Optimized Facade Design towards Nearly Zero-Energy Residential High-Rises

Facade Design Assessment Criteria for Residential High-Rise Buildings in the NL

2018 - 2019

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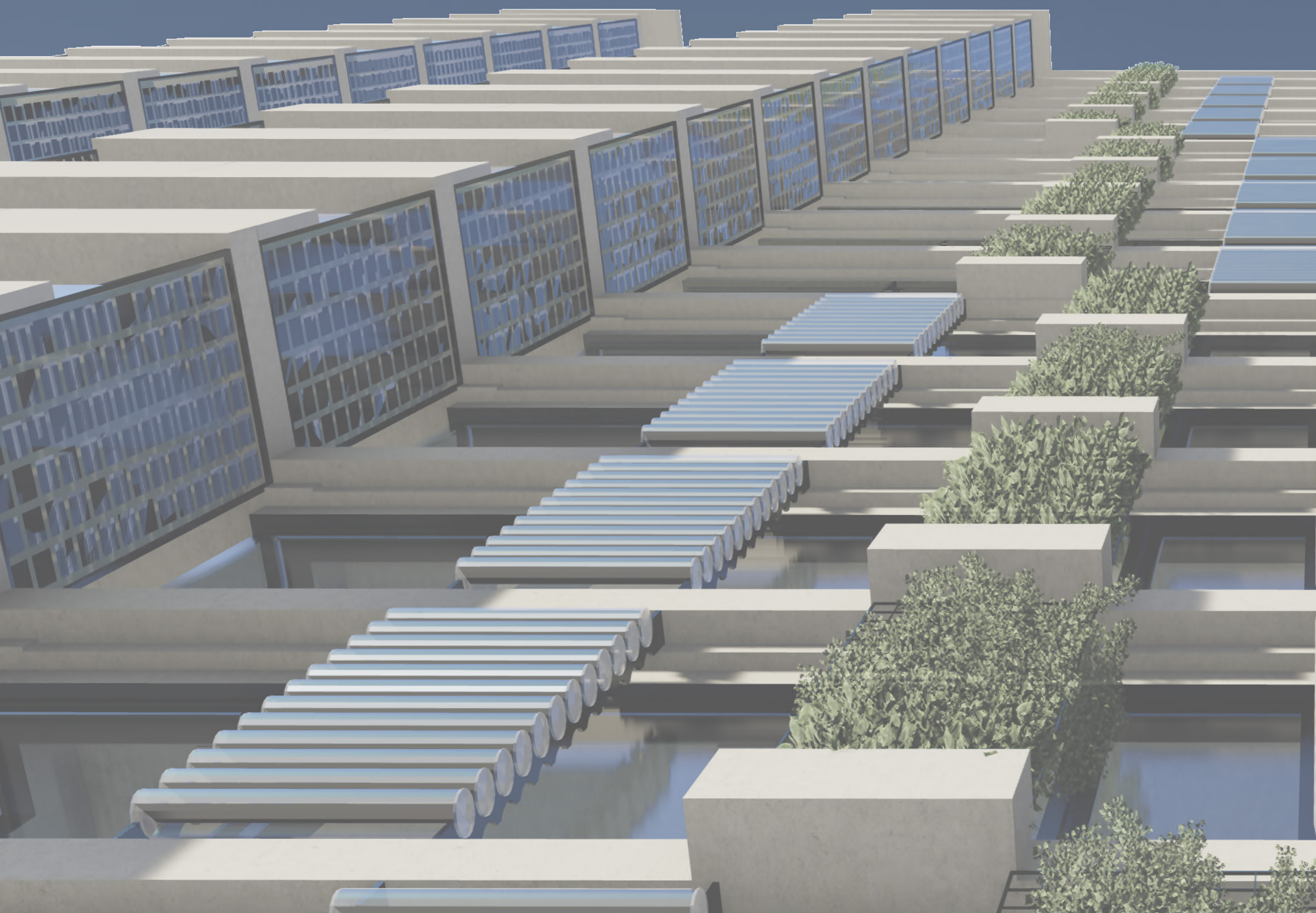

Focus and Restrictions – Passive Design Strategies for Nearly Zero-Energy Residential High-Rises, Building Energy Optimization with Parametric Simulations, BENG Regulations for Residential Buildings in the Netherlands.

Abstract

This study analyzes the impact of the facade design on the energy performance, daylight and thermal comfort of residential high-rise buildings in temperate climates, with the help of energy simulations. The advantages of different facade design strategies are assessed based on the Cooltoren building in Rotterdam by V8 Architects. The aim is to find the most optimal facade parameter combinations in terms of performance and indoor comfort and to provide facade design guidelines for Architects and Engineers to consider similar passive design solutions in the design of nZEB residential high-rises in temperate climates.

The following facade parameters are considered as variables for the optimization process: window to wall ratio, glazing type, shading system, natural ventilation strategy, thermal insulation and energy generating systems. These variables lead to 480 possible facade design combinations which are assessed using Grasshopper components and compared with Design Explorer. Based on the results, a facade redesign is proposed for the analyzed case study and general design guidelines are provided for similar residential high-rises.

This study proves that the facade design plays an important role to reduce the energy demand, produce energy and improve the indoor comfort conditions. Based on the results of the optimization process, the primary energy demand of a high-rise building located in a temperate climate can be reduced with up to 30 kWh/m^2 with an optimized facade design alone.

Key words – 'nZEB', 'BENG', 'high-rise', 'zero-energy high-rise', 'sustainable high-rise', 'residential high-rise', 'high-rise facade', 'passive design strategies'

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Cristina Maria Mărginean

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Research Framework

1.01

Background

Human overpopulation is one of the most pressing driving forces that gives rise to environmental problems, like global warming. Today, 55% of the world's population lives in urban areas and by 2050 it is expected to be 68% *(United Nations, 16 May 2018)*. With the population expected to reach 9.7 billion by 2050 and people moving to cities, comes also the higher demand for housing, hence higher concentration of buildings in cities *(United Nations, 21 June 2017)*.

This densification of urban areas is expected to have a dramatic impact on climate change, on one hand because of the heat island effect and on the other hand because of the increased demand in resources. Already today, the building sector uses 35% of the global resources, 40% of the total energy, consumes 12% of the world's drinkable water and produces almost 40% of global carbon emissions *(Saint-Gobain, 22 August 2017)*.

Considering the significant impact that buildings have on the ecosystem, regulations concerning energy use were introduced globally. In Europe, there are two main legislative instruments on the energy performance of the EU building stock, the *2010 Energy Performance of Buildings Directive* and the *2012 Energy Efficiency Directive*. By introducing these two Directives, the Union's main objective is to reduce greenhouse gas emissions by 85-90% by 2050 in order to maintain the global temperature rise below 2°C, with respect to the Paris Agreement on climate change from December 2015. Member states will need to transpose these Directives into National Legislation by 2020 and establish a long-term strategy on how to improve the energy efficiency of the building stock *(European Commission, 2014)*.

Since 2012, the Netherlands follows the *'Nationaal Plan voor het bevorderen van bijna energieneutrale gebouwen'* - in short *BENG*. By introducing the *BENG* regulations, the aim is to achieve an energy performance coefficient value (EPC) close to zero for all new government buildings in the Netherlands by the end of 2018 and for other new buildings by the end of 2020 *(AgentschapNL, 2013a)*.

To reduce the EPC-value of new buildings, *BENG* regulations are setting limitations for maximum energy needs, maximum primary fossil fuel use and minimum share of renewable energy. Moreover, the current Building Decree 'Bouwbesluit' sets fixed values for internal heat gains (U-value, Rc-value), ventilation flow rates and and spatial daylight percentage, which must be taken also into account in order to achieve the prescribed energy performance standards *(Rijksdienst voor Ondernemend Nederland, 2017)*.

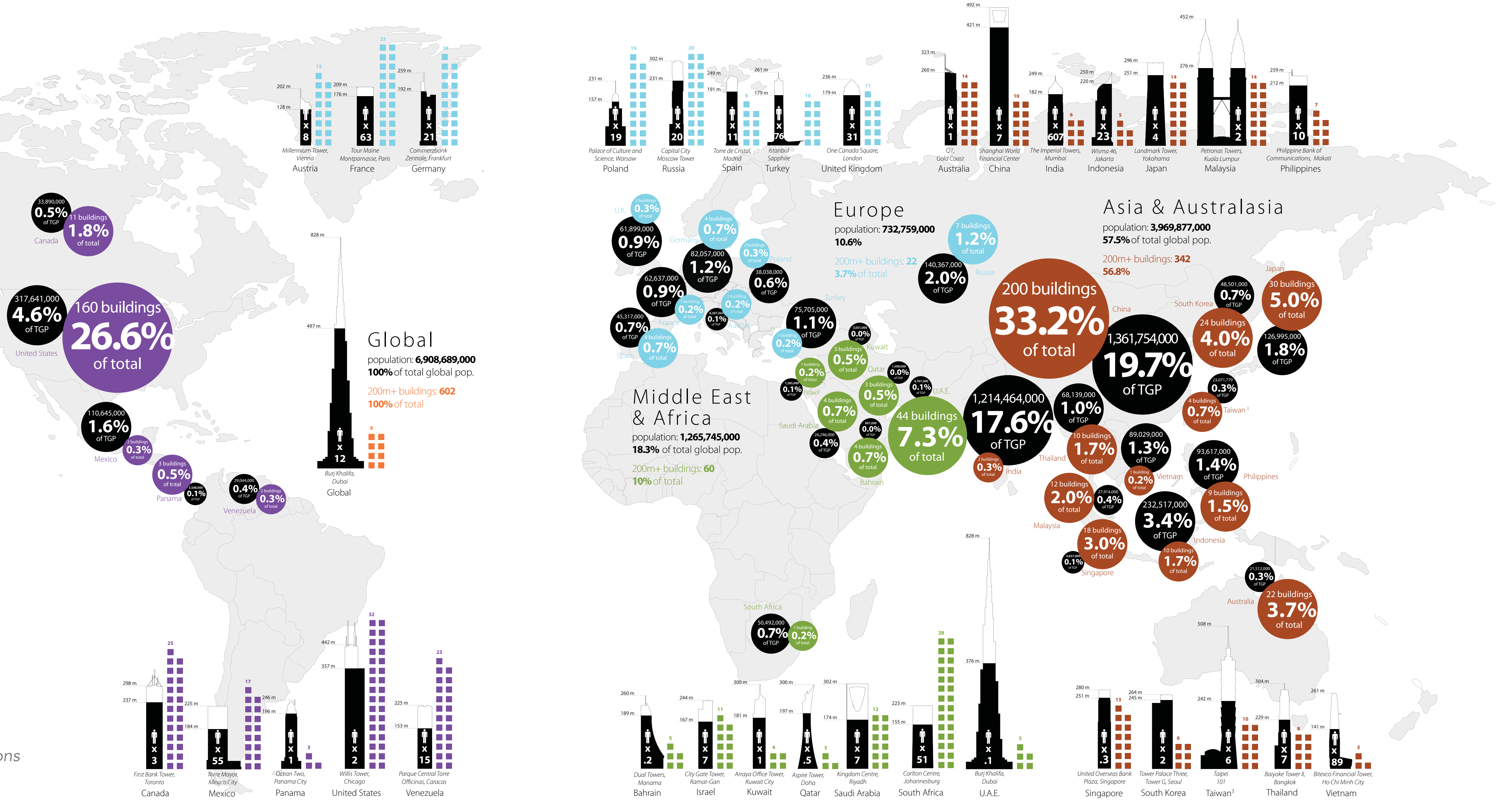


Figure 1.01: Global, regional and country populations compared to buildings 200 m+ in height.
Source: CTBUH, 13 April 2013

1.02

RESEARCH PROBLEM

Meeting future energy requirements can be quite challenging for certain building typologies, like high-rise buildings. Concentrating people on smaller plots by building vertically is a notorious solution to cope with urban agglomeration. Nowadays, high rise buildings are spreading more and more across the globe, with the number of tall buildings, higher than 200m, rising from 286 to 634 in the last decade alone *(CTBUH, 2012)*.

However, the sustainability of building vertically is questionable, considering that tall buildings require better performing materials, bigger in size and the overall energy consumption per square meter tends to be higher compared to low rise buildings *(Godoy-Shimizu et al, 2018; Lam et al, 2004; CTBUH, 2011)*. According to a recent study, carried out by the Energy Institute of the University College London, high-rise buildings taller than 20 stories are much more energy intensive than low-rise buildings. The research paper examines the impact of building height on the electricity use, fossil fuel use and CO_2 emissions by comparing 611 buildings of varying heights and of different ages from England and Wales. When comparing the energy demand of buildings lower than 5 stories with buildings higher than 21 stories, the mean intensity of electricity and fossil fuel consumption is greater by 137% and 42% respectively, while the CO_2 emissions are more than doubled *(Godoy-Shimizu et al, 2018)*.

Godoy-Shimizu et al (2018) proved that building height has a considerable effect on energy use, however, the reason behind it was not clearly determined. It is suspected and yet to be proven that high-rise buildings are more energy intensive than low-rise buildings due to the greater exposure to high wind speeds, more direct solar gains and lower temperatures.

With high-rise buildings spreading fast across the globe and strict national energy requirements being implemented to cope with the effects of climate change, high-rise buildings need to be designed in such a way that the design can adapt to any environmental factors which might affect the building performance. With this in mind, in the near future, all architectural design needs to be driven by performance optimization.

Several studies have proven that orientation, shape and envelope of the building are the main influential parameters that determine the energy performance of a high-rise, hence the thermal comfort of their occupants *(Raji, Tenpierik, Dobbelsteen, 2017)*. However, the orientation and shape of the building are usually limited by urban conditions, allowing no space for optimization. In this case, the design of the envelope is crucial, as it can significantly affect the future energy performance of the building.

Unlike low-rise buildings, high-rises are affected by three main environmental factors that change gradually with respect to height - air temperature, wind speed and daylight. The envelope of high-rise buildings needs to account for these changes in climate in order to insure a pleasant indoor comfort at any level.

> High rise buildings consume more energy per square meter than low rise buildings.

> 'What is the impact of facade design on energy, daylight and thermal comfort, to achieve a nearly zero-energy residential high-rise building in a temperate climate?'

1.03

RESEARCH OBJECTIVE

Considering the aforementioned aspects, it will be quite challenging for Architects and Engineers to design high-rises that comply to future energy efficiency targets. This study offers special consideration to the facade design of a residential high-rise building in a temperate climate, with the aim to maximize the energy efficiency and improve the indoor comfort through energy simulations. The objective is to provide facade design guidelines for Architects and Engineers to consider similar passive design solutions in the design of nZEB residential high-rises in order to reach future energy efficiency regulations.

1.04

RESEARCH QUESTION

The aim of this research paper is to answer the following question:

> *'What is the impact of the facade design on energy, daylight and thermal comfort, to achieve a nearly zero-energy residential high-rise building in a temperate climate?'*

In order to answer this main research question, a series of sub-questions will help reach the goal of the project:

- Which are the most influential facade parameters, which can:
  - Reduce the Energy Demand
  - Maximize the Energy Production
  - Improve Thermal Comfort
  - Improve Visual Comfort
- Which is the best combination of parameters in terms of energy demand, energy production, daylight and thermal comfort?
- How much can the *BENG* requirements for residential buildings be met in high-rises through an optimized facade design?
- Does a variation in facade with respect to height lead to better performance?

1.05
METHODOLOGY

By undergoing some literature research, the first step is to identify the criteria which define an nZEB building in the Netherlands. Secondly, preceding examples of nZEB high-rises are analyzed and the most influential parameters are filtered out, which have a significant impact on the overall energy performance and indoor comfort of high-rise buildings. These parameters will serve as variables for the simulation, which will be modelled in a later stage of this research study.

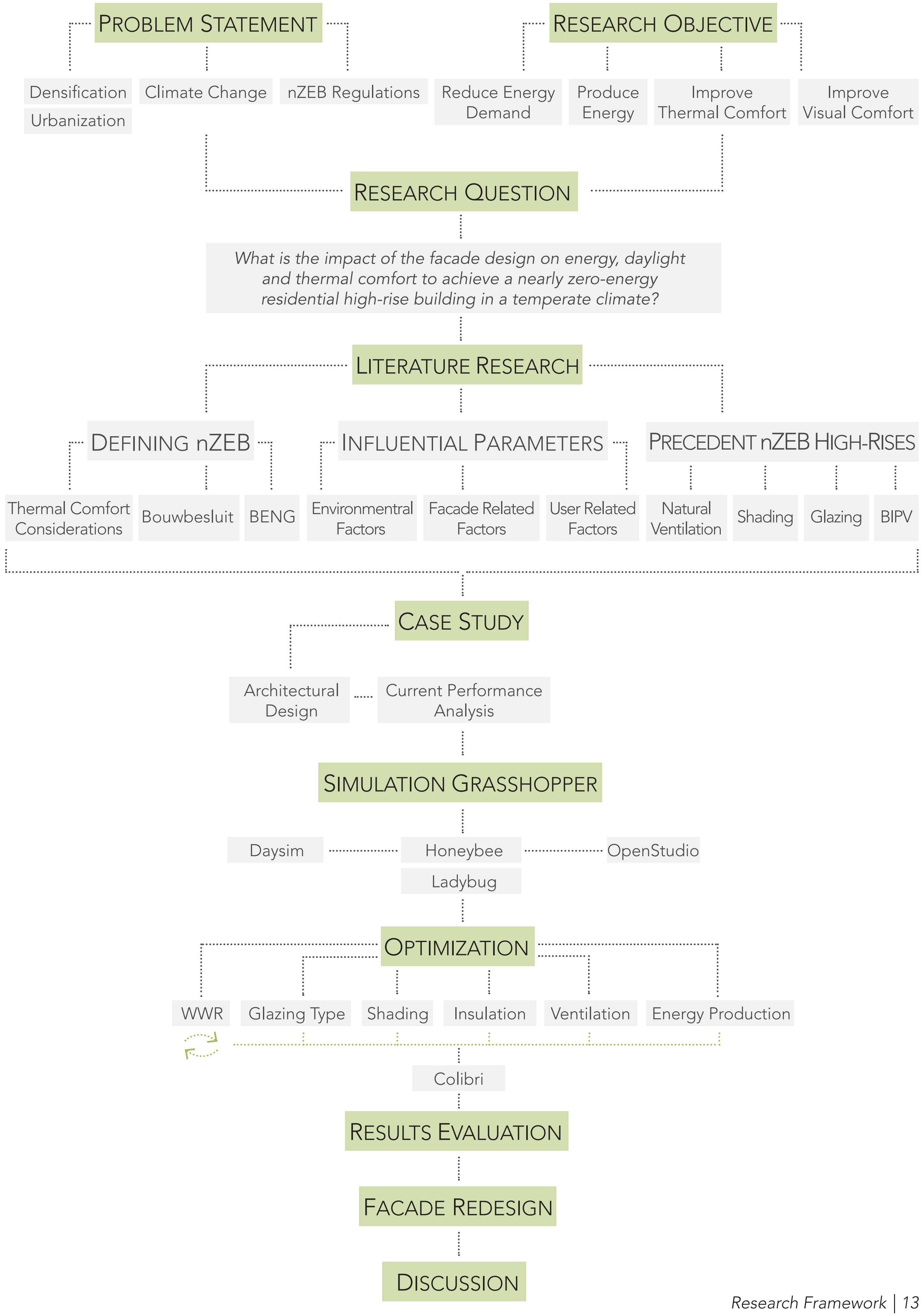
This research used the Cooltoren building by V8 Architects as case study - a 150m residential tower in Rotterdam. The building is reconstructed in Rhino and a performance simulation is set up in Grasshopper, using the plug-ins Honeybee and Ladybug. EnergyPlus and Daysim, are used to assess the influence of the selected parameters on the overall energy performance, thermal comfort and daylight. Using Colibri Iterator, the performance of all possible facade parameter combinations (480) is assessed and the results are compared using Design Explorer. The results of this optimization process are discussed and conclusions are drawn. Based on the results, a facade redesign is proposed for the analyzed high-rise building.

The following methodological scheme provides an overview of the structure of this research study. It describes the various steps that will be carried out in order to answer the research question.

1.06
BOUNDARY CONDITIONS

The application of boundary conditions is intended to define the detailed scope of this paper:

- This study focuses on residential high-rises in temperate climates.
- This study examines the energy performance of a specific case study in Rotterdam, Netherlands, with a specific shape and orientation.
- The parameters used as variables for the simulation process, are based on available technology on the market.
- Due to the substantial number of variables, the selected parameters were reduced to only a few combinations representing the extreme values of each parameter.
- A facade redesign is proposed which integrates available technology on the market.



02

Literature Review

2.01
Defining High-Rise

Tall buildings gained significance after the second world war to solve the housing deficit and create business and financial districts. While tall buildings proved to be very profitable and helped develop financial districts, residential towers that arouse during that period were associated rather with low-quality construction and poor living conditions. While tall high-rises continued to be very profitable over the years, it happened only years later when residential high-rises emerged, targeting middle-and upper-class families. In Europe, the fist high-class residential tall buildings appeared in Rotterdam. Today, the desire for verticality is high given the effects of densification, i.e. urbanization and the socio-economic advantages that tall buildings bring with them *(Gonçalves, 2015)*.

But what is considered a "tall building"? The criteria that define a tall building are very subjective. The *CTBUH (2010)* sets some numeric thresholds that define a tall building as building with at least 14 stories or more than 50m high. However, a 14-story building might not be considered tall in a high-rise city like Chicago. The *CTBUH (2010)* also refers to proportion as being a significant parameter because several buildings do not appear as tall due to their large footprint. The integrated 'tall building technologies' are a third parameter which define a tall building. Such technologies include vertical transportation, wind bracing etc. *CTBUH (2010)*.

A high-rise building is a tall building. According to *Emporis (n.d.)*, a high-rise is a 35-100 tall building or a building with 12-39 floors. A very tall high-rise building is referred to as a skyscraper. A skyscraper is a building with over 40 floors and is taller than 150m *(Skyscraper, n.d.)*. High-rise is up to 45 floors (150m), super-high-rise is above 150m *(Gonçalves, 2015)*.

Considering the numerous definitions of a 'high-rise', this study will consider the 150m height limit and a minimum number of 45 floors as defining criteria. This research uses the Cooltoren building in Rotterdam as a case study - a residential high-rise building in Rotterdam, 154.5m tall with 50 floors.

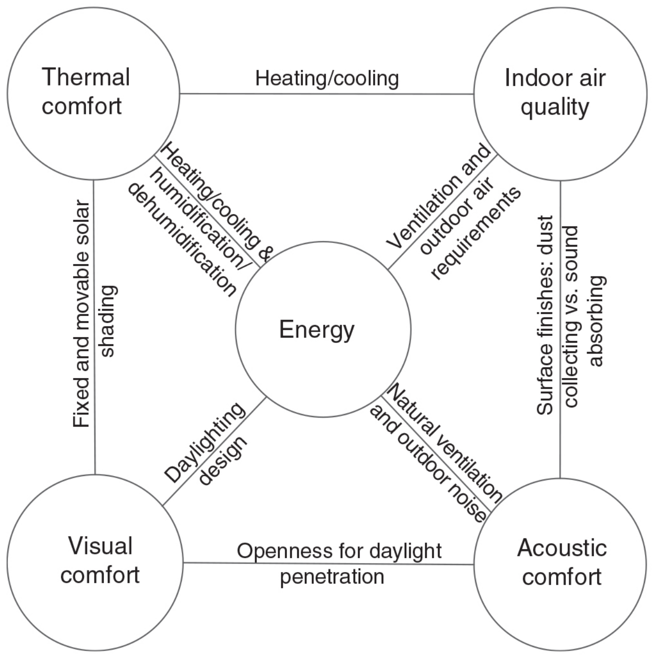


Figure 2.02.01: Interactions between forms of comfort and building energy use with examples
Source: (Athienitis and O'Brien, 2015)

2.02
Defining nZEB

The *Energy Performance of Buildings Directive (EPBD)* defines nearly zero-energy buildings (nZEB) as buildings with a very high energy performance, which make use of renewable energy resources to cover their low energy demand *(European Commission, 2010)*. The *EPBD* states that all new buildings have to be nZEBs by the end of 2020. However, the *EPBD* does not set any concrete numeric thresholds to define when a building can be considered nZEB. Therefore, the definition of nZEB is very interpretable and varies from country to country.

The *2010 Energy Performance of Buildings Directive* and the 2*012 Energy Efficiency Directive* are just a reference for the countries to define their own regulations depending on the climatic conditions and the countries level of ambition. The Netherlands follows the *'Nationaal Plan voor het bevorderen van bijna energieneutrale gebouwen'* - in short *BENG*. The *BENG* regulations on the energy efficiency of new buildings will be elaborated further in *Chapter 2.02.02*.

2.02.01
Comfort Considerations for nZEB

There are several factors that influence the performance of a 'nearly Zero-Energy Building'. According to *Athienitis and O'Brien (2015)*, energy efficiency is directly linked to the comfort level inside the building. The author describes the different forms of comfort which have an effect on the building's energy use:

- Thermal comfort
- Indoor air quality
- Acoustic comfort
- Visual comfort

Thermal Comfort

Thermal comfort Is defined by the *American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE)* as:

'That state of mind which expresses satisfaction with the thermal environment'
(ASHRAE, 2009).

Thermal comfort is perceived differently by any person and is highly influenced by behavioral, physiological as well as psychological factors. *Chen et al. (2006)* mentions seven important factors that influence the thermal sensation of people:

- Environmental factors: dry bulb temperature, water vapor pressure, air velocity, radiant temperature
- Individual factors: metabolic rate and clothing
- Length of time exposure.

However, in order to ensure a comfortable indoor environment, thermal comfort standards based on Fanger's Predicted Mean Vote, in short PMV, were adopted worldwide as a reference. The *European Standard EN15251:2007* sets limits for indoor conditions to ensure that the implemented European regulations on the energy efficiency of buildings do not undermine the comfort level of the occupants.

However, the *European Standard EN15251:2007* does not provide clear guidance on how to assess thermal comfort differences in naturally ventilated (NV) and mechanically cooled (AC) buildings. *EN15251:2007* only makes a distinction between buildings which are heated or cooled (HC) and those which are free-running (FR), where NV buildings will be HC in winter and FR during the summer and AC buildings are HC throughout the whole year. The next sections will provide an overview on the assessment procedure of thermal comfort in free-running and air-conditioned buildings according to the *EN15251:2007*.

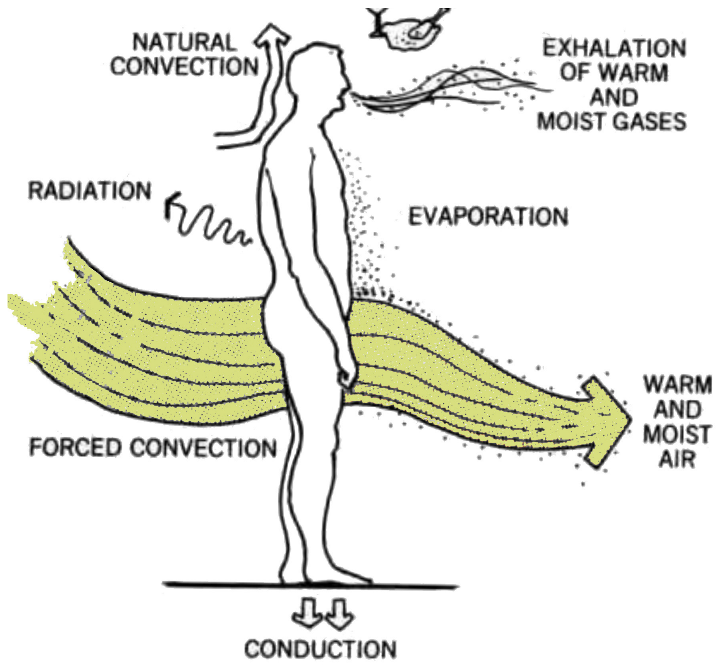


Figure 2.02.02: Methods of dissipating waste heat from a biological machine.
Source: Lechner, 2015

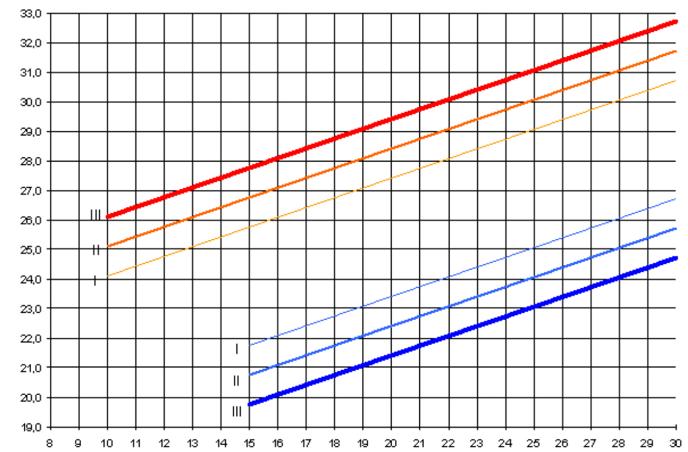


Figure 2.02.03: Design values for the indoor operative temperature for buildings without mechanical cooling systems
Source: Nicol, F.; Humphreys, M.; Rijal, H., 2008.

Category	Explanation	Suggested acceptable range °K	Suggested acceptable limits PMV
I	High level of expectation only used for spaces occupied by very sensitive and fragile persons	± 2K	± 0.2
II	Normal expectation (for new buildings and renovations)	± 3K	± 0.5
III	A moderate expectation (used for existing buildings)	± 4K	± 0.7
IV	Values outside the criteria for the above categories (only acceptable for a limited periods)	>4K	> 0.7

Table 2.02.01: Acceptable temperature range for free running buildings and PMV for mechanically ventilated buildings
Source: EN15251, 2007

Free-Running Buildings

For buildings which are in free-running mode, limiting values for the operative comfort temperature are set. A relationship between the comfortable indoor temperature and the running mean outdoor temperature is derived as such:

$$Tc = 0.33\ Trm + 18.8\ °C \qquad [1]$$

The CIBSE suggests that all new buildings, major refurbishments and adaptation strategies should conform to Category II from the *European Standard EN15251:2007*. Different building typologies are not taken into account, such as high-rises. The suggested acceptable temperature range for Category II buildings lies at ±3K. Subsequently, it follows from the equation *[1]* that the maximum acceptable temperature is:

$$Tmax = 0.33\ Trm + 21.8\ °C \qquad [2]$$

To assess whether the building is subjected to overheating, ΔT is calculated, which stands for the difference between Top, the operative temperature in the room and Tmax, the maximum acceptable temperature. If ΔT is negative, the building is overheating.

$$\Delta T = Top - Tmax \qquad [3]$$

Tc [°C] = operative indoor comfort temperature
Trm [°C]= running mean outdoor temperature
Tmax [°C] = limiting maximum acceptable temperature
Top [°C] = operative temperature in the room
ΔT [°K] = difference between Top and Tmax

Building Type	Category	Sedentary Activity	Temp. range for heating	Temp. range for cooling
			Clothing ≈1.0	*Clothing ≈0.5*
		[met]	*[°C]*	*[°C]*
Residential	II	1.2 met	20-25 °C	23-26 °C

Table 2.02.02: Temperature ranges for hourly calculation of cooling and heating energy
Source: EN15251, 2007 (Annex A)

Air-Conditioned Buildings

In case of air-conditioned buildings, indoor comfort limits are set using Fanger's Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD). The PMV-index is based on the seven-point thermal sensation scale proposed by *ASHARE* and can takes values from +3 to -3, where hot, warm, slightly warm, neutral, slightly cool, cool and cold to correspond to the scales of comfort -3, -2, -1, 0, +1, +2 and +3.

For new buildings, the PMV-index should range between -0.5 and +0.5. In addition, an operative temperature ranging between 23-26°C is necessary, with less than 10% of the people feeling uncomfortable *(EN15251, 2007)*.

The PMV and the PPD are also influenced by other important factors, such as:

- thermal resistance of the clothing
- metabolic rate
- air velocity
- relative humidity

Table 2.02.04 shows reasonable values for these parameters. These values will be used later as input values for the simulation parameter study, in order to achieve a pleasant indoor comfort temperature.

Indoor Air Quality

Ventilation is essential in order to ensure a good indoor air quality. It helps to regulate indoor temperatures, get rid of bad odors and pollutants and reduce moisture in order to avoid condensation. Ventilation in buildings can be induced in multiple ways which will be elaborated in *Chapter 2.03.02*.

Unmanaged ventilation can cause unpleasant draughts, especially in high-rise buildings. The *European Standard EN15251:2007* suggests for Category II buildings certain air flow rates related to the number of persons in the room and the floor area. The recommended ventilation rate per person is 7l/s, whereas the expected percentage of dissatisfaction (PPD) should not exceed 20%.

Category	Thermal state of the body as a whole	
	PPD %	Predicted Mean Vote
I	< 6	-0.2 < PMV < + 0.2
II	**< 10**	**-0.5 < PMV < + 0.5**
III	< 15	-0.7 < PMV < + 0.7
IV	> 15	PMV<-0.7; or +0,7<PMV

Table 2.02.03: Acceptable summer indoor temperatures (cooling season) for buildings without mechanical cooling systems.
Source: EN15251, 2007

season	thermal resistance of clothing	metabolic rate	air velocity	relative humidity
	[clo]	[met]	[m/s]	[%]
summer	0.5	1.2 met	0.15	50
winter	1.0	1.2 met	0.15	50

Table 2.02.04: Resaonable values for thermal resistance of clothing, metabolic rate, air velocity, relative humidity
Source: van der Linden et al., 2013

Category	Expected Percentage Dissatisfied	Airflow per person l/s/pers
I	15	1O
II	20	7
III	30	
IV	> 30	< 4

Table 2.02.05: Recommended ventilation rates for different categories
Source: EN15251, 2007 (Annex B)

Visual Comfort

Incoming daylight does not only affect the thermal comfort and energy performance of the building, it can also influence the visual comfort of the occupants. The *European Standard EN15251:2007* refers to the following parameters that influence the visual comfort level:

- D = Daylight factor
- Êm [cd/m²] = Maintained (average) luminance
- E [lux] = Illuminance (at a point or surface)
- UGR = Unified Glare Rating
- Ra = Color rendering index

The Daylight factor is the amount of indoor illumination relatively to the outdoor illumination. Illuminance is the perceived brightness of light on a surface. Daylight illuminances between 300 - 3000 lux are often perceived as desirable. Luminance indicates the brightness of light emitted or reflected by a surface. The Unified Glare Rating (UGR) is a glare index that can take values from 5 to 40, with low numbers indicating low glare. The Color Rendering Index can take values from 0 to 100 and indicates the accuracy of colors under artificial lighting compared to white natural light. *EN15251:2007* sets limits for the average luminance, Em > 500 lx, the unified Glare Rating, UGR<19% and the Color rendering index, 80<Ra. For this study, the aim is to achieve an UGR<19%.

Acoustic Comfort

Acoustic comfort is affected by the level of the sound perceived in a room. The sound pressure level is measured in dB, where the lowest sound pressure which can be heard by humans is called the hearing threshold (0dB) and the highest as the pain threshold (120dB) *(ecophon, n.d.; van der Linden et al., 2013)*.

EN15251:2007 defines requirements for indoor sound pressure levels in buildings of Category II. The sound pressure level, $L_{p,A}$, of residential buildings should range between 25-40dB for living rooms and 20-35 for bedrooms. Default design values are 32dB for living rooms, respectively 26dB for bedrooms *(EN15251, 2007)*. This study will not investigate the acoustic comfort level.

2.02.02
Energy Considerations for nZEB

Bouwbesluit

The Dutch Building Decree - *Bouwbesluit (2012)*, sets boundaries concerning the energy efficiency of new and renovated buildings. The most relevant regulations for this research are highlighted in this section.

According to *Articles 3.29 and 3.32*, different ventilation rates need to be considered for residential buildings, depending on the room function. For a kitchen, a minimum ventilation rate of 21dm³/s is requested, for living areas 0.09 dm³/s per m², 14 dm³/s for bathrooms, 7 dm³/s for toilets and 0.05 dm³/s per m² for common circulation areas like corridors.

In terms of daylight, a minimum of 10% of the total floor area should be provided for residential buildings *(Bouwbesluit, 2012. Article 3.38)*. Moreover, a living area shall have a lighting installation which can produce a lighting intensity of at least 2 lux, according to *Article 6.2*.

Considering the insulating performance of building materials, *Article 5.1* sets a minimum Rc value of 3.5 m²K/W for the envelope. The maximum heat transfer coefficient (U-value) for windows and doors is set at 1.65 W/m²K. *Article 3.2* includes regulations concerning sound insulation, where building components should provide a characteristic noise protection of at least 20 dB, but acoustic comfort is outside the scope of this paper.

Parameter		Residential Bouwbesluit	Residential EN15251	Bouwbesluit	EN15251
T Summer	[°C]	-	23-26 °C	-	23-26 °C
T Winter	[°C]	-	20-25 °C	-	20-25 °C
Humidity	[%]	-	50 %	-	50 %
Air flow rate	[l/s]	7l/s,pers	7l/s,pers	7l/s,pers	7l/s,pers
Daylight	[%] [lux]	10%	*>500lux*	*2.5%*	*>500lux*
Sound level	[dB]	-	20-35dB	-	35-45dB
Sound Insul.	[dB]	>20dB	-	>20dB	-
R-value	[m²K/W]	3.5m²K/W	-	3.5m²K/W	-
U-value	[W/m²K]	1.65W/m²K	-	1.65W/m²K	-

Table 2.02.06: Comparison between the numeric limitations set by the European Standard EN15251:2007 and the Bouwbesluit: 2012.
Source: EN15251, 2007. Bouwbesluit, 2012.

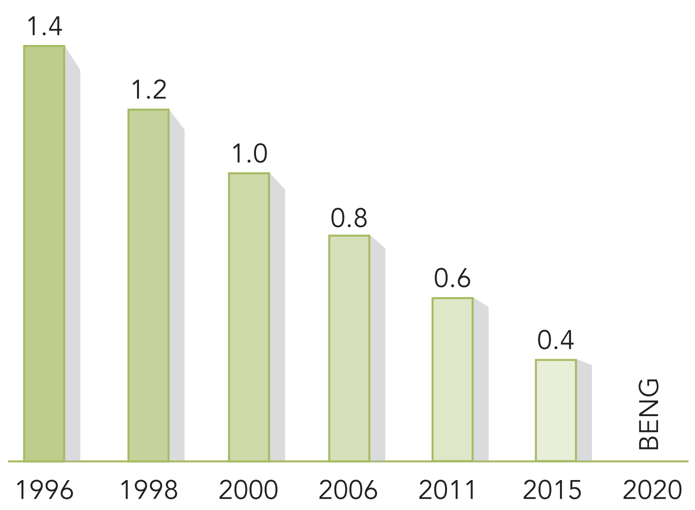


Figure 2.02.04: BENG Evolution
Source: Isobouw, n.d.

	Energy Need	Primary Fossil Energy Use	Share of Renewable Energy
	[kWh/m²/yr]	[kWh/m²/yr]	[%]
Resid. building (multi-family)	$A_{ls}/A_g \leq 2.2$: 70 $A_{ls}/A_g > 2.2$: $70+50*(A_{ls}/A_g-2.2)$	50	40
single-family house	$A_{ls}/A_g \leq 2.2$: 70 $A_{ls}/A_g > 2.2$: $70+50*(A_{ls}/A_g-2.2)$	30	50
Office	$A_{ls}/A_g \leq 2.2$: 90 $A_{ls}/A_g > 2.2$: $90+50*(A_{ls}/A_g-2.2)$	50	30
Education	$A_{ls}/A_g \leq 2.2$: 180 $A_{ls}/A_g > 2.2$: $180+50*(A_{ls}/A_g-2.2)$	80	40
Healthcare	$A_{ls}/A_g \leq 2.2$: 100 $A_{ls}/A_g > 2.2$: $100+50*(A_{ls}/A_g-2.2)$	60	40

Table 2.02.07: New BENG Requirements
Source: Isover, 20 Nov. 2018

BENG Regulations

In the Netherlands, the energy consumption of buildings is currently assessed through the "energieprestatiecoëfficient", in short EPC. The lower the EPC the more efficient the building is. The energy performance coefficient was introduced in 1995 and at that time it was 1.4. Ever since then, the EPC has become stricter, taking a value of 0.4 for all new buildings today.

Starting from 2020, all new buildings in the Netherlands will have to comply with the the *'Nationaal Plan voor het bevorderen van bijna energieneutrale gebouwen'* - in short *BENG*. By introducing the *BENG* regulations, the aim is to achieve an EPC value close to zero for all new government buildings in the Netherlands by the end of 2018 and for other new buildings by the end of 2020 *(AgentschapNL, 2013a)*.

The EPC is based on extensive calculations concerning the total primary energy use for hot tap water, space heating, space cooling, ventilation and lighting. The Dutch Building Code, *Bouwbesluit*, sets fixed values for temperature settings, internal heat gains, ventilation flow rates, heating demand for hot tap water and lighting which are used as input in the energy performance assessment.

In order to reduce the EPC-value of new buildings, *BENG* regulations are setting minimum requirements for maximum energy needs, maximum primary fossil fuel use and minimum share of renewable energy. The maximum energy needs refer to the energy required for heating and cooling. The primary fossil energy use is the total primary energy consumption for heating, cooling, hot tap water, lighting and fans. The share of renewable energy is defined by the ratio between the amount of renewable energy and the primary fossil energy use.

Table 2.02.07 shows the numeric limitations set by *BENG*, depending on the type of building and the level of compactness - determined by the loss area (A_{ls}) divided by the floor area (A_g).

2.03
Influential Parameters

Taking into consideration the nZEB limitations defined by the *EN15251:2007*, *Bouwbesluit* and *BENG*, there are three categories of factors which have a significant influence on the energy efficiency and the indoor comfort conditions of a high-rise building:

- Environmental factors
- Facade related factors
- User related factors

2.03.01
Environmental Factors

Building envelopes need to be designed to withstand various external factors, such as noise, wind, rain, heat, cold and solar radiation. Especially in high-rise buildings, architects and engineers need to take into account higher wind velocities, more direct sunlight and lower air temperatures which can have a significant effect on the indoor environment.

As mentioned already in the previous chapter, indoor thermal comfort is linked to air temperature, air velocity, mean radiant temperature and relative humidity. *Table 2.02.06* provides an overview of the numeric limitations set by the *EN15251:2007* and the *Bouwbesluit* in order to ensure a comfortable indoor climate. These values can be managed through the means of the facade, which is a direct connection between the indoor environment of the building and the external environmental factors acting on the building - sun, wind, rain, urban noise and pollution.

Sun

Solar radiation has a big impact on the energy performance of buildings. Especially tall buildings allocate big amounts of heating, cooling and lighting loads, which can be reduced by adopting environmentally sustainable design principles. The orientation of the building, shape and design of the envelope are essential parameters that can determine the amount of incoming daylight, respectively solar radiation throughout the year. However, shape and orientation are in most cases restricted by context, which means that the facade needs to account for these factors in order to ensure a pleasant indoor environment.

Depending on the building orientation, the design of the facade should vary on each side, depending on the amount of solar radiation hitting the building. Hight is another variable that needs to be accounted for in high-rises. In this context, the upper levels of high-rise buildings are exposed to more direct sunlight and slightly lower air temperatures, with a decrease in temperature of -1 °C per 100m *(Wood, 9 Oct. 2018)*.

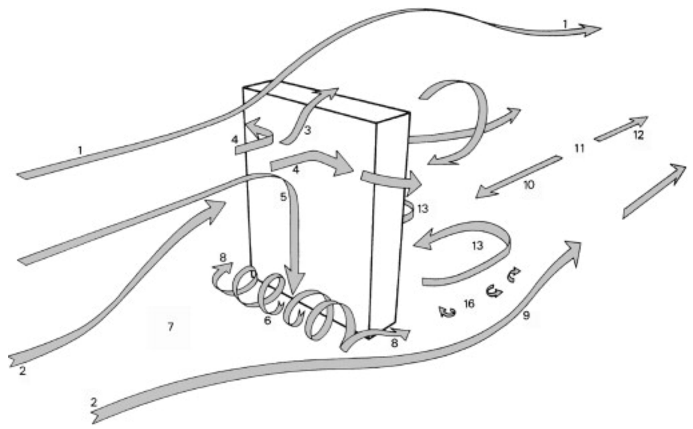


Figure 2.03.01: Schematic representation of wind flow pattern around a high-rise building
Souce: Beranek and van Koten, 1979

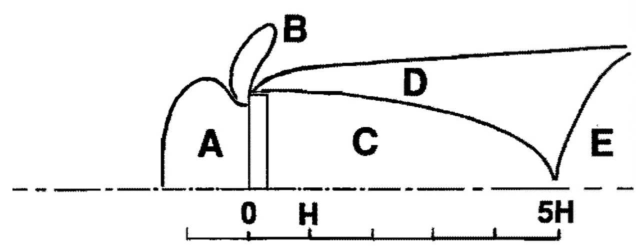


Figure 2.03.02: Flow zones around the obstacle: frontal vortex (A), corner streams (B), recirculation zone (C), shear layers (D) and far wake (E)
Source: Bottema, 1993

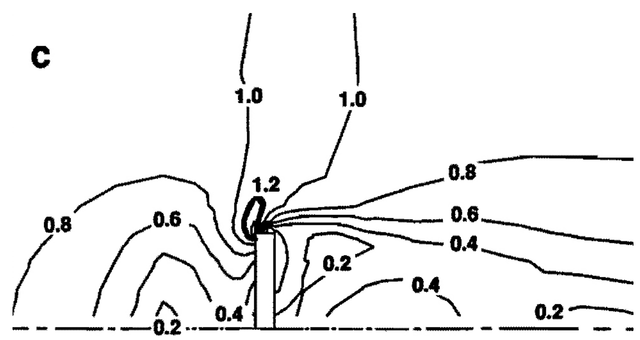


Figure 2.03.03: Normalized wind speed U(z)/Uiz) = 0.2, 0.4,...,1.2 (thick line), 1.4
Source: Bottema, 1993

Wind

Several studies by *Bottema (1993)* and *Tsang et. al (2012)* proved that building height has significant effects on high-rises by creating wind-flow areas. *Bottema (1993)* describes the wind patterns around a tall building and demonstrates an increase of wind speed with height:

$$v = v_{ref}^{*} \ln(h/z_0) / \ln(h_{ref}/z_0) \qquad [4]$$

v = wind speed at height z above ground level.
v_{ref} = reference speed, i.e. a wind speed we already know at height z_{ref}
h = height above ground level for the desired velocity, v
h_{ref} = reference height, i.e. the height where we know the exact wind speed
z_0 = roughness length in the current wind direction (a roughness class of 3.5 refers to a large city with many trees and buildings)

According to *Kamei & Maruta (1979)*, an increase in height also leads to more downward wind flow, which can be critical for the pedestrians. Approximately 1/3 of the wind, hitting the windward side of the building, is moving upwards, whereas the rest is diverted downwards, forming a vortex at ground level *(Wood & Salib, 2013)*. The increased wind speeds caused by the downdraught effect are rather unpredictable and need to be assessed through wind simulations.

