schiphol'. http://www.windfinder.com/windstats/windstatistic_amsterdam-schiphol.htm

- Neufert, Ernst, and Peter Neufert. *Architects' Data Third Edition*. Oxfort: Blackwell Science Ltd, 2000

- Bean, Robert. *Lighting Interior and Exterior*. Elsevier, 2004.

- Voorden, van den, ir. M. *Bezonning; stedebouwfysica gc49.* Delft: TH Delft, 1979.

- Buonocore, Pablo and Micheal A. Critchley. *Tageslicht in der Architectur*. Niggli, 2001

- Natural frequency. 'Radiance and Daylight Factors'. 2007. http://naturalfrequency.com/articles/radiancedf

- Lawrence Berkeley Laboratory. Material Emissivity Properties. http://snap.fnal.gov/crshield/crs-mech/emissivity-eoi.html

- Artifice, Inc. Specularity. http://www.artifice.com/support/user_guide/documents/tips/specularity.html

- Zaha Hadid Architects. Heydar Aliyev Centre. http://www.zaha-hadid.com/cultural/heydar-aliyev-cultural-centre

- Fairs, Marcus. Zaragoza Bridge Pavilion by Zaha Hadid. Dezeen magazine (16 June 2008). http://www.dezeen.com/2008/06/16/zaragoza-bridge-pavilion-by-zaha-hadid

- Curtis, William j.r. *Modern Architecture since 1900.* London: Phaidon Press Limited, 2005

- Heinzelmann, Florian. 'Lightweight Origami structure & daylighting modulation.' Paper presented at the annual IASS Symposium, Valencia, Spain, September 2009

- 3Dlens.com. Fresnel Lens Polarizer. http://www.3dlens.com/

- Konica Minolta. T-10 Series. http://www.konicaminolta.eu/measuring-instruments/products/light-display-measurement/illuminance-meters/t-10-series/introduction.html

- TechnoTeam Bildverabeitung GmbH. http://www.technoteam.de

- Lash, D. 'Assessing the daylight transmittance of atria roofs in real buildings', PhD diss., Sheffield Hallam University, United Kingdom, 2004

- Cornell University Ergonomics Web. DEA3500: Ambient Environment: Lighting and Color. http://ergo.human.cornell.edu/studentdownloads/DEA3500notes/Lighting/lightingnotes1.html

- Williams, Chris J.K.. '*The analytic and numerical definition of the geometry of the british museum great court roof*'. UK: University of Bath

- Wiki.naturalfrequency.com. Shading: solar incidence. http://wiki.naturalfrequency.com/wiki/solar_incidence

- Curvature analysis. http://www.rhino3d.com/5/help/commands/curvatureanalysis.htm

- Vinyl Council Australia. Cladding and roofing membranes. http://www.vinyl.org.au/Claddingandroofingmembranes

- Eekhout, Mick. *"Composite Stressed Skin Roofs for Liquid Design Architecture"*.

- Zaha Hadid Architects. Mobile Art Chanel Contemporary Art Container. http://www.zaha-hadid.com/architecture/chanel-art-pavilion/

- *Handboek gevels. (D6000 Gevelvullingen van kunststof).* Den Hague, 2011

APPENDICES

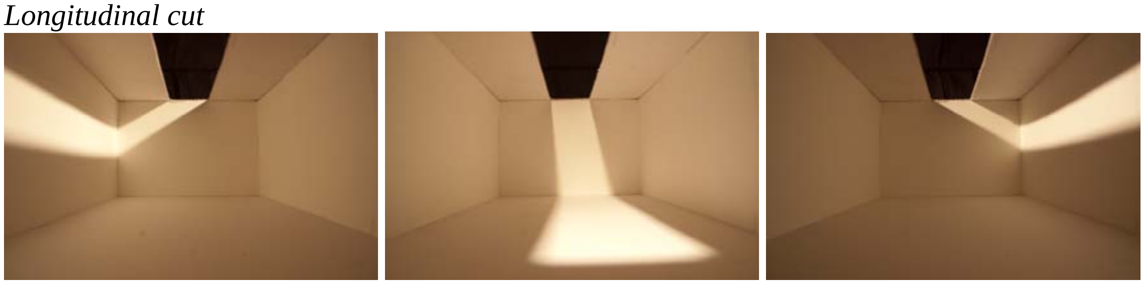
Appendix 1: primary daylight study

These are the images from the primary daylight study. This study is used to investigate different material and geometrical properties and get a feeling with the light and daylight. The daylight studies are conducted with different roof geometries and materials. A lamp simulates the light at 09:00, 12:00 and 19:00