Rain

Facades need to be rain-tight and keep humidity out of the building. Especially in high-rises, facade joinery is very important, as it has to resist wind-driven rain. In case water has penetrated the construction, facade joints need to allow for ventilation, in order to avoid further moisture buildup.

Rotterdam Climate

Rotterdam has a warm, temperate, sub-oceanic climate with significant rainfall throughout the year.

Solar radiation

The Netherlands has an average annual solar radiation value of 2.80 kWh/m²/day, with the highest values in June, reaching an average of 4.98 kWh/m²/day, and minimum average values of 0.61 kWh/m²/day *(Solar Electricity Handbook, n.d.)*.

Humidity

Data shows that Rotterdam has an average percentage of humidity of 84.0%, with 90% in December, the most humid month of the year and 79% in May, the driest month *(Weather and Climate, n.d.)*.

Rainfall

Rotterdam has on average 180 days of precipitation per year with an average rainfall of 39mm in April, the driest month of the year and 77mm in October, the wettest month *(Weather and Climate, n.d.)*.

Temperatures

Rotterdam has a maximum average temperature of 23 °C in July and the minimum average temperature is 1 °C in January *(Meteoblue, n.d.)*.

Wind speeds

The wind direction is mainly south-west with average wind speeds varying from 1m/s-10m/s between June and October and strong winds of 3m/s-17m/s from December to April *(Meteoblue, n.d.)*.

Average summer wind speed = 5.3m/s
Average winter wind speed = 7.7m/s

Table 2.03.01 shows the average wind speeds in summer and winter at 150m altitude. The wind speeds were calculated by using *Formula [4]*.

Climate Change

The Netherlands has experienced the effects of climate change in the past few years. Increased temperatures have been registered as well as stronger wind speeds. In the recent years, temperatures have reached even 39°C in summer and -14 °C in winter and wind speeds of 70 km/h (19.4m/s) have been recorded *(myweather2, n.d.)*.

It is estimated that the temperatures in the Netherlands will increase in the future, with significant heat waves in summer. The number of rainy days is assumed to decrease but the intensity of the rain showers will be higher, which could lead to potential flooding.

Parameter		10m	150m
v_{Summer}	[m.s]	5.3	10.98
v_{Winter}	[m.s]	7.7	15.96

Table 2.03.01: Average wind speeds in Rotterdam at ground level and 150m height

2.03.02
Facade Related Factors

Facades are fully technical components that establish the connection between the indoor climate and the exterior outdoor conditions. As already mentioned, facades need to be designed in such a way, so they can stand up to changing climatic influences. However, today, facades are not any more limited to just withstand exterior environmental factors. They are complex building components that have a significant impact on the building's appearance, visual comfort, acoustic comfort, thermal comfort, indoor air quality and even contribute to the building's energy production.

There are different types of facades, designed for specific conditions. The optimal combination of several components will in the end determine the overall performance the facade. Each component is responsible for a certain function - daylight control, temperature control, ventilation etc.

This chapter will provide an overview of the different layers of the facade while highlighting the strengths and weaknesses of different design strategies. Special consideration will be given to facade components which could perform effectively in high-rise buildings.

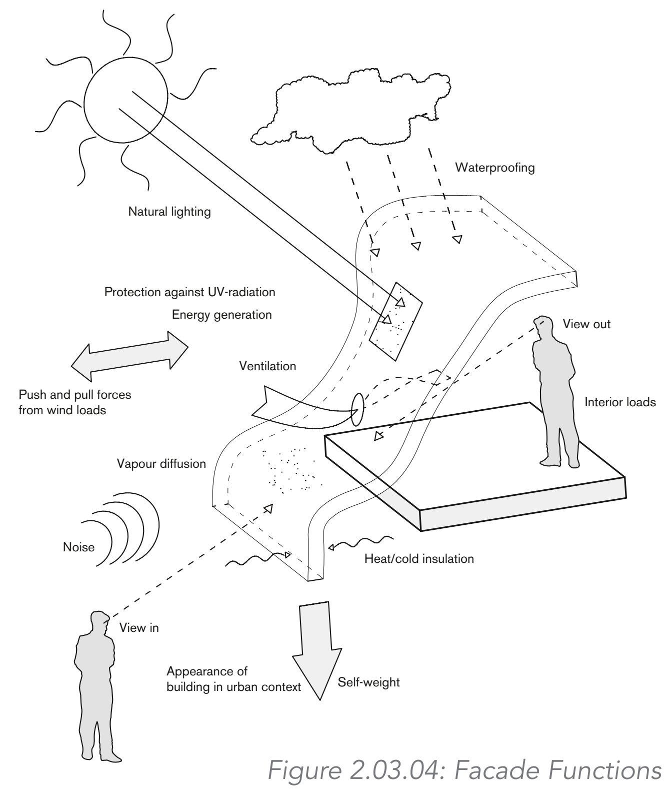


Figure 2.03.04: Facade Functions
Source: Knaack et al., 2007.

01
Facade Typology

Facade technologies have evolved fast over the last decades, mainly due to the severe energy requirements, higher comfort level standards demanded by users and frequent unpredictable extreme climatic events which are associated with climate change. This evolution has led to the development of different facade typologies, which will be highlighted in this chapter.

Facades can be classified in two main categories - single skin facades and double skin facades. As the name already suggests, a single skin facade is composed of a single glass layer, mostly including openable windows to regulate the indoor temperature. Double skin facades are composed of two glass layers with an air cavity in between. The air cavity forms a thermal buffer zone in between the two layers which helps to reduce heat losses in winter. The second glass layer can include ventilation openings which can be opened in summer to control incoming wind speed and induce stack driven ventilation.

This chapter will present the strengths and weaknesses of each facade category in order to define the most suitable choice for the studied high-rise building in a later stage of this study. The information was retrieved from the book *'Facades: Principles of Construction' by Knaack U. et al. (2007)*.

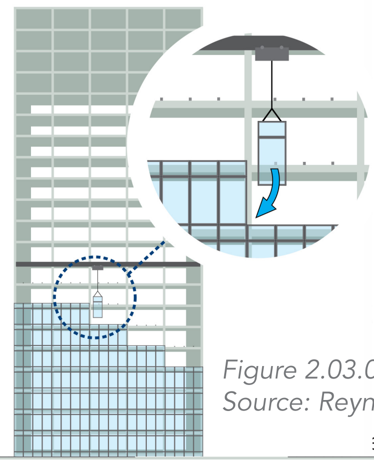


Figure 2.03.05: Unitized Facade
Source: Reynaers, n.d.

Single Skin Facades

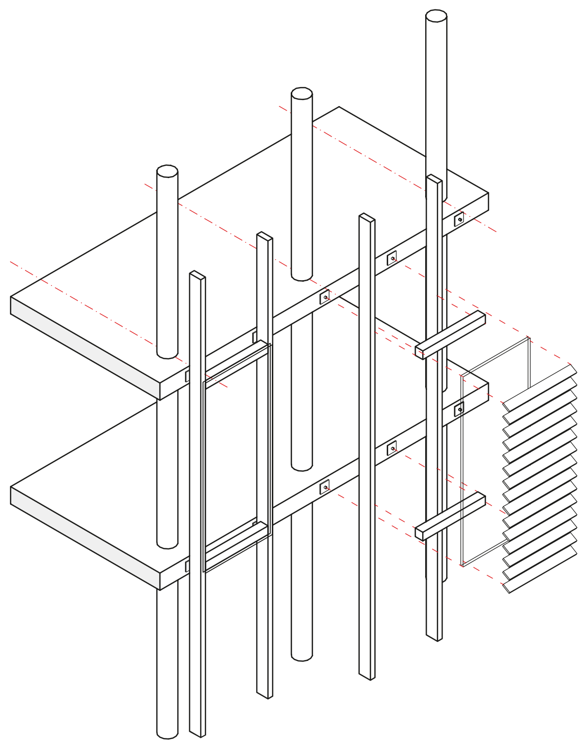


Figure 2.03.06: Stick Curtain Wall Assembley
Source: Knaak et al., 2007

Stick Wall System

- Easy and fast fabrication
- Economic solution for low-rise buildings with small facade area
- Can be handled and transported easily

- High labor requirements due to assembly on site
- Scaffolding required during installation
- Storage time and space required for materials until installation
- Susceptible to water leakage
- Unpredictable building movements

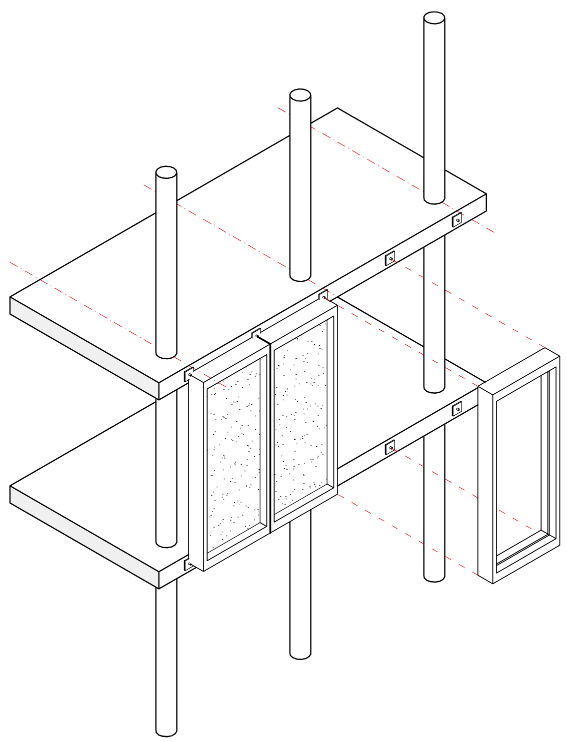


Figure 2.03.07: Unitized Curtain Wall Assembley
Source: Knaak et al., 2007

Unitized System

- High quality facade units of any shape due to high degree of prefabrication
- Low labor requirements due to rapid assembly on site
- Economic solution if the distance between mullions is repetitive
- Facade performance can be assessed in the factory

- Crane is necessary for high-rises to mount the panels on the top stories
- High transportation cost and extreme care necessary when handling the prefabricated units

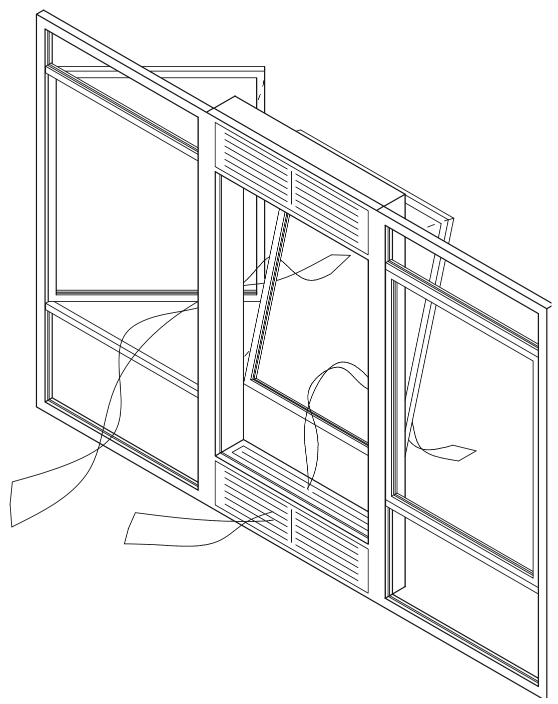


Figure 2.03.08: Alternating Single-Skin Facade
Source: Knaak et al., 2007

Alternating Single-Skin Facade

- Increased user control over the interior environment - openable windows in the single skin facade provide natural ventilation
- Pre-heated air from the cavity of the double facade can reduce heating demand in winter
- High degree of prefabrication

- Facade system only effective in low-rise buildings where the user can open the window

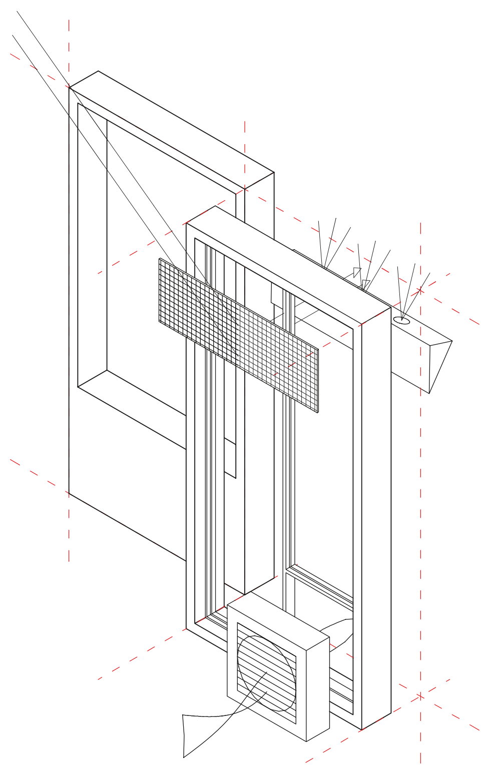


Figure 2.03.09: Integrated Single-Skin Facade
Source: Knaak et al., 2007

Integrated Single-Skin Facade

- Integrated building services can spare useful space engaged for service components inside the building
- Air quality and velocity is regulated at each floor

- High degree of engineering involved
- Limited user control over the interior environment
- Building appearance might be affected

Doule Skin Facades

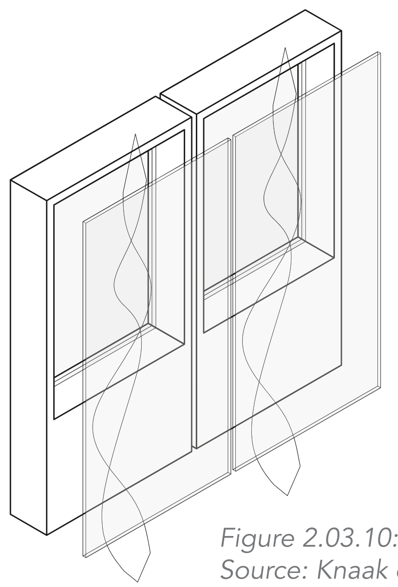


Figure 2.03.10: Second Skin Facade
Source: Knaak et al., 2007

Second Skin Facade

- Low coonstruction labour by simply adding a second glass layer onto the existing facade
- Secondary thermal and acoustic insulation

- Limited control over the interior environment, therefore risk of overheating, especially in last floors due to stack effect
- Development of extreme updrafts in tall buildings due to pressure differentials with height
- Undivided cavity increases fire risk
- Exhausted air from the floors below influence the air quality of the top floors
- Urban noise is hindered but not the sounds from neighboring rooms

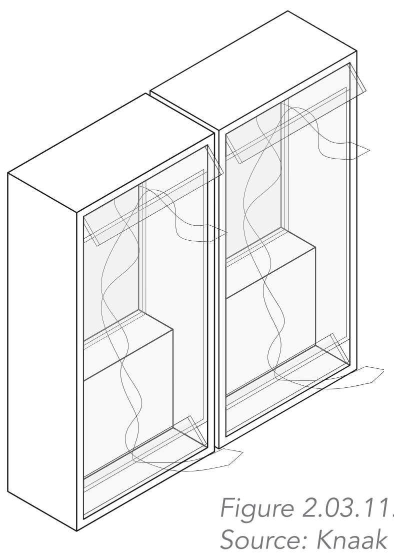


Figure 2.03.11: Box Window Facade
Source: Knaak et al., 2007

Box Window Facade

- Increased user control over the interior environment
- Divided cavity prevents fire from spreading vertically and horizontally
- Secondary thermal and acoustic insulation

- Thermal and acoustic insulation is lower compared to Second Skin Facade
- Exhausted air from the floors below influence the air quality of the top floors
- Big ventilation openings might cause undesired wind drafts in high located floors

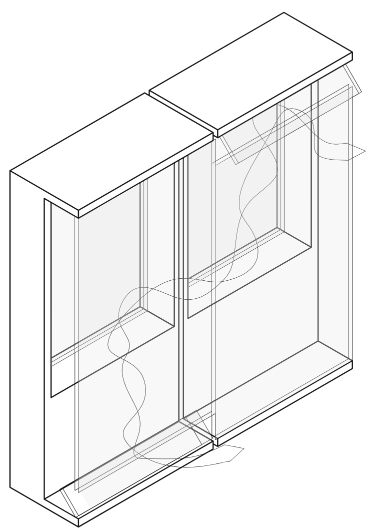


Figure 2.03.12: Corridor Facade
Source: Knaak et al., 2007

Corridor Facade

- Increased user control over the interior environment
- Divided cavity prevents fire from spreading vertically
- Secondary thermal and acoustic insulation when ventilation openings are closed
- Clean air entering the cavity at each floor due to staggered ventilation flaps

- Noise and smell from neighboring rooms is not hindered
- Big ventilation openings might cause undesired wind drafts in high located floors

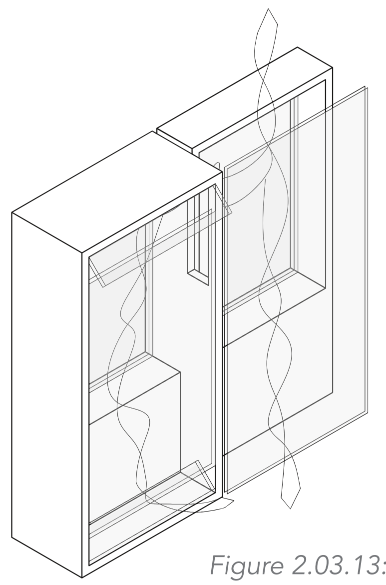


Figure 2.03.13: Shaft Box Facade
Source: Knaak et al., 2007

Shaft Box Facade

- Increased user control over the interior environment
- Secondary thermal and acoustic insulation when ventilation openings are closed
- Very effective ventilation strategy - exhaust air is drawn into a separate shaft

- High degree of engineering and construction labor involved
- Undivided cavity increases the chance of fire spreading vertically along the shaft
- Big ventilation openings might cause undesired wind drafts in high located floors

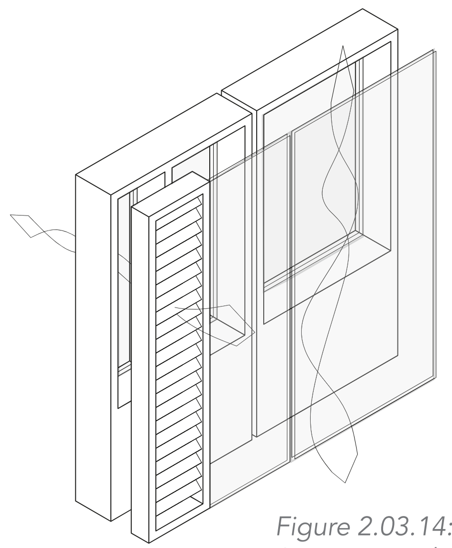


Figure 2.03.14: Alternating Facade
Source: Knaak et al., 2007

Alternating Double-Skin Facade

- Increased user control over the interior environment
- Secondary thermal and acoustic insulation when grating openings are closed

- Exhausted air from the floors below influence the air quality of the top floors
- Noise and smell from neighboring rooms is not hindered
- Integrated grating might cause undesired wind drafts in high located floors
- Undivided cavity increases the chance of fire spreading vertically along the shaft

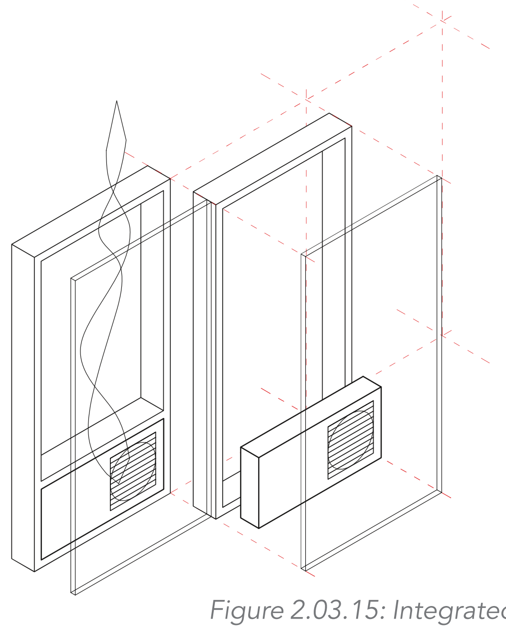


Figure 2.03.15: Integrated Facade
Source: Knaak et al., 2007

Integrated Double-Skin Facade

- Integrated building services can spare useful space engaged for service components inside the building
- Secondary thermal and acoustic insulation
- Air quality and velocity is regulated at each floor

- High degree of engineering involved
- Undivided cavity increases fire risk
- Limited user control over the interior environment

02

WINDOW to WALL RATIO

The window to wall ratio (WWR) refers to the percentage of glazing area with respect to the wall area. The window to wall ratio is an important facade parameter because it influences the amount of solar gain and the amount of light transmitted into the building, therefore it can significantly affect the energy performance of a building, respectively the thermal and visual comfort of the occupants.

Raji, Tenpierik, and van den Dobbelsteen (2017) suggest that in a temperate climate a WWR of 20-30% results in the highest energy performance if shading elements are excluded. However, *Goia et al. (2013)* found that a WWR of 35-45% performs best when external sun shading is added. The WWR also depends on the facade orientation and the thermal performance of the envelope and can vary between 30% and 50%. In terms of energy efficiency, the maximum recommended WWR in a temperate climate is 60%, in combination with efficient glazing and external sun shading. Higher WWRs would imply increased transmission heat losses through the facade, which result in up to 10% higher total energy consumption *(Raji, Tenpierik, and van den Dobbelsteen, 2017)*. As far as visual comfort and luminance criteria are concerned, glazing ratios between 50% and 70% are ideal. *(Ochoa et al., 2012)*

According to *Steemers (2002)*, glazing ratios should vary not only depending on the orientation, but also with respect to building height. At a low level, urban context obstructs the sunlight availability, whereas at higher levels, increased irradiation values can lead to overheating problems. *Steemers (2002)* determined optimum glazing ratios of 38% at ground level and 25% at 30m for London and shows that glazing ratios should reduce with height.

Figure 2.03.16: WWR 40%
Source: Commercial Windows, n.d.

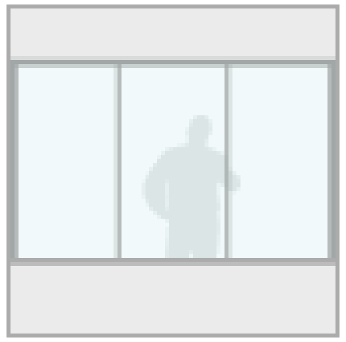


Figure 2.03.17: WWR 50%
Source: Commercial Windows, n.d.

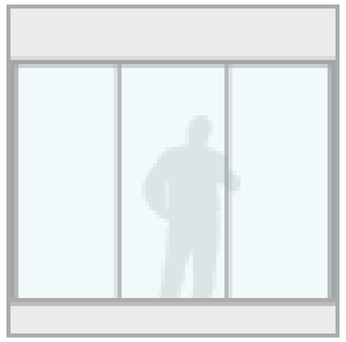


Figure 2.03.18: WWR 60%
Source: Commercial Windows, n.d.

Figure 2.03.19: Residential High-Rise Facade
Source: Textures, n.d.

03

Glazing

According to *Lang (2009)*, 25-35% of the total energy use of a building in the US is wasted due to the inappropriate choice of glazing. The performance of the glazing is determined by four important glazing characteristics *(Syed, 2012)*:

- U-value [W/m²K] - Heat transmission coefficient
- SHGC/g-value - Solar heat gain coefficient
- VLT [%] - Visible light transmission
- LSG - Light to solar gain ratio

Heat Transmission Coefficient (U-Value)

The heat transfer coefficient (U-value) is a measure for the amount of heat that is transferred through a building component. The U-value is the reciprocal of the R-value *[5]*, which is a measure for the ability of a material to resist heat flow through a certain thickness *[7]*. To clarify, the lower the U-value, the less heat is lost through the structure, same as the higher the R-value, the better the insulating properties.

In most cases, the U-value is used to rate the thermal performance of doors or window units. In case of building insulation materials, the R-value is referred to. For buildings in the Netherlands, the *Bouwbesluit* stipulates a maximum U-value for windows of 1.65 W/m²K *(Bouwbesluit, 2012)*.

$$U = 1/R \qquad [5]$$

$$R = r_e + r_{glass} + r_{cavity} + r_{glass} + r_i \qquad [6]$$

$$r = d/\lambda \qquad [7]$$

$$\lambda = a + r + t \qquad [8]$$

The heat resistances for inside and outside are standardized in the dutch regulations and are:

re=0.04 m²K/W
ri=0.13 m²K/W

U-value [W/m²K] = heat transmission coefficient
R-value [m²K/W] = thermal resistance
d [m] = thickness of the material
λ [W/mK] = thermal conductivity of the material

a=absorption coefficient
r=reflection coefficient
t=transmission coefficient

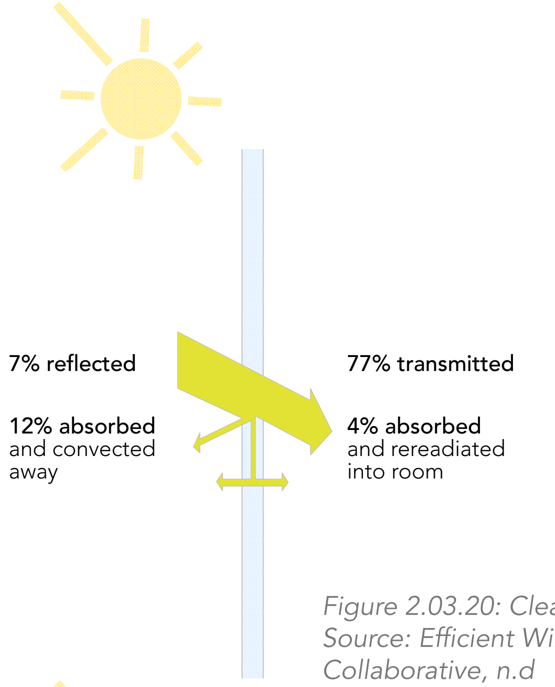


Figure 2.03.20: Clear Glazing Source: Efficient Windows Collaborative, n.d

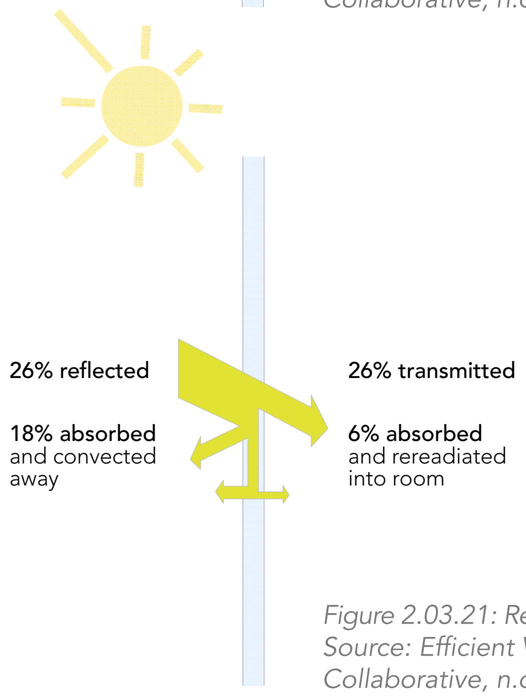


Figure 2.03.21: Reflective Glazing Source: Efficient Windows Collaborative, n.d

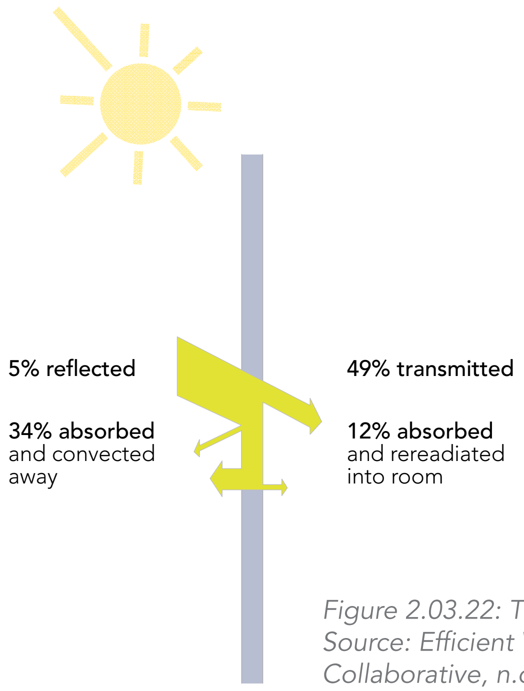


Figure 2.03.22: Tinted Glazing Source: Efficient Windows Collaborative, n.d

Solar Heat Gain Coefficient (SHGC)

The four basic properties of glazing that affect radiant energy transfer are: transmittance, reflectance, absorptance, and emittance. The Solar heat gain coefficient (SHGC), also known as the g-value indicates the amount of solar energy (heat) that is transmitted inside the building through the glazing. The SHGC can take a value between 0 and 1, where 1 indicates that 100% of the solar energy is transmitted inside and 0% means that all the energy is reflected. A single pane of glass has a SHGC of 0.8, which means that 80% of the solar energy is transmitted through the glazing and only 20% is reflected.

The SHGC value is a significant glazing property, as it can affect the overall energy performance of the building. The use of glazing with a high SHGC could increase cooling loads in summer while a low SHGC would require more heating during winter. Therefore, it is essential to use glazing with a SHGC that provides the most optimal balance between annual heating and cooling load. Clear glazing has a high SHGC value. The SHGC can be reduced by applying color tints, reflective coatings, spectrally selective coatings, low-e coatings or through the use of electrochromatic glazing. These features will be elaborated further in the following chapter.

Visible Light Transmittance (VLT)

The visible light transmittance (VLT) or visible transmittance (VT) indicates the amount of visible light that is transmitted through the glazing and therefore affects the visual comfort of the occupants. It is defined in percentage, where a high value means that a high degree of light can enter the building, respectively no light is transmitted if the value is 0%.

Light to Solar Gain Ratio (LSG)

The light to solar gain ratio (LSG) is defined as the ratio between the VLT of glazing and its SHGC *[9]*. A high LSG value means that the glazing is more efficient for daylight, therefore reducing lightning loads, without excessive amounts of heat.

$$LSG = VLT/SHGC \qquad [9]$$

LSG - light to solar gain ratio
VLT [%] - visible light transmittance
SHGC - solar heat gain coefficient

Glazing Types

Considering the aforementioned parameters, we can distinguish between six common glazing types:

- insulating glazing
- tinted glazing
- reflective glazing
- low-e glazing
- spectrally selective glazing
- electrochromatic glazing

Insulating Glazing

↓ U-value ↓ SHGC ↓ VLT ↓ LSG

Insulating glass units (IUG) consist of two or three glass panes separated by a vacuum or gas filled cavity. Double and triple glazing are frequently used in construction due to their excellent thermal and acoustical insulation properties. The thermal insulating performance (U-value) of the IUG depends on the following parameters:

- thickness of the glass
- number of glass panes
- distance between the panes
- type of gas between the panes

When assessing the thermal performance of a glazing unit, it is essential to consider also the frame. The U-value stipulated in the *Bouwbesluit* refers to the thermal performance of 1.65 W/m²K for the combined assembly, glass and frame. The thermal performance of the assembly can be calculated as follows *(Warm, November 2013)*:

$$U_w = (A_g \times U_g + A_f \times U_f + I_g \times \Psi_g)/ (A_g + A_f) \qquad [10]$$

U_w [W/m²K] = overall value of the window
U_g [W/m²K] = heat transfer coefficient of the glazing
U_f [W/m²K] = heat transfer coefficient of the frame
Ψ_g [W/mK] = average thermal bridge of edge bond (0.04 W/mK for warm edge, 0.08 W/mK for aluminium spacer)
A_g [m²] = glazing area
A_f [m²] = frame area
A_w [m²] = A_g + A_f
I_g [m] = length of edge bond

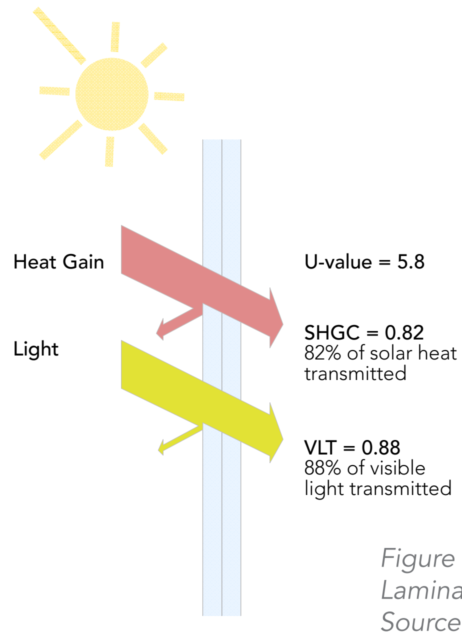


Figure 2.03.23: Clear Laminated Glazing
Source: Efficient Windows Collaborative, n.d

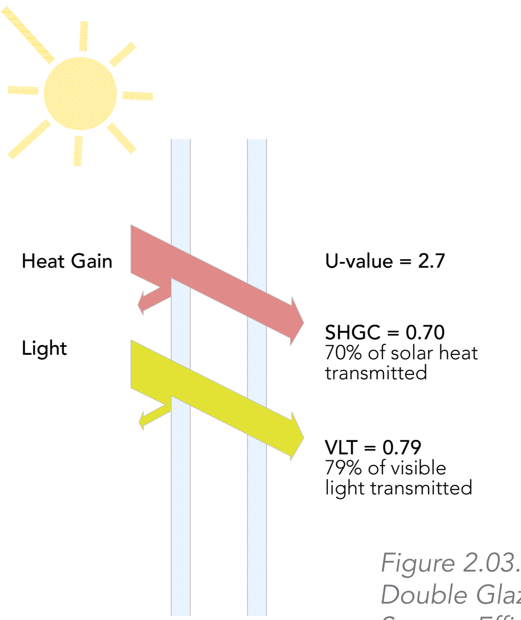


Figure 2.03.24: Clear Double Glazing
Source: Efficient Windows Collaborative, n.d

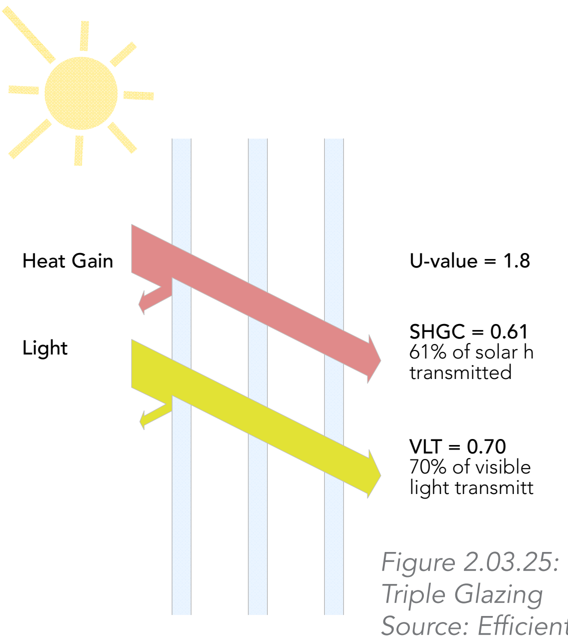


Figure 2.03.25: Clear Triple Glazing
Source: Efficient Windows Collaborative, n.d

Tinted Glazing

↑ U-value ↓ SHGC ↓ VLT ↓ LSG

Tinted glazing is obtained by adding metal oxides in the composition of the glass during the manufacturing process. The resulting glass is darker than the typical clear glass. Due to the heat absorbing properties of darker colors, this type of glazing would lead to higher indoor temperatures while reducing the daylight transmission.

Reflective Glazing

↓ U-value ↓ SHGC ↓ VLT ↓ LSG

Reflective glazing is obtained by applying a reflective metallic coating on the inner surface of the glazing, either on the cavity face of the inside pane or the cavity face of the outside pane. Similar to the tinted glazing, the reflective glazing has a reduced visible transmittance and is used to reduce solar heat gains. It is a commonly used glazing type in architecture due to its mirror effect to the outside and its ability to provide visual privacy during the day. During the night however, the reflectivity changes towards the interior. Moreover, the mirror effect can have a negative impact on the surrounding, as sun is reflected away onto the adjacent buildings.

Low-e Glazing

↓ U-value ↓ SHGC ↓ VLT ↓ LSG

Low-e coatings are thin metallic films which are applied onto the glazing. Low-e coatings are spectrally selective, by letting the short-wave radiation (visible light) through, while reflecting the long-wave heat (infrared radiation) back inside. Therefore, low-E coatings are ideal for heating-dominated climates. Depending on the position of the coating, low-e glazing can retain heat in cold climates when applied on the inside pane, or keep out heat if applied on the exterior pane.

Low-E coatings can be used also in combination with tinted glazing or reflective coatings to achieve better results. According to *Syed (2012)*, applying a spectrally selective low-e coating on the inside of a double-glazing unit is the most effective way to reduce the SHGC value.

Electrochromatic Glazing

↓ U-value ↓ SHGC ↓ VLT ↓ LSG

This type of glazing has received considerable attention in the last years, due to its increased degree of control compared to other glazing types, which leads to reduced energy costs over a longer period of time. Electrochromatic glazing is a relatively new technology of 'smart windows', which change from clear to dark, at a push of a button. Electrochromatic windows work by applying five thin layers of tinted coating on the glazing, while the degree of tint is controlled by the amount of voltage applied to the glass (≈ 1-5V DC). Once the glazing is switched to the desired state, no power is needed to maintain the degree of tint. *(EControl -Glass, n.d.)*

In order to supply the individual glass panels with electricity, a wiring circuit needs to connect the glazing modules to the power supply. The modules can work in combination with Photovoltaic Systems to provide the necessary electricity.

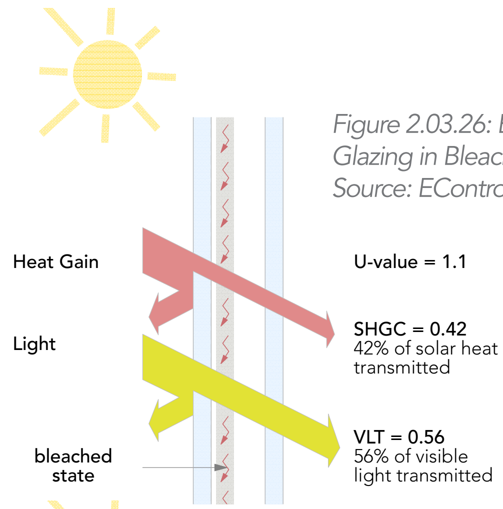


Figure 2.03.26: Electrochromatic Glazing in Bleach State
Source: EControl -Glass, n.d.

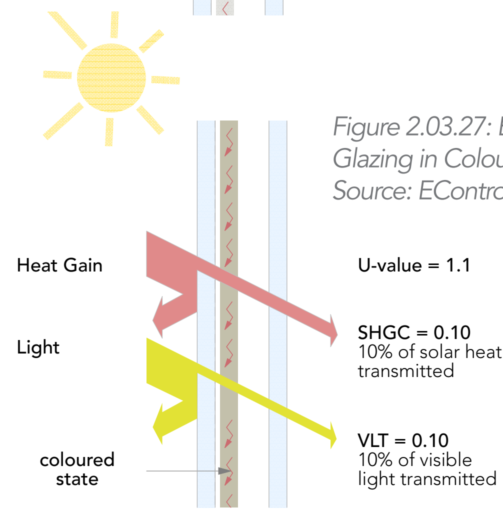


Figure 2.03.27: Electrochromatic Glazing in Coloured State
Source: EControl -Glass, n.d.

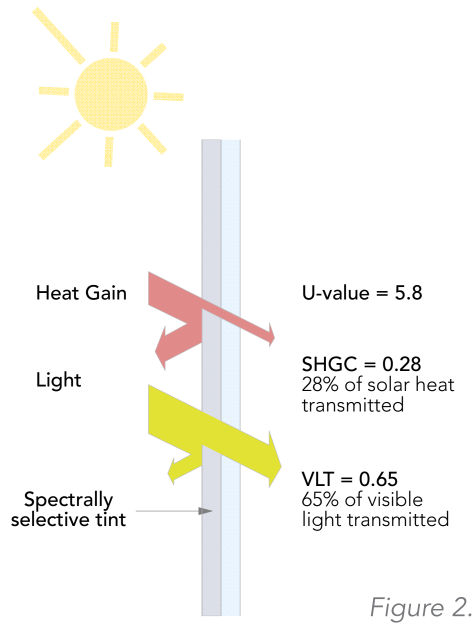


Figure 2.03.28: Tinted Laminated Glazing
Source: Efficient Windows Collaborative, n.d

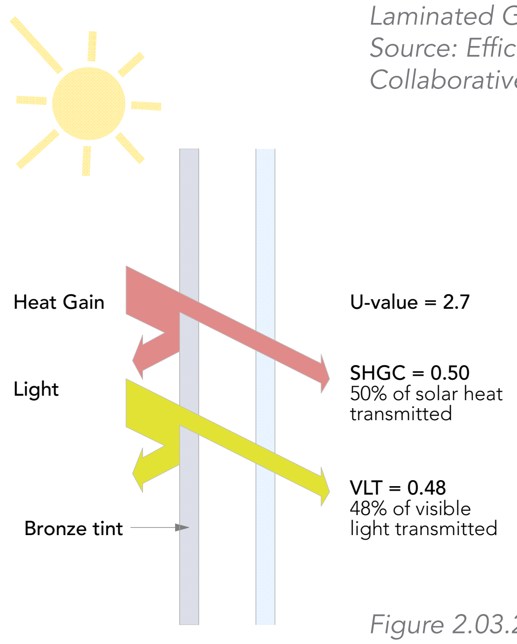


Figure 2.03.29: Tinted Double Glazing
Source: Efficient Windows Collaborative, n.d

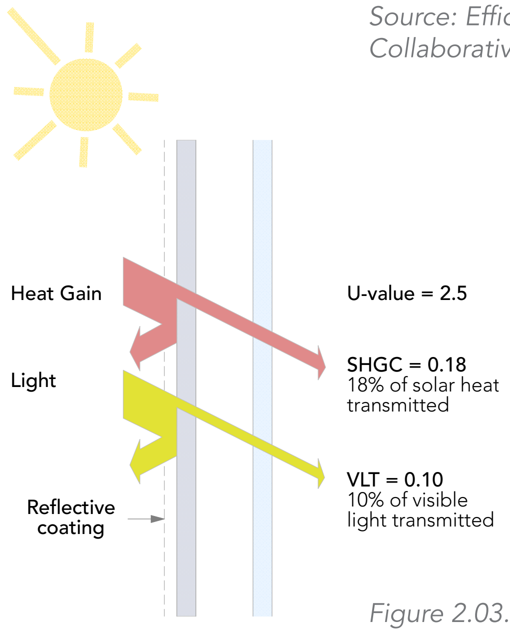


Figure 2.03.30: Tinted Reflective Double Glazing
Source: Efficient Windows Collaborative, n.d

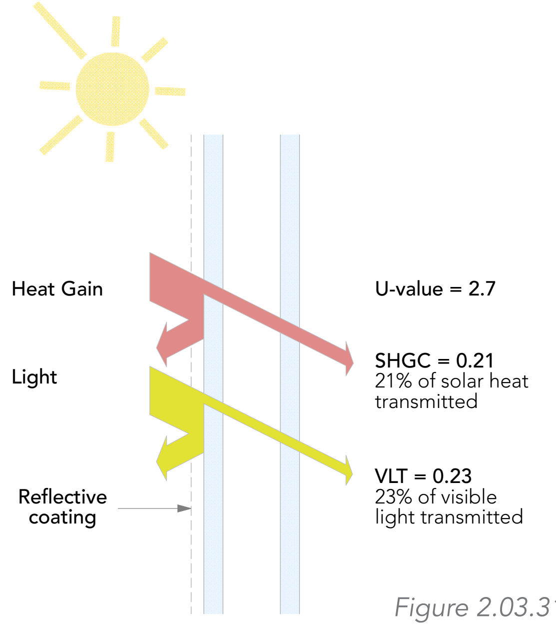


Figure 2.03.31: Reflective Double Glazing
Source: Syed, 2012

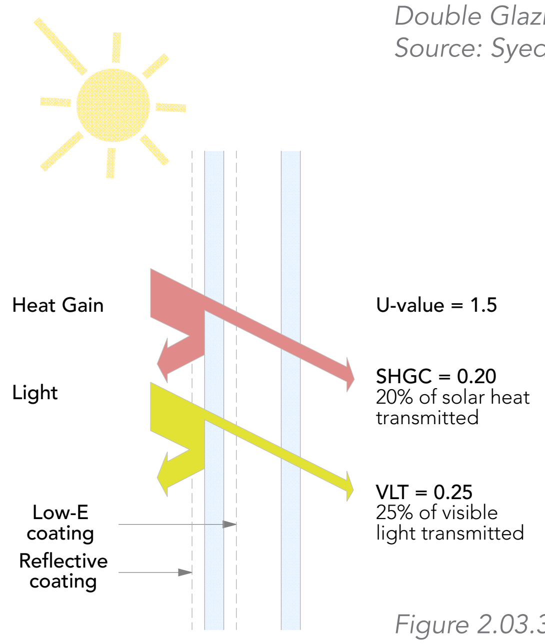


Figure 2.03.32: Reflective Low-E Double Glazing
Source: Syed, 2012

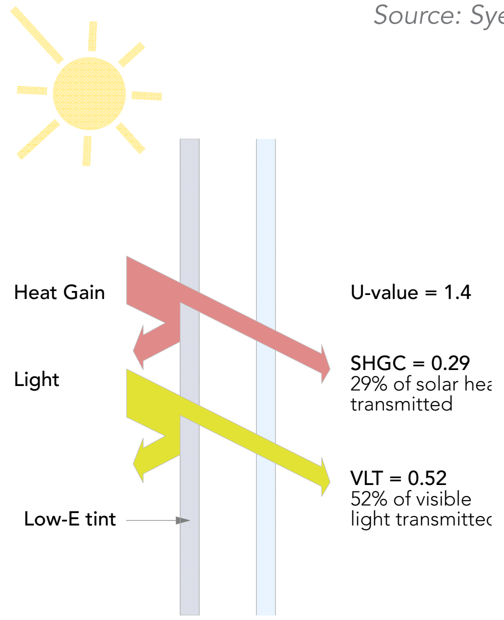


Figure 2.03.33: Tinted Low-E Double Glazing
Source: Syed, 2012

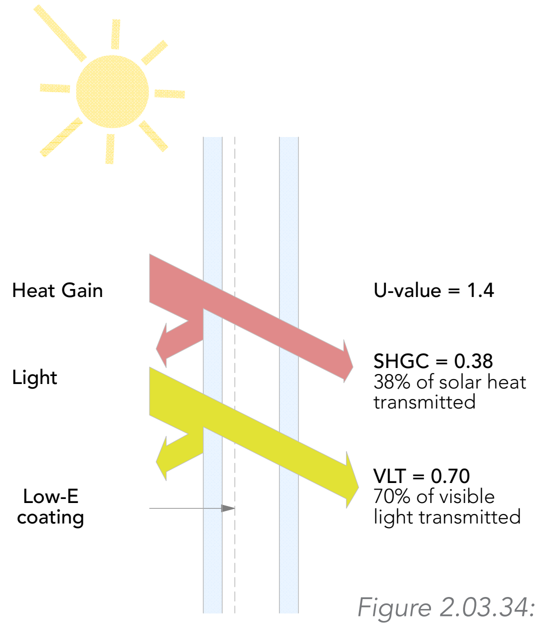


Figure 2.03.34: Low-E Double Glazing
Source: Efficient Windows Collaborative, n.d

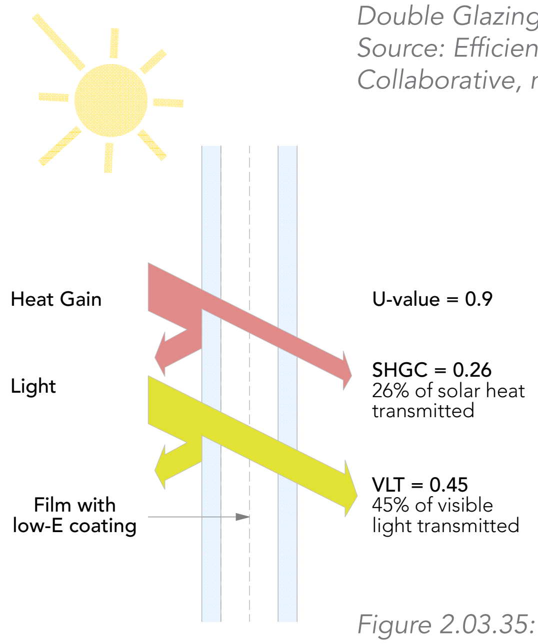


Figure 2.03.35: Low-E Suspended Triple Glazing
Source: Efficient Windows Collaborative, n.d

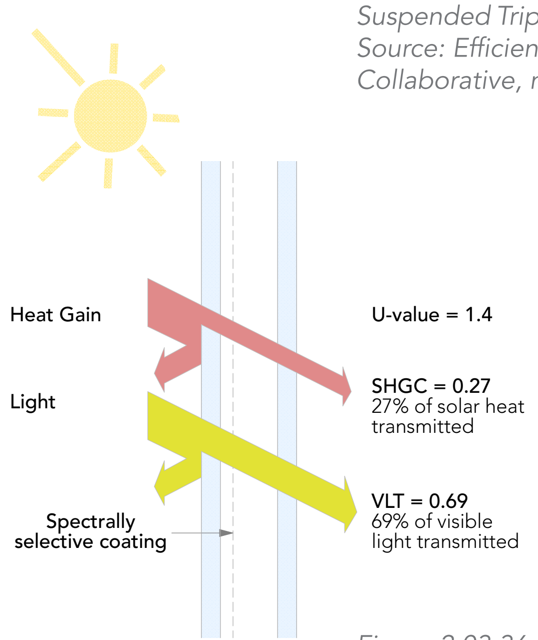


Figure 2.03.36: Spectrally Selective Double Glazing
Source: Efficient Windows Collaborative, n.d

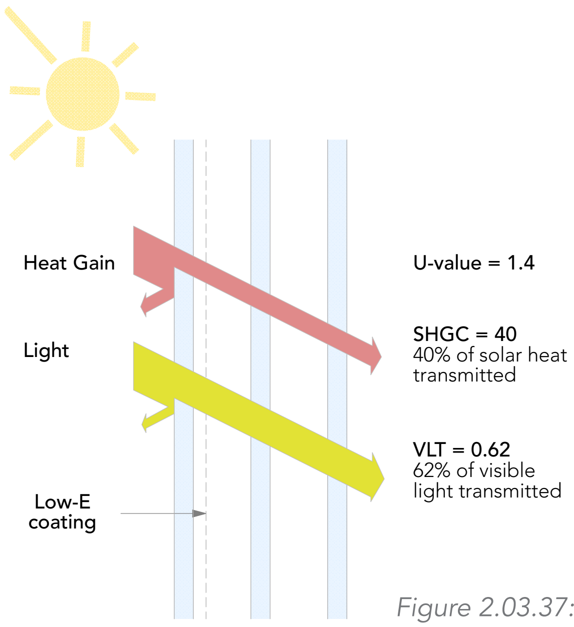


Figure 2.03.37: Low-E Triple Glazing
Source: Perfectview, n.d

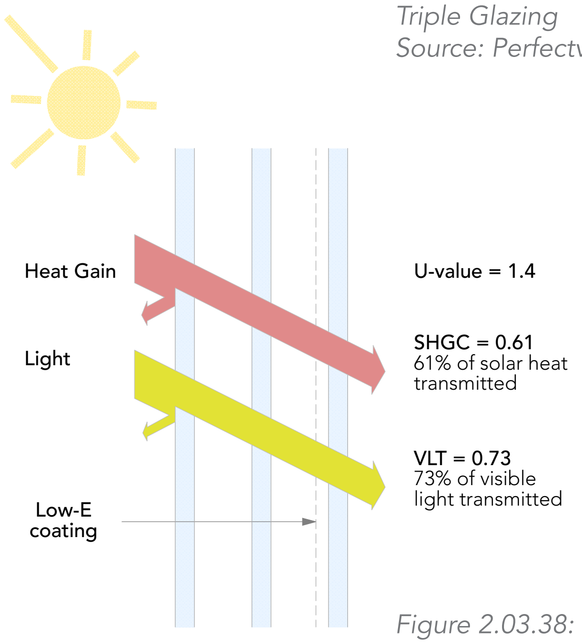


Figure 2.03.38: Low-E Triple Glazing
Source: Perfectview, n.d

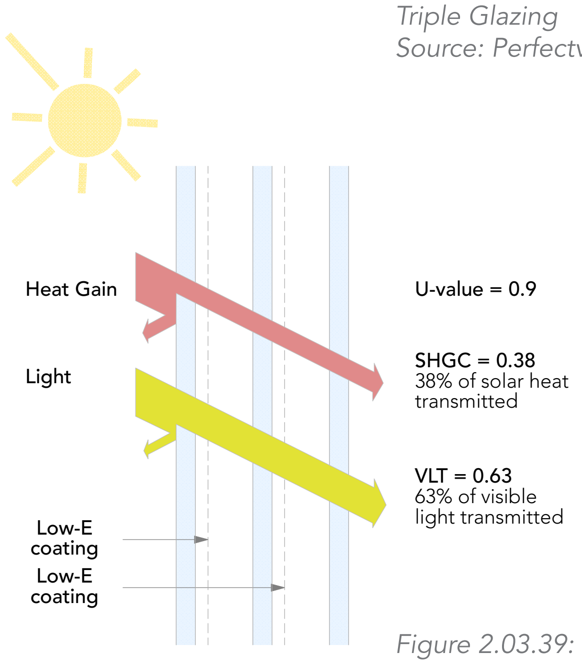


Figure 2.03.39: Double Low-E Triple Glazing
Source: Efficient Windows Collaborative, n.d

04

Shading Systems

Shading elements are an important add-on to the facade, as they can prevent unwanted solar heat from entering the room in the first place, thereby helping to minimize the cooling loads in summer. Moreover, they improve the visual comfort and the productivity of the occupants by reducing glare from direct sunlight. There are different types of sun shading systems, that can be either fixed or moveable. The most common fixed sun shading systems are:

- simple and light directing overhangs
- fixed louvres
- fritted glazing
- fixed metal meshes
- green facade layer

As movable sun shading systems we consider:
- adjustable and moveable louvres
- venetian blinds
- sliding shading
- kinetic shading devices

Overhangs

As already the name suggests, overhangs are placed over the window to protect the occupants from the high summer sun. Overhangs can be an effective solution for south-facing facades, but they will not be as efficient for west-orientated rooms, as overhangs do not block the low afternoon sun, so the solar gains can be quite high.

Light-directive overhangs are usually encountered for deep rooms, where work spaces are located far from the facade. They are located at a lower position of the window, thereby reflecting the light onto the room ceiling, deep into the room.

Louvres

Louvres are vertically or horizontally arranged fins that can be either fixed or adjustable by angling. Motorized louvres are more effective than the fixed ones, as they are able to screen of sunlight from any angle. The fins are usually made of aluminum, wood, textiles or even colored glass. However, an important downside of louvres is the difficult cleaning process of the glazing behind the fins.

Figure 2.03.40: Overhangs
Source: Bridge Louvre Company, 28 Jan. 2015

Figure 2.03.43: Vertical Blinds
Source: Brustor, n.d.

Figure 2.03.41: Vertical Louvres
Source: Solinear, n.d.

Figure 2.03.44: Fritted Glazing
Source: Arcon, n.d.

Figure 2.03.42: Horizontal Louvres
Source: Solinear, n.d.

Figure 2.03.45: Haver & Boecker (n.d).
Source: Haver & Boecker, n.d.

Venetian Blinds

Venetian blinds are a commonly used shading solution, as they offer the user a high degree of control over the amount of sunlight that is entering the room. They are basically retractable louvres which can be either user controlled, manually or through a wall-mounted switch, or automatically-controlled depending on the sun intensity or the temperature.

Venetian blinds can be mounted either on the inner side of the window, to the outside or in between two window panes. External venetian blinds are the most effective in terms of solar heat gain reduction. Interior blinds perform slightly worse than exterior blinds but they are protected from weather conditions, which would result in lower maintenance costs.

Fritted Glazing

Fritted glazing is obtained by printing ceramic-based paint onto the glazing. Patterns of any kind can be imprinted on the glass which is why this is a commonly adopted method by architects to produce graphic statements on buildings. Fritted glass is also considered an effective solution to control glare and can help reduce solar heat gains if used in combination with high performance coatings. The SHGC of fitted glazing can vary, depending on the frit density, its location in the window assembly and the frit color, most commonly white *(Commercial Windows, n.d.)*.

Metal Meshes

Metal mesh screens are usually mounted in front of the glazing unit to mitigate the amount of solar radiation hitting the building. The SHGC and the visual comfort of the occupants depends on the mesh spacing.

Sliding Shading

Sliding shading elements are frequently encountered in residential buildings as an add-on to balconies to offer seclusion. A big variety of materials can be mounted between the track rails, the most encountered ones being wooden panels, metal meshes and textiles.

Vertical Greening

Several studies have been carried out on the effect of green facades on the energy performance of buildings. It has been proven repeatedly that vertical greening can improve the indoor climate considerably *(Raji, Tenpierik, van den Dobbelsteen, 2015)*.

Living walls can improve the building's thermal performance by reducing the level of solar irradiation in summer and making use of the solar heat gains in winter when there is no foliage. The shading efficiency of vertical greening systems depends on the foliage density and the coverage ratio.

But vertical greenery does not only mitigate the daylight level, it also helps reduce the cooling loads of the building by creating a cool microclimate environment through evapotranspiration between the glazing and the vegetation layer. The cooling effect can be further enhanced by using vertical greening in combination with natural ventilation, due to the higher evapotranspiration rate *(Raji, Tenpierik, van den Dobbelsteen, 2015)*.

Kinetic Shading

Kinetic shading devices are high dynamic facade systems that respond to climatic factors in order to maintain a comfort indoor environment. They are usually employed to react to different levels of solar radiation, control the air flow into the building or purely for aesthetic purposes.

Kinetic facades are very complex facade systems that make use of advanced technology and smart materials. The performance of kinetic facades is assessed through dynamic stimulations which can be very complex and go beyond the scope and depth of this research paper.

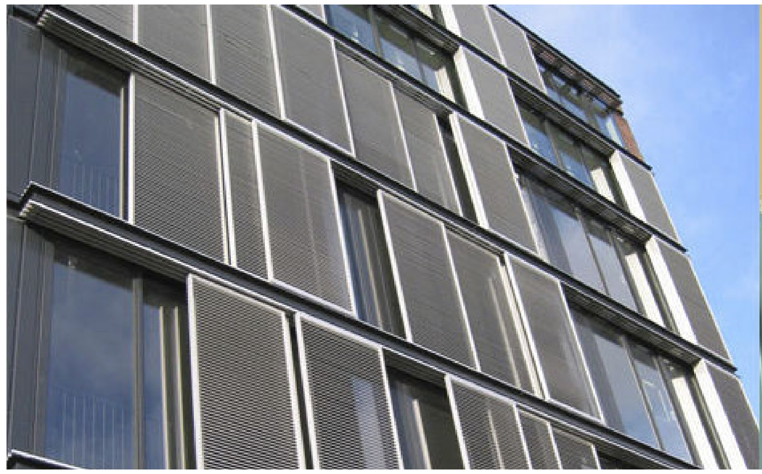


Figure 2.03.46: Sliding Shading
Source: Studio 66 Outdoor Design, n.d

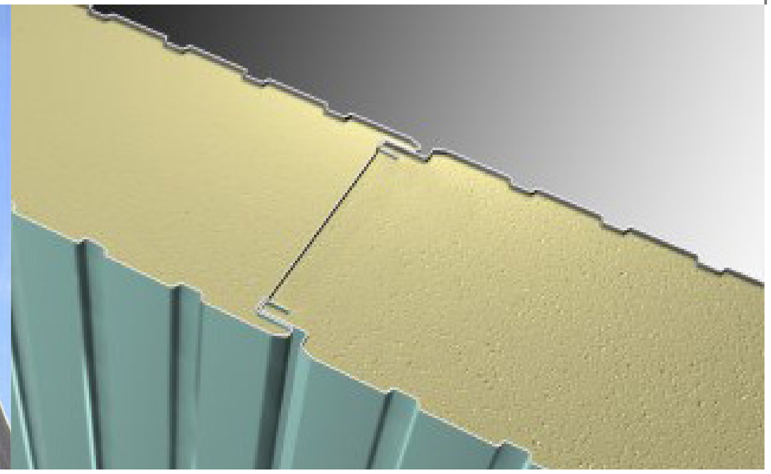


Figure 2.03.49: Vertical Blinds
Source: Globe Panels, n.d

Figure 2.03.47: Vertical Greening
Source: Efficient Windows Collaborative, n.d

Figure 2.03.50: Fritted Glazing
Source: Green Attics, n.d

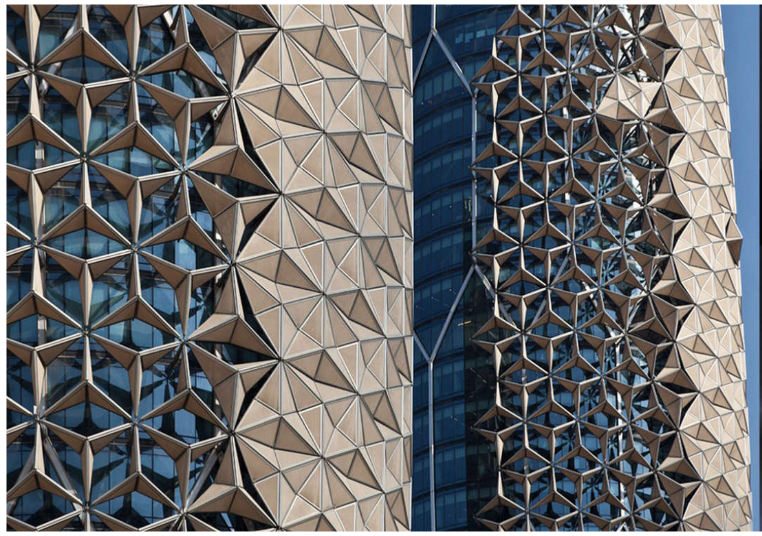


Figure 2.03.48: Kinetic Facade
Source: Aedas Architects, 13 Jan.2017

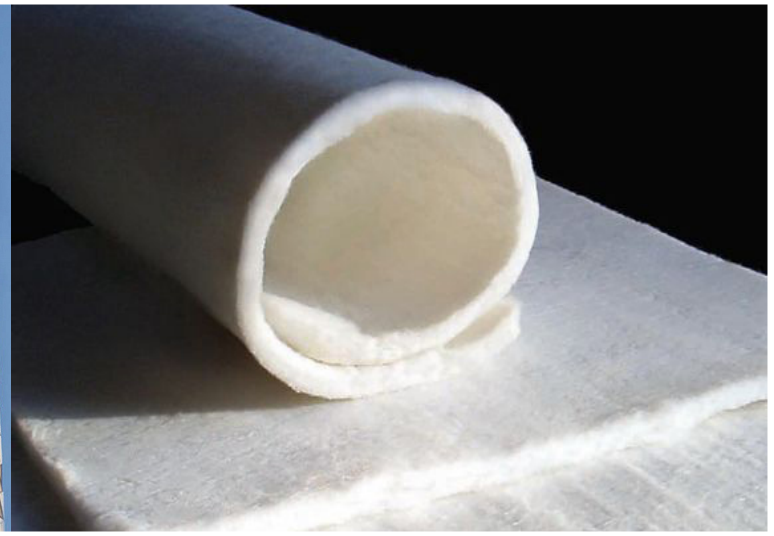


Figure 2.03.51: Metal Meshes
Source: Aspen Aerogels, n.d

05

Insulation

Thermal insulation is an important parameter to reduce the need for fossil fuels and improve the comfort in buildings. The proper use of thermal insulation is essential in cool-temperate climates, where the space heating demand is dominant. By optimizing the glazing ratio, incorporating efficient glazing and using a good thermal insulation material, heat losses can be significantly reduced.

The type of insulation, positioning and air tightness are very important to ensure the effectiveness of the building envelope. For heating dominated climates, it is best to place the insulation to the inside. However, it is not enough to insulate the building well, airtightness is also of great importance. Especially in high-rises, infiltration rates increase with altitude, due to higher wind velocities. A tightly sealed building is more energy efficient and requires less insulation to achieve a high level of comfort.

The efficiency of thermal insulation materials is defined by the thermal resistance, R-value, which is a measure for the ability of a material to resist heat flow through a certain thickness *[7]*. The higher the R-value, the better the thermal performance of the material. The Dutch Buildings Decree, *Bouwbesluit* sets a minimum of R = 3.5 m^2K/W for the thermal resistance of the envelope.

Thermal insulation materials are categorized in two main groups according to their chemical composition - inorganic fibrous materials like glass wool and rockwool, which account for 60% of the market and organic foamy materials like polystyrene and polyurethane, which account for 27% of the market *(Papadopoulos, 2004)*. Other materials account for the rest 13%.

Inorganic Insulation Materials

Inorganic materials are classified in fibrous materials, such as:

- glass wool
- rock wool

and cellular materials, such as:

- calcium silicate
- cellular glass.

Organic Insulation Materials

Organic insulation materials are categorized in petrochemical materials, derived from oil/coal, such as:

- expanded polystyrene (EPS)
- extruded polystyrene (XPS)
- polyurethane (PUR)
- phenolic foam
- polyisocyanurate foam (PIR)

and renewable materials, derived from plans/animals, such as:

- cellulose
- cork
- wood fiber
- hemp fiber
- flax wool
- sheep wool
- cotton insulation

High Performing Insulation Materials

Vacuum Insulation Panels, Aerogels, and Phase-Change Materials are today the most promising thermal insulation materials on the market. Vacuum Insulation Panels offer the best thermal performance today, due to the evacuation of air, which reduces the thermal conductivity of the material to almost zero. Aerogels, on the other hand, are the lightest insulating materials. They have a nonporous structure containing 80-99% air which results in a highly transparent insulation material with a low thermal conductivity. Phase-Change Materials, also known as PCMs, are not so much a thermal barrier as they are an energy storage technology. PCMs, go through a change in their physical state, i.e. from solid to liquid and thus absorb and release thermal energy in order to maintain a regulated temperature.

Insulation	d [cm]	λ [W/m*K]	R [W/m²*K]
Rockwool	11-14	0.031-0.040	3.5
EPS	12-14	0.035-0.040	3.5
XPS	11-14	0.030-0.040	3.5
PUR	9-14	0.025-0.040	3.5
Mineral foam	12-18	0.035-0.051	3.5
Cellular of foam glass	16-19	0.045-0.055	3.5
Celulose	13-16	0.038-0.045	3.5
Cork	13-18	0.038-0.050	3.5
Woodfibre	14-28	0.040-0.081	3.5
Hemp Fibre	13-16	0.038-0.045	3.5
Flax Wool	13-16	0.038-0.045	3.5
Sheepwool	13-15	0.038-0.044	3.5
Vacuum Insulation	3-4	0.07-0.10	5
Aerogel	6.5	0.013	5
PCM	~	~	~

Table 2.03.02: Typical Insulation Materials
Source: Konstantinou, 2012. Taasi, n.d.

Figure 2.03.52: Direct Facade Greening
Source: Green Attics, n.d

Figure 2.03.53: Indirect Facade Greening
Source: Aspen Aerogels, n.d

Vertical Greening

Green walls also have thermal insulation properties. They act as a thermal buffer and reduce the heat flux through the building envelope by regulating the ambient air temperature and wind speed.

Vegetation on the facade can effectively reduce cooling loads due to its evapo-transpiratory cooling effect and provide shade in summer. In winter, shading by vegetation is unfavorable. However, its insulating properties have a higher positive effect then the negative effect of the shading, which means that the application of green walls would also reduce winter heating demand *(Raji, Tenpierik, van den Dobbelsteen, 2015)*.

Perini et al. (2011) conducted a field measurement in the Netherlands and compared the surface temperature differences between a bare wall and three different vertical greening systems. While small temperature differences were recorded for indirect (20cm air cavity) and direct (attached) green walls, living wall systems with planter boxes had a temperature difference of around 5 K. This can be justified by the higher shading effect of planter boxes and higher evapotranspiration due to constant irrigation of living wall systems.

McPherson et al. (1988) investigated the effect of vegetation on the thermal performance of a building as an insulation against wind. They recorded a 50% reduction of wind while it passed through the vegetation layer.

Based on the literature reviews, the efficiency of greening systems depends on vegetation type, foliage density, foliage height, air cavity distance, orientation but also on environmental factors like temperature, relative humidity, solar radiation and wind velocity. The maximum efficiency of greenery systems is reported during summer, by means of shading, cooling through evapotranspiration and regulating temperature fluctuations by serving as an insulation against wind. In winter, green walls can reduce the cold winter wind and provide additional thermal insulation.

06

Ventilation Systems

Ventilation systems are aiming to supply heat, cold and fresh air into the building. They are necessary in order to maintain a healthy and comfortable environment for the occupants. They help to control the indoor temperature and humidity level, as well as to remove bad odors which can affect the concentration level of the occupants and can lead to the so-called sick building syndrome (SBS) *(Gonçalves, 2015)*.

Mechanical Ventilation

Before the invention of the air conditioning system in 1950, it was passive strategies that shaped the design of high-rise buildings, making use of orientation, shape, daylight and natural ventilation to control the indoor climate. The development of air conditioning systems allowed for higher glazing ratios in high-rise buildings, which marked the beginning of the 'glass-box' towers. Fully air-conditioned high-rise buildings with curtain wall facades and intriguing architectural features arose rapidly, because the mechanical control of indoor climate made it possible to design buildings regardless of the environmental conditions *(Gonçalves, 2015).*

Today, we can distinguish between two main categories of mechanical ventilation systems:

- Centralized ventilation
- Decentralized ventilation

Centralized units are systems in which air temperature is controlled from one central unit in the building, whereas decentralized systems are individualized units that regulate the air temperature from different locations.

Centralized HVAC systems can take up entire floors in high-rise buildings, due to the abundant amount of air that needs to be filtered. They also require longer ductwork and are usually less efficient due to poor duct connections. Therefore, decentralized mechanical conditioning, which is integrated into the building envelope, is more suitable for high-rises.

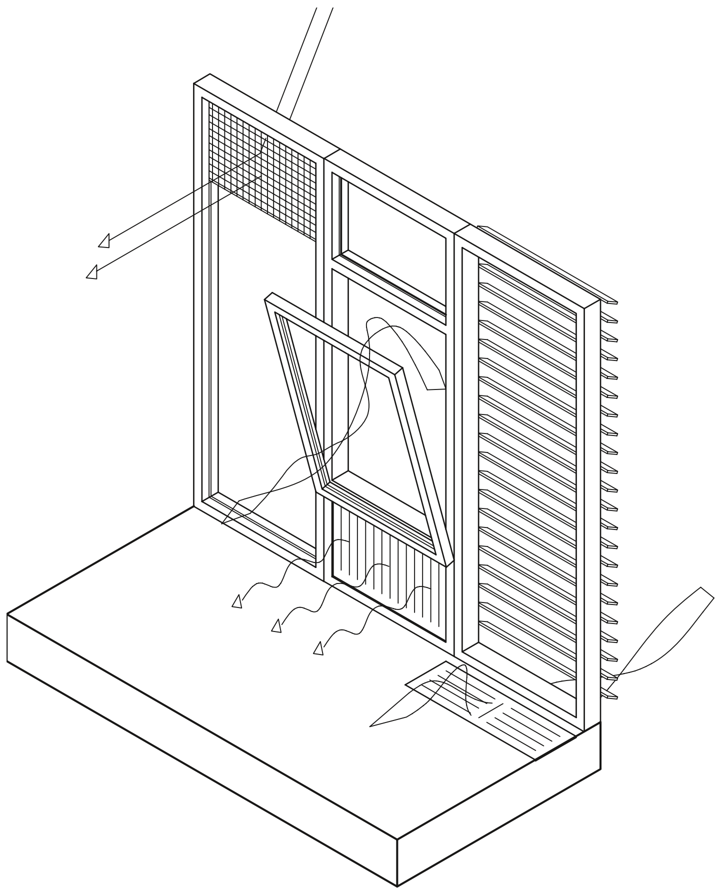


Figure 2.03.54: Facade Functions: ventilation, heating, cooling, shading and lightning
Source: Knaak et al., 2007

Decentralized systems are:

- Horizontal and vertical facade ventilation units
- Underfloor units
- Ceiling units

Moreover, facade ventilation units can incorporate a multitude of functions such as:

- Filtration of outdoor air
- Heat recovery
- Thermal conditioning

Natural Ventilation

It has been proven that users with increased control over their naturally ventilated environment are more tolerant to higher or lower indoor air temperatures *(Wood & Salib, 2013)*. Considering this, natural ventilation in buildings can provide the most optimal balance in terms of energy efficiency and thermal comfort.

Double skin facades are used in high-rises to balance wind speeds and heat the incoming air before entering the building. However, the efficiency of natural ventilation is affected by the wind pressure acting on the facade. Taking this into consideration, special attention needs to be addressed to the size of the ventilation openings with respect to the height of the building. Small ventilation openings or integrated motorizes flaps will prevent unpleasant wind drafts which might affect the users comfort level.

Hybrid Ventilation

'Hybrid' or 'mixed mode' ventilation systems are mechanical systems which work in combination with natural ventilation. Natural ventilation might not be possible during extreme weather conditions, especially in high rise buildings where the last floors are exposed to higher wind speeds and lower temperatures. By making use of natural and mechanical ventilation combined, the thermal comfort of the occupants is maximized while minimizing the energy demand.

07

Energy Generating Systems

The integration of energy generating elements on building envelopes is essential in order to comply to the requirements set by future energy regulations. Especially for high-rise buildings it can be quite challenging to meet the energy balance imposed by *BENG*. The use of fossil fuels is limited though regulations and the roof area available for additional energy production is not sufficient. Taking this into consideration, this chapter will focus on common energy generating systems which take advantage of renewable energy sources and can be integrated onto facades.

PV Systems

Renewable Energy: Sun

There are two possibilities to integrate PV systems onto building envelopes, either as BAPV, Building Applied Photovoltaics or BIPV, Building Integrated Photovoltaics. BAPV are usually added to the existing envelope of a building as part of a retrofit to improve the energy efficiency of old buildings. Nowadays, BIPVs are applied on new buildings because they replace building elements instead of being added to the envelope. PV cells can reach different efficiencies, depending on the type of the PV cells *(energyinformative, n.d.)*:

- Monocrystalline silicon solar cells (MSC) 15-22%
- Polycrystalline silicon solar cells (PSC) 13-16%
- Thin film solar cells (TFSC) 7-13%
- Amorphous Silicon (a-Si) 6-8%
- Cadmium Telluride (CdTe) Solar Cells 9-11%
- Copper Indium Gallium Selenide (CIGS) Solar Cells 10-12%

According to the *University of Applied Sciences and Arts of Southern Switzerland (SUPSI, 2017)*, the most encountered PV technology is the crystalline silicon, although thin film modules are starting to become very popular for facade integrated PV systems. According to the research, thin film technology is used for 8% of the BIPV products on roofs and 44% of the BIPV products on facades. BIPVs have several applications on the facade, as:

- Accessories
- Warm facades
- Cold facades
- Solar glazing

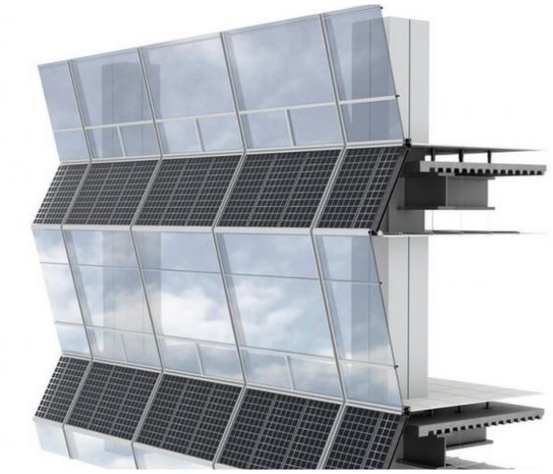


Figure 2.03.55: PV Overhangs
Source: Adrian Smith + Gordon Gill Architecture, 23 Jan. 2014

Figure 2.03.57: BIPV Warm Facade
Source: Schüco, 5 Apr. 2017

Figure 2.03.56: BIPV Balcony Railing
Source: LOCI, n.d

Figure 2.03.58: BIPV Cold Facade
Source: Esuva, n.d

Cold facades and solar glazing are the most encountered facade applications for BIPVs.

Figure 2.03.59: Solar Glazing
Source: Joe Quirke, 27 Nov. 2017.

Accessories

Solar cells can be integrated on facade add-ons like balcony rails or shading elements. The most common accessories with embedded solar cells are shading systems. BIPVs can be found on overhangs, sliding shading screens and even on louvre fins. Thereby, BIPVs can harvest solar energy while providing shade for the occupants. Shading elements can be connected to automatic tracking systems to maximize the energy production.

Warm facades

Warm facades consist of opaque solar cells which are combined with transparent glazing as part of a curtain wall system. This method of PV integration can lead to indoor overheating problems, because the dark colored PV modules tend to absorb light and heat up.

Cold facades (Cladding)

Cool facades involve a gap between the PV module and the mounting frame of the module to the facade, so that ventilation is ensured. This way, the PV system does not overheat and its efficiency is maximized.

Solar glazing

Solar facades consist of classic, transparent or semitransparent solar cells integrated into the glazing unit. Crystalline or microperforated amorphous modules which are integrated in between two glass panes with a certain distance between the cells are the most encountered solar facades. The distance between the cells can vary and determines the level of transparency.

Highly transparent glazing can be manufactured by incorporating solar cells which absorb only infrared and ultraviolet light into the glazing composition. Thus, visible light can be transmitted into the building. While conventional PV panels have an average efficiency of 15%, transparent and semitransparent solar modules have an average efficiency of 5%, respectively 7.2%. The higher the transparency the lower the efficiency *(Greenmatch, 9 Oct. 2018)*.

Solar Collectors

Renewable Energy: Sun

Solar collectors make use of solar radiation to heat up water or air flowing through ducts in the solar collector panel. The amount of heat energy captured per square meter of collector surface area varies, but typically it can range from 300 to 900kWh/m²/yr *(IEA, 2011)*. The most common solar collector types are:

- Flat plate collectors
- Evacuated Tube Collectors

Flat plate collectors

Flat plate collectors have a black absorbing cover that absorbs the solar heat and transfers it to the liquid/air flowing through the tubular circuit underneath. Thermal insulation will prevent the heat from escaping.

Evacuated tube collectors

Evacuated tube collectors consist of parallelly arranged transparent cylindrical glass tubes filled with liquid or air. Each tube consists of a thin outer tube and a thin inner tube with a selective coating in between that absorbs sunlight but prevents heat loss *(David Darling, n.d.)*.

Figure 2.03.60: Solar Tube Collector as Balcony Railing
Source: Keampfen, 2001

Figure 2.03.61: Solar Tube Collector as Sunshading
Source: Laura Aelenei, n.d.

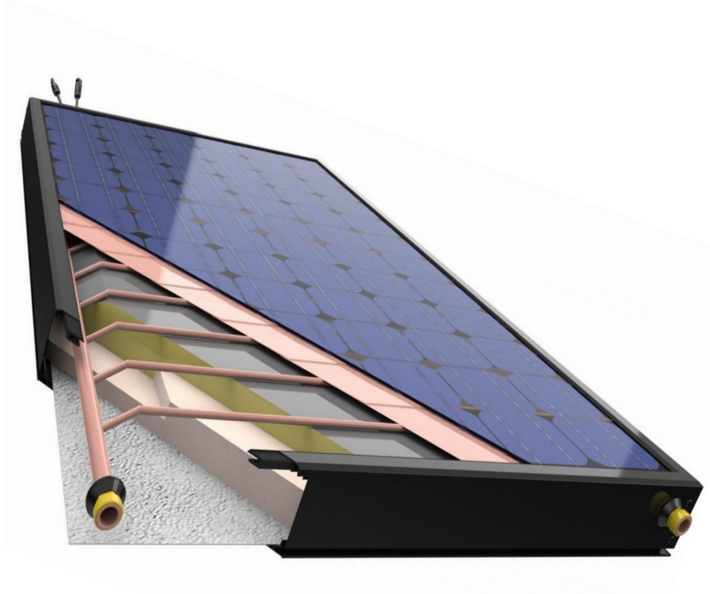


Figure 2.03.63: Cross section Volther Powervolt PV/T panel
Source: Solimpeks, n.d.

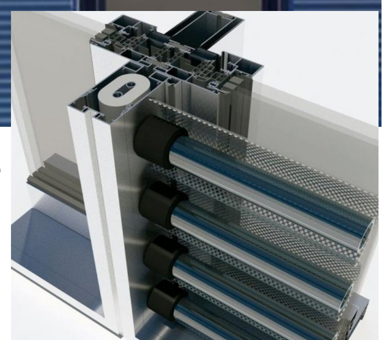


Figure 2.03.62: Solar Thermal Facade
Source: Ecofriend, 20120
Laura Aelenei, n.d.

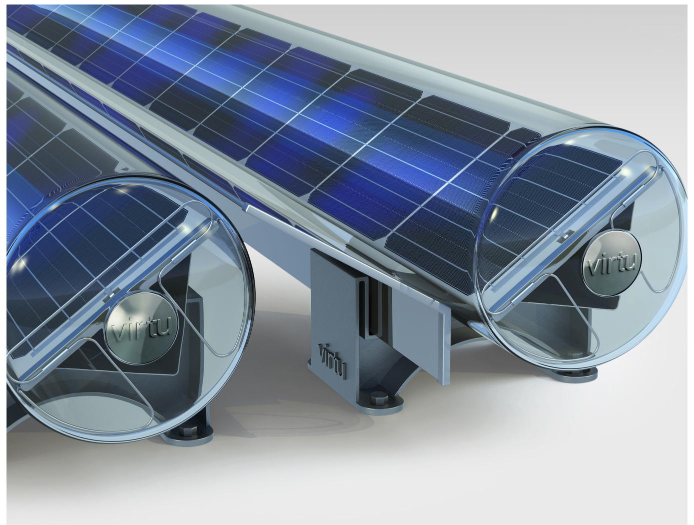


Figure 2.03.64: Naked Energy
Source: Naked Energy, n.d.

PV Thermal Systems

Renewable Energy: Sun

Photovoltaic thermal hybrid solar collectors, in short PVT, are solar collectors which work in combination with Photovoltaic Systems. As PV panels tend to heat up, the efficiency of PV cells in conventional PV panels decreases due to the increasing cell temperature. By combining PV cells and solar collectors in one module, this heat is absorbed by the water flowing through the solar collector, thus cooling down the PV unit and maximizing its efficiency.

A study on the application of solar collectors in high-rise buildings carried out by ECN (Energy research Centre of the Netherland) proved that, the thermal efficiency of a PV/T system is slightly lower compared to a that of a simple solar collector *(Jong et. at, 2005)*. However, the heat loss is compensated by the increased electricity production. In addition, PV/T panels take less space and the amount of material used, as well as the installation time required are reduced compared to conventional PV or Solar Collector modules.

To date, the most encountered PV/T systems on the market are air/water based Flat Plate PV/T panels. Other emerging technologies are hybrid parabolic PV/T Systems or vacuum sealed PV/T tubes. Unlike conventional PV/T panels, the hybrid solar tubes developed by *Naked Energy* can be installed on the facade at an angle. A diffuse reflector surface mounted between the tubes reflects the sunlight on the absorber to maximize the energy production during all seasons. The system has a thermal efficiency of 60%, respectively 20% electric efficiency *(Naked Energy, n.d.)*.

Algae Panels

Renewable Energy: Biomass

Algae panels can be mounted on the roof or used as shading elements. Algae can grow inside the glazing unit by collecting solar energy and carbon dioxide, respectively liquid nutrients which need to be supplied through the bioreactor-panels. The produced heat and biomass will be used to supply the building with renewable energy. The resulting biomass can be burned in a boiler as part of a small combined heat and power plant to generate heat and electricity. 40-70% of the generated energy is converted into heat, while 20-45% into electricity *(IETD, n.d.)*. The following conversion formulas were retrieved from *Schlagermann et al. (9 Apr. 2012)*:

1kg oil-poor algae = 20MJ (20% - 30% dry weigh) [11]
1kg oil-rich algae= 30MJ (50% dry weigh) [12]

*1kg oil-rich algae= 5.55 kWh ≈ 30%*5.55 kWh elect.* [13]
*≈ 50%*5.55 kWh heat*
*1kg oil-rich algae= 8.33 kWh ≈ 30%*8.33 kWh elect.* [14]
*≈ 50%*8.33 kWh heat*

Wind Harvesting Envelope

Renewable Energy: Wind

A relative new innovation are building integrated wind harvesting systems that generate power. Such energy generating systems are designed to blend in with the architectural features, unlike the wind turbines which take up valuable space on the roof and are aesthetically unpleasing.

The PowerNEST is an envelope integrated energy generating solution for high-rises that makes use of the high wind velocity at high altitudes. The last floor of a high-rise building is allocated for harvesting wind energy with an installation of funnels integrated into the facade and a set of vertical wind turbines arranged along the floor edge *(IBIS Power, n.d.)*.

Figure 2.03.65: Algae Panels
Source: Vicente Mora, n.d.

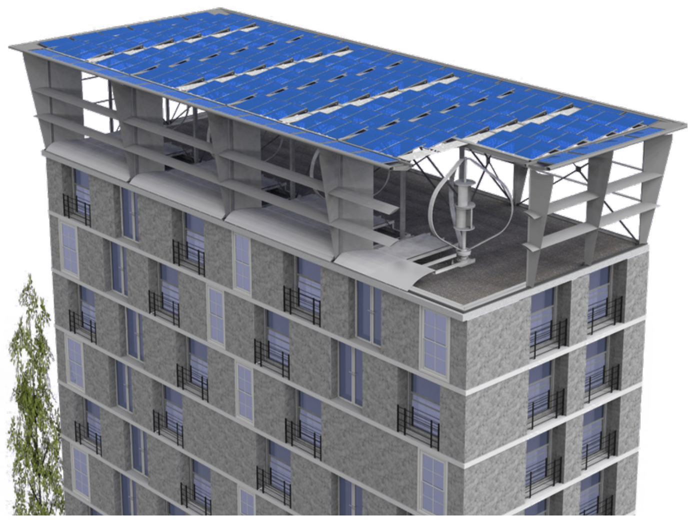


Figure 2.03.66: PowerNest
Source: Kanyemesha, 16 Mar. 2018

Equipment	Internal Loads	
Fridge	160	[W]
Dishwasher	14.0	[W]
Oven	700	[W]
Microwave	1080	[W]
Toaster	450	[W]
Washing Machine	1020	[W]
Dryer	225	[W]

Table 2.03.03: Internal Heat Loads from Equipment

2.03.03

User Related Factors

Each human being perceives the indoor environment differently, due to cultural differences, individual preferences, behavior, difference in clothing level etc. Moreover, the different daily behavior of the occupants highly influences the indoor comfort level. One average person of 70kg exhales 400 ml/h of water, eliminates another 400 ml/h due to perspiration and breathes out 500 liters of CO_2 *(Larson, 31 May 2016)*. Moreover, the human body radiates approximately ≈ 350,000 J of energy per hour, which is equivalent to ≈ 100W *(PhysLink, n.d.)*. In order to regulate the temperature, humidity, CO_2 level at a comfortable and heathy state, it is necessary to frequently ventilate the room.

Studies have shown that indoor comfort levels are perceived differently in naturally ventilated and mechanically ventilated buildings. It has been proven that user controlled natural ventilation can improve user satisfaction and lead to more tolerance for temperature fluctuations when compared to mechanically ventilated buildings or buildings with an integrated BMS (Building Management System) *(Wood & Salib, 2013)*.

Other user related factors can be considered also internal heat gains from appliances of daily use and lighting. *Table 2.03.03* shows the sensible heat load of frequently used household equipment. The internal heat gain from different light sources can be calculated as follows *(Suszanowicz, 2017)*:

$$Q_{H,0} = A_f * E_v * \cdot n^{-1} * H_e * t_0 \qquad [15]$$

$Q_{H,0}$ - internal heat gain [kWh/yr.]
A_f - floor area [m^2]
E_v - illuminance [lx]
E_v - luminous efficacy [lm/W]
H_e - heat emission coefficient [W/W]
t_0- annual operating hours [kh/yr.]

2.04

Examples

Overview in Appendix A

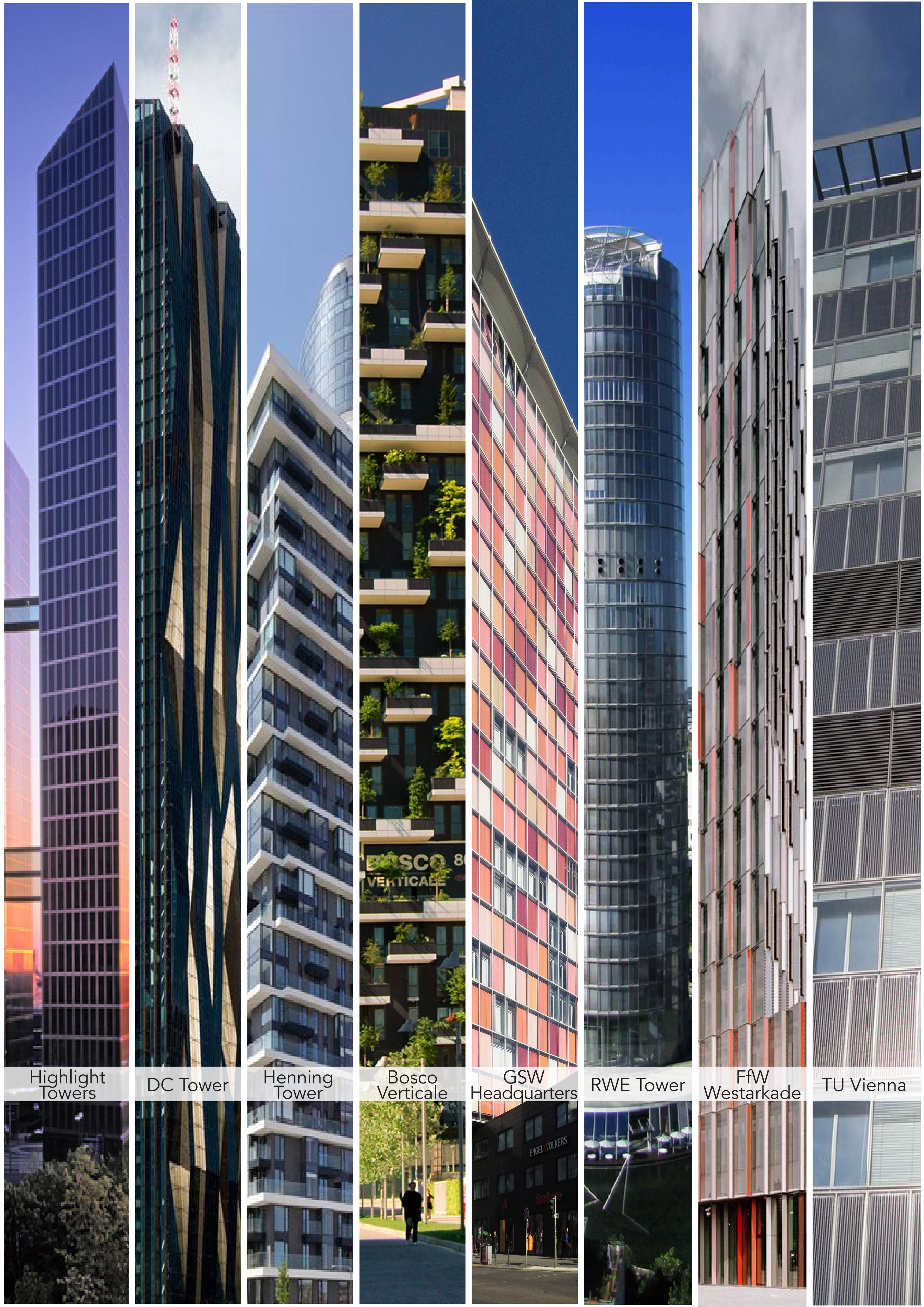
All the aforementioned influential factors need to be considered when designing an energy efficient high-rise building. Still, there is a lot of freedom to play with the facade parameters and there is a substantial amount of combinations. Therefore, it is interesting to see how previous high-rise buildings function and what design choices were made.

Looking at preceding examples, it is quite obvious that for residential buildings, rather a single skin facade is used, mainly because there is not so much need for cooling and it allows for a higher degree of user control. Almost in all cases, the ventilation was mainly controlled by users and by a Building Management System (BMS) when the weather conditions do not allow for natural ventilation. Mainly interior blinds and exterior louvres where used as shading elements, but also vertical greening. The glazing is mainly double glazing with a low-E coating in combination with reflective and tinted glazing. As energy generating systems, the most encountered elements are BIPVs.

Appendix A offers a complete overview of the analyzed examples. High-rises were chosen which present innovative solutions with regard to energy efficient facade design principles.

Examples of Sustainable High-rises

Overview in Appendix A



Source: Rainer Viertlböck, n.d.
Source: Domus Web, n.d.
Source: Conne van d Grachten, 12 Sept. 2018.
Source: The Skyscraper Center, n.d.
Source: Wiki Arquitectura, n.d.
Source: ImgCop, n.d.
Source: Brigida Gonzalez, n.d.
Source: David Alexander, n.d.

2.05

Overview

2.05.01 Benchmarks

Thermal Comfort

EN15251, ASHRAE 2004

EN15251:2007 refers to the indoor comfort of a building. As far as thermal comfort is concerned, *EN15251:2007* makes a distinction between free-running buildings, which are NV in summer and HC in winter and airconditioned buildings which are HC throughout the entire year. This study will assess the thermal comfort conditions of a residential high-rise building functioning in free running mode.