No roof

Translucent roof

Longitudinal cut



Longitudinal cut – translucent material

Longitudinal cut – 2.5 cm thickness

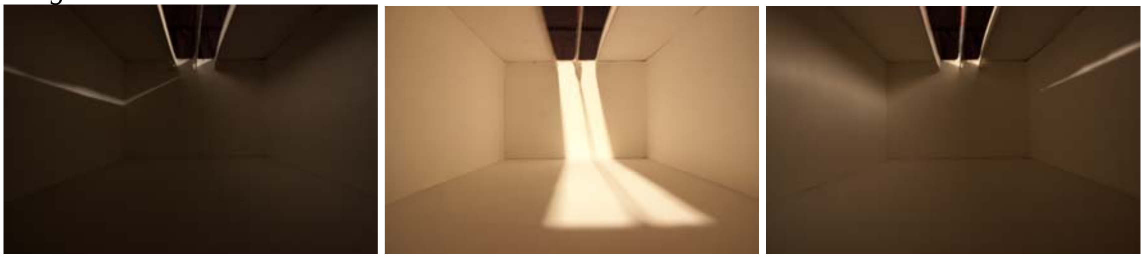
Longitudinal cut – 2.5 cm thickness – translucent material

Longitudinal cut – 2.5 cm thickness – high reflective material

Longitudinal cut – 1.0 cm thickness

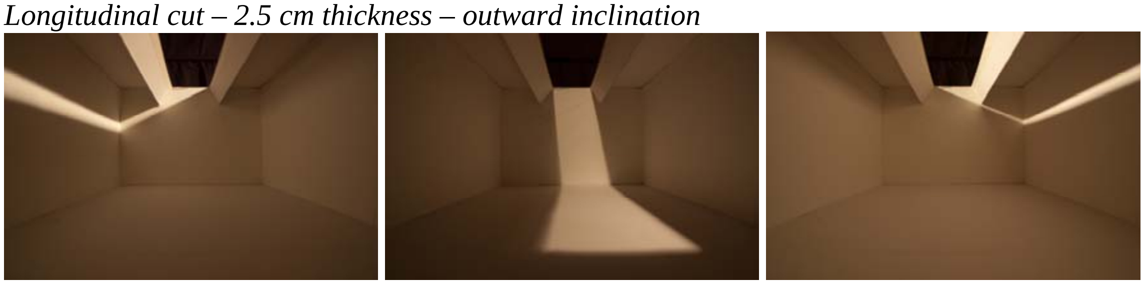
Longitudinal cut – 1.0 cm thickness- translucent material

Longitudinal cut – 1.0 cm thickness – extra louver

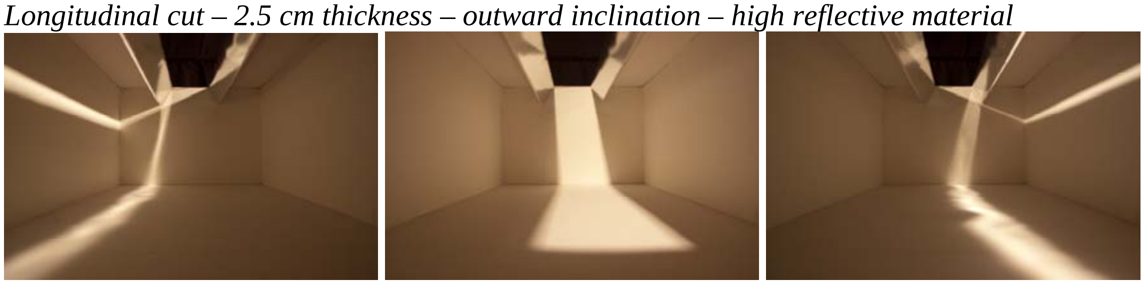


Longitudinal cut – 2.5 cm thickness – inward inclination

Longitudinal cut – 2.5 cm thickness – outward inclination



Longitudinal cut – 2.5 cm thickness – outward inclination – high reflective material



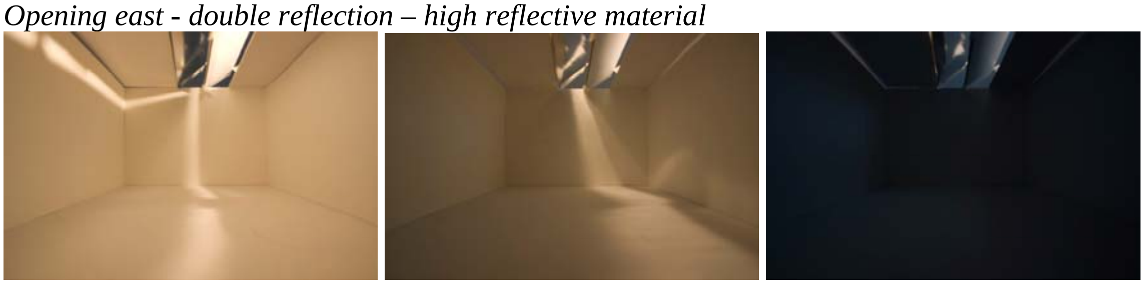
Longitudinal cut – 2.5 cm thickness – varying inclination – high reflective material