According to *ASHRAE Standard 55* people who live naturally ventilated buildings can adapt to more variable indoor thermal comfort conditions. Taking into consideration the acceptable operative temperature ranges for naturally conditioned spaces described in *Figure 2.05.01*, adaptive setpoints of 21°C for heating and 28°C for cooling are considered for this study, as described further in *Chapter 3.03*.

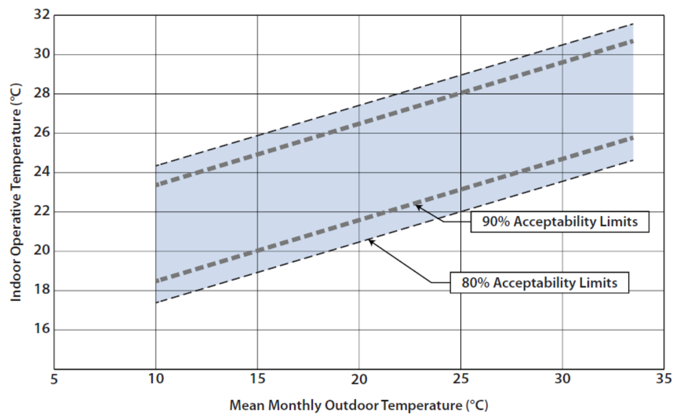


Figure 2.05.01: Adaptive standards for nat. ventilated buildings
Source: ASHRAE, 2009

In order to assess the degree of indoor comfort, the aim is to reach a PMV-index ranging between -0.5 and +0.5 and a PPD of maximal 10%, as suggested by the *EN15251:2007*.

Daylight

Bouwbesluit, EN15251

In terms of daylight, a minimum of 10% of the total floor area should be provided for residential buildings, according to the *Bouwbesluit* and an UGR<19 as suggested by the *EN15251:2007*.

Energy Performance

BENG

BENG sets minimum requirements for maximum energy needs, maximum primary fossil fuel use and minimum share of renewable energy depending on the type of building and the level of compactness. Taking into consideration the limitations for the energy efficiency of residential buildings, the aim is to maximize the energy performance of the studied building and see how much the *BENG* limitations can be met with the optimized facade design alone.

	Energy Need [kWh/m²/yr]	Primary Fossil Energy Use [kWh/m²/yr]	Share of Renewable Energy [%]
Resid. building (multi-family)	$A_{ls} / A_g \leq 2.2$: 70 $A_{ls} / A_g > 2.2$:	50	40

Table 2.05.01: New BENG Requirements
Source: Isover, 20 Nov. 2018

In order to reach these values, the *Bouwbesluit* sets additional limitations for ventilation rates for residential buildings *(Table 2.05.02)*. Moreover, a minimum R-value of 3.5 m²K/W is required for the envelope and a maximum U-value of 1.65 W/m²K for windows and doors.

Function	Ventilation Rate
Kitchen	21.0 *[dm³/s]*
Bedroom	0.09 *[dm³/s] per m²*
Bathroom	14.0 *[dm³/s]*
Toilet	7.0 *[dm³/s]*
Corridors	0.05 *[dm³/s] per m²*

Table 2.05.02: Ventilation Rates per Room Function
Source: Bouwbesluit, 2012

Target Values

Energy Performance

BENG

Energy needs

≤ 70 kWh/m²/yr

Primary fossil fuel use

≤ 50 kWh/m²/yr

Share of renewable energy

≥ 40%

* primary energy factor = 2.14
* COP acc. to current HVAC systems described in Chapter 5

Daylight

BOUWBESLUIT

min. 10% of total floor area

EN15251

UGR<19%

Thermal Comfort

EN15251

-0.5 < PMV < 0.5

10% < PPD

2.05.02 Influential Facade Parameters

Facade Typology

Double skin facades proved to be very efficient in high-rise buildings to cope with high wind speeds, while providing natural ventilation. However, they are mainly encountered in office buildings in order to reduce the high amount of cooling loads in summer by inducing natural ventilation. This study focuses on residential high-rise buildings, a rather heating dominated building typology. Taking into account also the increased amount of material, cost and complex design planning, the double skin facade typology was considered to be unnecessary to reach the scope of the project. Therefore, a single-skin facade is considered to be more suitable for the studied high-rise typology.

WWR

In a temperate climate, the maximum recommended WWR is 60%, in combination with efficient glazing and external sun shading, as higher values would imply increased transmission heat losses through the facade. However, considering that the winter months in the Netherlands are rather mild, this study will go up to a WWR of 80% to achieve a high degree of transparency, while combining it with efficient glazing, a sun shading system and natural ventilation to avoid overheating. This being said, this study will investigate the influence of the following window to wall ratios: 35%, 50%, 65% and 80%.

Glazing

For buildings in the Netherlands, the *Bouwbesluit* stipulates a maximum U-value of 1.65 W/m²K for windows. This value will serve as reference, however, the SHGC and VLT also play an important role.

This study will analyze the performance of double and triple glazing in combination with different coatings. The following glazing types were considered to be common potential solutions to achieve the desired results.

Glazing Type	Uglass	Uframe	Utot	SHGC	VLT
	[W/m²K]	[W/m²K]	[W/m²K]	[%]	[%]
HR++ (current situation)	no specif.	no specif.	1.21	60	60
Double Glazing	1.1	1.6	1.16	60	80
Double Glazing	1.1	1.6	1.16	30	60
Triple Glazing	0.8	1.6	0.9	60	80
Triple Glazing	0.8	1.6	0.9	30	60

Table 2.05.03: Glazing Types as Variables

The objective is to find the most suitable glazing in combination with WWR and shading elements, to keep the heat out in summer while still providing a high degree of sunlight throughout the year.

Shading

Shading devices are an important aspect of many energy-efficient building design strategies. Looking at the analyzed examples, it has become evident that blinds are used in most cases to control the incoming sunlight. Shading elements perform best when they are placed to the exterior. However, in case of high-rises, they are usually placed on the inside or in between a glass cavity, to protect them from the harsh weather conditions.

This study will consider the following shading designs for the simulation: interior blinds, electrochromatic glazing and exterior shading. The shading systems will be automatically activated depending on the solar irradiation level (20W/m² ≈ 2500 lux).

Insulation

The *Bouwbesluit (2012)* stipulates a minimum R-value of 3.5 m²K/W for the envelope. It is unquestionable that the higher the R-value is, the better the overall performance of the building. Taking into consideration also the cost factor, high performance materials such as vacuum insulation, aerogels and PMC were excluded. An R-value of 4.5 and 6.0 m²K/W will be considered for the simulation. Moreover, this study will analyze the wind insulation performance of vertical vegetation and perforated screens in combination with natural ventilation.

Ventilation

As already mentioned, the building will function in 'hybrid' mode, while making use of natural ventilation when the weather conditions allow it and mechanical ventilation throughout the rest of the year. Most of the analyzed high-rise examples rely on hybrid ventilation. No high-rise building was built so far, which relies on natural ventilation alone. Therefore, the ventilation for the chosen case study will also rely on 'hybrid ventilation' with BMS control. *Table 2.05.02* provides an overview of the ventilation rates stipulated by the *Bouwbesluit* for residential buildings.

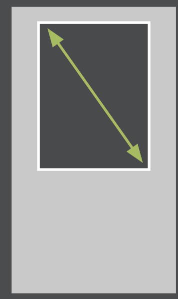
This study will consider three different scenarios to induce natural ventilation. Tilting windows are the first and most encountered ventilation strategy. In order to balance high wind speeds in high rises, vertical greening and perforated window screens will be assessed in combination with fully openable windows in order to increase the amount of natural ventilation at high altitudes. The conditions under which natural and mechanical ventilation are induced, are described in *Chapter 3.04.03*.

Energy Generating Systems

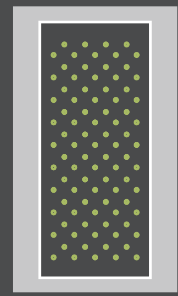
The area available on the facade for energy generating systems will depend on the WWR. Additional area provided by building accessories, such as balcony railings and exterior shading will be also taken into account.

To date, the most effective energy generating system to be integrated onto the envelope, are PV/T systems, as their overall efficiency can reach up to 60-80%. This study will consider integrated PV/T elements with an electric efficiency of 20% and a thermal efficiency of 60% as the main energy source.

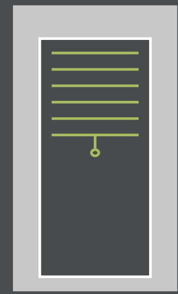
Facade Variables



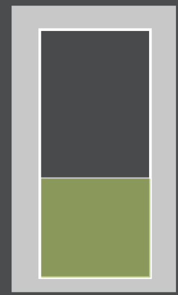
WWR
35%
50%
65%
80%



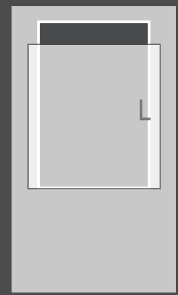
Glazing
DoubleG_0 (1.21, 0.6, 60%)
DoubleG_1 (1.16, 0.6, 80%)
DoubleG_2 (1.16, 0.3, 60%)
TripleG_1 (0.9, 0.6, 80%)
TripleG_1 (0.9, 0.3, 60%)



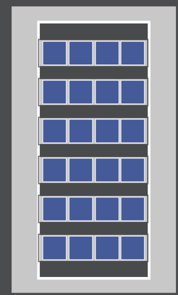
Shading
None
Interior Blinds
Electrochromatic Glazing
Exterior Louvres (PV/T)



Insulation
R = 4.5m²K/W
R = 6.0m²K/W
Vertical Vegetation (wind insulation)



Natural Ventilation
Tilting Windows
Open W. + Vertical Vegetation
Open W. + Perforated Panel



Energy
WWR 35%: PV/T Facade
WWR 50%: PV/T Facade
WWR 65%: PV/T Louvres
WWR 80%: PV/T Louvres
BIPV Balconies

03

Case Study

3.01

The Case Study

The Cooltoren

This research will be conducted on the following case study - The Cooltoren by V8 Architects. The Cooltoren is a 154.5m tall apartment tower located in the Baankwartier of Rotterdam. It was designed in 2016 by V8 Architects and is expected to be completed by 2020, when it is going to become the highest building in Rotterdam.

The architectural concept relates to the surrounding environment at different levels, on the one hand through the plinth and on the other hand through its 70m virtual height limit. This particular middle level is articulated by the large balconies with thick railing, which are continuous all around the building. Towards the top, the horizontal accentuation of the facade develops gradually into increasingly slender bands and thus, the facade becomes more and more transparent.

The Cooltoren includes 282 apartments ranging from 60 to 400 m². The top 6 floors and the 3 middle floors include penthouses, while the rest of the apartments are distributed along the rest of the building height. This study will analyze the energy performance, daylight and indoor comfort conditions at two extreme levels - the 8th. floor at 25m height and the 44.th floor 130m height. These two floors are identical in terms of building layout, so that their performance can be compared later on.

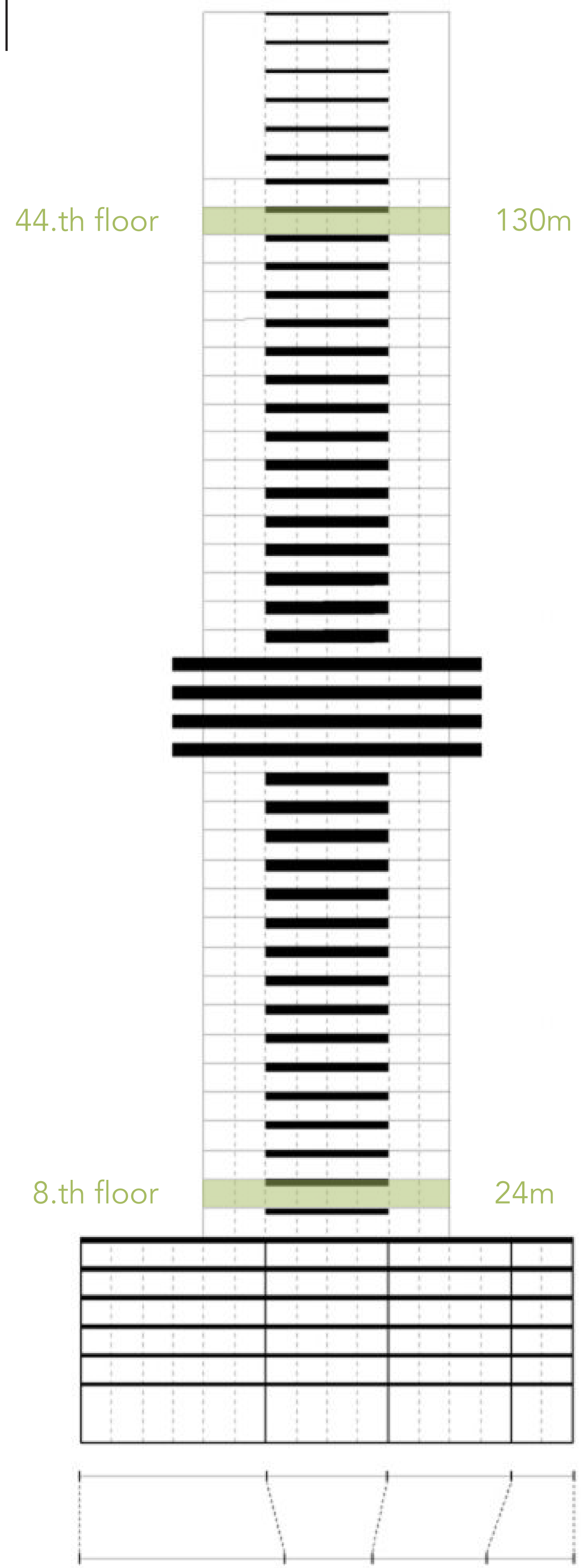


Figure 3.01.01: Conceptual Elevation
Source: V8 Architects, n.d.

Location
Rotterdam, NL

Design Architects
V8 Architects

Project Data:
2016 - 2020
154.5m
50 stories
30,392 m²

Square Shape
7.21m Depth

Ventilation:
- Mixed-Mode
  Wind-driven
  Mechanical
  Control: User

Facade:
- Single-Skin
- Glazing:
  HR++

Shading:
- No Shading Elem.

Energy Production:
- PV Roof
  Roof: 108.80m², 0% obstr
  132.60m², 85% obstr
  165 Wp/m²
  Total: 248.8 kWh/yr
- Heat & Cold Storage
- Mech. Vent. with 95% Heat Recovery
- Heating/Cooling System with high COP

Annual Consumption:
To be evaluated

Source: V8 Architects, n.d.

3.02

Architectural Design

01 Plan Layout

As already mentioned, the two floors which will be analyzed are identical in terms of layout. Each floor includes 6 apartments of 84 - 182m^2 gross area. The bedrooms and kitchens are organized around the core and reach 7.21m in depth. All bedrooms and some of the kitchens have access to an open outdoor space of 10 m^2.

Figure 3.02.01: 8.th, 44th Apartment Areas
Source: V8 Architects, n.d.

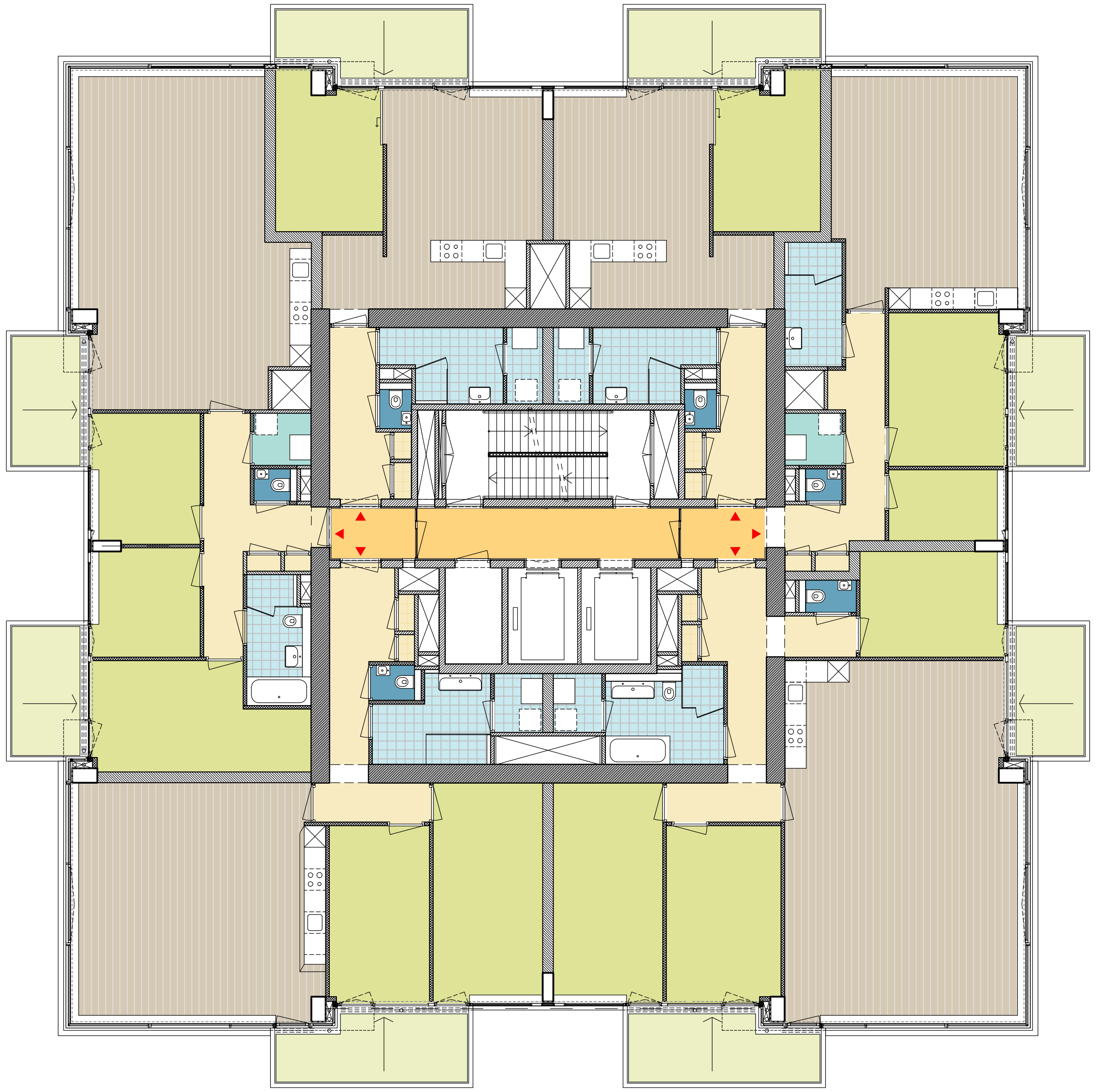


Figure 4.02.02: 8.th, 44th Floor Plan M1:200
Source: V8 Architects, n.d.

02 Window to Wall Ratio

Transparency was of utmost importance for the architectural design. The current window to wall ratio is 65% with no shading elements integrated, which could lead to potential overheating and glare problem.

Glazing Type	Orienatation	Utot	SHGC	VLT
		[W/m²K]	[%]	[%]
HR++	north	1.21	60	60
HR++	east	1.21	35	60
HR++	south	1.21	35	60
HR++	west	1.21	35	60

Table 3.02.01: Window Glazing Properties

03 Glazing

The fixed and tilting windows, as well as the sliding balcony doors are provided with HR++ glazing and aluminum frames. This type of insulating glazing is basically normal double glazing with a metal oxide coating.

The tilting and fixed window openings present a glass-frame assembly U-value ≤ 1.21 W/m^{2}K while the sliding doors have a U-value ≤ 1.58 W/m^{2}K. The SHGC is 0.35 on the east, west, south facades, respectively 0.6 to the north and the VLT ≥ 60%.

04 Shading

The building is located in a low urban context, so that no shade is projected onto the high-rise building. Only the balconies provide some shade for the bedrooms. Besides this, no sun protection has been integrated into the current architectural design to block the direct sunlight. Only a curtain rail track is mounted on the inside, above the windows, giving the occupants the possibility to add curtains.

Source: V8 Architects, n.d.

05 Materials and Insulation

In order to reduce the thermal bridging problems, the main facade construction is made of a stony cavity structure. The prefabricated sandwich concrete walls have an 80mm outer concrete case with nose and a 150mm inner concrete leaf. The 130mm cavity is filled with Rockwool insulation of R = 4.5 m²K/W.

The floor construction incorporates only 20mm of EPS sound insulation of R = 3.5 m²K/W, which would imply some heat exchange between the adjacent apartments. However, this study will not account for heat exchange between the upper and lower levels. The apartment floors are radiant floors which heat or cool the apartments by making use of a WKO underground storage system.

Type	Material	Rc	U-value	SHGC	VLT	Shading
		[m²K/W]	[W/m²K]	[%]	[%]	
Closed Facade	Stony Cavity Structure	4.5				No
Sliding Door	HR++, alum.		1.58			No
Tilting Window	HR++, alum.		1.21	60 North 35 East 35 South 35 West	≥60	No
Fixed Window	HR++, alum.		1.21			No
Panel	Mineral Wool 60mm, alum.		1.65			No

Table 3.02.02: Thermal Insulation of Facade Elements

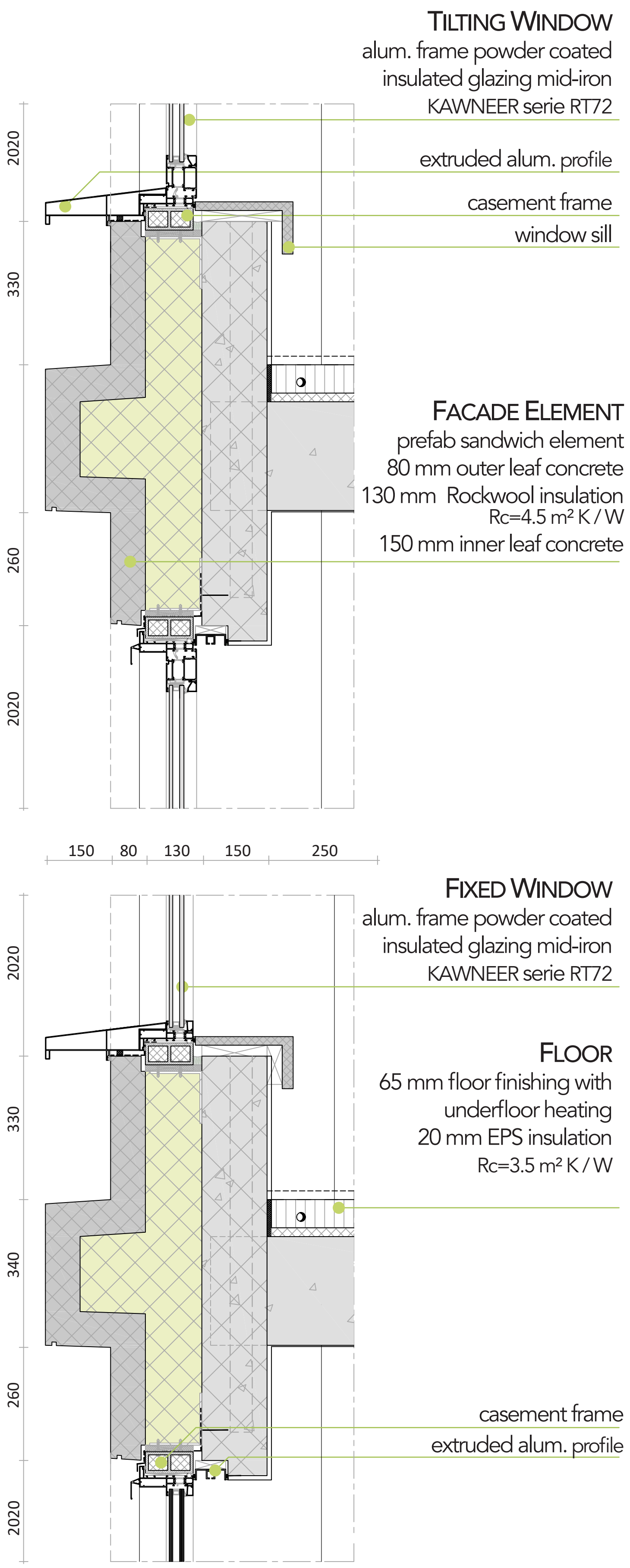


Figure 3.02.03: Facade Detail M1:15
Source: V8 Architects, n.d.

Figure 3.02.04: Brink Renovent Excellent 300
Source: Brink, n.d

PV System	Area	Angle	Orienatation	Obstruction	Power
	[m²]	[°]			[Wp/m²]
PV System 1	108,8	30°	south	minimal	165
PV System 2	132,6	30°	south	85%	165

Table 3.02.03: Energy Generation Area

Electricity Production = 116131MJ = 32252.6 kWh
Ag = 30392.20 m²
Afloor = 746.6 m²

32252.6 kWh/ 30392.20 = 1.061 kWh/m²
*1.061 * 746.6m² = 792.14 kWh/floor*

06 Ventilation

The current state of the high-rise building makes great usage of highly efficient active systems. The apartments are ventilated by means of natural and mechanical air supply and mechanical exhaust, on the basis of energy-efficient DC fans with a heat recovery efficiency of 95% and full bypass (with CO_2 zoning control). For the mechanical ventilation of the apartments, the Brink Renovent Excellent 300 Plus ventilation unit was used, with a maximum ventilation capacity of 166 m³/h.

The air infiltration measured at a pressure difference of 10 Pa is $Q_{v,10}$ = 0.241 dm³/s per m².

07 Heating & Cooling

The apartments are heated by means of radiant floor heating. Hot water is generated through the use of a collective thermal storage system (WKO) with groundwater used as energy buffer. The hot water supply is ensured in combination with external heat supply (Eneco Rotterdam secondary grid) with an energy efficiency of 2.3. The power generation efficiency (COP) of the heat pump lies at 3.95 for heating and 15.0 for cooling.

08 Energy Generating Systems

147 PV panels contribute to the energy production of the building. The panels are placed on a strongly ventilated roof construction at an angle of 30° with a south facing orientation. An area of approximately 1.65 m² has been accounted for each panel, with an energy performance of 270 Wp / panel. Energy generation systems have not been integrated into the facade.

3.03

Overview
Input Information

Before assessing the performance of this case study, it is essential to summarize the information which will serve as input for the simulation workflow.

Weather Data

An overview was provided on the climate of the Netherlands in *Chapter 2.03*. However, the presented data will not be used as weather data input for this study. More detailed values for wind speed and solar irradiation will be used from the hourly weather data of Amsterdam provided on *energyplus.net/weather*. The .epw file includes hourly weather data measured at 10m height. To account for the difference in climatic conditions throughout the year, the provided data will be used to calculate the hourly conditions for specific altitudes.

Ventilation Rates

The Dutch Building Decree stipulates different ventilation rates per function for residential buildings. An overview of the specified ventilation rates is provided in *Table 3.03.04*.

Infiltration Rates

An infiltration rate of 0.241 dm³/s per m² is considered for the rooms exposed to the outdoors, as specified in the Building Physics report of the Cooltoren provided by Wolf+Dikken.

Zone Function	Ventilation Rate	Occupancy	Equipment Loads	Lighting Loads	Infiltration Rates
Kitchen	21.0 *[dm³/s]*	1 Pers. per 20 m²	2975 *[W]*	3 *[W/m²]*	0.241 *[dm³/s] per m²]*
Bedroom	0.09 *[dm³/s] per m²*	1 Pers. per 12 m²	2 *[W/m²]*	3 *[W/m²]*	0.241 *[dm³/s] per m²]*
Bathroom	14.0 *[dm³/s]*	1 Pers. per 10 m²	-	3 *[W/m²]*	-
Toilet	7.0 *[dm³/s]*	1 Pers. per 2 m²	-	3 *[W/m²]*	-
Storage	14.0 *[dm³/s]*	1 Pers. per 3 m²	1245 *[W]*	3 *[W/m²]*	-
Corridor	0.05 *[dm³/s] per m²*	1 Pers. per 10 m²	-	3 *[W/m²]*	-
Core	0.05 *[dm³/s] per m²*	1 Pers. per 40 m²	-	3 *[W/m²]*	-

Table 3.03.04: Internal Loads per Function
Source Ventilation Rates: Bowbesluit, 2012. Article 3.29

Internal Loads

Occupancy

A certain number of people per m² is approximated for each function at peak occupancy as presented in *Table 3.03.04*. *Appendix B* provides an overview of the occupancy schedules assigned per room function.

Equipment Loads

The following equipment loads are specified for the kitchens, bedrooms and storage rooms.

Zone Function	Equipment Loads	
Kitchen	2975	*[W]*
Fridge	160	*[W]*
Dishwasher	14.0	*[W]*
Oven	700	*[W]*
Microwave	1080	*[W]*
Toaster	450	*[W]*
Bedroom	2	*[W/m²]*
Storage	1254	*[W]*
Washing Machine	1020	*[W]*
Dryer	225	*[W]*

Table 3.03.05: Equipment Loads per Function

Lighting Loads

Internal Loads from lighting of 3 W/m² are considered for each room, assuming that efficient LED light bulbs are used.

Shading Setpoint

A shading setpoint of 20W/m² ≈ 2500 lux is considered for the operable shading systems. Dynamic shading will be activated when the total horizontal irradiation exceeds this setpoint. Fixed shading is considered to be always ON.

Shading Materials

The following characteristics were considered for the materials assigned to the different shading systems:

Properties	Interior Blinds	Exterior Louvres	
	Plastic	Wood	PV/T
Reflectance	0.7	0.1	
Transmittance	0.15	0.15	
Emissivity	0.9	0.9	
Thickness	0.001	0.001	
Conductivity	0.03	0.03	
Color			1,1,50
Roughness			0
Specularity			0

Properties	U-value	SHGC	VLT
Electrochromatic Glz (colored state)	1.1 *[W/m²K]*	0.1	10%

Table 3.03.06: Material Properties Shading

Construction Materials

The construction layers are specified as described in *Chapter 3.02*, with a variable insulation value for the exterior walls. The color of the balconies is also assigned.

Properties	Exterior Walls	Balconies
Roughness	medium smooth	
R-value	4.5/6.0 *[m²K/W]*	
Thermal Absorbtion	0.9	
Color		225, 225, 225
Roughness		0
Specularity		0

Table 3.03.07: Material Properties Construction

Energy Generation Systems

PV/T panels are to date the most efficient energy generating systems. Depending on the WWR and the applied shading system, PV/T panels are integrated differently onto the facade construction. If the glazing ratio is 35%, standard 1m wide PV/T panels with 6 rows of PV cells can fit on the wall area in between the windows. In case of 50% ratio only 4 rows of PV cells can fit between the windows. If the ratio is higher than 50% no PV/T systems can fit on the walls any more. Therefore, PV/T tubes developed Naked Energy will be placed in front of some windows to generate energy while providing some shade, without blocking the view. A thermal efficiency of 60%, respectively 20% electric efficiency is assumed, as stipulated by the manufacturer *(Naked Energy n.d.)*.

Energy Generation Systems	WWR 35%	50%	65%	80%
PV/T Facade	✓	✓		
Electric Efficiency	20%	20%		
Thermal Efficiency	60%	60%		
PV/T Louvres			✓	✓
Electric Efficiency			20%	20%
Thermal Efficiency			60%	60%
BIPV Balconies	✓	✓	✓	✓
Electric Efficiency	20%	20%	20%	20%

Table 3.03.08: Energy Generation Systems

Comfort Input Conditions

In order to assess the average annual indoor comfort conditions, it is assumed that the occupants have an indoor clothing level of 1.0 clo, which is roughly the insulation provided by a 3-piece outfit. A metabolic rate of 1.2 met is considered, which is equivalent for a standing person at rest.

Natural Ventilation Specifications

The degree of natural ventilation is related to the operable glazing fraction and the wind speed. For this study, natural ventilation is induced either through tilting windows or fully openable windows used in combination with vertical vegetation or perforated panels. An operable glazing fraction of 0.25 is considered for tilting windows, respectively 1 for a fully openable window and the balcony doors.

Active Systems Specifications

The current active systems are considered for the optimization - radiant floors for heating and cooling and mechanical ventilation with 95% heat recovery. H/C through radiant floors works in combination with a WKO (Heat and Cold Storage) for which the following performance coefficients apply:

	Heating	Cooling
COP	3.95	15.0

Table 5.04.08: COP Heating & Cooling
Source: NEN 7120 C2/A1, 2017

Hot Water

In order to calculate the hot water consumption, a total number of 17 people per floor is assumed, in accordance to the type of apartments planned. The COP for hot water is 3.95.

Heating, Cooling & Ventilation Setpoints

Taking into consideration the temperature ranges suggested by the benchmarks, the following setpoints will be used for heating, cooling, mechanical and natural ventilation, to ensure a comfortable indoor environment. H/C and Ventilation will be activated only when the room is occupied and the temperature setpoints are met. The temperature conditions under which H/C, respectively MV and NV are active, can be visualized in the following diagram:

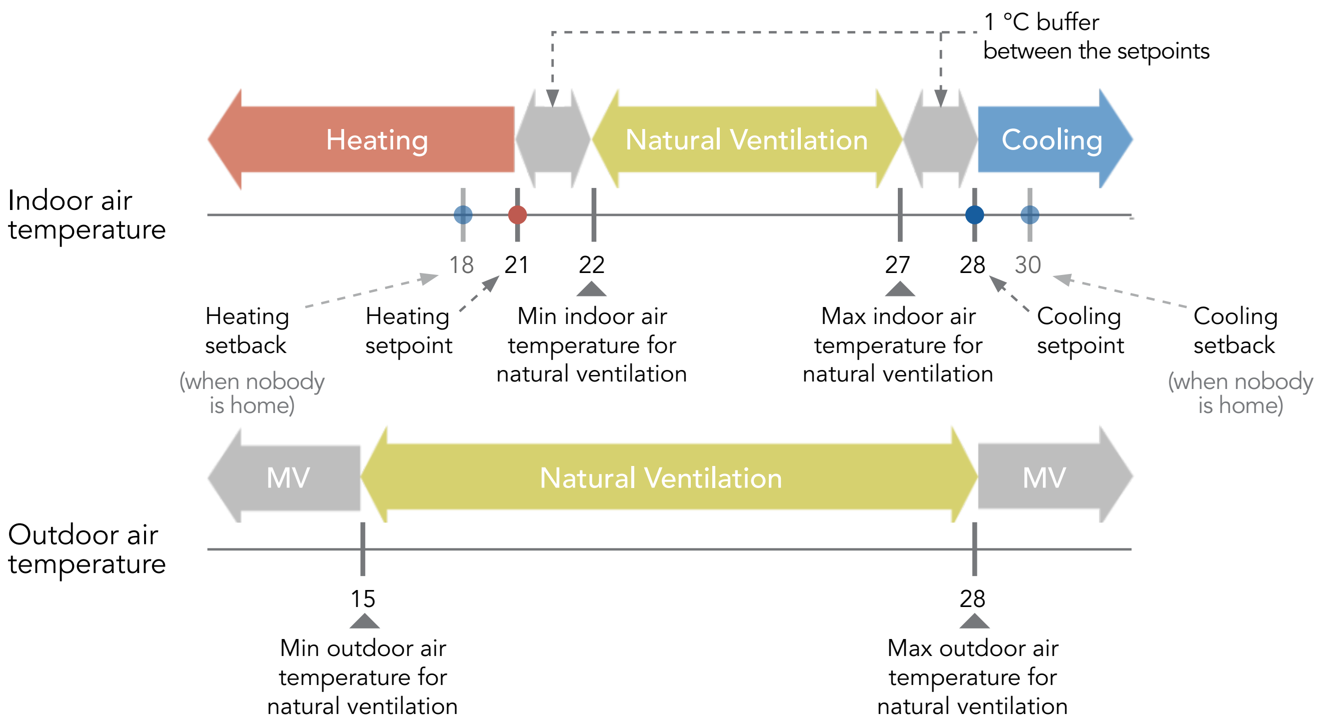


Figure 3.03.01: H/C, MV & NV Setpoints
Source: Zhang, 16 Sep 2016

Input Information

Weather Data
.epw NLD_Amsterdam

Ventilation Rates
* different for each room function acc. to Bouwbesluit
(Table 3.03.04)

Internal Loads
* different for each room function
Persons per Function (Table 3.03.04)
Equipment Loads per Function (Table 3.03.05)
Lighting Loads per Function (Table 3.03.04)

Infiltration Rate
* acc. to Building Physics Report for Cooltoren by Wolf+Dikken
0.241 [dm^3/s per m^2]

Shading Setpoint
* ON if horiz. solar irradiation exeeds setpoint
Control Setpoint = 20 [W/m^2] ≈ 2500 lux

Nat. Vent. Specifications
Operable Glazing Fraction
Sliding Balcony Doors = 1
Tilting Windows = 0.25
Openable Window 1m wide + Veg. = 1
Openable Window 1m wide + Perf. Panel = 1

Nat. Vent. Setpoints
Min. Outside Temp. = 15 °C
Max. Outside Temp. = 28 °C
Min. Indoor Temp. = 22 °C
Max. Indoor Temp. = 27 °C
Max Wind Speed = 7m/s °C

Hot Water Consumption
Total Nr. of Pers/Floor = 17
COP Hot Water = 3.95

H/C & MV Specifications
COP Heating Radiant Floors = 3.95
COP Cooling Radiant Floors = 15
* Mech. Vent. controlled on demand acc. to occupancy
Max. Ventilation Capacity = 166 m^3/h
Heat Recovery = 95%

H/C & MV Setpoints
Heating Setpoint 1 = 21 °C
(Kitchens, Bedrooms, Bathrooms)
Heating Setpoint 2 = 20 °C
(Toilets, Storages, Corridors, Core)
Heating Setback = 18 °C
Cooling Setpoint = 28 °C
Cooling Setback = 30 °C

Materials
Shading Materials (Table 3.03.06)
* different for each shading
Construction Materials (Table 3.03.07)

Energy Generation
PV/T Facade/Louvres
Thermal Efficiency = 60%
Electric Efficiency = 20%
Coverage = 95%

BIPV Balconies
Electric Efficiency = 20%
Coverage = 80%

Comfort Input Conditions
Clothing Level = 1.0 clo
Metabolic rate = 1.2 met

04

Simulation

4.01

Introduction

Residential high-rise buildings have gained more and more popularity in the last decades. In Rotterdam alone, there are 4 apartment towers which are going to be built by 2021, ranging from 110m to 212m in height - The Terraced Tower (2019), Baan Toren (2019), The Sax Tower (2020), Zalmhaven Tower (2021). Given the future *BENG* energy regulations, which are going to be applied for all new buildings in the Netherlands, it is essential to estimate the energy performance of the building and the indoor comfort conditions from an early design stage, in order to provide good living conditions for the occupants.

Simulating the behavior of a high-rise building is more complex than a low-rise one, considering the fact that this typology is subjected to different microclimate conditions which change gradually with height - slightly lower temperatures, direct solar irradiation and most importantly, increased wind pressures which can lead to higher infiltration rates through the building envelope.

These changing environmental factors are usually not taken into account and the performance of high-rises is assessed by simulating just one middle floor, where average values are considered for climatic influential factors. This is because of the long simulation time required to assess the energy performance at different levels.

However, making design decisions based on just one middle floor could lead to an unrealistic overall performance and an unpleasant indoor environment at higher levels. This study will analyze the difference in energy performance, daylight and thermal comfort at two floor levels, at 25m and at 130m height. The two floors are identical in terms of layout so that the results can be compared in the end.

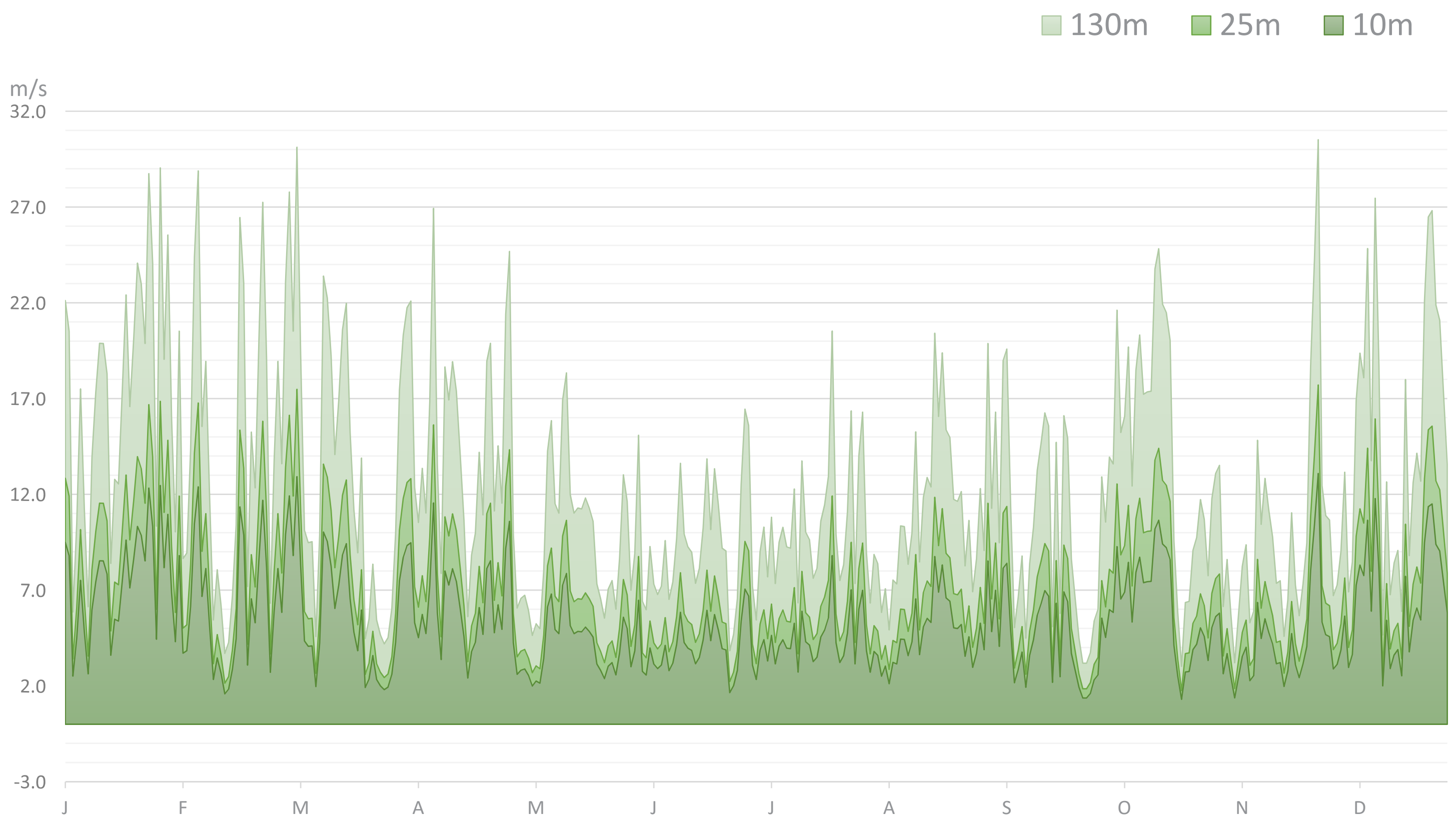


Figure 4.01.01: Wind speed with altitude

4.02

Workflow

The building was reconstructed in Rhino while making use of the floor plans and sections provided by V8 Architects. The 8th floor and the 44th floor, located at 25m, respectively 130m were chosen for the analysis.

The energy performance and indoor conditions were assessed and compared at these two levels by undergoing a multizone optimization using Grasshopper. The plug-ins Honeybee, & Ladybug were used for the energy and thermal comfort simulation while Radiance & Daysim were used for the daylight analysis. Last but not least, Colibri Iterator was used to run all the possible combinations of parameters and turn the results into Design Explorer comparable data sets.

This chapter offers a detailed description of the simulation workflow in Grasshopper and some preliminary analysis which was carried out throughout the process in order to limit the variables depending on their influence on the results. The results of the optimization process with Colibri will be discussed in *Chapter 5*.

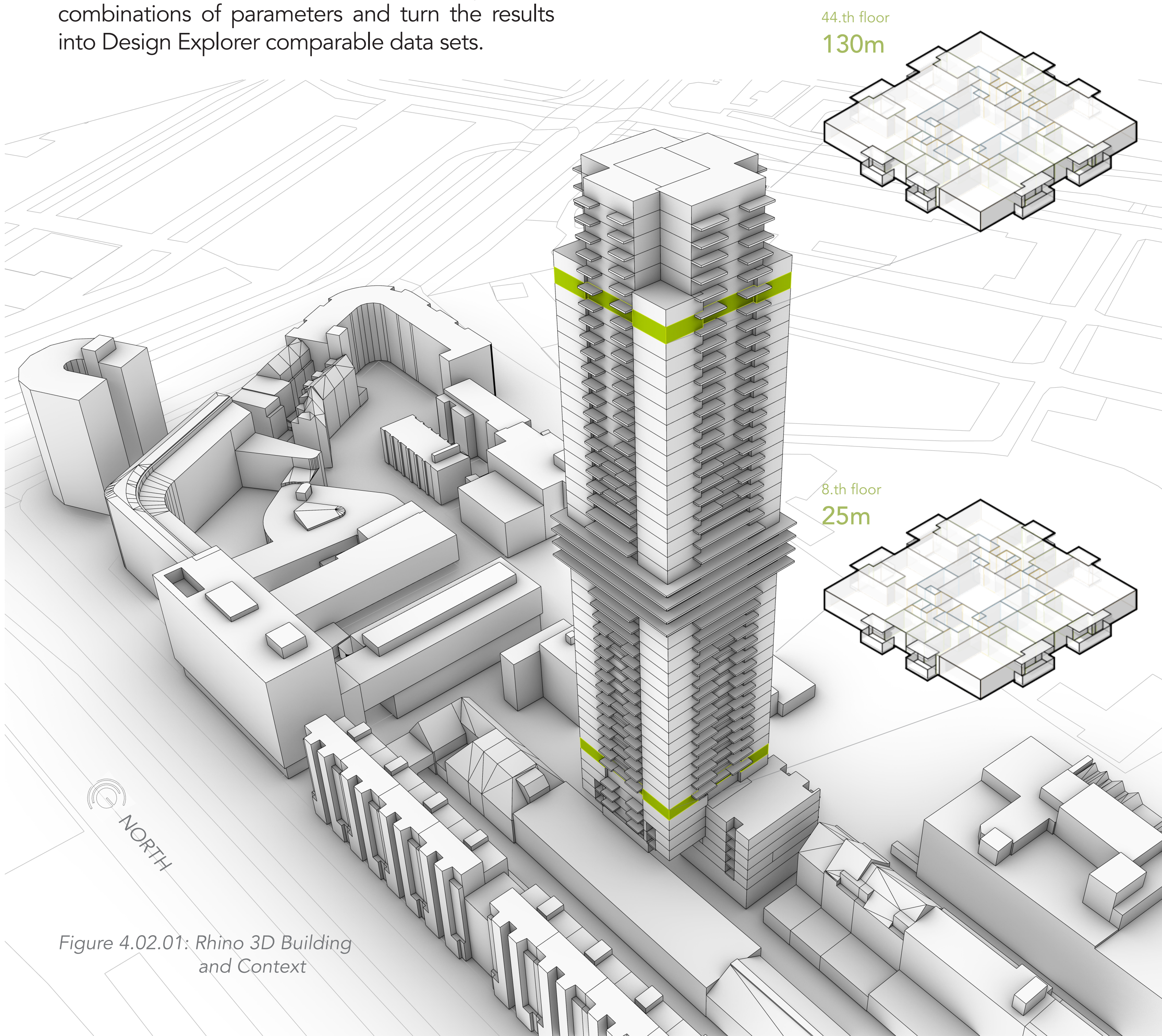


Figure 4.02.01: Rhino 3D Building and Context

4.02.01
GEOMETRY

Residential buildings involve a substantial amount of detail when it comes to the energy performance assessment. Each apartment consists of multiple rooms with different functions, which need to be differentiated in simulation programs, as they require different ventilation rates and present different internal heat loads.

The simulated building has an almost rectangular floor plan shape of 27.3x27.3m. The floors are 2.95m high with a clear apartment height of 2.6m. The balconies are a characteristic add-on for residential buildings, which will add a certain level of complexity to the simulation.

The geometry which lies at the basis of the workflow is a set of 44 boxes which represent the total number of rooms per floor. The rooms were constructed as simple boxes in Rhino and converted into 'Zones' with Honeybee. In order to be able to identify the zones in a later stage of the simulation the rooms were labeled with the corresponding 'function_apartment number', for example 'kitchen_1'.

All Zones were assigned the same 'Midrise Apartment' Building Program. The different functions were then differentiated by applying the appropriate internal heat loads, ventilation rates and heating/cooling system specific for each function.

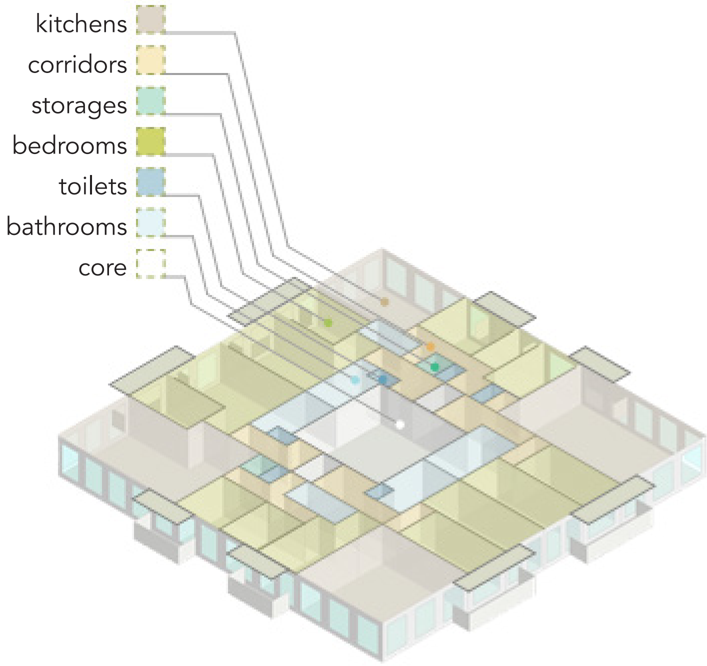
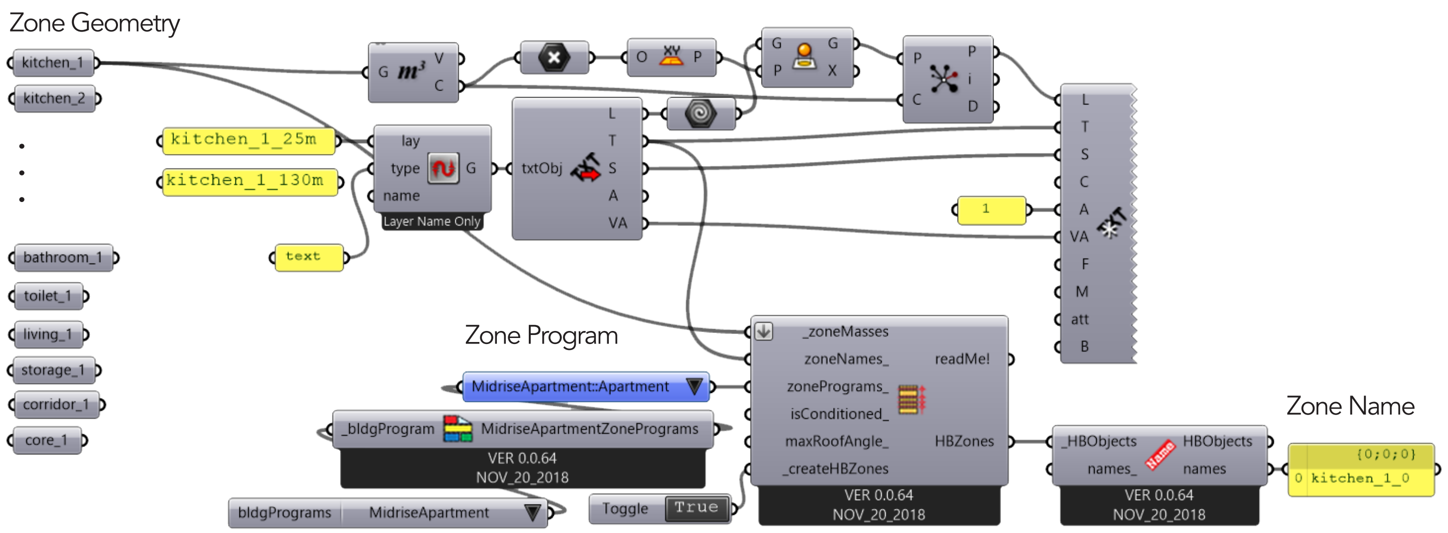


Figure 4.02.02: Floor Zones Rhino

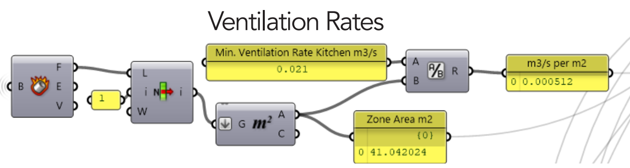
Room		Ventilation Rate
Kitchen/Living Room	[dm³/s]	21.0
Bedroom	[dm³/s] per m²	0.09
Bathroom	[dm³/s]	14.0
Toilet	[dm³/s]	7.0
Storage	[dm³/s]	14.0
Corridor	[dm³/s] per m²	0.05
Core	[dm³/s] per m²	0.05

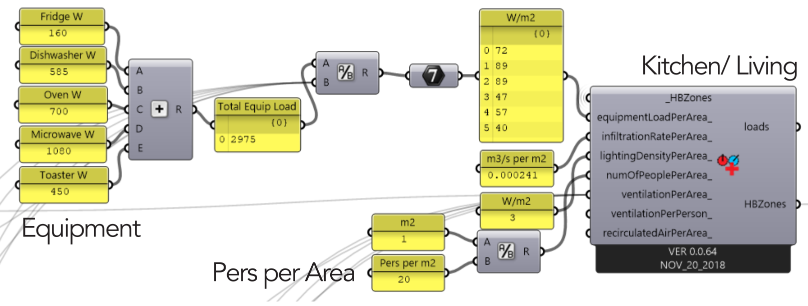
Table 4.02.01: Required Ventilation Rates
Source: Bowbesluit, 2012. Article 3.29 & 3.32



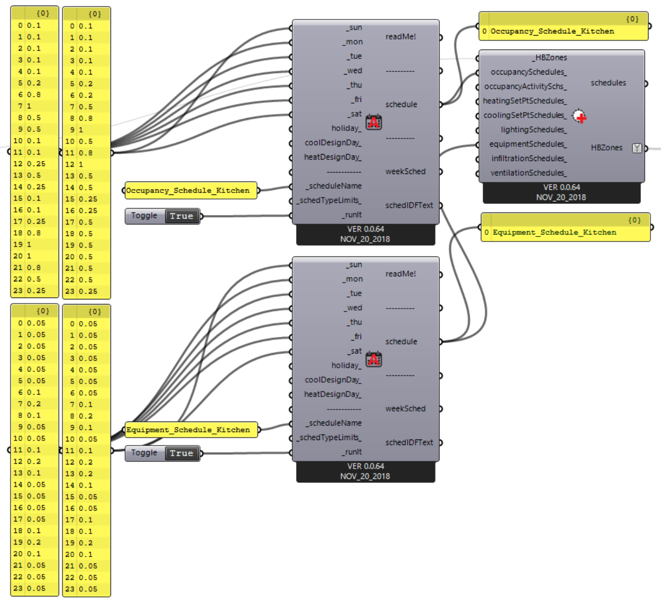
Zone Function	Ventilation Rates		Lighting Loads [W/m²]	Infiltration Rates [dm³/s] per m²
Kitchen	21.0	[dm³/s]	3	0.241
Bedroom	0.09	[dm³/s] per m²	3	0.241
Bathroom	14.0	[dm³/s]	3	-
Toilet	7.0	[dm³/s]	3	-
Storage	14.0	[dm³/s]	3	-
Corridor	0.05	[dm³/s] per m²	3	-
Core	0.05	[dm³/s] per m²	3	-

Table 4.02.02: Internal Loads per Function
Source Ventilation Rates: Bowbesluit, 2012. Art. 3.29, 3.32





Occupancy and Equioment Schedule Kitchen



Zone Function	Occupancy	Equipment Loads
Kitchen	1 Pers. per 20 m²	2975 [W]
Bedroom	1 Pers. per 12 m²	2 [W/m²]
Bathroom	1 Pers. per 10 m²	-
Toilet	1 Pers. per 2 m²	-
Storage	1 Pers. per 3 m²	1245 [W]
Corridor	1 Pers. per 10 m²	-
Core	1 Pers. per 40 m²	-

Table 4.02.03: Internal Loads per Function
Source Ventilation Rates: Bowbesluit, 2012. Article 3.29

4.02.02
INTERNAL LOADS

The minimum required ventilation rates per function were derived from the Dutch building decree, *Bouwbesluit*. The minimum ventilation rates which were assigned for each zone function are summarized in *Table 4.02.02*.

4.02.02
SCHEDULES

Depending on the area of each zone and the type of function, the maximum number of people per zone was estimated. For example, if we look at the current floor plan, a kitchen/ living area of 20 m² could be estimated for 1 person. This would imply that in a three-person apartment with a kitchen/ living area of 60 m², 3 persons would be present at full occupancy. *Table 4.02.03* provides an overview of the estimated number of persons per area for each function.

A customized week and weekend schedule were created for each room function, taking into consideration a normal working schedule, where just 1 person stays at home during the day. The occupancy values range from 0 to 1, where 1 means that the room is fully occupied at that specific hour of the day and 0 means no occupancy.

The most occupied rooms are the kitchens/living rooms and the bedrooms, the kitchens/ living rooms mainly mornings and evenings and the bedrooms during the night. The bathrooms, toilets, storages and corridors are occupied only for a short period of time. *Appendix B* includes the hourly occupancy rates for each function, which can be visualized also in the following Figures.

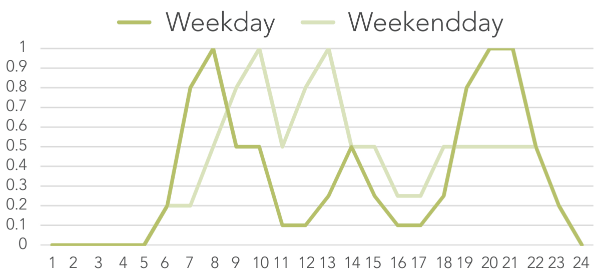


Figure 4.02.03: Occupancy Kitchens

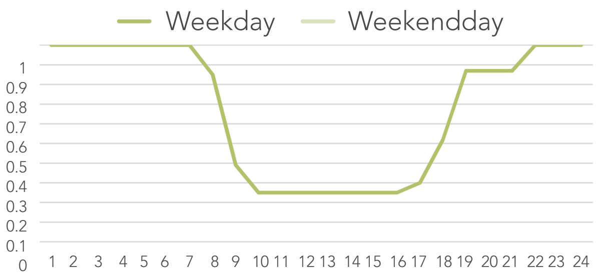


Figure 4.02.04: Occupancy Kitchens

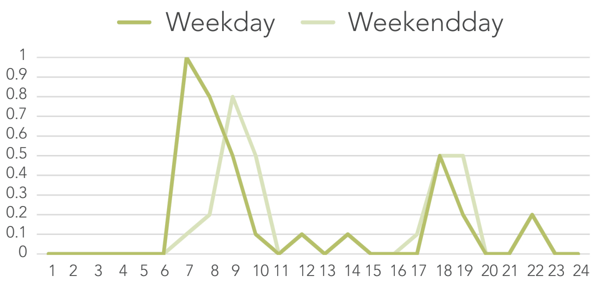


Figure 4.02.05: Occupancy Kitchens

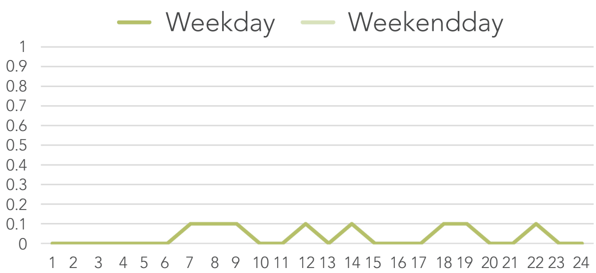


Figure 4.02.06: Occupancy Kitchens

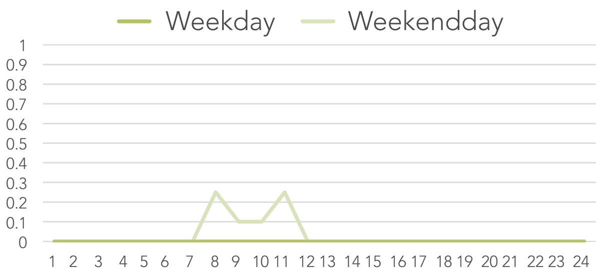
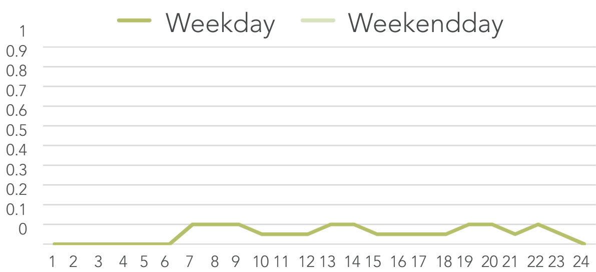


Figure 4.02.07: Occupancy Kitchens



A customized schedule was created also for the kitchen equipment and the washing machine in the storage rooms. A value of 1 means that the equipment is used one full hour, 0.2 that it is used 12min/h and 0 that equipment is not being used.

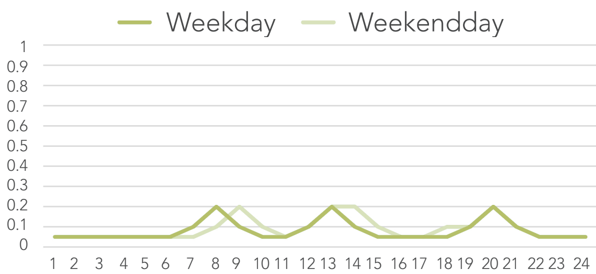


Figure 4.02.08: Occupancy Kitchens

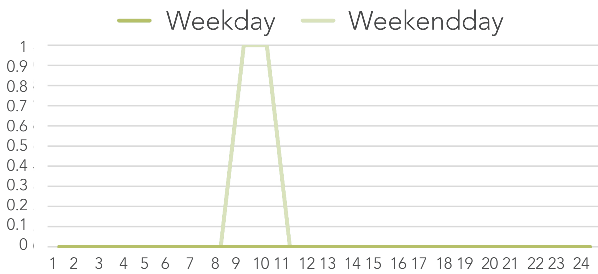
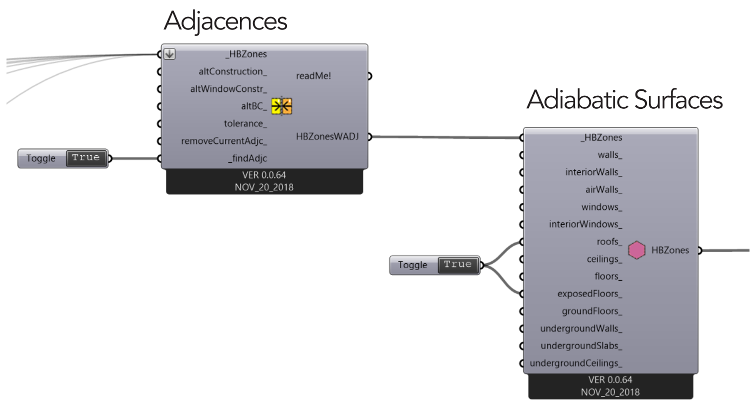
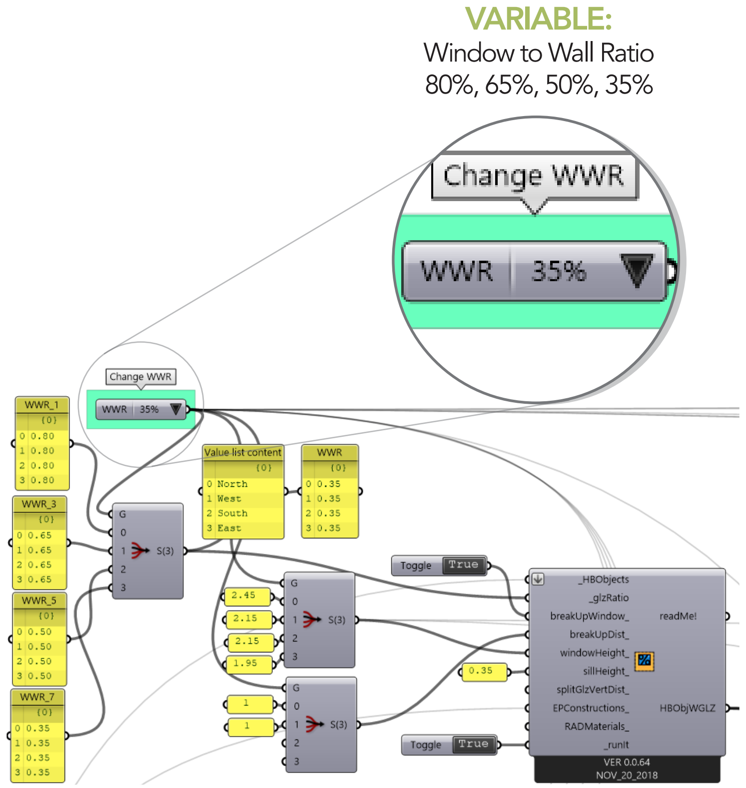


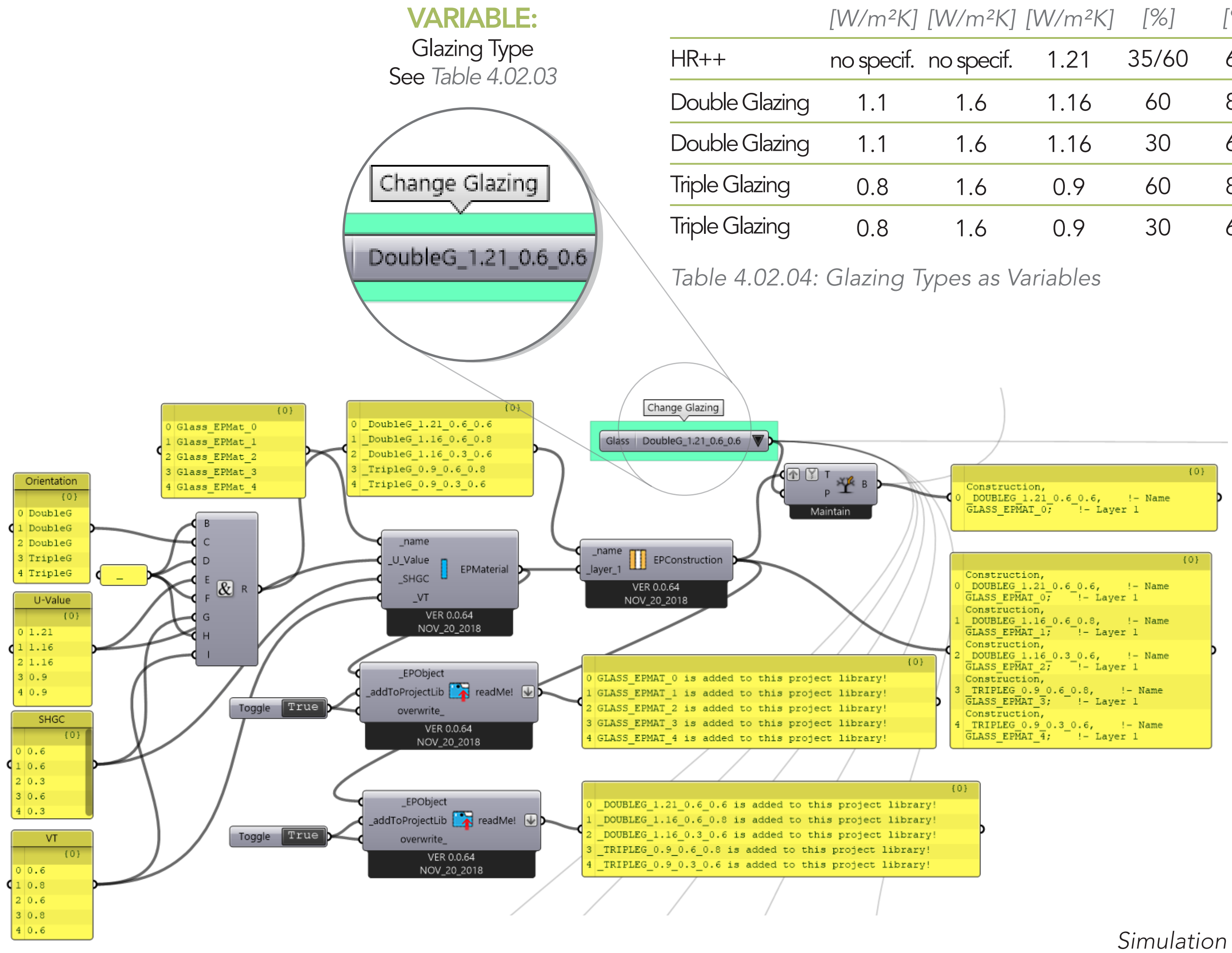
Figure 4.02.09: Occupancy Kitchens

5.02.04
Geometry Surfaces

By solving the zone adjacencies, the program identifies each surface type, making the difference between exterior walls, interior walls, floors and ceiling. This study will account for heat flows only between adjacent rooms situated at the same level and will not take into consideration heat exchange between different floors. Therefore, the floor and ceiling surfaces will be set as adiabatic.







4.02.05
WWR & Glazing Type

Windows will be assigned to the exterior wall surfaces based on the window to wall ratio and the glazing properties. The current design of the Cooltoren building presents a glazing ratio of 65% including HRR++ windows with the glazing properties presented in *Table 4.02.04*.

Four other types of standard double and triple glazing with aluminum window frames were considered as potential design solutions. The following glazing types were chosen, because they are frequently applied in the building sector. The reason behind this lies in the low U-value, balanced SHGC and the high VLT. The presented U-values are equivalent to the frame+glass assembly and were calculated with *Formula [10]* presented in *Chapter 2*.

Glazing Type	Uglass	Uframe	Utot	SHGC	VLT
	[W/m²K]	[W/m²K]	[W/m²K]	[%]	[%]
HR++	no specif.	no specif.	1.21	35/60	60
Double Glazing	1.1	1.6	1.16	60	80
Double Glazing	1.1	1.6	1.16	30	60
Triple Glazing	0.8	1.6	0.9	60	80
Triple Glazing	0.8	1.6	0.9	30	60

Table 4.02.04: Glazing Types as Variables

Preliminary Analysis

Impact of the WWR on the Energy Performanece

In order to define the most influential glazing ratios, a preliminary analysis was carried out and the impact on the energy performance and daylight was examined. The following glazing ratios were simulated: 35%, 45%, 50%, 55%, 65%, 75%, 80%. The impact of these ratios was assessed in combination with the following parameter combination, which resembles the current situation of the design:

Parameter	Type
WWR	35%, 45%, 50%, 55%, 65%, 75%, 80%
Glazing Type	U-value=1.21W/m²K, SHGC=60%, VLT=60%
Insulation	Rc = 4.5 m²K/W
Shading	None

Table 4.02.05: Current Design Parameters

As can be noticed on the graphs, there is a small improvement between the different glazing ratios. Based on the impact of the different glazing ratios on the overall performance, a difference of 5%-10% between values was considered to be too small in order to have a significant impact on the results.

Taking into consideration previous literature studies, glazing ratios of 30-40% have proven to be the most effective in terms of energy performance, whereas ratios of 70% would provide a better visual comfort for the occupants *(Raji, Tenpierik, and van den Dobbelsteen, 2017; Goia et al., 2013; Ochoa et al., 2012)*. The results of the preliminary analysis suggest the same. Using lower glazing ratios is the most effective way if no other parameters are taken into account. However, the indoor climate can be balanced also with high performance glazing and shading elements, while keeping the glazing ratios high in order to provide enough daylight.

For the purpose of this study, glazing ratios of 35%, 50%, 65% and 80% were selected to analyze their impact on the overall energy performance, daylight and thermal comfort conditions. These values will serve as future WWR variables for the optimization process with Colibri.

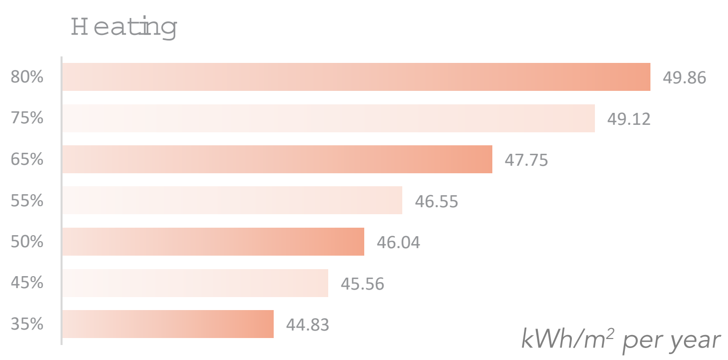


Figure 4.02.10: Heating Load for different WWRs

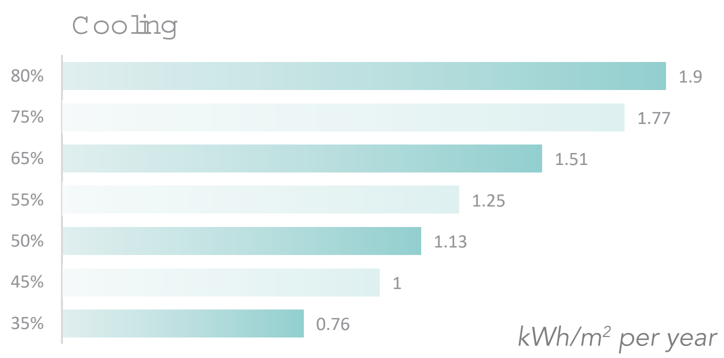


Figure 4.02.11: Cooling Load for different WWRs

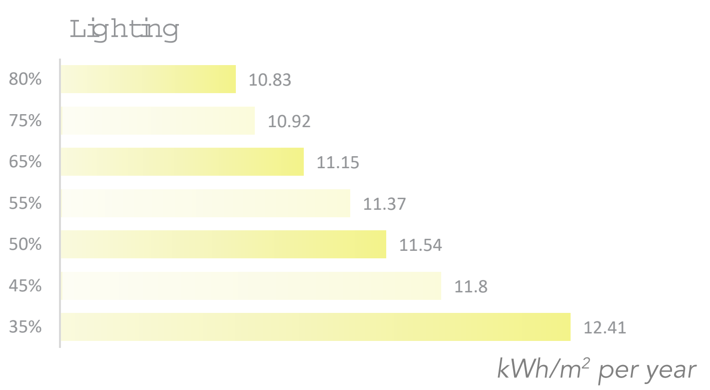


Figure 4.02.12: Electric Lighting Load for different WWRs

4.02.06

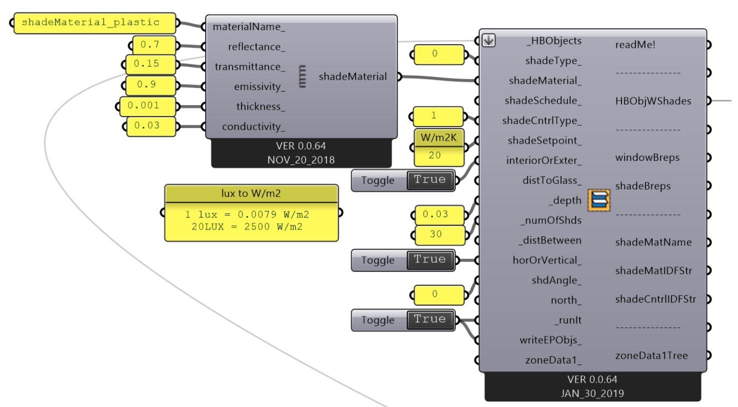
Shading Elements

Looking at precedent residential high-rises it becomes evident that certain shading elements are more frequently encountered. Interior blinds are most commonly used, although exterior shadings have proven to be far more effective. On high-rises, exterior shading elements are rarely applied because they are subjected to rough climate conditions and require a high degree of maintenance, which is very difficult at such high altitudes. The current design includes no pre-mounted shading elements. However, a mounting slot is provided for curtains.

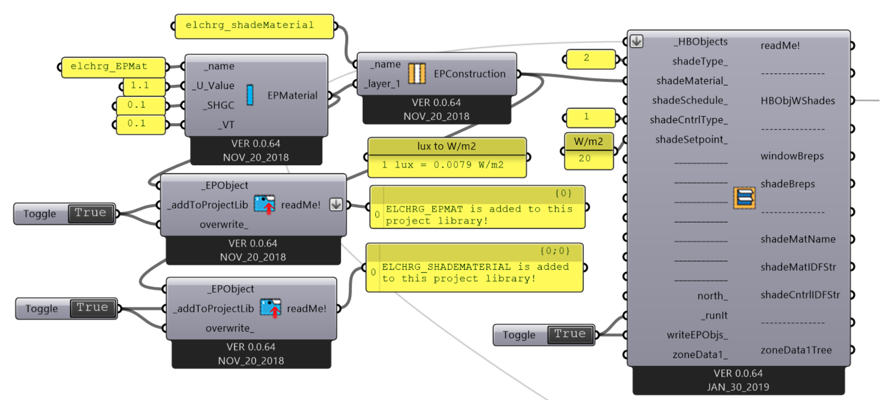
For the purpose of this study, four shading possibilities will be considered - no shading, interior blinds, electrochromic glazing and also exterior shading. Electrochromic glazing is becoming more and more poplar, due to the ability of the glazing to react to sunlight. Exterior Louvres were considered for 35% and 50% WWR while PV/T solar tubes mounted in front of the glazing will serve as exterior shading elements for 65% and 80% WWRs.

The shading will be activated if the total horizontal solar irradiance exceeds a shading set point of 20W/m² ≈ 2500 lux. However, it is important to mention that the shading will be activated completely, partially or not activated at all, so that the minimum illumination threshold is always reached.

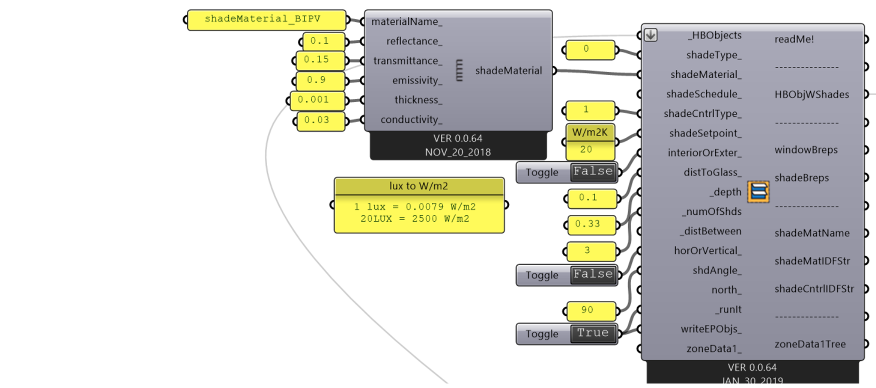
Interior Blinds



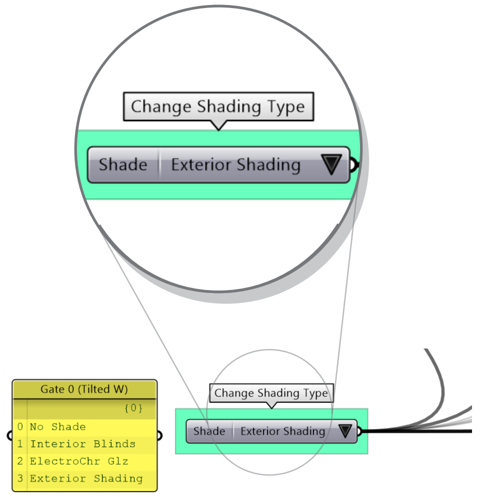
Electrochromatic Glazing



Exterior Shading



VARIABLE:
Type of Shading
1-None, 2-Interior Blinds,
3-Electrochr. Glazing, 4-Exterior Shading



WWR

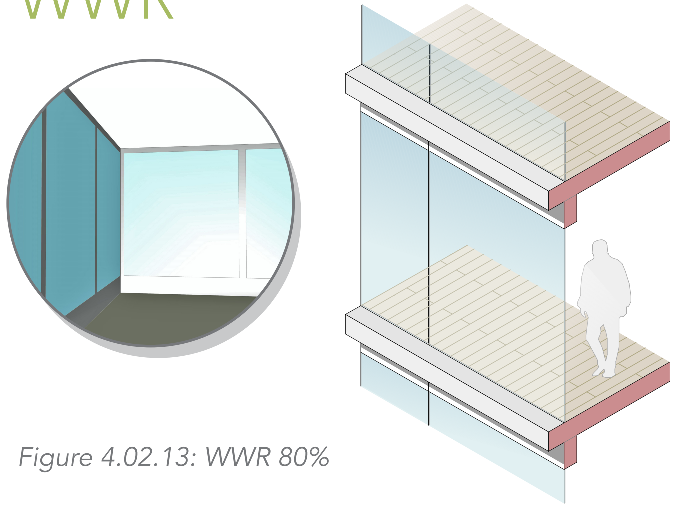


Figure 4.02.13: WWR 80%

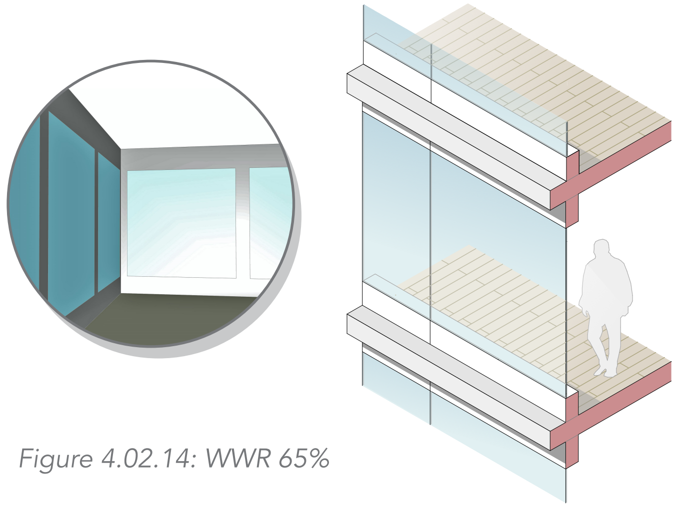


Figure 4.02.14: WWR 65%

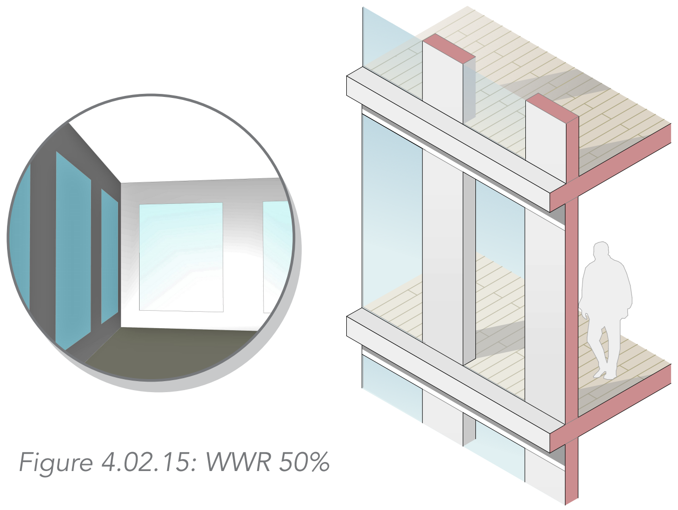


Figure 4.02.15: WWR 50%

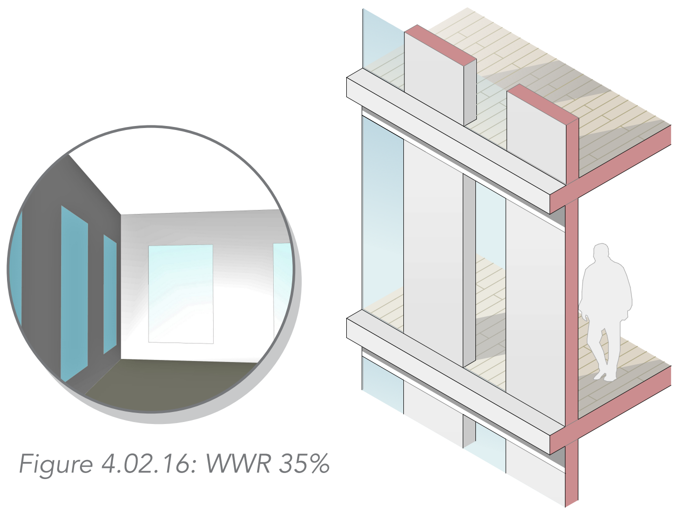


Figure 4.02.16: WWR 35%

Shading

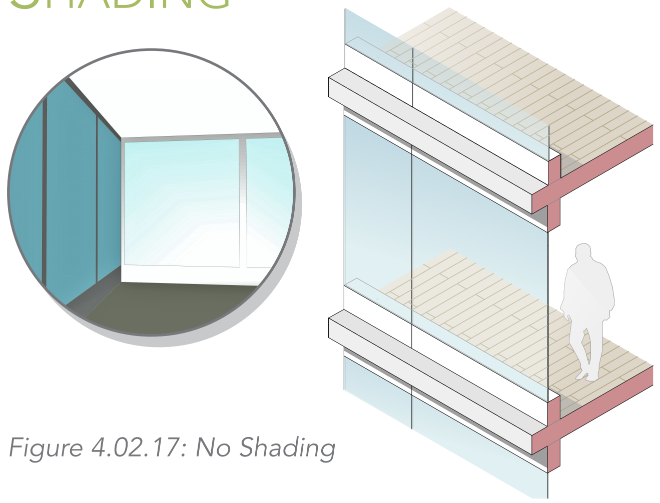


Figure 4.02.17: No Shading

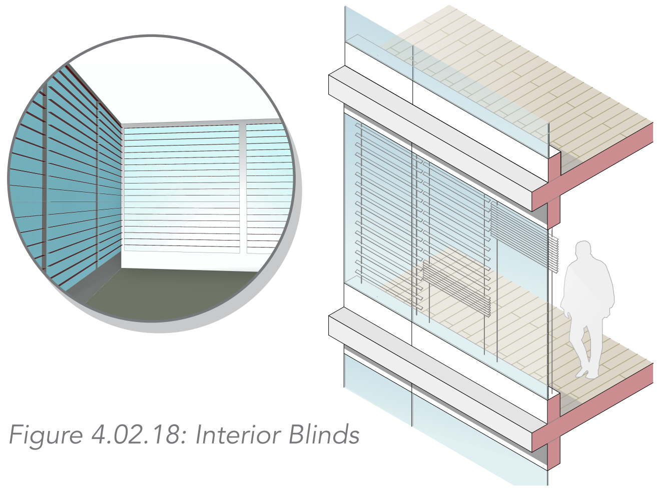


Figure 4.02.18: Interior Blinds

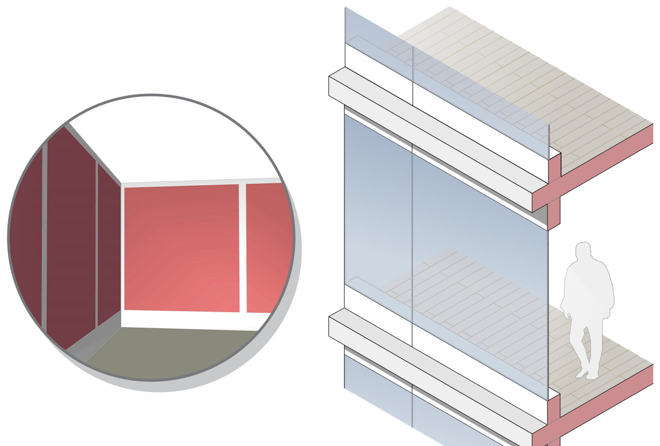


Figure 4.02.19: Electrochromatic Glazing

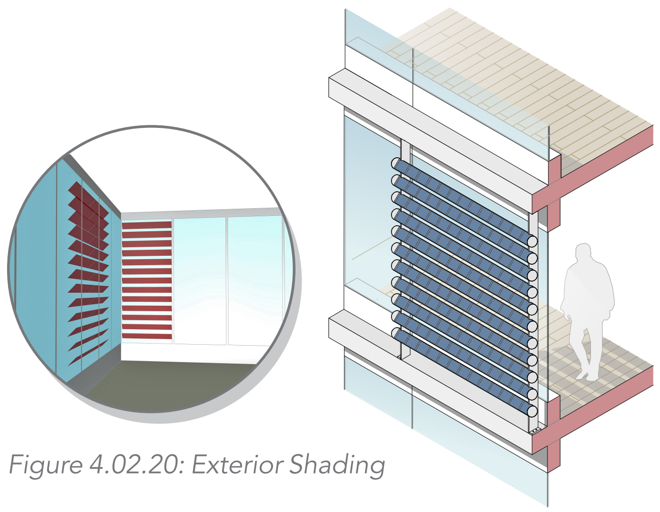


Figure 4.02.20: Exterior Shading

Energy Production

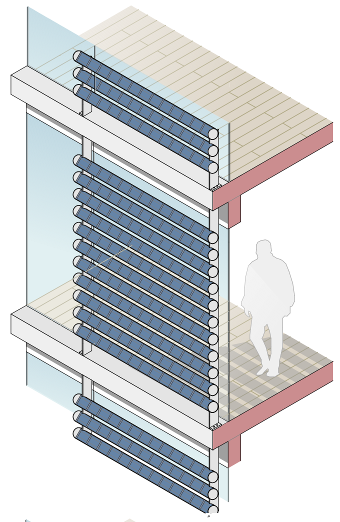


Figure 4.02.21: PV/T WWR 80%, WWR 65%

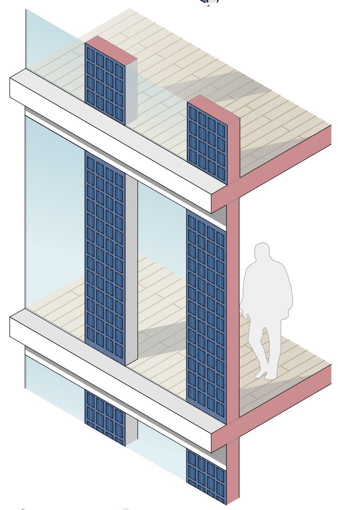


Figure 4.02.22: PV/T WWR 50%

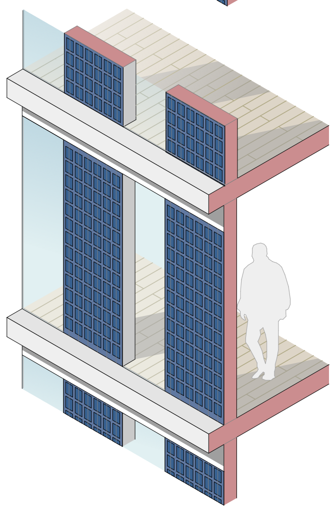


Figure 4.02.23: PV/T WWR 35%

4.02.07

Energy Production

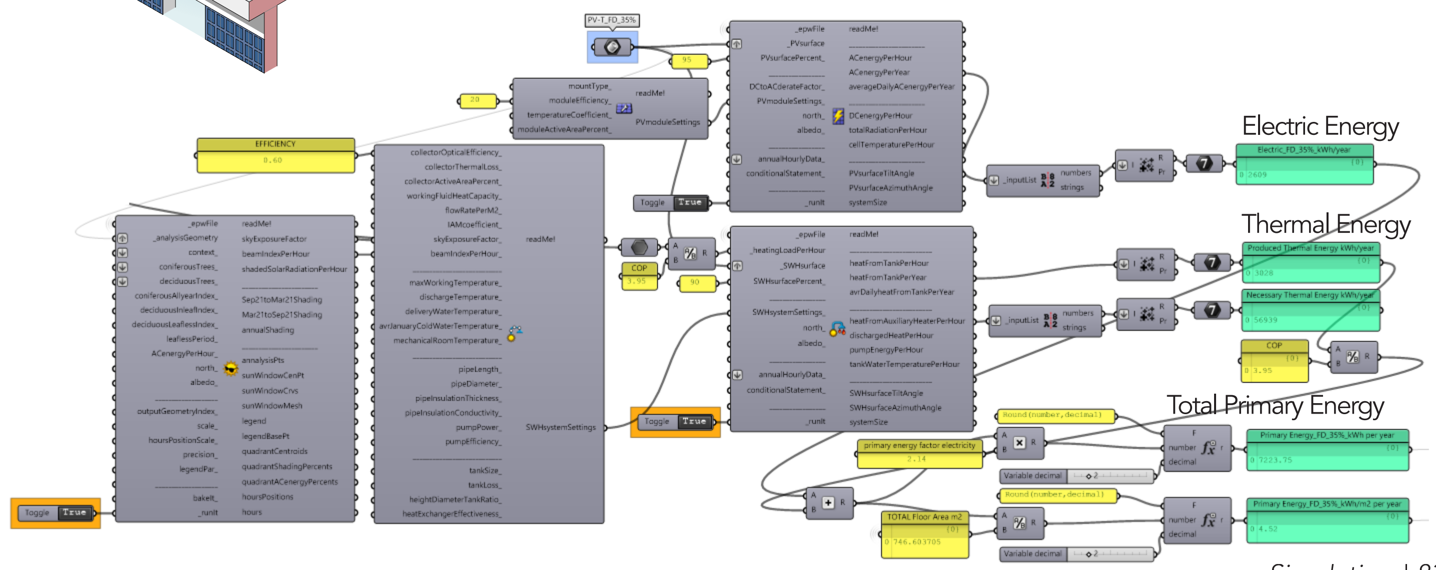
In order to maximize the energy production on the facade, PV-Thermal panels were considered for the simulation, with an electric efficiency of 20%, respectively 60% thermal efficiency. The overall efficiency of the PV/T system is 80% with 20% of the solar energy being radiated back.