Opening east

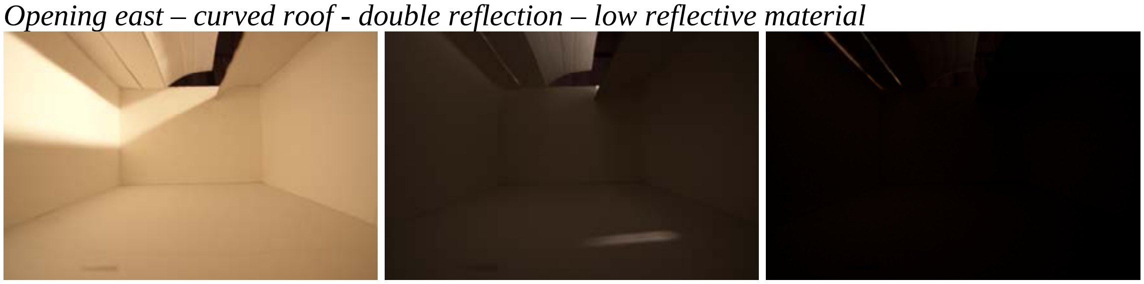
Opening east - translucent material

Opening east - double reflection – low reflective material

Opening east - double reflection – high reflective material



Opening east – curved roof - double reflection – low reflective material



Opening east – curved roof - double reflection – low reflective material

Cross cut – single width

Cross cut – double width

Opening north

Opening north – double reflection – high reflective material

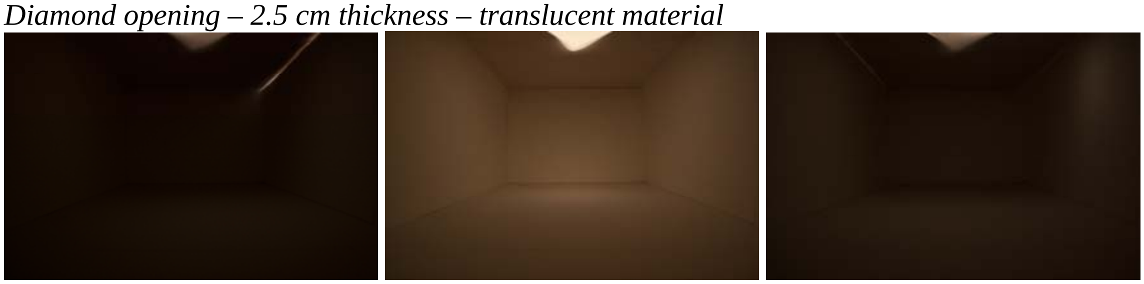
Square opening – 2.5 cm thickness

Square opening – 2.5 cm thickness – inclined south

Longitudinal openings – 2.5 cm thickness – inclined cross members

Diamond opening – 2.5 cm thickness

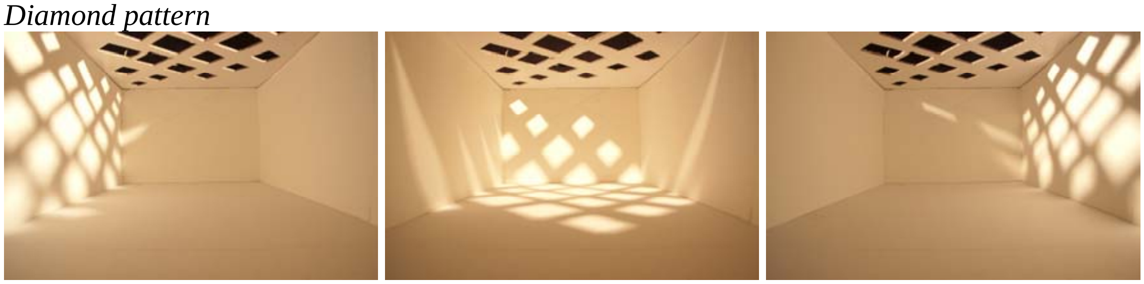
Diamond opening – 2.5 cm thickness – translucent material



Diamond opening – 2.5 cm thickness – inclined south

Diamond opening – 2.5 cm thickness – inclined south - translucent material

Diamond pattern



Diamond pattern – 1.0 cm thickness

Diamond pattern – 1.0 cm thickness – translucent material