The area available for energy production depends on the WWR and the selected shading system. If the WWR is 35%, the wall area between each window can be filled with standard 99cm wide PV/T panels with 6 rows of PV cells. If the ratio is 50%, 67cm wide PV/T panels with 4 rows of cells can fit between the windows. For WWRs higher than 50%, the distance between the windows is too small for PV panels to be placed on the facade wall. In this case, PV/T solar tubes by Naked Energy will be mounted in front of the glazing area, while still allowing for some indirect sunlight.

WWR	Area PV/T	Electric Efficiency	Thermal Efficiency
35%	95% x 40 $[m^2]$	20%	60%
50%	95% x 29 $[m^2]$	20%	60%
65%	95% x 43 $[m^2]$	20%	60%
80%	95% x 43 $[m^2]$	20%	60%

Table 4.02.05: Area available for PV/T depending on the WWR

In order to calculate the total primary energy produced on the facade, the thermal energy is divided by the COP of the floor heating system, 3.95. Both electric and thermal energy are then multiplied by the primary energy factor for electricity, 2.14, in accordance with *NEN 7120 C2/A1 (2017)*. The sum represents the total primary energy production in kWh per year.



4.02.08

Natural Ventilation

For this study, three different scenarios are taken into consideration to induce natural ventilation. The first scenario is the current situation, where air can enter the rooms through tilting windows and sliding balcony doors. However, the number of hours when natural ventilation is admissible is limited by the high wind speeds which dominate especially at 130m. As already mentioned in *Chapter 2*, Green Facades have proved to reduce incoming wind speeds up to 50%, if the vegetation layer is mounted at 20cm distance from the facade *(McPherson et al.,1988)*. This is why, in the second scenario, natural ventilation is induced through 1m wide fully openable windows used in combination with vertical greening. Thus, the incoming air velocity can be reduced, allowing for more hours of natural ventilation.

Last but not least, in the third scenario, the effect of a perforated screen in front of a 1m wide fully openable window will be assessed. Perforated metal panels mounted at the facade, are a frequently encountered design strategy for high-rises to lower the speed of the incoming air. According to *Heisler and DeWalle (1988)*, artificial wind barriers with a porosity of roughly 70%, can reduce wind speeds up to 25%. This is just a rough assumption to assess the behavior of perforated screens as facade elements. However, in order to minimize the air velocity as much as possible, it would be necessary to assess the most optimal opening diameter of the perforations, the distance between them and the porosity percentage more in detail. As this is not the scope of this study, a wind speed reduction of 25% was assumed for the simulation.

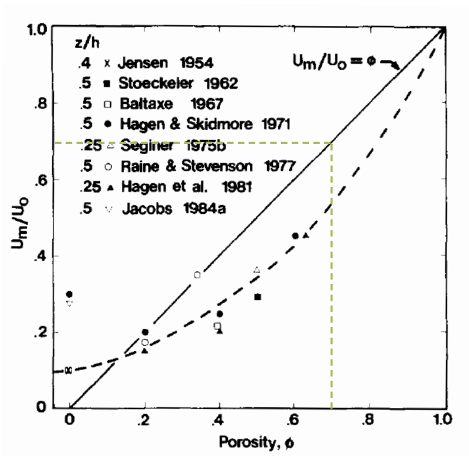


Figure 4.02.24: Minimum relative windspeed Um/Uo versus porosity Ø for artificial barriers. The dashed curve is a visually estimated average.
Source: Heisler and DeWalle (1988)

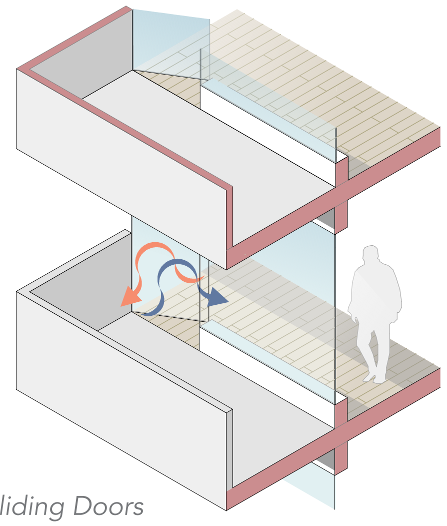


Figure 4.02.25: Sliding Doors

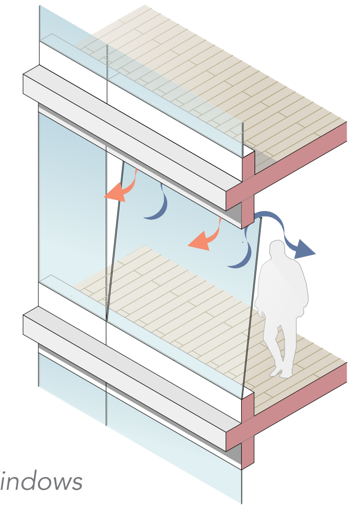


Figure 4.02.26: Tilting Windows

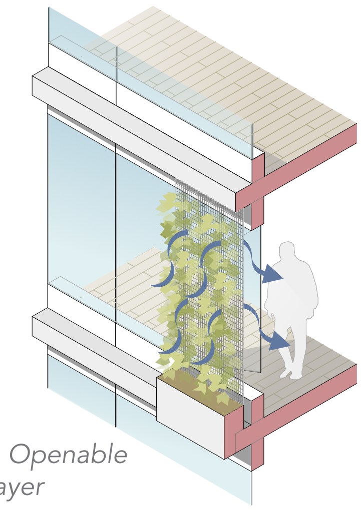


Figure 4.02.27: 1m wide Openable Window + Vegetation Layer

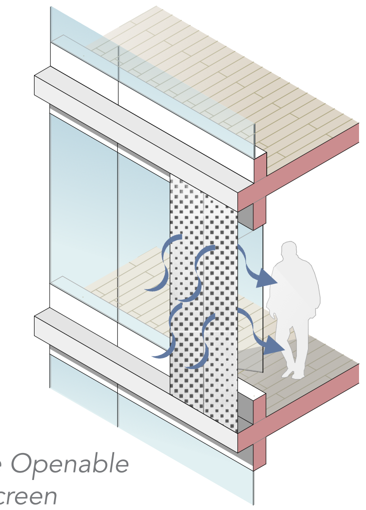


Figure 4.02.28: 1m wide Openable Window + Perforated Screen

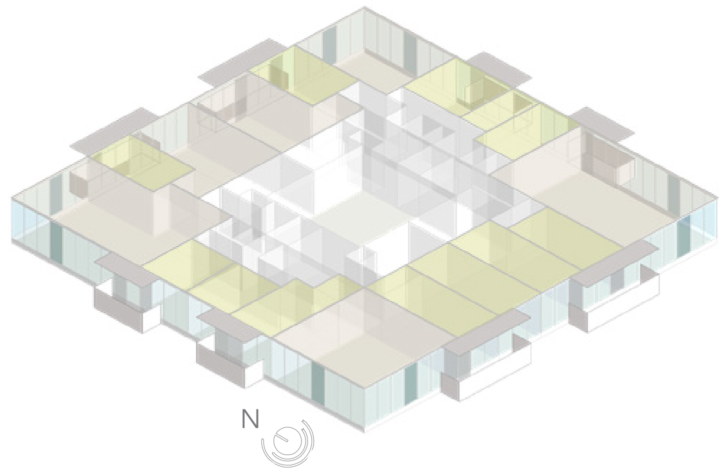


Figure 4.02.29: Location Balcony Doors and Tilting Windows

NV Strategy	Glazing Area	Fraction of Glz Area Operable
Tilting Windows	1 *[m]* Width x Glz Height*	0.25
Openable Window + Vegetation Layer	1 *[m]* Width x Glz Height*	1
Openable Window + Perforated Screen	1 *[m]* Width x Glz Height*	1

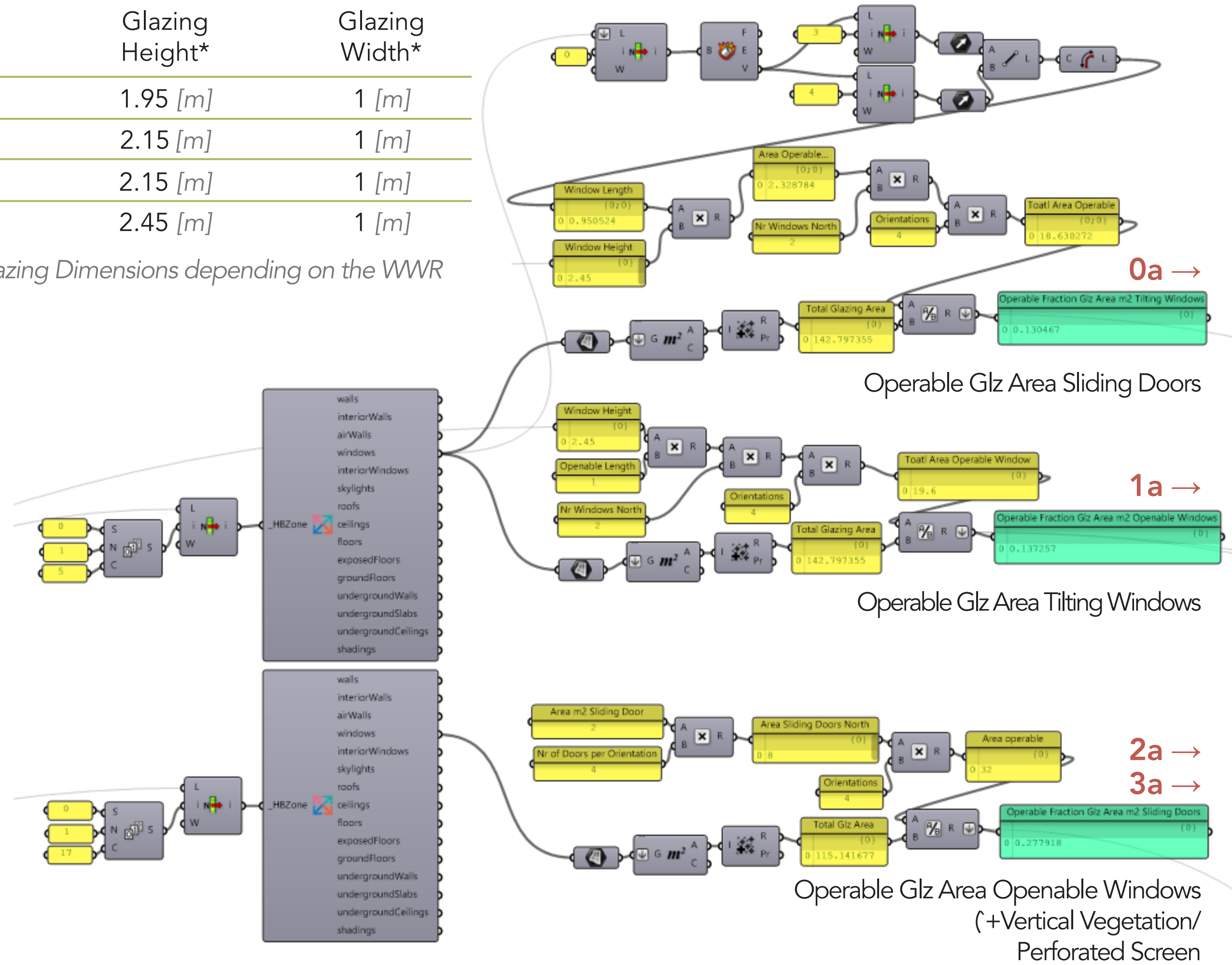
Table 4.02.06: Operable Glz Fraction for different NV scenarios

WWR	Glazing Height*	Glazing Width*
35%	1.95 *[m]*	1 *[m]*
50%	2.15 *[m]*	1 *[m]*
65%	2.15 *[m]*	1 *[m]*
80%	2.45 *[m]*	1 *[m]*

Table 4.02.07: Glazing Dimensions depending on the WWR

In order to assign the different ventilation methods to the zones, it is essential to differentiate the rooms which are presented with sliding doors and the ones with operable windows. The bedrooms and two kitchens have access to balconies through sliding doors while the corner kitchens/living rooms have tilting windows to allow natural air to enter the rooms.

For each of the three natural ventilation scenarios, the operational glazing area needs to be defined. The operational glazing fraction is represented by a number between 0 and 1, where 1 means that the whole glazing area can be opened, respectively 0 if fully closed. *Table 4.02.06* shows the operable glazing fraction assumed for each ventilation scenario. All three scenarios are assessed in combination with operable balcony doors, for which an operable glazing fraction of 1 was assumed, i.e. fully openable.



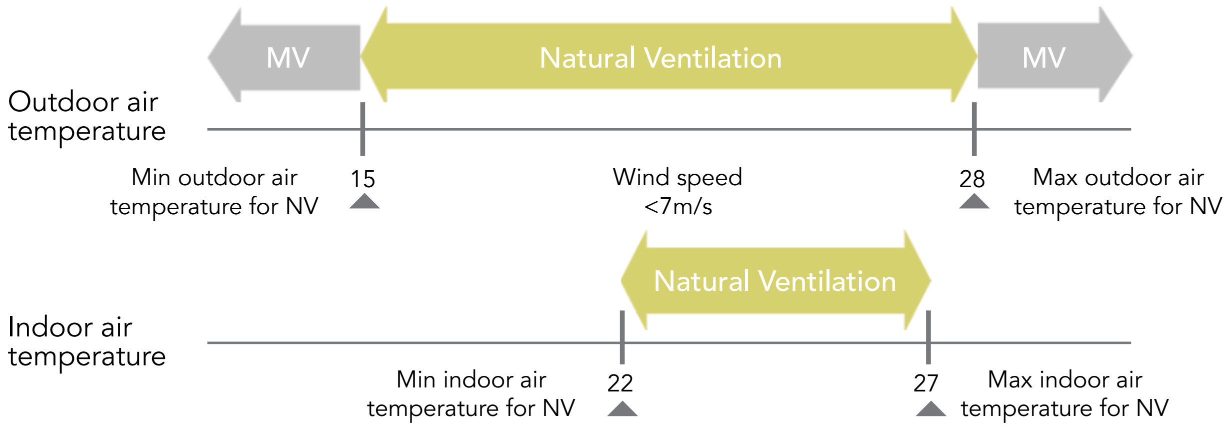


Figure 4.02.30: MV & NV Setpoints

For each of the three ventilation strategies, a ventilation schedule will be assigned, which defines the hours at which natural ventilation is possible. The assigned ventilation schedules are defined in relation to the outdoor temperature and the hourly wind speed calculated at 25m and at 130m height. It was assumed that natural ventilation is enabled when the outdoor temperature is between 15°C - 28°C and wind speeds do not exceed 7m/s.

Higher wind speeds than 7m/s were found to cause uncomfortable wind draughts which would affect the indoor comfort level. The following charts show the number of hours throughout the year when NV is possible, taking into consideration outdoor weather conditions. It can be seen that openable windows in combination with vertical greening or perforated window screens can allow for more NV throughout the year, because incoming air is reduced to comfortable speeds.

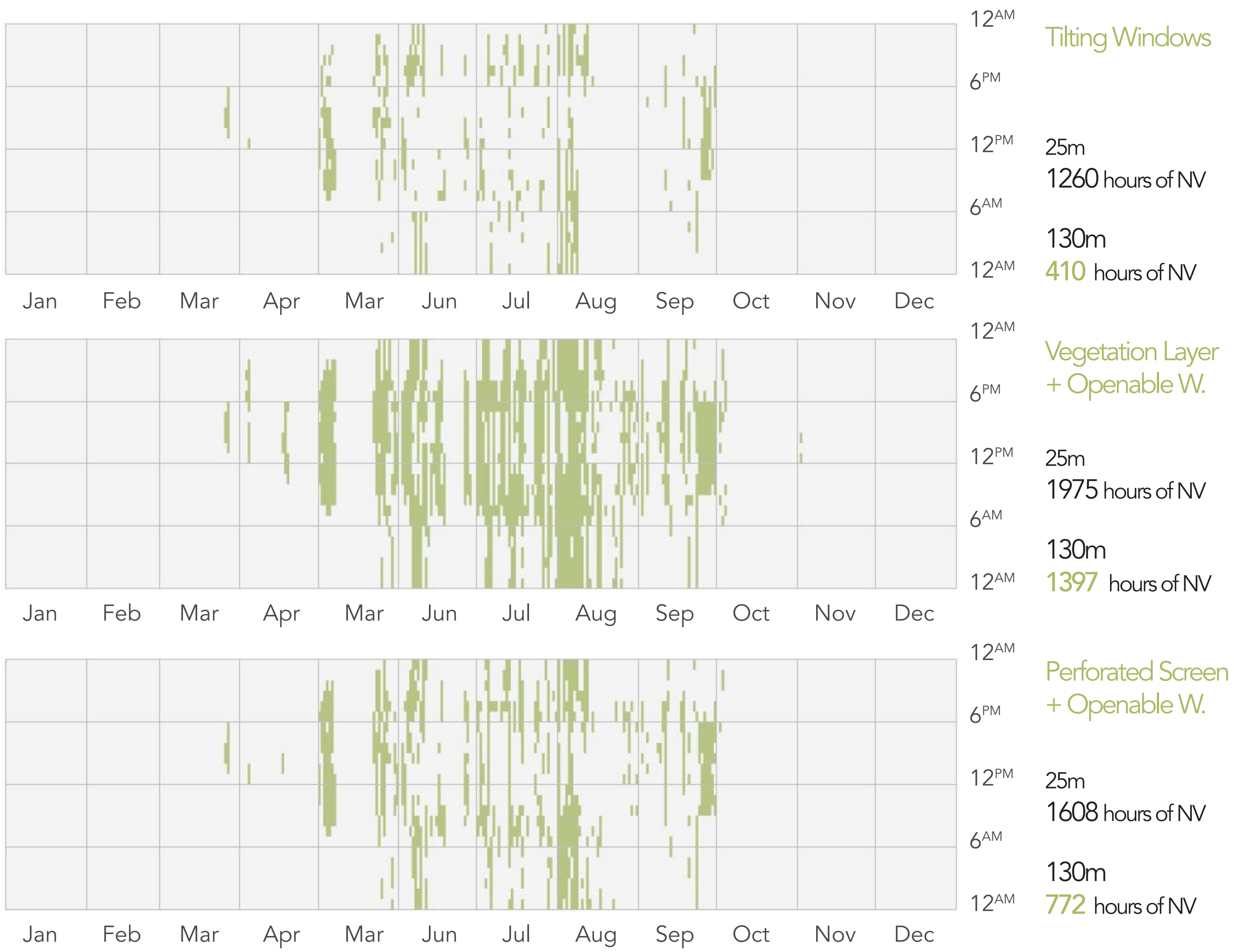
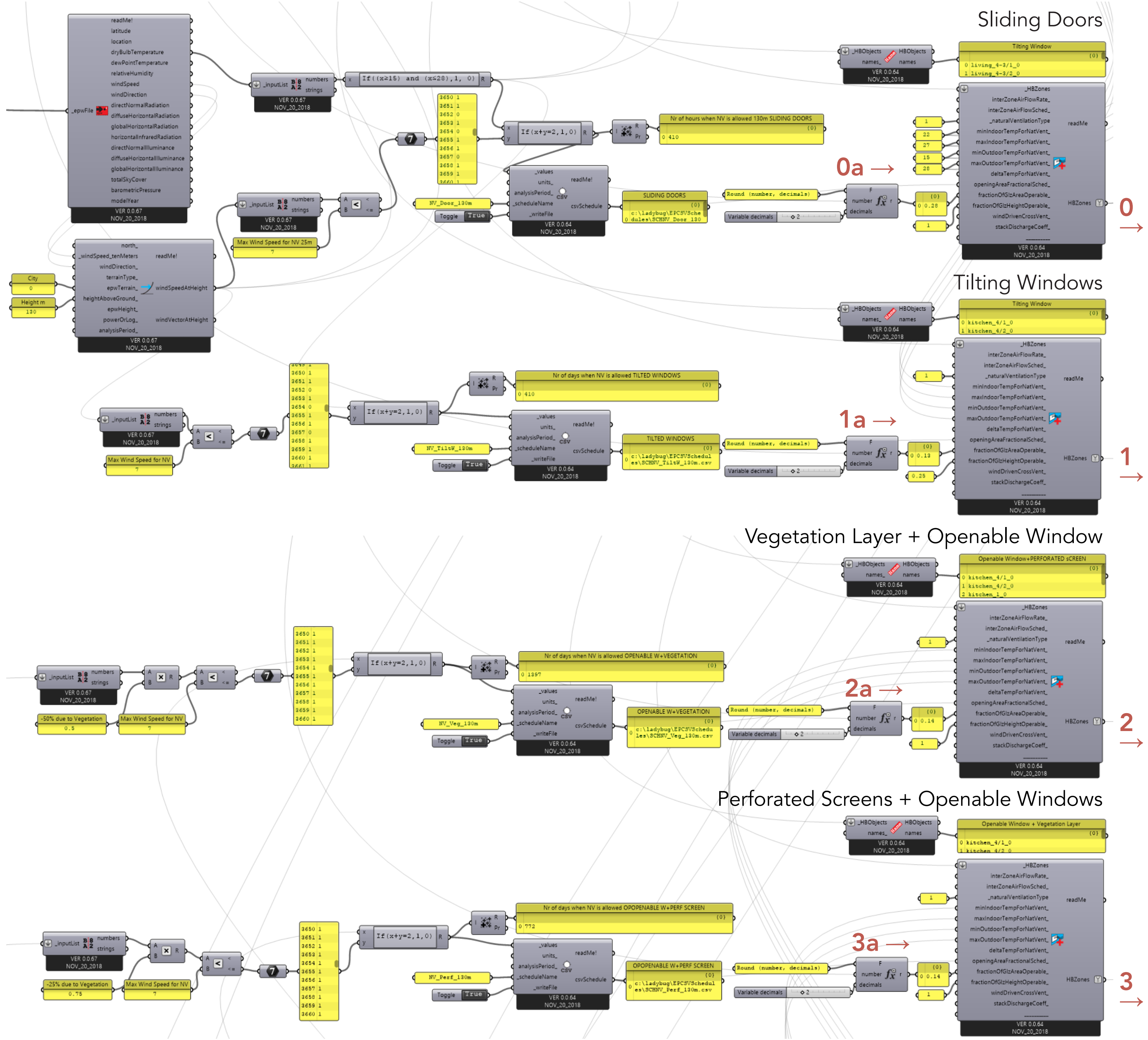
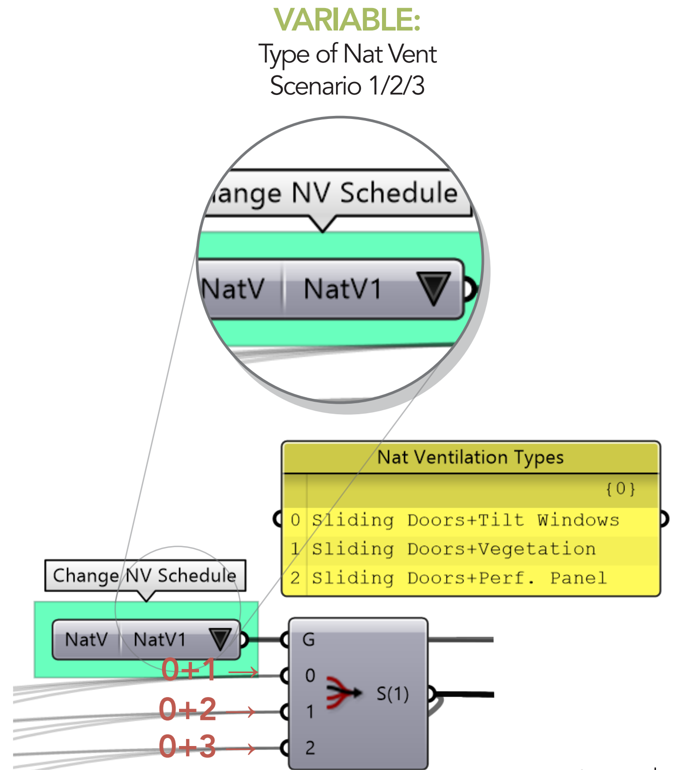


Figure 4.02.31: NV Schedules



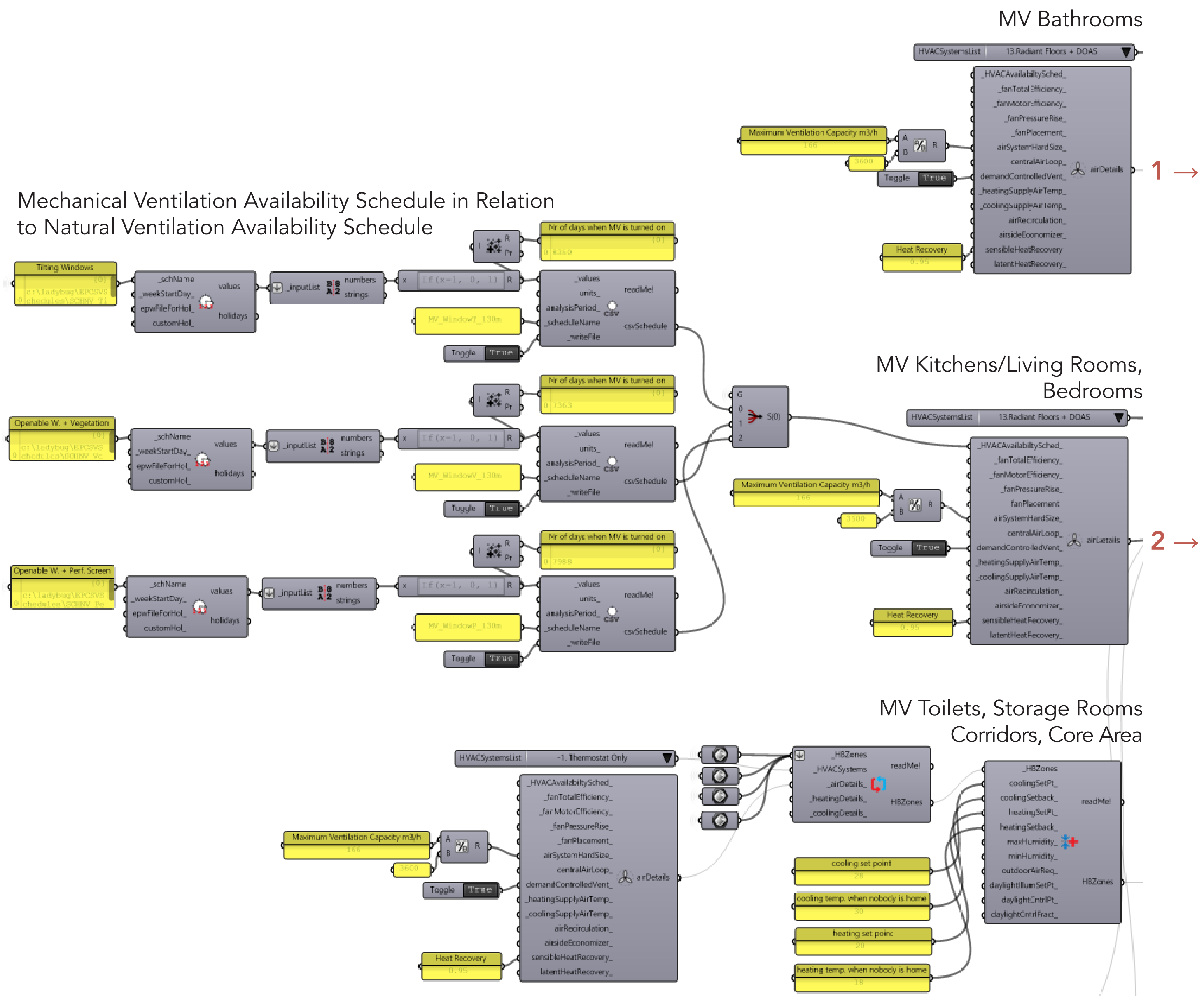
The operable glazing fraction and the natural ventilation schedule defined for each of the three scenarios will be assigned to the appropriate zones. In addition, a last conditional parameter will be specified for each NV strategy - the indoor temperature has to be between 22°C - 27°C in order to enable natural ventilation. The number of hours within this temperature range varies with the WWR, glazing choice, shading type and insulation value. Thus, the number of hours of natural ventilation will also vary depending on the choice of other facade parameters.



4.02.09

MECH. VENTILATION

Mechanical ventilation is enabled whenever the indoor, outdoor temperatures and wind speeds do not allow for natural ventilation. The amount of mechanical ventilation depends on the use of facade parameters which affect the indoor temperatures, i.e. WWR, glazing choice, shading system, NV strategy and thermal insulation. The amount of mechanical ventilation is also defined by the required minimum ventilation rates in relation to the occupancy. Mechanical ventilation is induced using the current specifications of the ventilation system, the Renovent Excellent 300, for which a maximum ventilation capacity of 166m^3/h was specified with 95% heat recovery.



4.02.10

HEATNG & COOLING

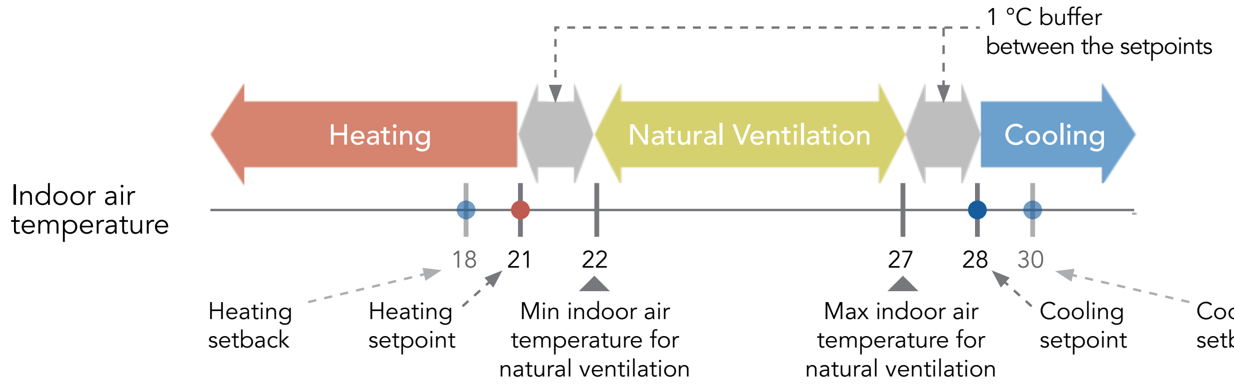
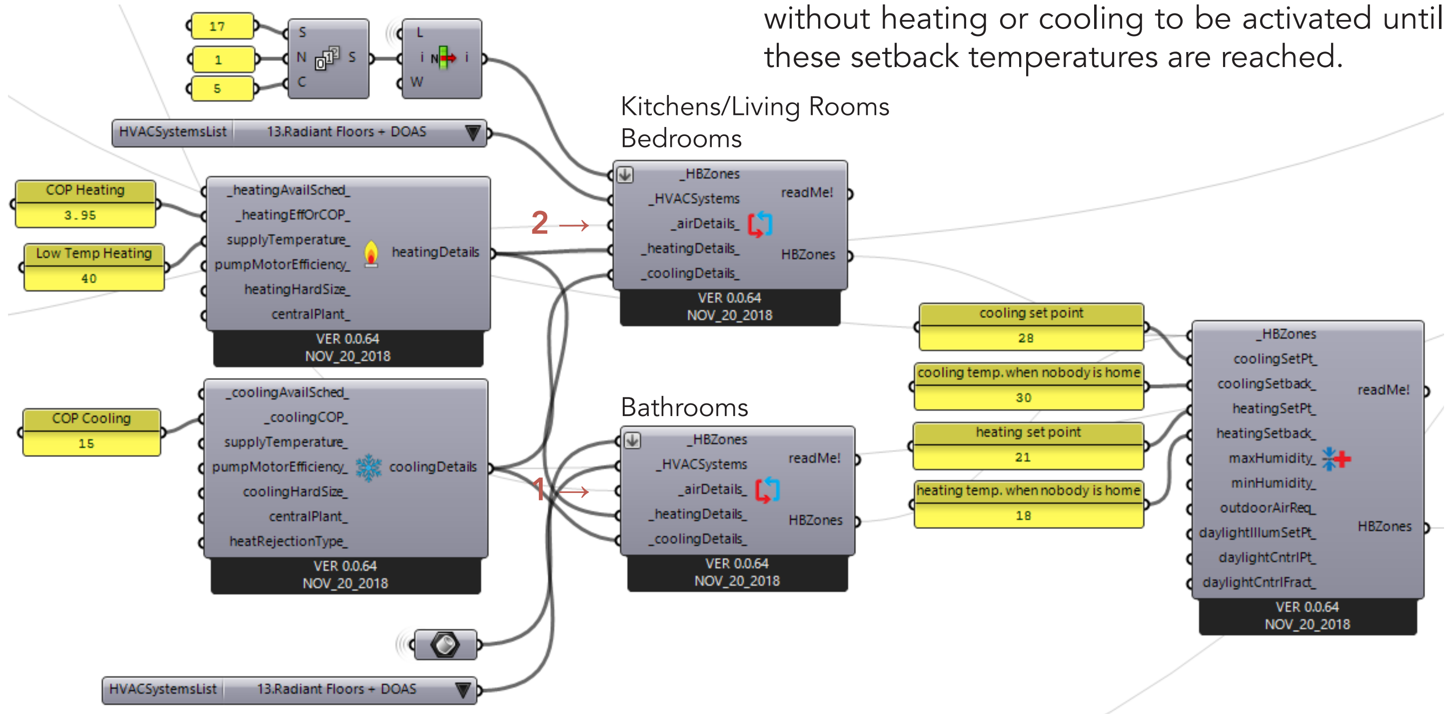


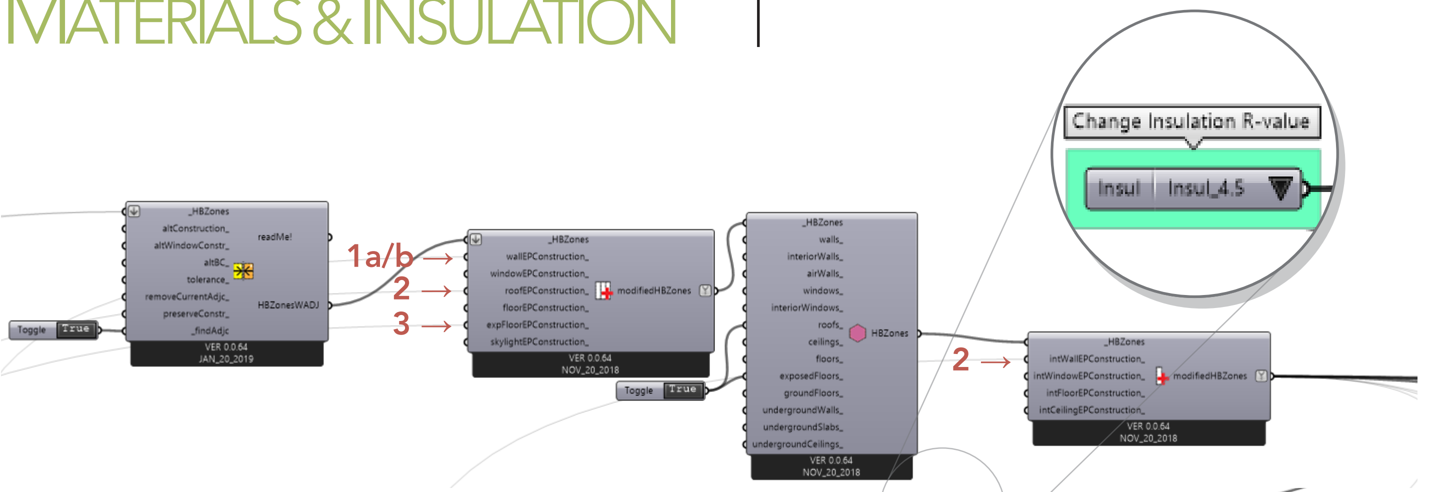
Figure 4.02.32: Heating/Cooling Setpoints and Setbacks

The current heating and cooling systems were assigned to the corresponding zones while providing the same system specifications. Hot and cold water for radiant floor heating/ cooling is generated through the use of a collective thermal storage system (WKO) with groundwater used as energy buffer. The COP for radiant floor heating and hot water supply is 3.95, while the COP for cooling is 15.0. The rooms which are presented with radiant floors, are the kitchens/ living spaces, bedrooms and bathrooms. The toilet rooms, storage rooms, corridors and the core area are neither heated, nor cooled. *Figure 4.02.32* shows the specified setpoints for heating, 21℃ and cooling, 28℃ . When the rooms are unoccupied, the temperature can drop until 18℃ , respectively rise to 30℃ without heating or cooling to be activated until these setback temperatures are reached.



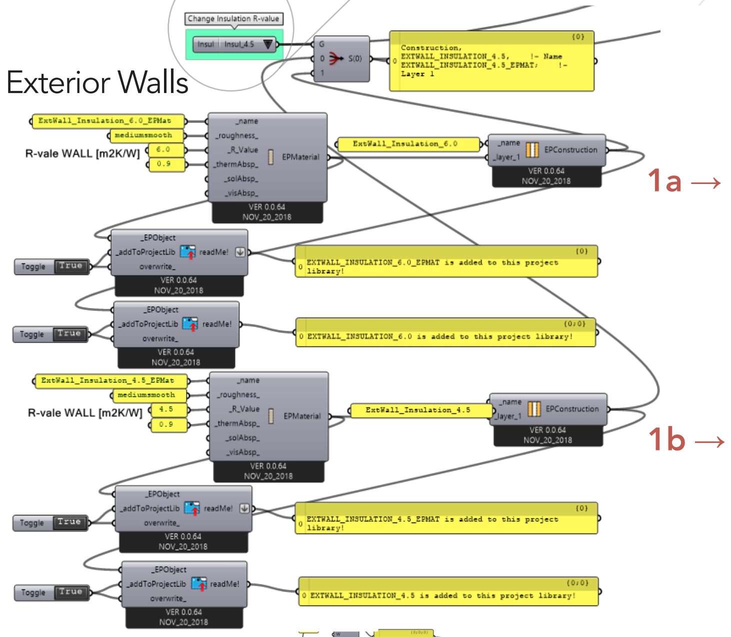
4.02.11
MATERIALS & INSULATION

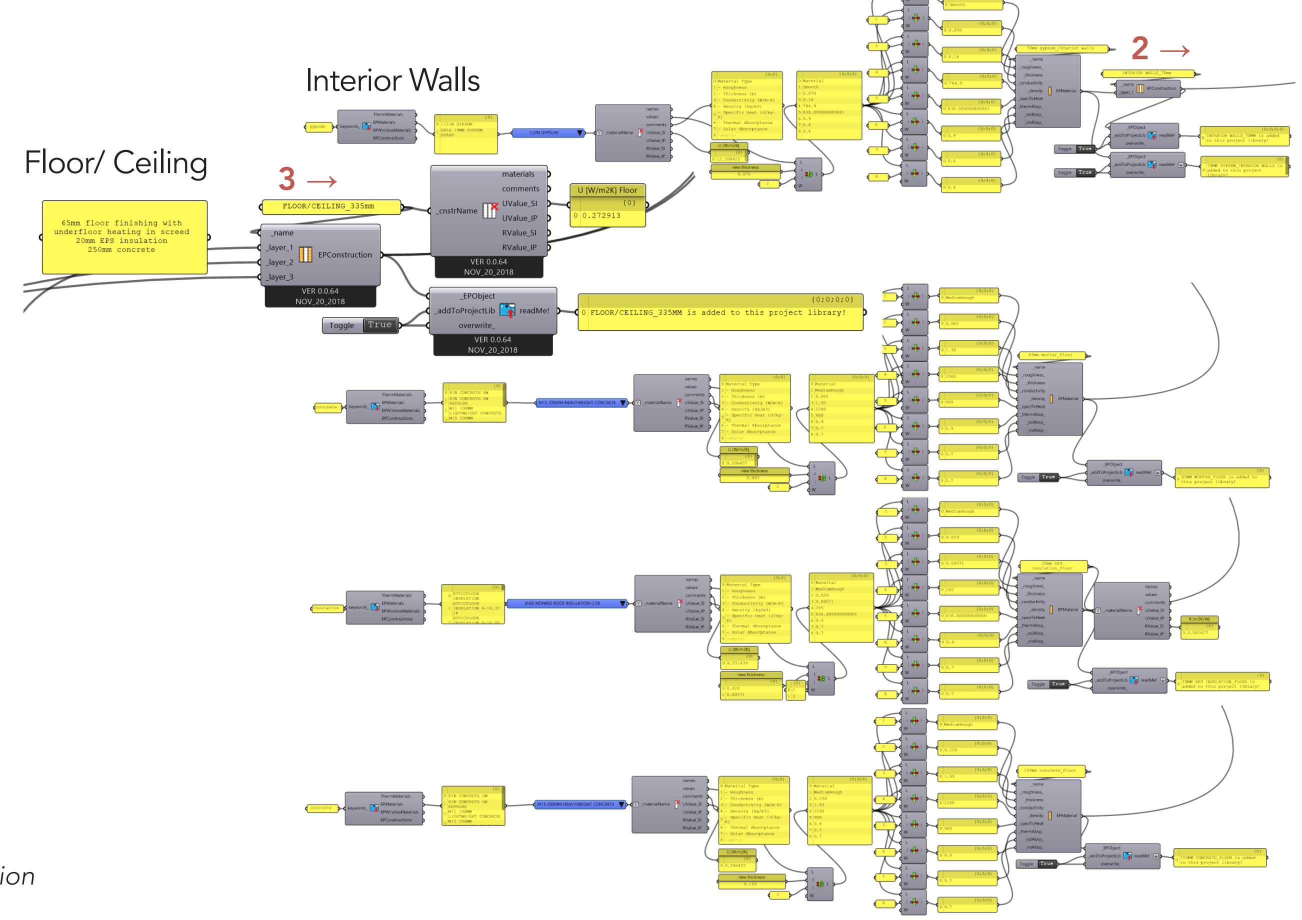
VARIABLE:
Type of Insulation
1- 4.5 m²K/W, 2- 6.0 m²K/W



As a next step, the construction of the exterior walls, floors, and interior walls was determined. The construction of each surface was created by specifying the properties of each material layer, as presented in *Chapter 3.03*. The same materials were recreated in Grasshopper, with the same building properties as in the current architectural design.

For the following optimization process, the insulation value of the exterior walls will be improved. Besides the current value of 4.5 m²K/W, an R-value of 6.0 m²K/W will be considered.



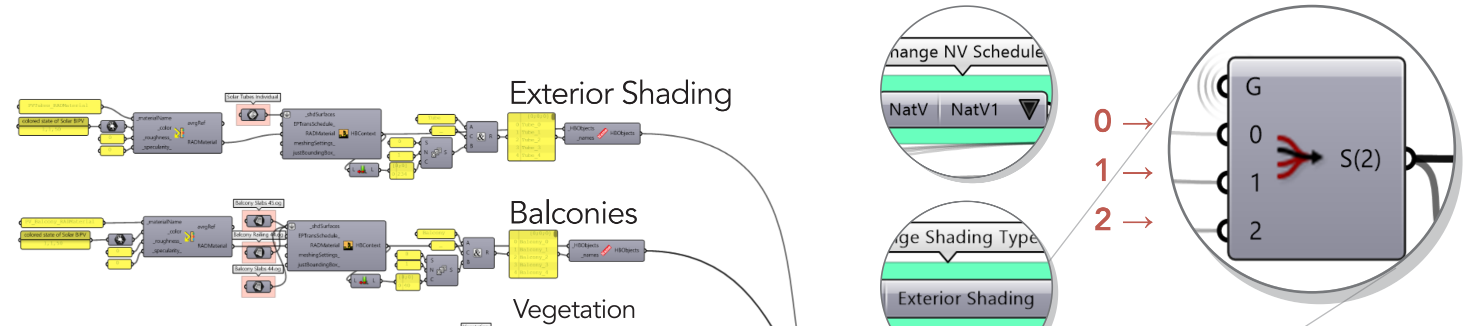


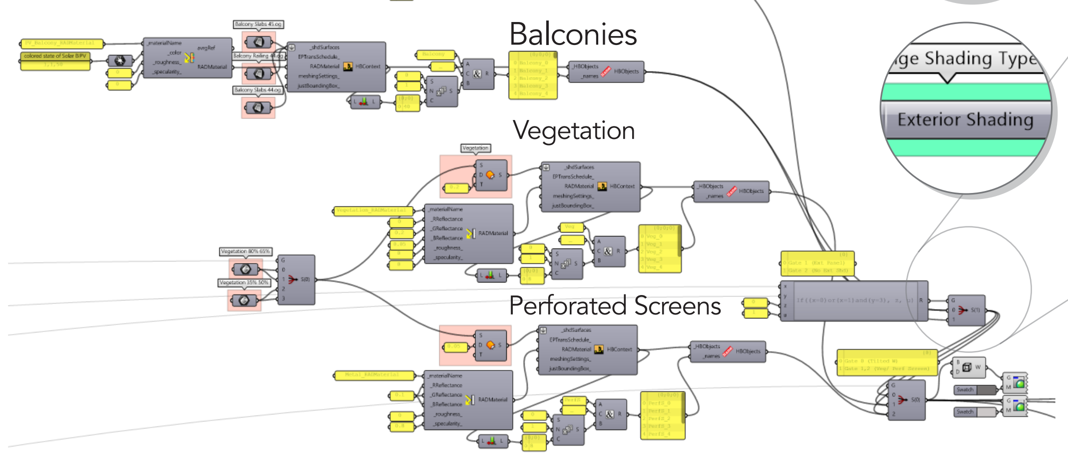
4.03
RESULT

4.03.01
DAYLIGHT SIMULATION

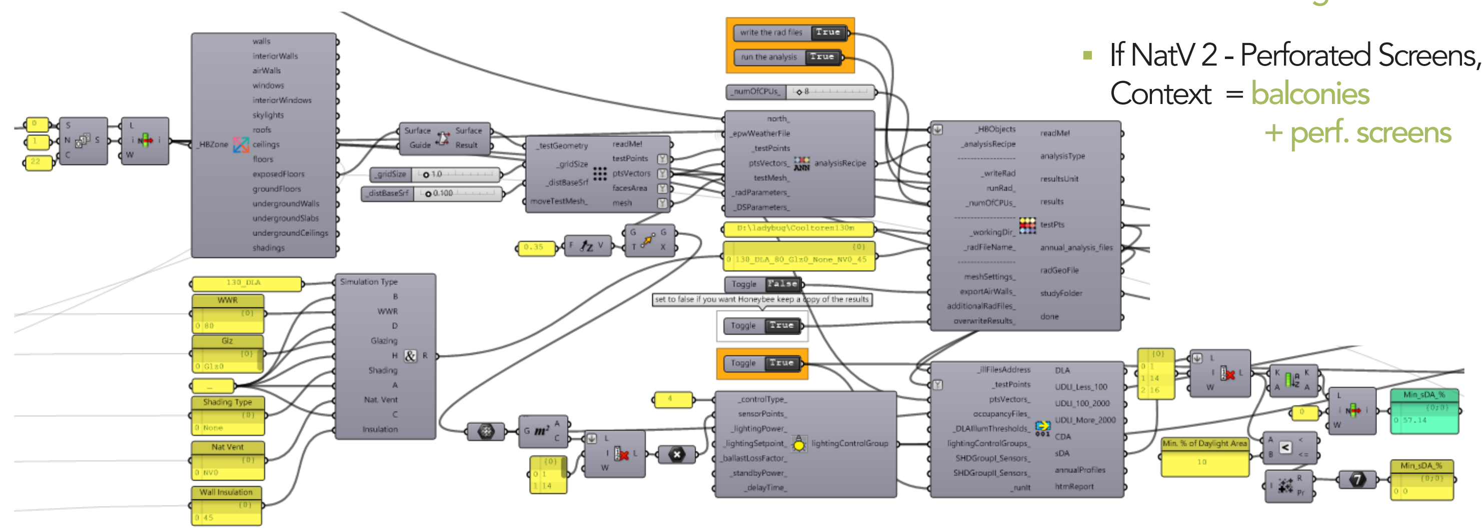
For the design optimization, two main simulations are necessary - a daylight simulation using Daysim and Radiance and an energy balance simulation using Open Studio. Running a daylight simulation is essential, as it will calculate the annual illuminance profiles for the different parameter combinations, which will affect the lighting demand of each zone. The results of the simulation will serve as input values for the lighting schedules of each zone, which will be overwritten before running the energy balance simulation.

Context geometry needs to be considered for both simulations, as it can cast shadow on the evaluated geometry and affect the overall results. In this case, the balconies will be considered as context geometry. Depending on the selected ventilation strategy, vertical greenery or perforated panels will be also considered as context geometry. If exterior shading is used, this will be also added as context. The surrounding urban context should be taken into consideration as well, but in this case, all the neighboring buildings are lower than the simulated levels of the building.





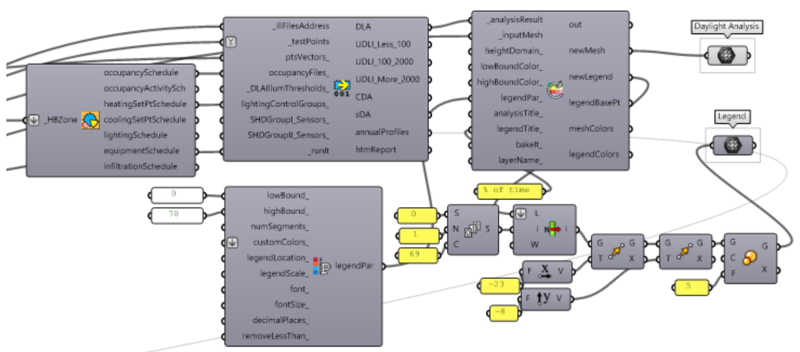
- If NatV 0 - Tilting Windows, Context = balconies
- If ExtL - Exteriour Louvres Context = balconies + exterior shading
- If NatV 1 - Vertical Greening, Context = balconies + vegetation
- If NatV 2 - Perforated Screens, Context = balconies + perf. screens



The *Bouwbesluit* stipulates a minimum amount of daylight of 10% of the total room area. In order to verify the percentage of daylight in each room, the results of the Spatial Daylight Autonomy will be assessed (sDA). The sDA describes the percentage of floor area which receives at least 300lux for at least 50% of the annual occupancy hours. A minimum illumination threshold of 300 lux was considered, as specified in the *Bouwbesluit*. However, taking into consideration a normal working schedule from 8am-5pm and assuming that just one person per household stays home, the sDA will be always lower than 10% because the building is mostly occupied during hours with low sun exposure - during night, mornings and evenings. Therefore, the sDA will be calculated for the entire year, without taking into consideration the occupancy schedule.

In order to derive the lighting schedules, the annual illumination profiles will be calculated with respect to the occupancy hours. The output values will serve as input for the lighting schedules of each zone and will change simultaneously with the varying design parameters, in particular with the window to wall ratio and glazing type.

The lighting schedule will not be affected by the dynamic shading systems. The shading systems will be activated completely (1), partially (0.25, 0.5, 0.75) or not activated at all (0), so that a minimum amount of daylight of 300lux is always provided during daytime. To be more precise, the electric light will only be turned on if there is insufficient daylight while the shading is closed. Therefore, the lighting schedule will only be affected by the occupancy, the glazing ratio and the glazing type. However, the dynamic and fixed shading systems will affect the heating and cooling loads, depending on the shading degree.



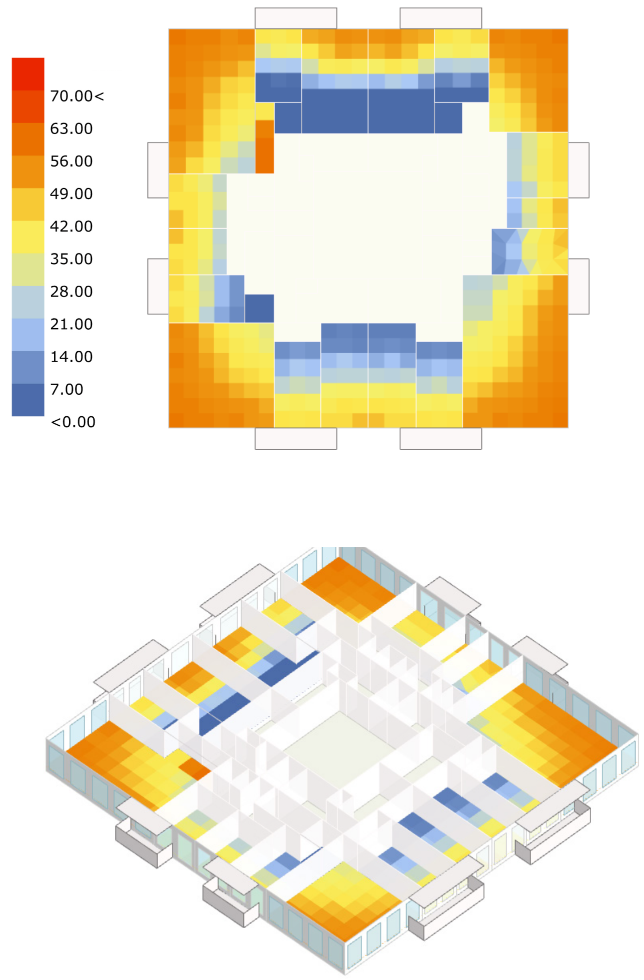


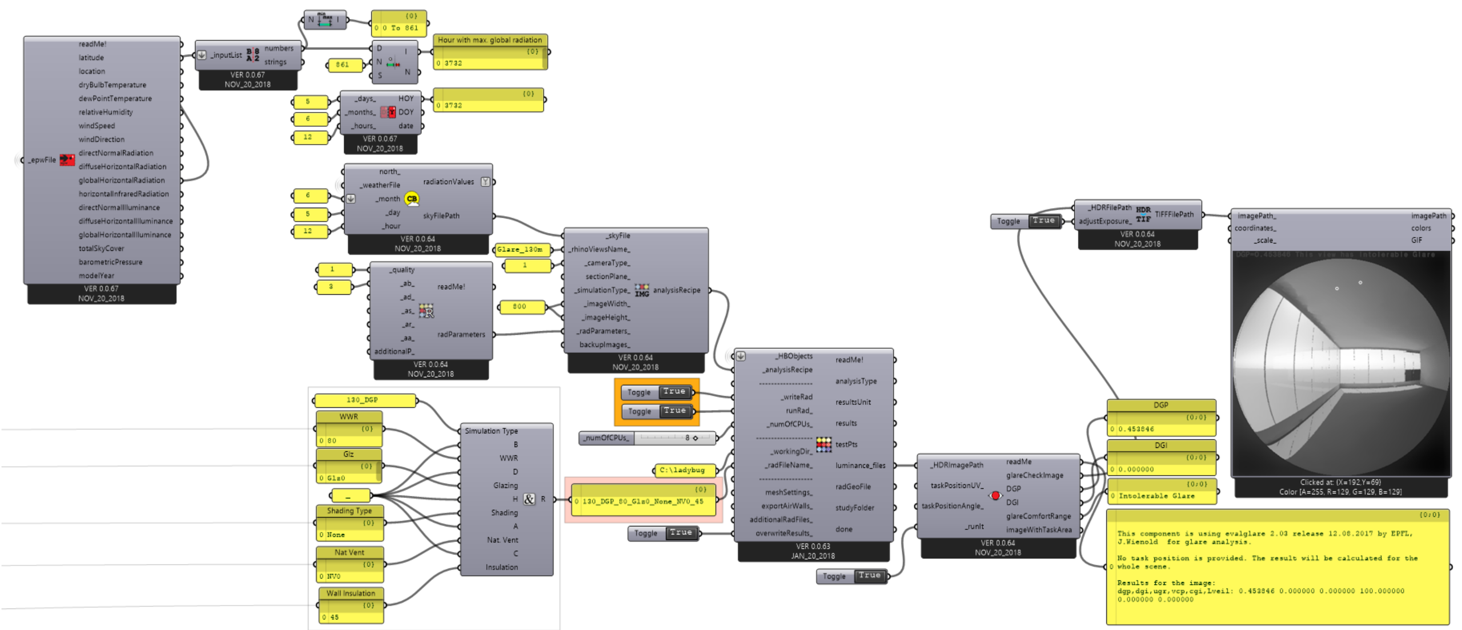
Figure 4.03.01 & Figure 4.03.02:
Spatial Daylight Autonomy Perspective & Top View

4.03.02
Glare Analysis

Figure 4.03.03: Daylight Glare Probability

The Glare Analysis takes additional amount of time to run. Due to the substantioal amount of simulation time required for running the daylight and energy simulations, the annual glare probability will be assessed only for the redesign proposal, which is considered to perform best in terms of energy performance and thermal comfort. The glare probability will be evaluated based on the resulting UGR (Universal Glare Ratio), which should be <19% as mentioned by the *European Standard EN15251:2007*.

For the Glare Analysis, Radiance components were used. The glare probability was calculated only for one corner room, kitchen_6, which has the highest amount of incoming daylight, having a large glazing area orientated towards the south and east. The glare probability was evaluated at 12am, on the 5th June, which was found to be the hour of the year with the highest amount of global horizontal radiation. A view of the occupant was defined towards the corner of the room, so that the user is subjected to lateral as well as direct front daylight. It is more likely for glare to occur in this room, due to its long sun exposure. However, other rooms and different view directions would need to be analyzed in order to make a precise statement. Due to the limited time frame, this study will analyze the aforementioned situation.



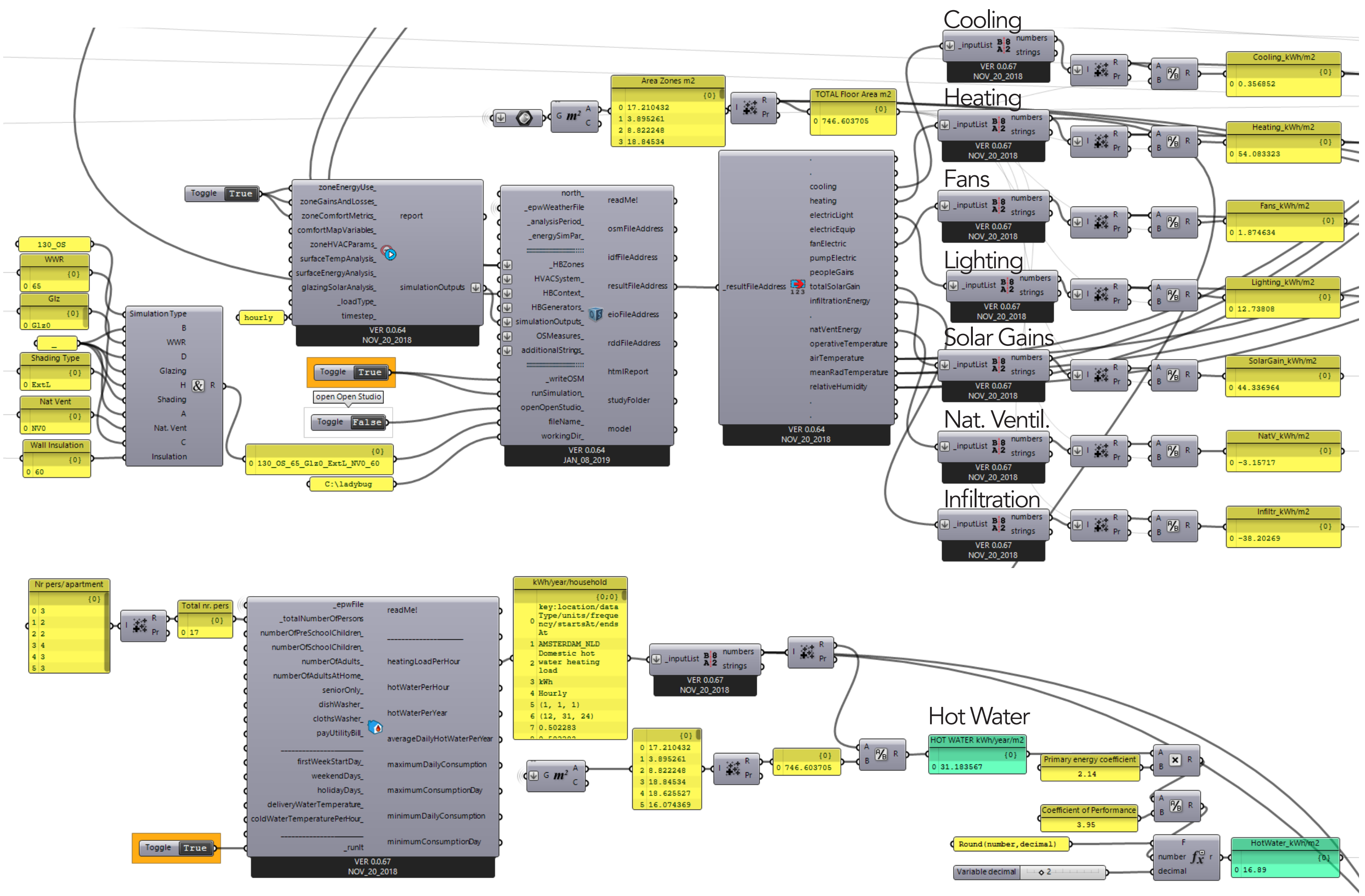
4.03.03

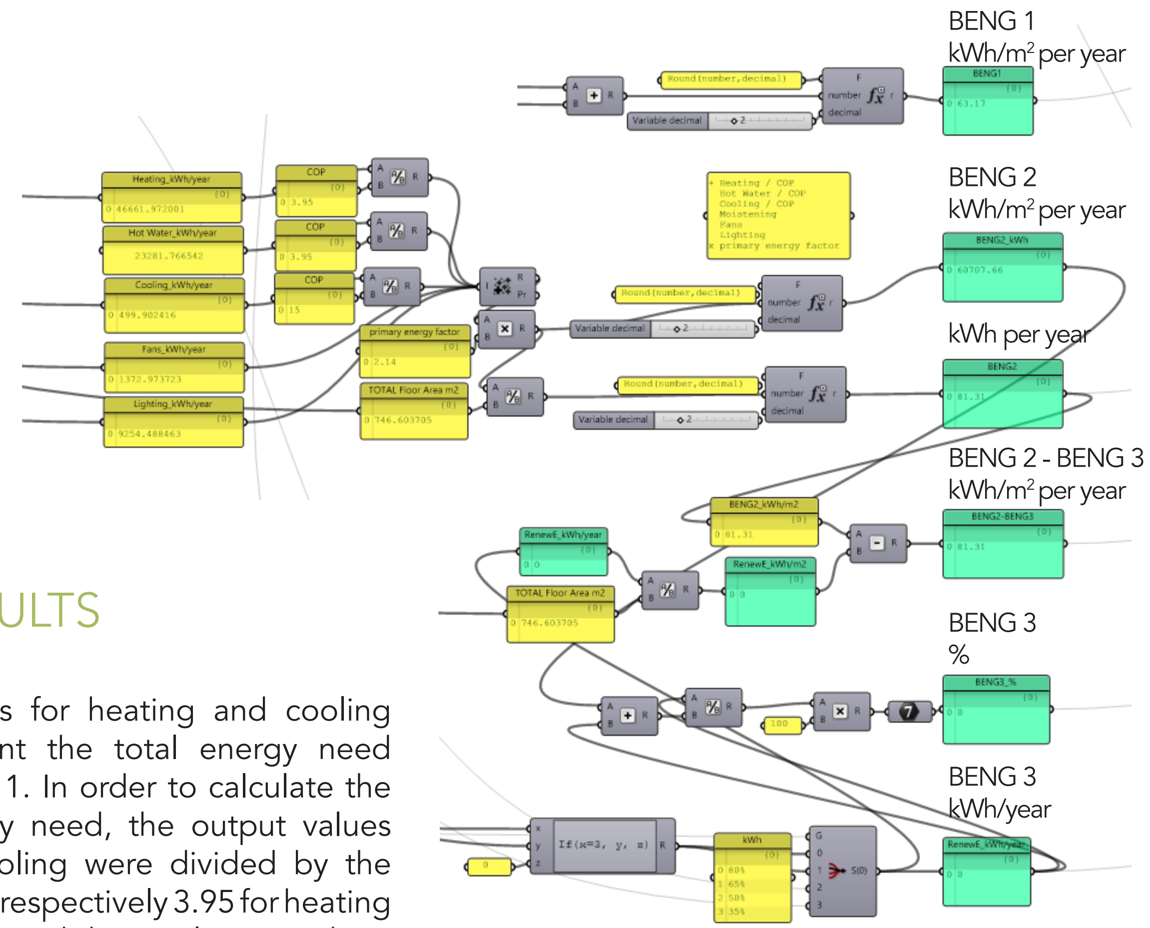
Energy Balance

For the energy balance simulation, the Open Studio component will be used. The Open Studio component has the exact same features as that of the Energy Plus component and some additional features that the Energy Plus component does not include, like defining the HVAC system. The Energy Plus plug in for grasshopper enables the user to model only a simple Ideal Loads System, which is a considerable limitation for this research. By using the Open Studio component, the ventilation system, as well as heating and cooling systems could be modeled for each zone, as described in *Chapter 4.02.09* and *Chapter 4.02.10*.

Another important limitation which is worth mentioning is the way the solar distribution is calculated for the heating and cooling loads. Both Open Studio and Energy Plus can calculate the shadow only for rectangular rooms. If the rooms are concave/L-shaped, they need to be divided by an 'air wall' so that air can still flow from one room to the other. Because of this reason, the geometry of the initial floor plan needed to be adapted slightly and 4 Zones were divided into 8 Zones by 'air walls', so that the solar distribution can be calculated by the Open Studio component.

The resulting values in kWh were divided by the total floor area to convert them into kWh/m². The demand for hot water was calculated separately, while taking into consideration the total number of persons per apartment.





BENG Results

The resulting values for heating and cooling in kWh/m² represent the total energy need according to BENG 1. In order to calculate the total primary energy need, the output values for heating and cooling were divided by the corresponding COP, respectively 3.95 for heating and 15.0 for cooling and the resulting numbers together with the lighting loads and the fans consumption were multiplied by the primary energy factor for electricity, 2.14. The total result represents the total primary energy need. By subtracting the primary energy production from the primary energy need, BENG 2 is obtained.

The total primary energy produced by the PV/T area was calculated with the specifications described in *Chapter 4.02.07*. Afterwards, BENG 3 was calculated, based on the following formula, as indicated by the *Handreiking BENG (2017)*:

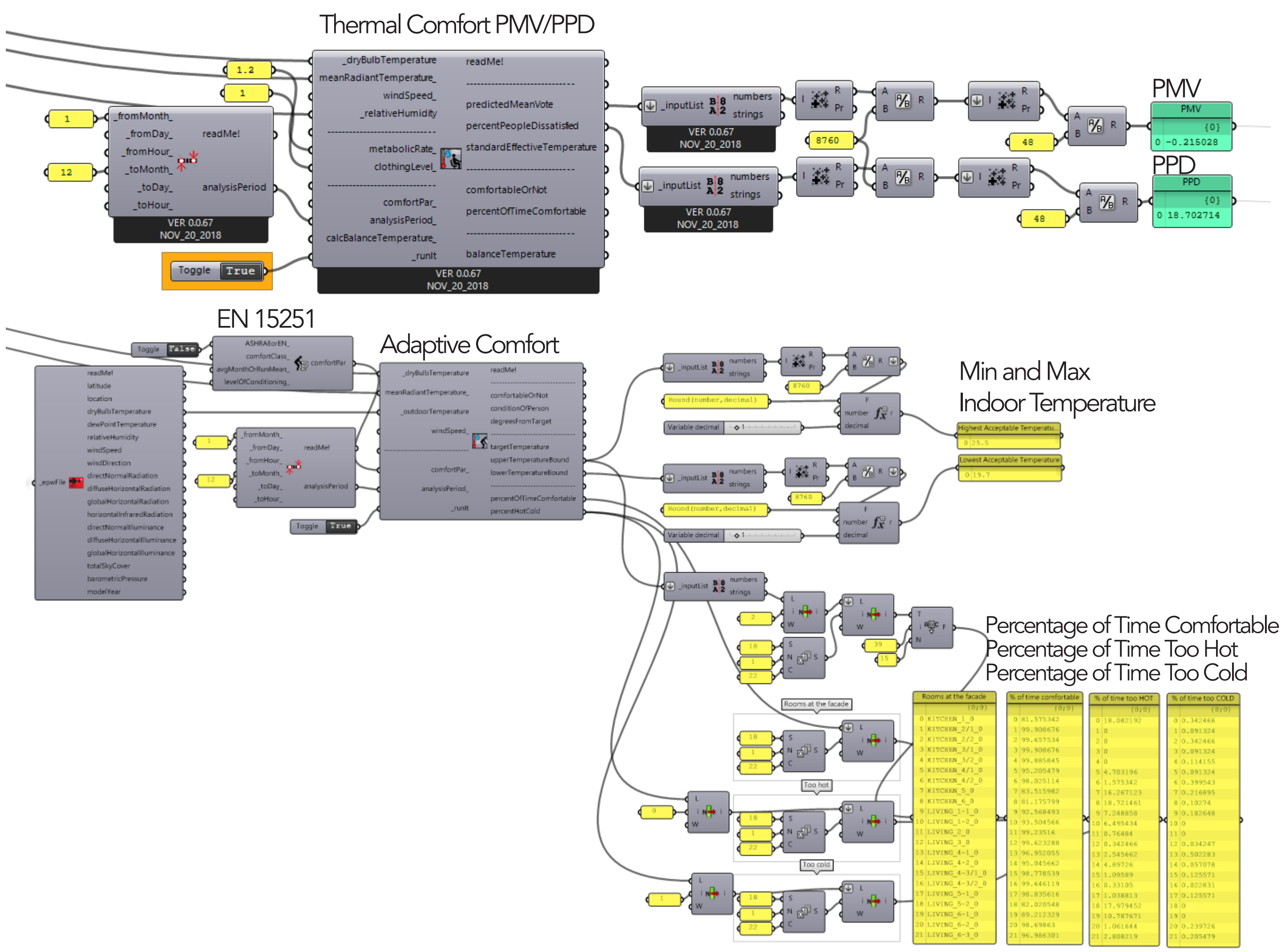
$$\text{Percentage of Renewable Energy [\%]} = \frac{\text{Produced Primary Energy}}{\text{(Primary Energy Need + Produced Primary Energy)}} * 100 \qquad [16]$$

BENG 3 was calculated taking into consideration only the PV/T systems integrated on the facade. The aim was to see how much energy can be produced with energy generating systems integrated on the facade alone.

4.03.04
Thermal Comfort

This study will assess the most optimal facade design in terms of energy performance, daylight and also thermal comfort. Therefore, the PMV and PPD were calculated for each design parameter combination. For this, an average clothing level of 1 was assumed and a metabolic rate of 1.2 met was considered.

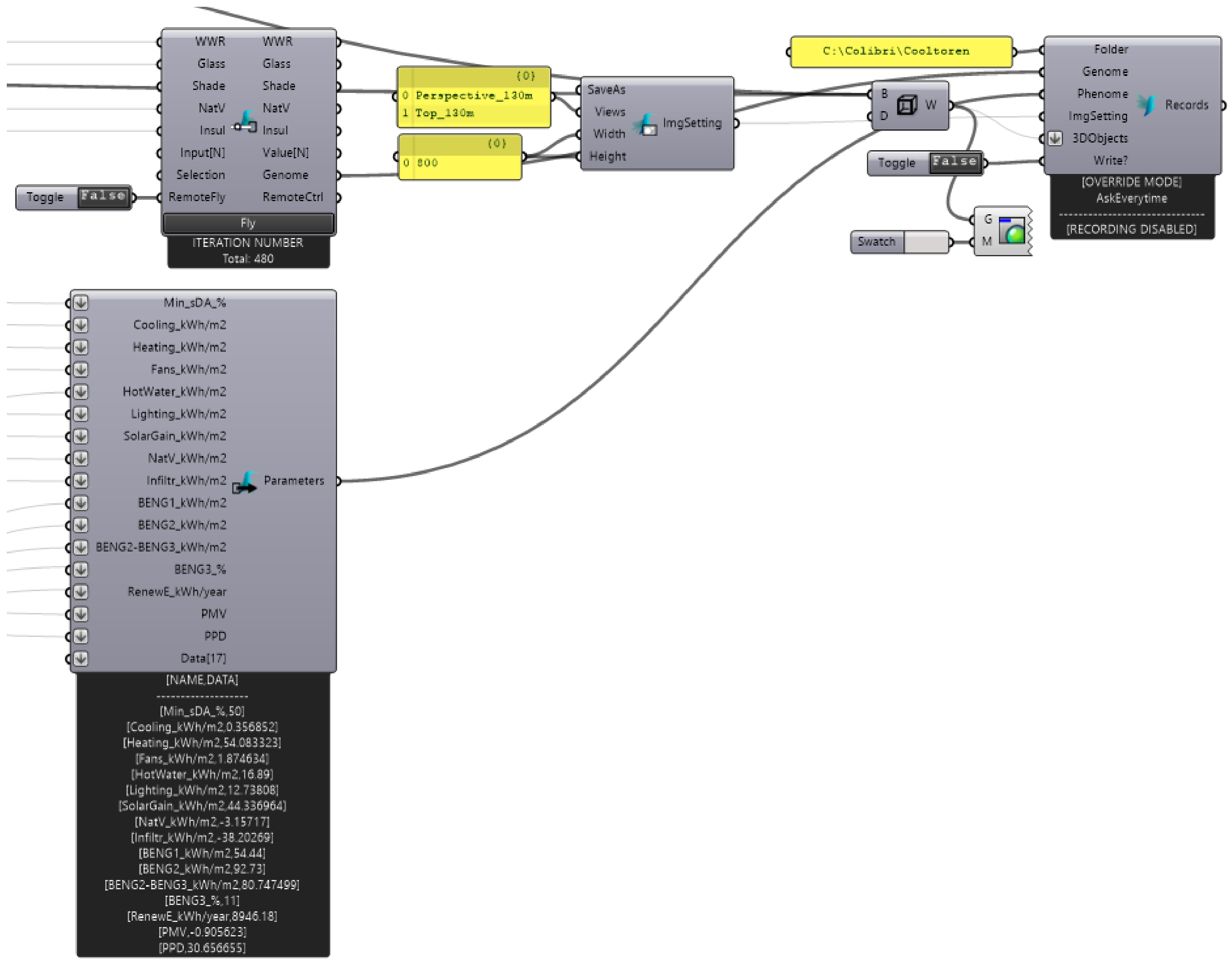
A more in-depth analysis on the percentage of time comfortable in each room will be carried out for the facade redesign proposal. Thus, possible overheating problems can be evaluated for differently orientated rooms.



4.04
Optimization

After setting up the simulation workflow, Colibri Iterator is used to combine all the variables simultaneously. Colibri gathers the inputs and outputs from the grasshopper definition and writes all the data into a data.csv file. It also generates and names images of the specified views to show for example the spatial daylight distribution for each design parameter combination. After generating all the required data, the files can be uploaded into Design Explorer where the results can be visualized.

Colibri Iterator will run for 480 parameter combinations for each of the two analyzed floors, with an average simulation time of 15min/combination. To be more precise, all 480 calculations take approximately 5 days to run for one floor. The results will be presented and discussed in *Chapter 5*.



05

Results

5.01

RESULTS 25m

The input, output values and images generated throughout the simulation were stored and transformed into Design Explorer compatible data sets. Instead of changing one iteration at a time in Grasshopper, the performance of the different parameter groups can be easily compared using Design Explorer.

Looking at the performance of the different parameter combinations at 25m, it can be noticed that all 480 combinations provide a minimum of 10% daylight for more than 50% of the time, if we consider a minimum illumination threshold of 300 lux, as specified in the *Bouwbesluit*.

The final energy need varies at 25m between 48 - 81 kWh/m² with the limit of 70 kWh/m² for BENG 1 being achieved by 425 out of 480 combinations (89%). The total primary energy need, including energy production, varies between 62 - 91 kWh/m², without achieving the 50 kWh/m² requirement for BENG 2 with energy production systems integrated on the facade walls alone. BENG 3 takes values between 0-15%, far below the 40% limit.

Looking at the PMV rates it becomes clear that the indoor comfort conditions are for all 480 parameter groups below the preset limits of ± 0.5. However, the PPD values are between 16-17%, which exceeds the targeted limit of 10%.

Output Parameter		25m
sDA	*[%]*	27 – 57
BENG 1	*[kWh/m²]*	47 – 82
BENG 2	*[kWh/m²]*	73 – 91
BENG 2*	*[kWh/m²]*	62 – 91
BENG 3	*[%]*	0 – 15
PPD	*[-]*	-0.36 – -0.19
PMV	*[-]*	16 – 17%

** BENG 2 including energy production*
Table 5.01.01: Results 25m

The results for the 25m level can be visualized with Design Exporer by following these steps:

1 **Open** Design Explorer
https://tt-acm.github.io/DesignExplorer/

2 **Copy** Google Drive Link
https://drive.google.com/open?id=1cyp6eVT6RnsOEcE_RJXat6XzpfYq7S_-

Google Drive

3 **Insert** Google Drive Link in Design Explorer under:

Get Data

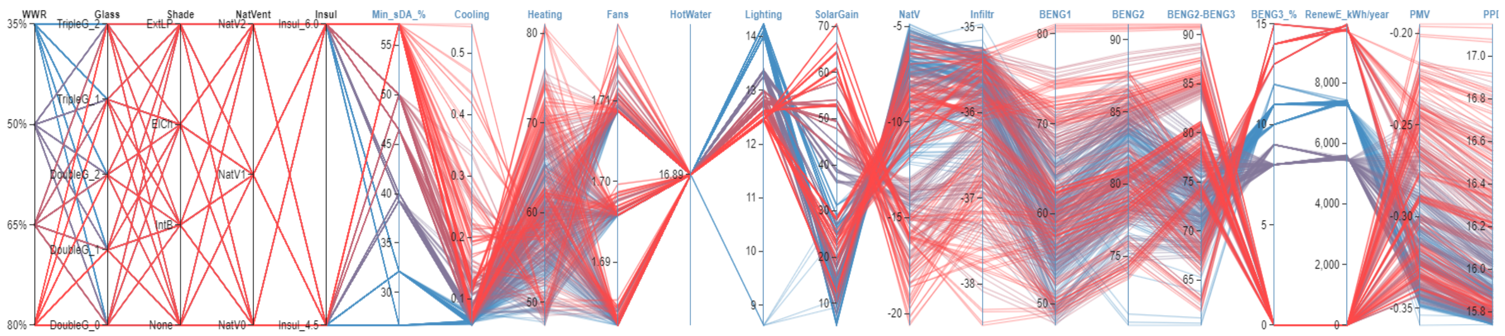


Figure 5.01.01: Design Explorer Results 25m

5.02

RESULTS 130m

The results of the spatial daylight autonomy indicate that all 480 combinations provide a minimum of 10% daylight for more than 50% of the time also at 130m height.

The final energy need varies at 130m between 52 - 89 kWh/m² with the limit of 70 kWh/m² for BENG 1 being achieved by 354 out of 480 combinations (74%). The total primary energy need, including energy production, varies between 65 - 95 kWh/m², without achieving the 50 kWh/m² requirement for BENG 2 with energy production systems integrated on the facade walls alone. BENG 3 ranges between 0-14%, also below the 40% limit.

The indoor comfort conditions at 130m are similar to the ones at 25m, with a slight increase in energy consumption being recorded. The PMV rates are below the preset limits and the PPD values vary between 17-19%, exceeding the 10% target limit.

Output Parameter		130m
sDA	*[%]*	29 – 57
BENG 1	*[kWh/m²]*	52 – 89
BENG 2	*[kWh/m²]*	76 – 95
BENG 2*	*[kWh/m²]*	65 – 95
BENG 3	*[%]*	0 – 14
PPD	*[-]*	-0.37 – -0.18
PMV	*[-]*	17 – 19%

** BENG 2 including energy production*
Table 5.02.01: Results 130m

The results for the 130m level can be visualized with Design Exporer by following these steps:

1 **Open** Design Explorer
https://tt-acm.github.io/DesignExplorer/

2 **Copy** Google Drive Link
https://drive.google.com/open?id=1Q4r_G_CqsNj1TGkAFQfQ1adRFTqi2JXs

Google Drive

3 **Insert** Google Drive Link in Design Explorer under:

Get Data

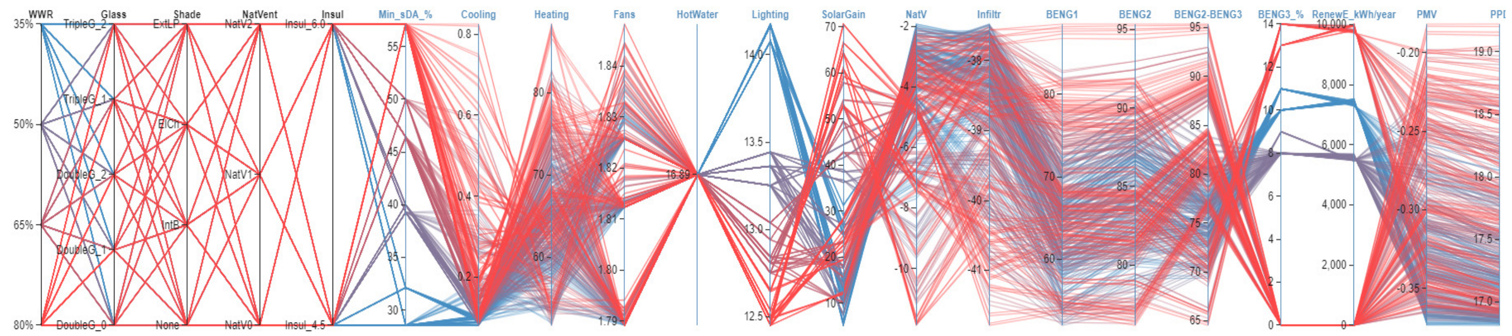


Figure 5.02.01: Design Explorer Results 130m

5.03

Comparison 25m vs. 130m

5.03.01 Facade Performance

The following graphs represent the results of the 480 facade design combinations at 25m and at 130m level. As can be deduced from the results, the performance of the various facade designs is very similar at the two altitudes. This answers one of the sub-questions of this research study:

Does a variation in facade with respect to height lead to better performance?

The question arose under the hypothesis that higher wind speeds would reduce the amount of natural ventilation, i.e. increase the amount of mechanical ventilation and higher velocities lead to higher infiltration rates with altitude. However, even with an increase in mechanical ventilation and slightly higher heat losses, the difference in performance at the two altitudes is very similar, with an increase of just 4.5 - 7.4 kWh/m² (8-9%) of the total primary energy need being recorded at 130m height, as shown in *Figure 5.03.01*.

To answer the question, the facade design combinations which perform best at 130m, perform even better at 25m, so in this case, a variation in facade with height would not lead to a better performance. Nevertheless, the increase in energy consumption is exponential with height and needs to be evaluated also for supertall skyscrapers, reaching between 300-600m in height, as the difference in climate conditions between the lowest and the highest level is more significant and would therefore have a bigger impact on the indoor conditions, i.e. the total energy performance of the building.

The results for the 600m level can be visualized with Design Explorer by following these steps:

1 **Open** Design Explorer
https://tt-acm.github.io/DesignExplorer/

DesignExplorer

2 **Copy** Google Drive Link
https://drive.google.com/open?id=1CCz-WoEf7KBtiAad0jHRYDY73TkqXcEK

Google Drive

3 **Insert** Google Drive Link in Design Explorer under:

Get Data

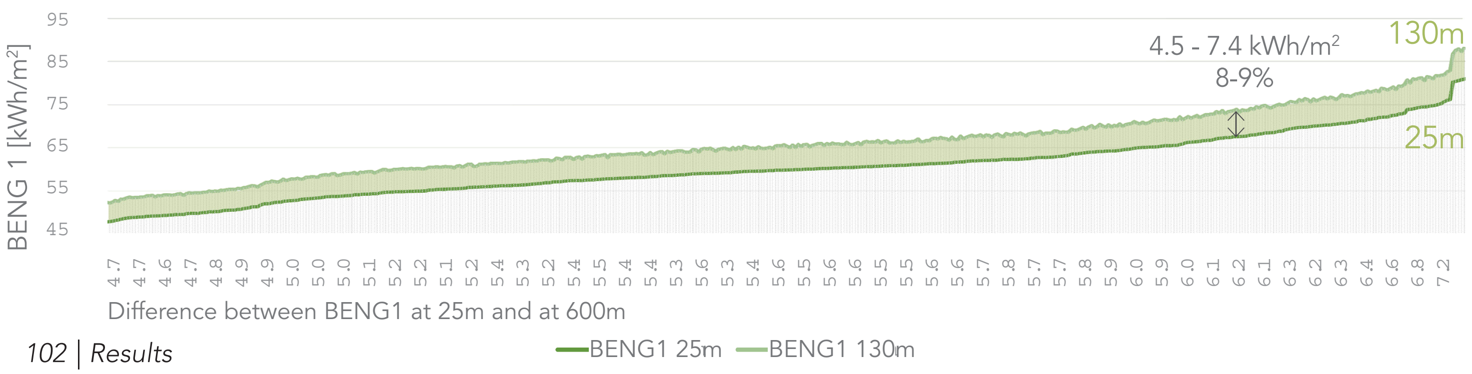
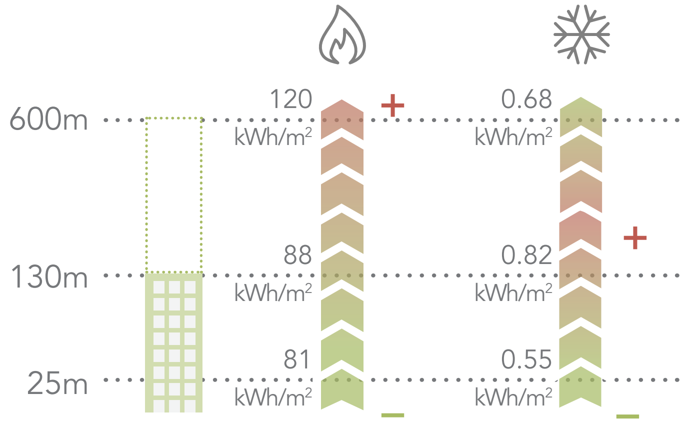


Figure 5.03.01: Comparison 25m vs. 130m

Comparison 25m vs. 600m

In order to be able to truly answer the question, whether a variation in facade with height is more beneficial, the same building was simulated as if it would be 600m tall and the difference in performance between the 25m and the 600m level was analyzed. Now, the difference in performance is more significant between the two altitudes, varying between 24.9 - 39.3 kWh/m² (33-34%), with no facade design option being able to reach the BENG regulations, as can be seen in *Figure 5.03.02*. In addition, it can be noticed that, while the heating loads further increase with height, cooling loads start to reduce again after a certain height limit, due to increased infiltration and lower temperatures at higher altitudes. Therefore, it is advisable that for higher buildings, the performance of the top as well as the middle floor is investigated. This aspect should be further investigated for office high-rises, where cooling loads have a more significant impact on the overall energy performance.

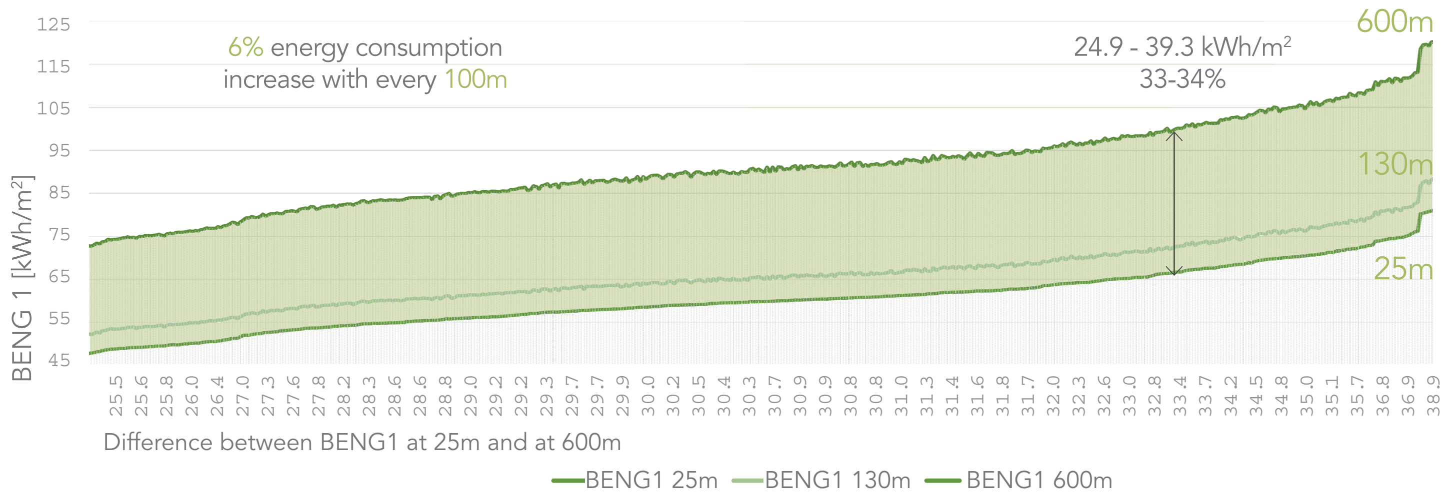
By undergoing this third simulation, it became evident that a variation in facade with height would not improve the energy performance of residential high-rises. The facade design combinations which perform best at 600m are also the same ones which perform best at 25m. However, it is important to mention that choosing the right facade design is more important at higher altitudes because it has a more significant impact on the energy performance, considering that the difference in performance between the best and worst performing design choice is 30 kWh/m² at 25m and 50 kWh/m² at 600m.



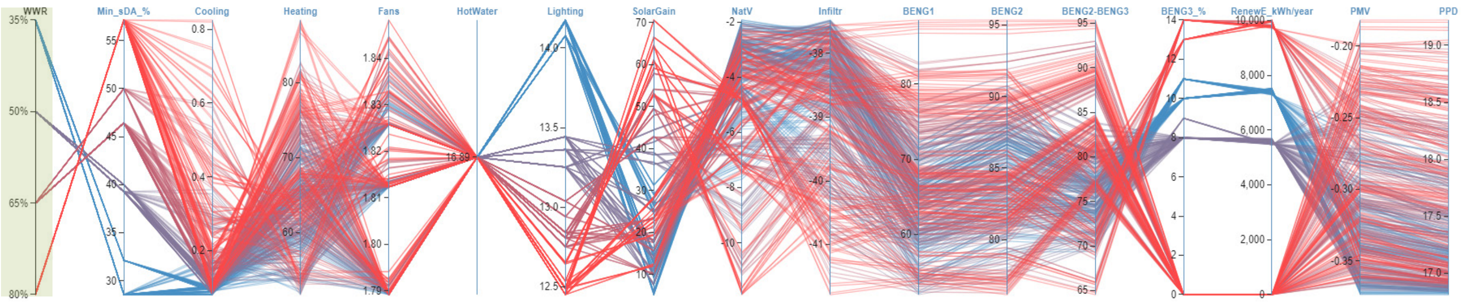
Due to the fact that difference in energy performance, from one design to another, is lower at 25m, a cheaper facade design which performs slightly worse cold be an option in practice for the lower situated floors. The cost factor was not a priority for this study and therefore a variation in facade will not be applied. The best performing facade design will be chosen based on energy and thermal comfort considerations.

The following pages describe the impact of different facade parameters on daylight, energy performance and thermal comfort, with the aim to provide some facade design selection guidelines. Due to the fact that the results are quite similar for both altitudes, the interpretation of the results will be based on the 130m level. The conclusions drawn will help to decide on the best performing parameter combination which fits between the defined performance boundaries. In a later stage, the outdoor comfort conditions on the balconies at 25m and at 130m will also be compared.

Figure 5.03.02: Comparison 25m vs. 600m



Conclusions



WWR

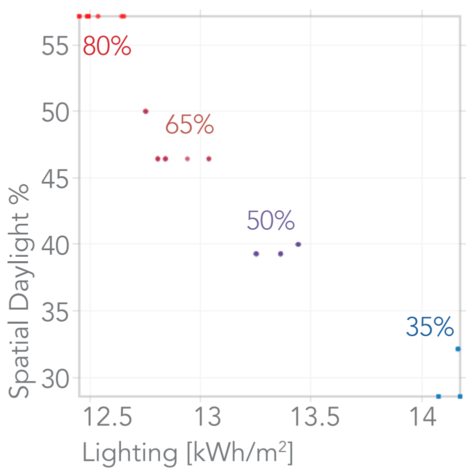
Figure 5.03.03: Impact Window to Wall Ratio

Double Glazing | No Shading | NV Tilting W. | Insulation 4.5 m²K/W

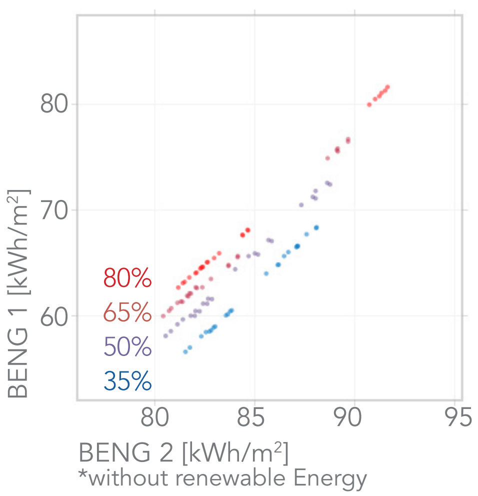
The WWR has a great influence over the performance of the overall facade, as it determines the amount of incoming daylight and solar gains. The higher the glazing ratio, the deeper into the space the daylight penetrates, i.e. the lower the electric lighting consumption. With higher glazing ratios comes also higher solar gains in summer and heat losses in winter, i.e. increased cooling and heating loads. This implicitly suggests that larger windows with standard double glazing and no shading are most probably leading to higher BENG 1 values, which describes the total amount of heating and cooling in kWh/m² per year.

BENG 2 stands for the total primary energy need in kWh/m² per year and is influenced also by the electrical lighting and mechanical ventilation loads. Higher glazing ratios are more probably to lead also to higher BENG 2 values, but it depends also on the choice of other design variables, such as glazing type, shading, NV strategy and insulation. The amount of energy produced on the facade is highly influenced by the WWR, as it determines the area available for building integrated energy systems. This aspect will be discussed in the following chapters. Higher WWRs have a negative influence on the thermal comfort, as the PPD increases with increased amount of glazing.

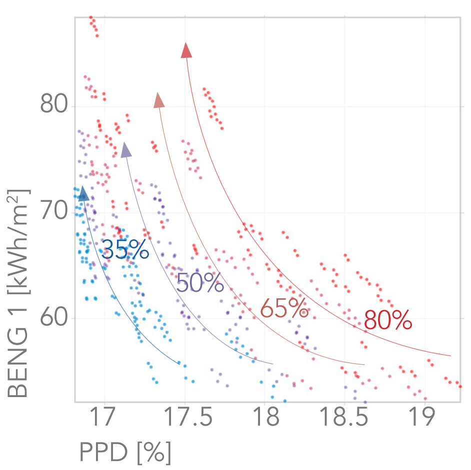
Daylight

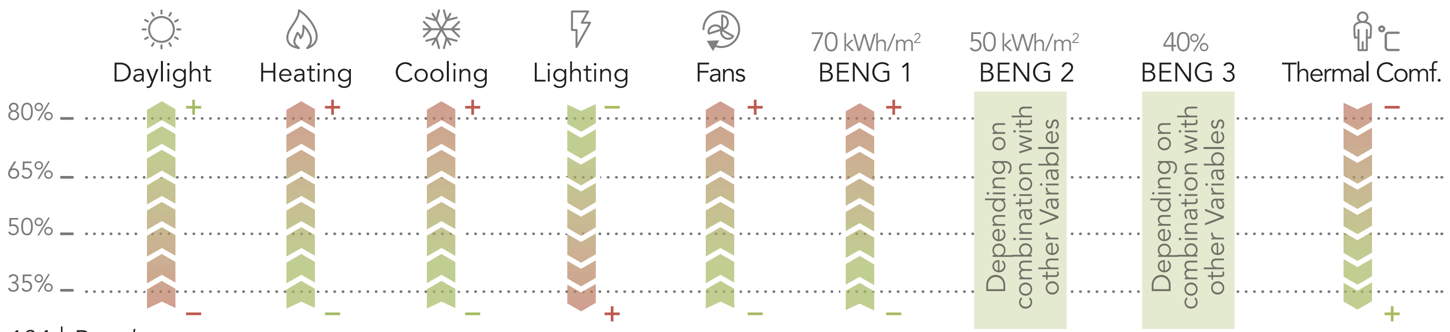


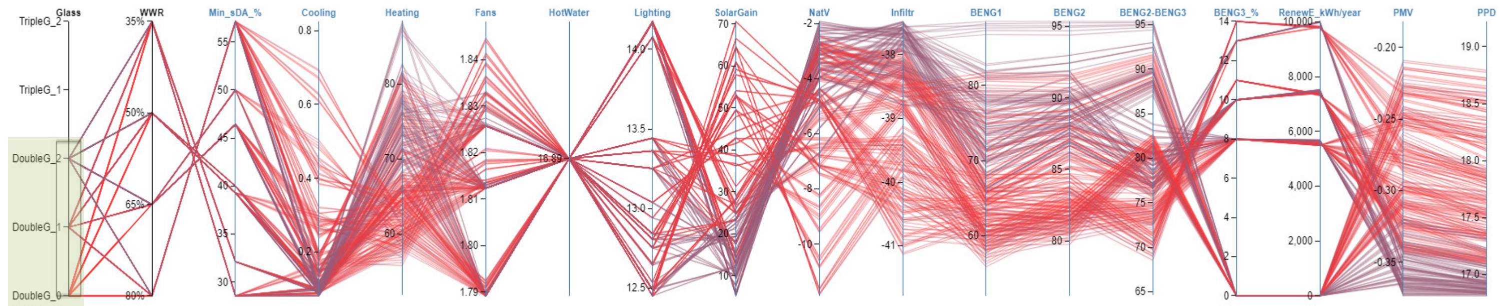
Energy Performance

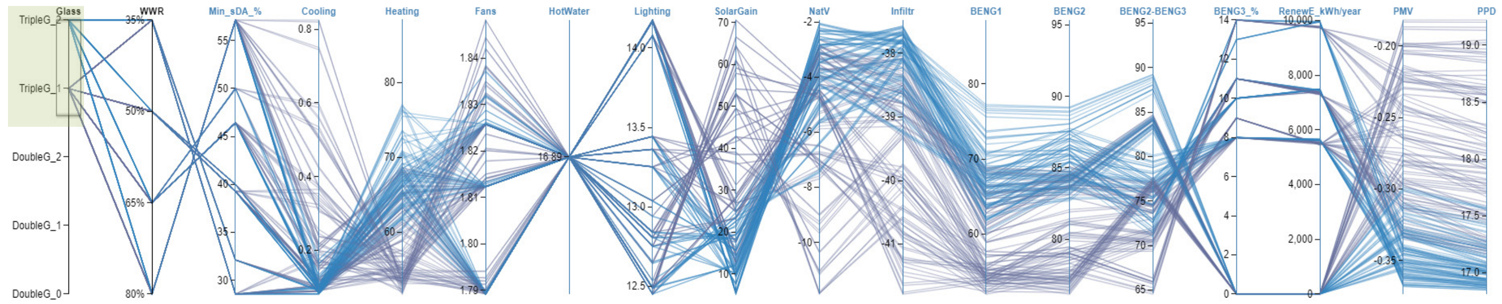


Thermal Comfort









WWR & Glazing

Figure 5.03.04: Impact Double Glazing
Figure 5.03.05: Impact Triple Glazing

No Shading | NV Tilting W. | Insulation 4.5 m²K/W

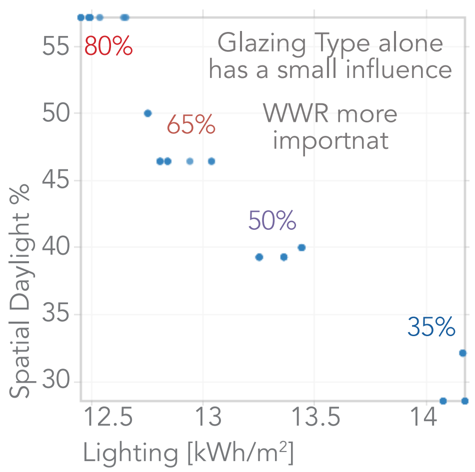
The type of glazing is another important parameter, as it can regulate the amount of solar energy which enters the space (SHGC) whilst conserving the heat (U-value). Looking at the results it becomes clear that high window ratios of 80% should be used only in combination with triple glazing. For WWRs of 80% and 65%, TripleG_1 should be used to achieve low heating values and DoubleG_2 or TripleG_2 for low cooling values. DoubleG_0 and DoubleG_1 can be used in combination with WWRs lower than 50% to achieve a balance between heating and cooling loads, while TripleG_1 lead to the lowest heating loads and DoubleG_2 or TripleG_2 to reduced cooling.

The heat demand dominates for the analyzed case study, which is why the best performing glazing options are the ones with a high SHGC, 0.6. However, glazing types with a low SHGC, 0.3, lead to less overheating and therefore perform better for thermal comfort.

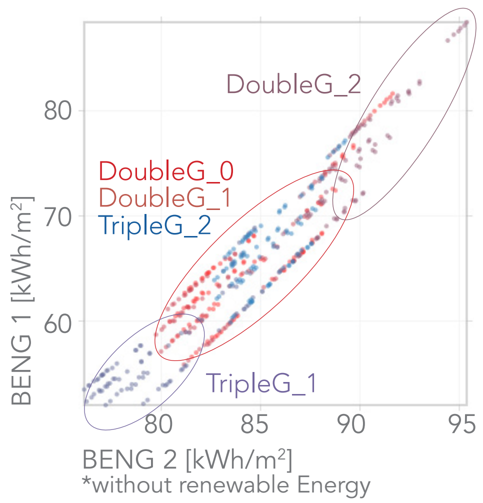
Glazing Type	Utot	SHGC	VLT
	[W/m²K]	[%]	[%]
DoubleG_0	1.21	60	60
DoubleG_1	1.16	60	80
DoubleG_2	1.16	30	60
TripleG_1	0.9	60	80
TripleG_2	0.9	30	60

Table 6.03.01: Glazing Types as Variables

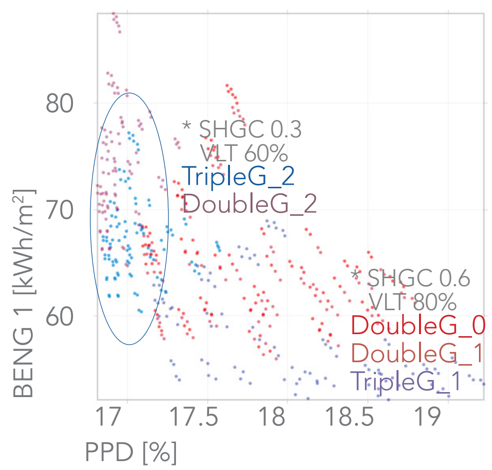
Daylight

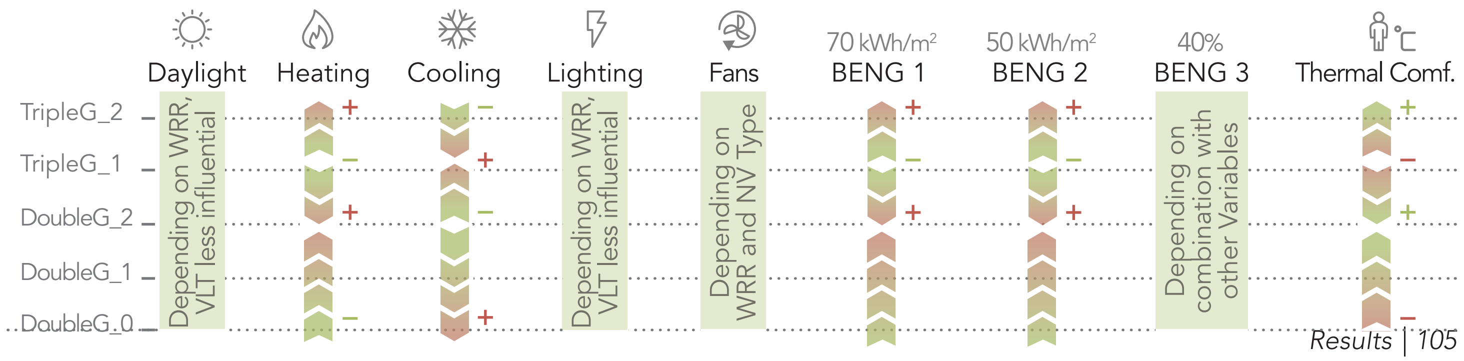


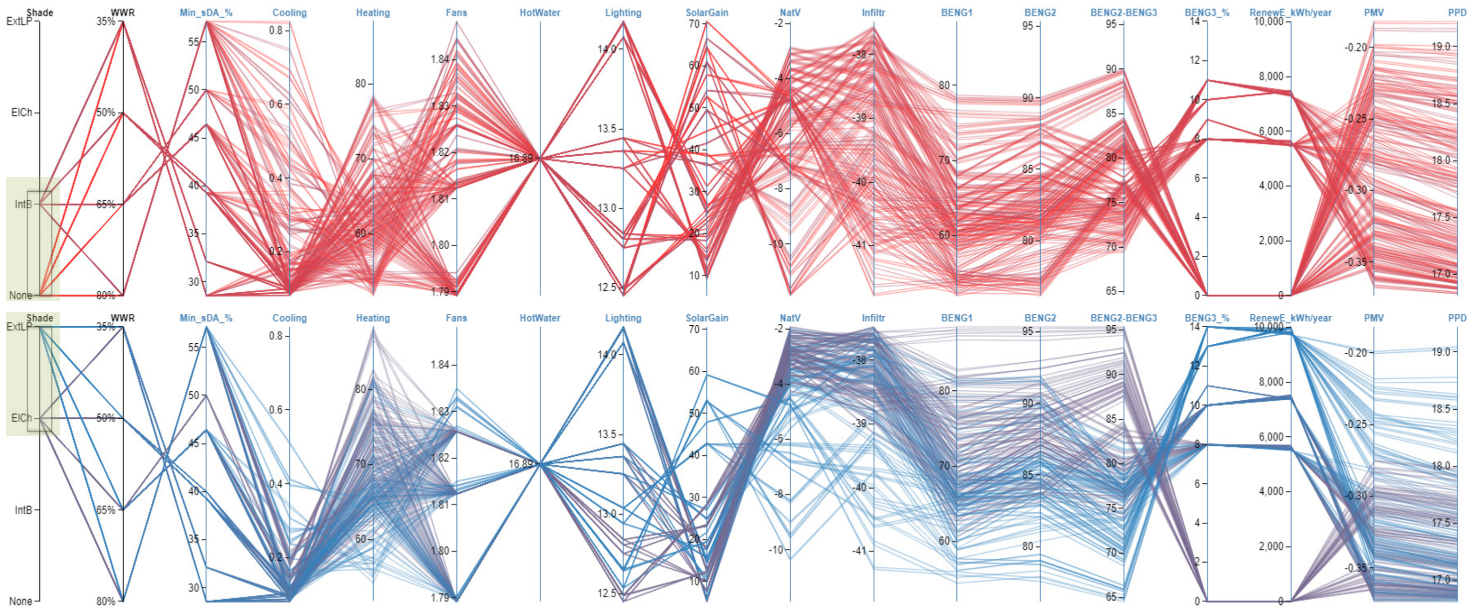
Energy Performance



Thermal Comfort







WWR & Shading

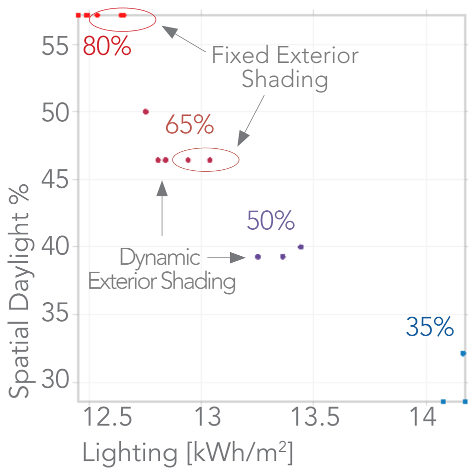
Double Glazing | NV Tilting W. | Insulation 4.5 m²K/W

Figure 5.03.06: Impact No Shading and Interior Blinds
Figure 5.03.07: Impact El.chrom. Glazing and Exterior Shading

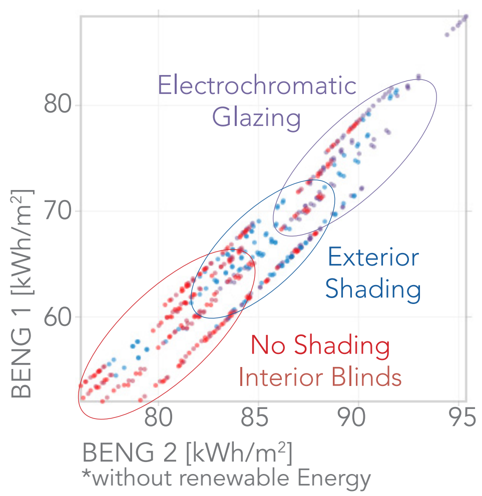
This study analyzes the effect of interior blinds, electrochromic glazing and dynamic exterior louvres for window ratios under 50%, respectively fixed exterior shading for 65% and 80% WWR. The closing level of dynamic shading is adjusted depending on the amount of incoming daylight and has therefore little effect on the electric lighting consumption. Fixed exterior shading has a bigger impact on the spatial daylight autonomy and lighting. However, in this case, the exterior shading area is small compared to the overall glazing area (65%, 80%) and the amount of incoming daylight is rather determined by the WWR.

The impact on energy is determined in combination with the WWR. For WWRs between 35% and 50%, no shading system is needed, but interior blinds can be used to slightly lower heating and cooling loads. For high WWRs, exterior shading is more efficient to reduce cooling loads. Electrochromic glazing generally leads to lower cooling loads, however the heating loads increase. In this case, electrochromic glazing leads to the lowest energy performance. The analyzed shading systems have a small impact on the indoor comfort, with only electrochromic glass having a noticeable positive effect. Thermal comfort is influenced rather by the WWR and the glazing type.

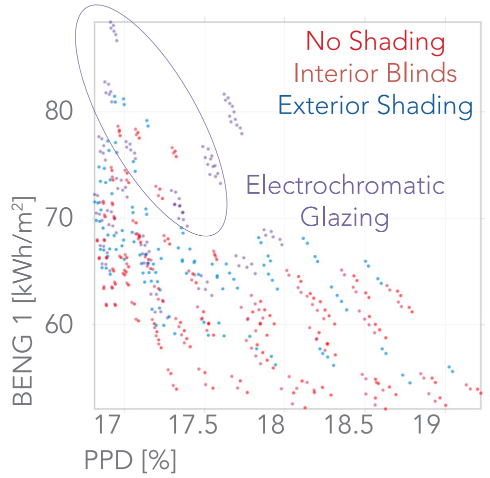
DAYLIGHT

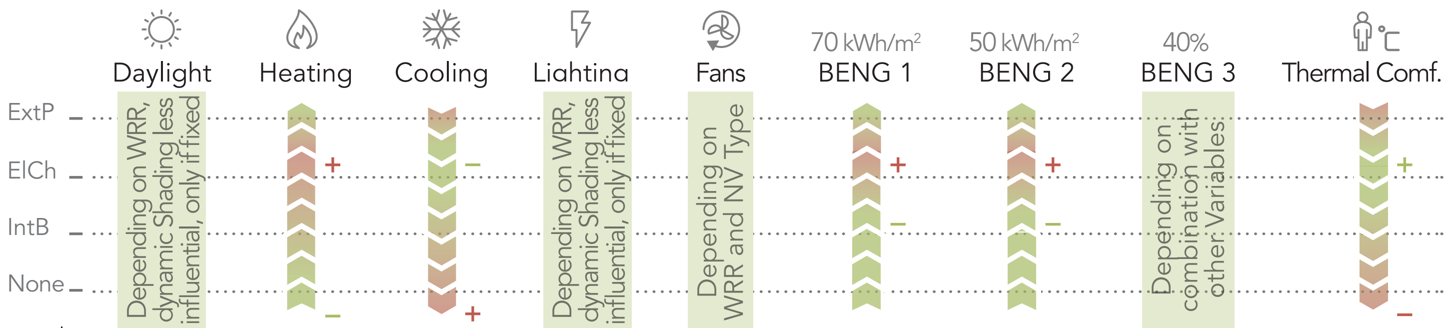


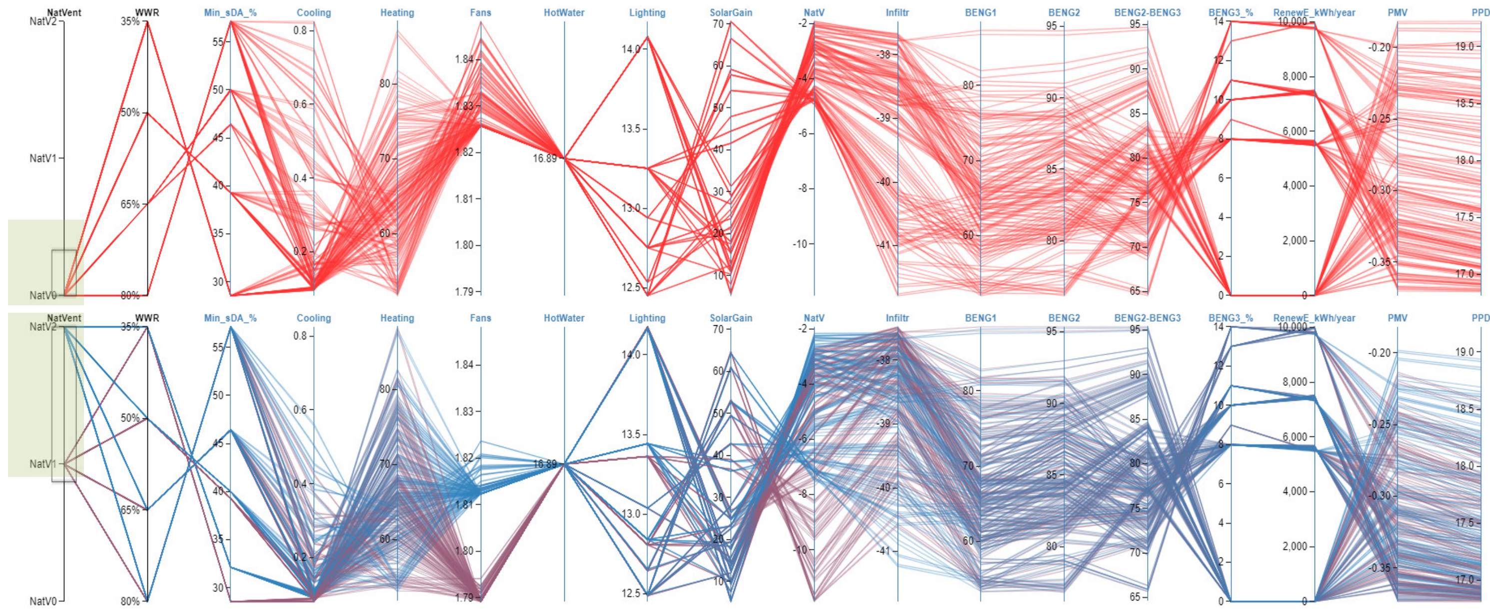
ENERGY PERFORMANCE



THERMAL COMFORT







WWR & Natural Ventilation

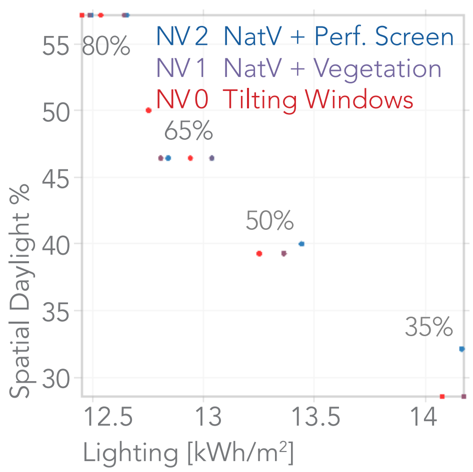
Double Glazing | No Shading | Insulation 4.5 m²K/W

Figure 5.03.08: Impact Tilting Windows
Figure 5.03.09: Impact Vegetation & Perforated Screen

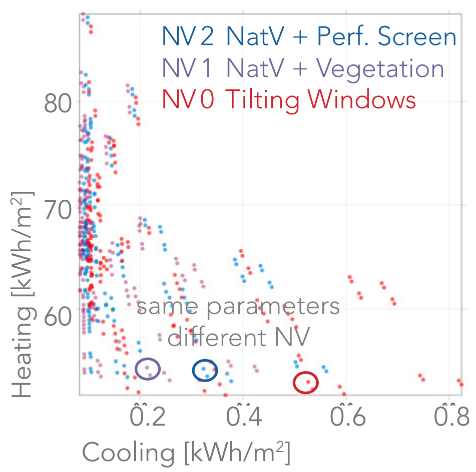
In terms of natural ventilation, three different strategies are analyzed - induced through tilting windows, and 1m wide openable windows in combination with vegetation or perforated ventilation screens. Vegetation and perforated panels generate some shade to the interior, but the impact on the spatial daylight autonomy is very small and therefore insignificant. The different strategies influence the amount of induced NV, i.e. the MV consumption. NV in combination with vegetation can reduce wind speeds up to 50% and is therefore the most efficient strategy, especially at high altitudes where wind can double in speed.

The higher the WWR, the larger also the operable glazing area, i.e. the higher the impact of NV. In combination with 65% and 80% WWR, NV in combination with vertical vegetation can minimize cooling loads considerably. NV can also reduce the need for MV, but the difference in energy used for MV is small between the different NV strategies. The NV strategy used could have a higher impact on the overall performance of office buildings, where MV and cooling loads are higher. As far as thermal comfort is concerned, an increased degree of NV in combination with vegetation or perforated screens leads to increased comfort levels.

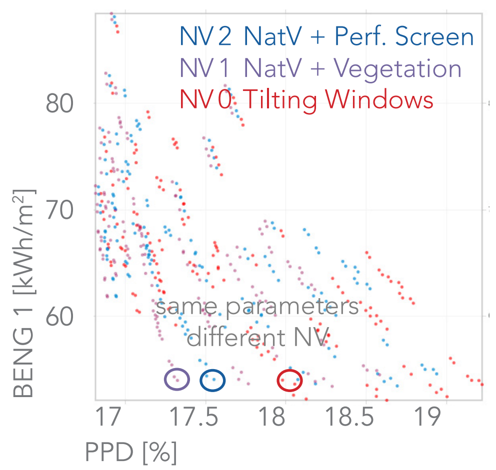
DAYLIGHT

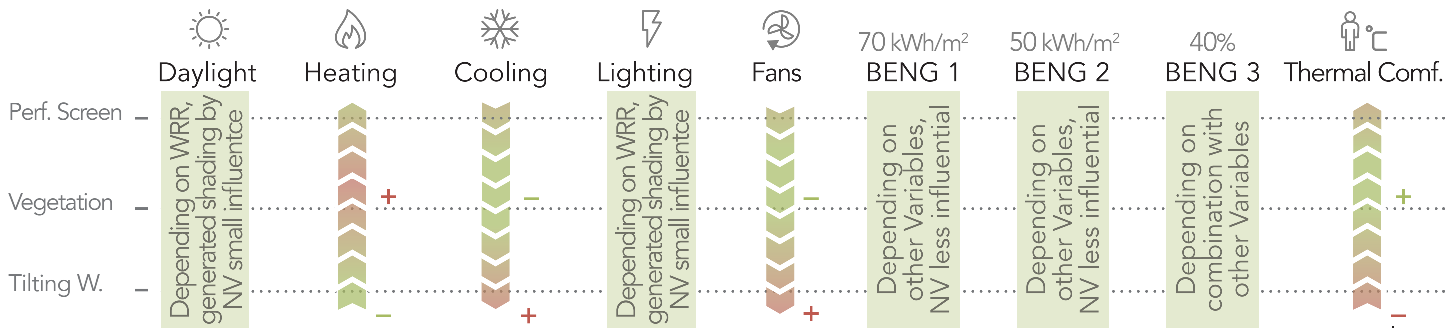


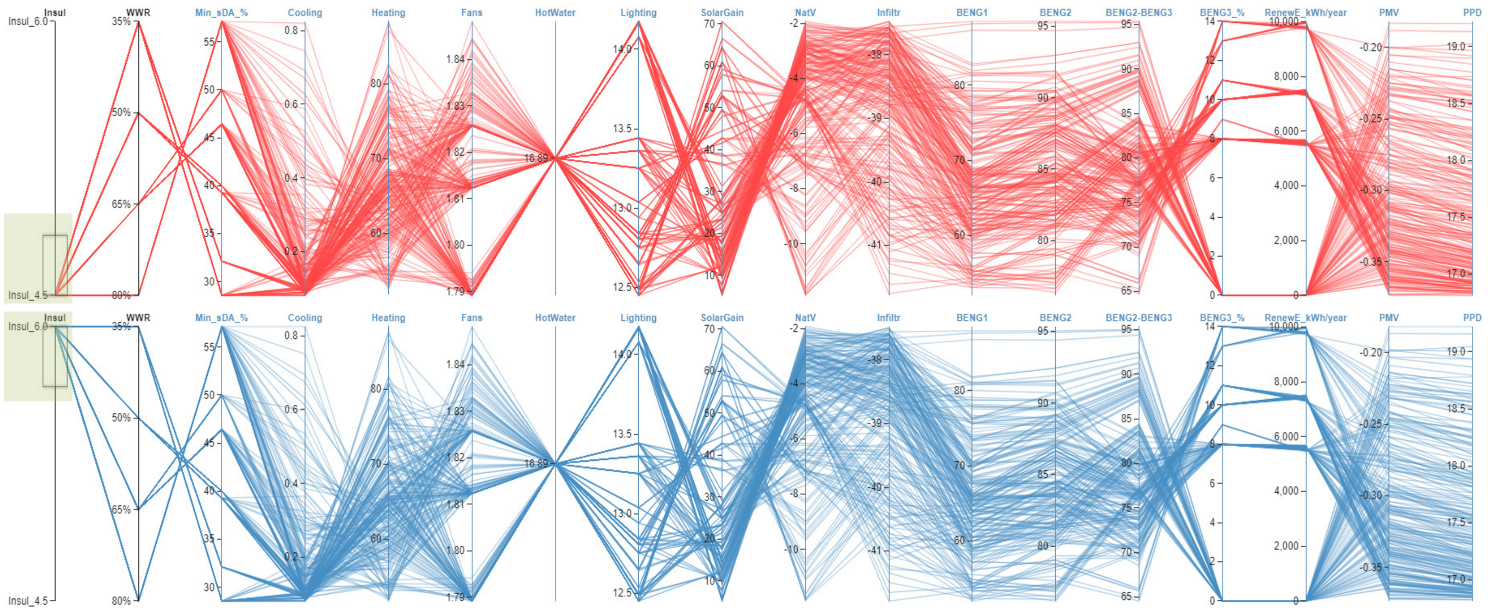
ENERGY PERFORMANCE



THERMAL COMFORT







WWR & Insulation

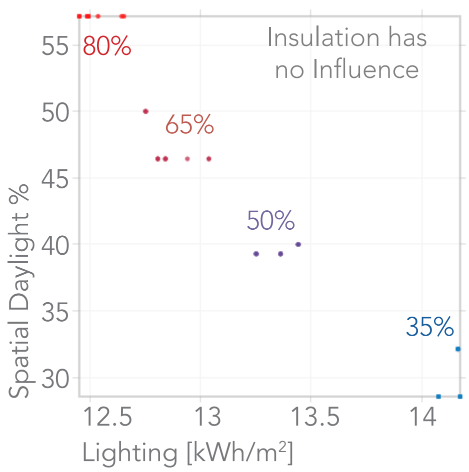
Double Glazing | No Shading | NV Tilting W.

Figure 5.03.10: Impact R-value 4.5 m²K/W
Figure 5.03.11: Impact R-value 6.0 m²K/W

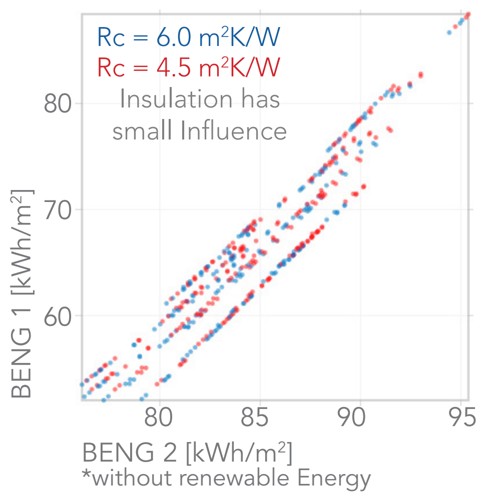
The impact of the thermal insulation on the overall energy performance is highly related to the WWR. The lower the WWR, the higher the impact of the insulation on the energy consumption. However, the analyzed insulation values, 4.5 m²K/W and 6.0 m²K/W, do not have a significant effect on energy consumption and the difference between the results is small.

Other variables such as WWR, glazing type and shading are more important to be optimized in order to increase the overall energy performance. Nevertheless, as a general rule, it can be concluded that higher R-values can reduce heating loads due to lower heat losses and slightly increase cooling loads. Thermal insulation has no noticeable effect on the indoor comfort conditions.

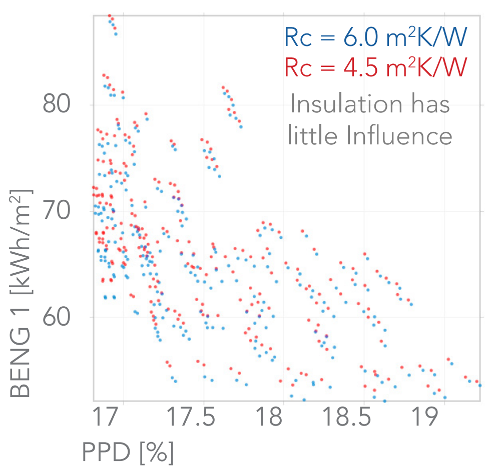
Daylight

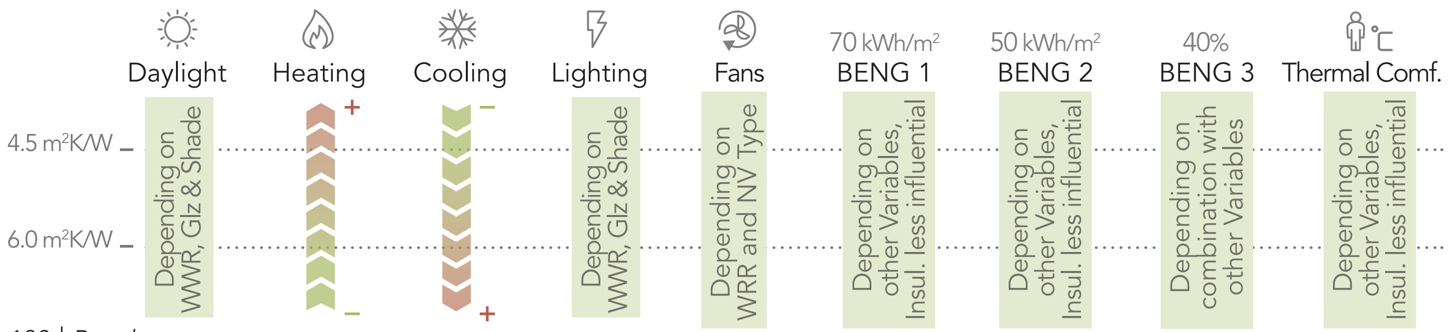


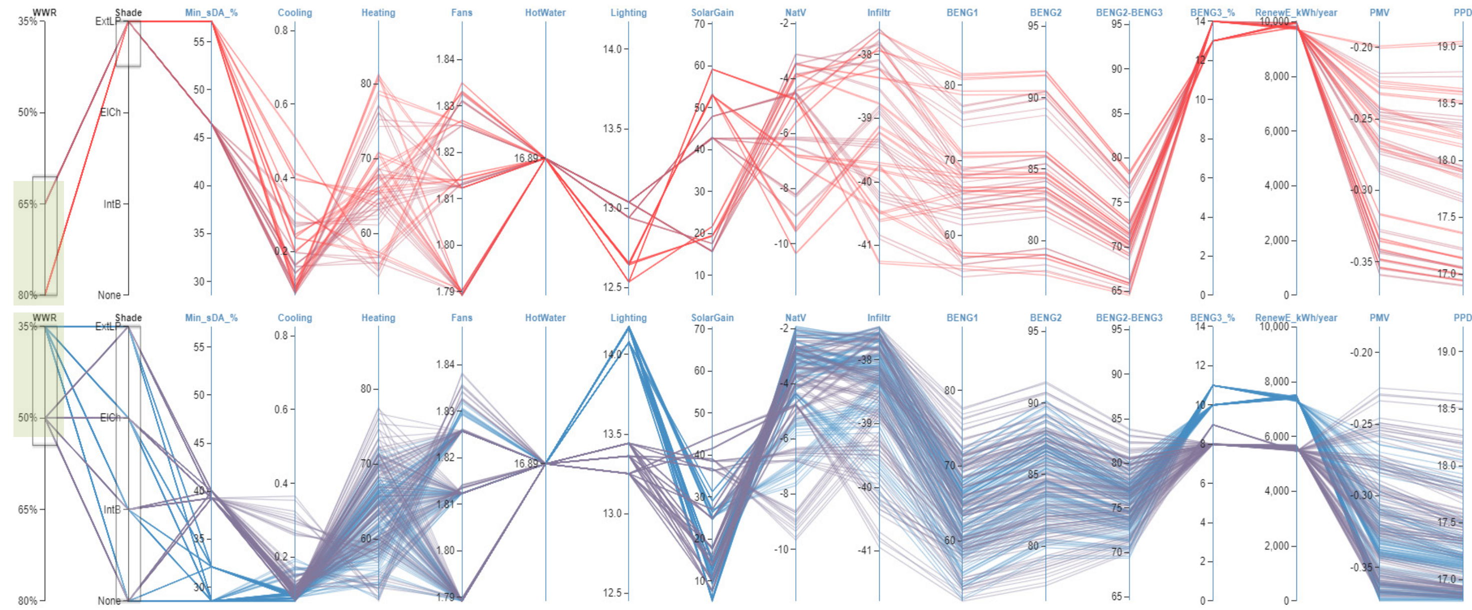
Energy Performance



Thermal Comfort







WWR & Energy Production

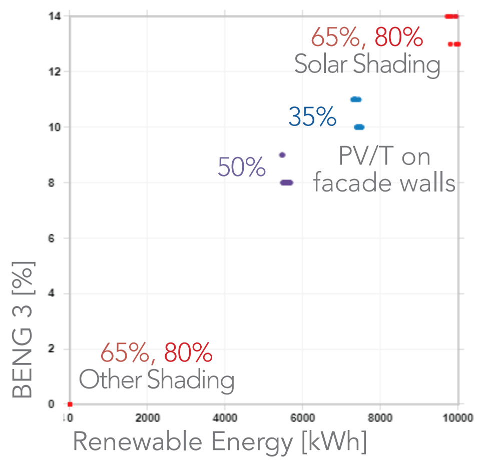
Double Glazing | No Shading | NV Tilting W. | Insulation 4.5 m²K/W

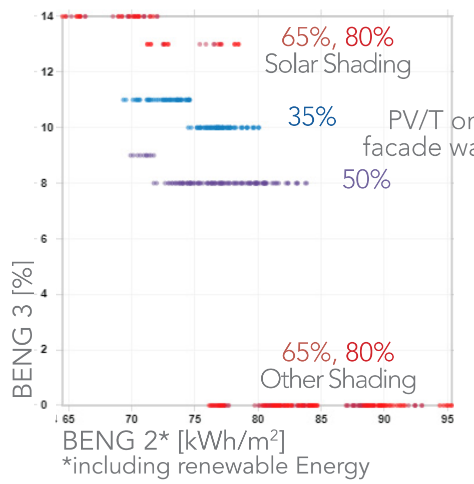
Figure 5.03.12: Impact Energy Production WWR 35% & 50%
Figure 5.03.13: Impact Energy Production WWR 65% & 80%

In order to reach future energy regulations, energy generating systems will need to be integrated onto the facade of future high-rise buildings. The amount of area available for energy production is to date determined by the WWR. The lower the WWR, the more area available for harvesting energy. The higher the WWR, the less space is available between the windows to integrate PV/T panels. For 35% glazing, PV/T panels with 6 rows of PV cells can fit on the facade walls. For 50% glazing, only 4 of PV cells can fit between the windows. In case of higher WWRs, standard PV/T panels can no longer fit between the windows.

This study proposes the use of energy generating shading to produce energy, while still providing a high degree of transparency with increased glazing levels. Solar shading is only applied for 65% and 80% WWRs, as there is insufficient area for PV/T panels to be mounted on the facade walls. The area of the solar shading is approximately the same area available for PV/T in case of 35% WWR. However, it can be noticed that PV/T solar shading with 45° degree inclination leads to lower values for BENG 2*, compared to BIPV/T units mounted vetically on the walls at 90° for 35% WWR. BENG 3 is also slightly higher, as pointed out in the table below.

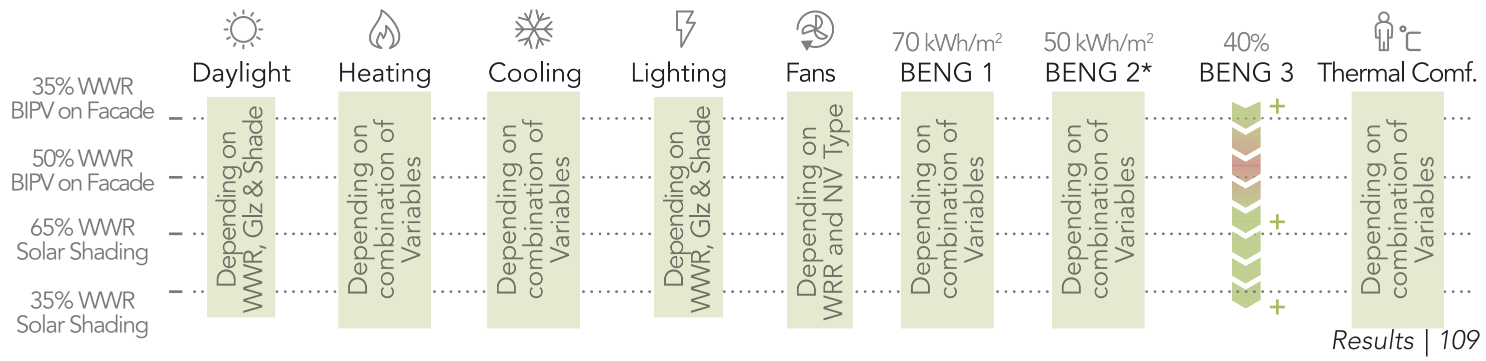
Energy Performance





WWR	Area PV/T	BENG 3
	[m²]	*[%]*
35%	40	11%
50%	29	8%
65%	43	13%
80%	43	13%

Table 6.02.03: Energy Production in relation to WWR



5.03.02 Outdoor Comfort

25m vs. 130m

A particular feature of the facade of residential high-rises are the balconies. Therefore, another important aspect needs to be addressed when designing the facade of a high-rise building - the outdoor comfort. Wind can reach unpleasant speeds at high altitudes and the amount of time spent on the balconies is reduced due to the unpleasant outdoor conditions.

The percentage of time comfortable outside is determined by calculating the Universal Thermal Climate Index (UTCI) using the Ladybug component for outdoor comfort. The UTCI is the temperature of what the weather "feels like" and is calculated by taking into account radiant temperature, relative humidity, and wind speed. A UTCI between 9 and 26°C indicates no thermal stress, so comfortable conditions outdoors. A UTCI between 26 and 28°C indicates slight heat stress, respectively between 0 and 9°C, slight cold stress (comfortable for short periods of time).

Analyzing the results of the Outdoor Comfort Simulation it became clear that the high wind speeds blowing from SW prevent the occupants from using the balconies facing W. The percentage of time spent on the balconies facing N or S is not much higher either.

	25m		130m	
Orientation	Summer May-Aug	Annual	Summer May-Aug	Annual
North	41%	20%	24%	11%
East	67%	27%	53%	20%
South	50%	20%	31%	12%
West	40%	17%	20%	8%

Table 5.03.02: Percentage of daytime comfortable on balconies

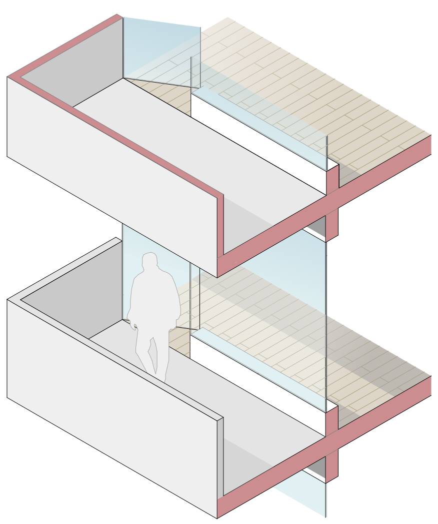


Figure 6.03.14: Outdoor Comfort Balconies

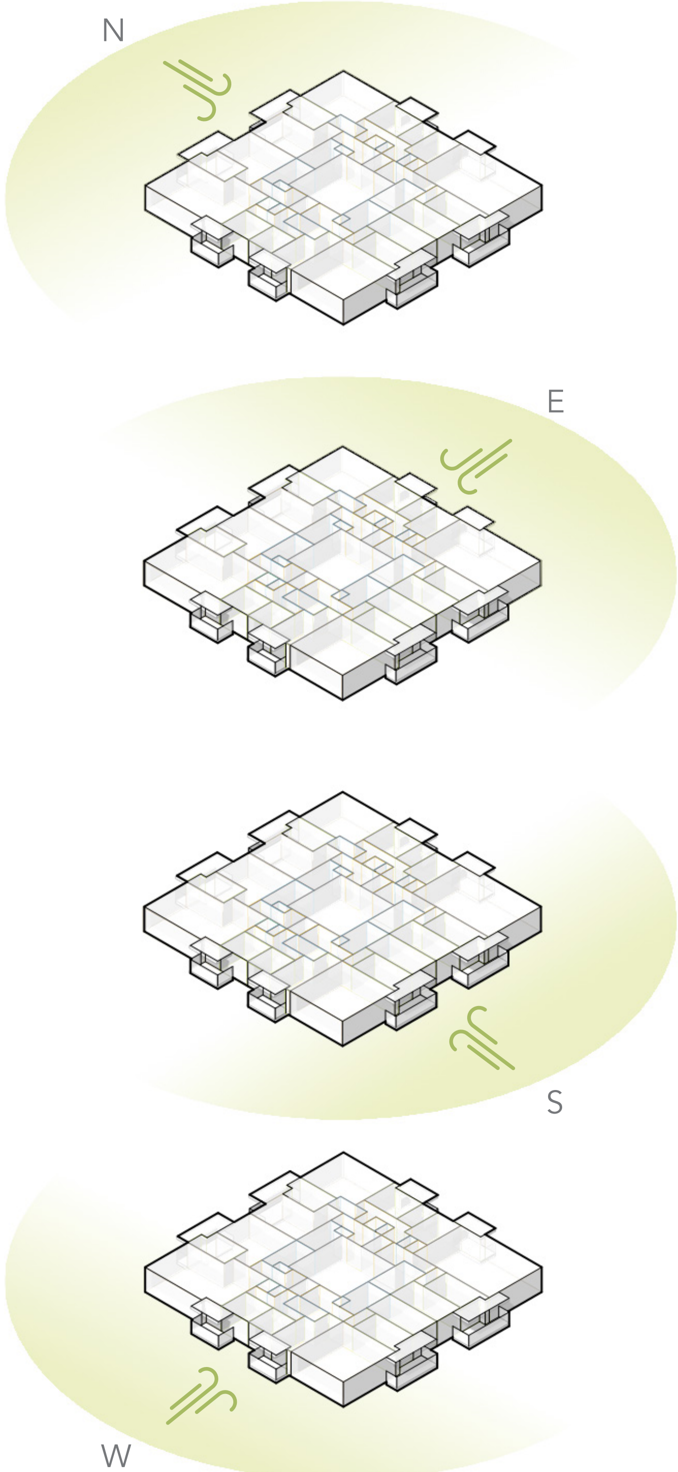


Figure 6.03.15: Wind Directions

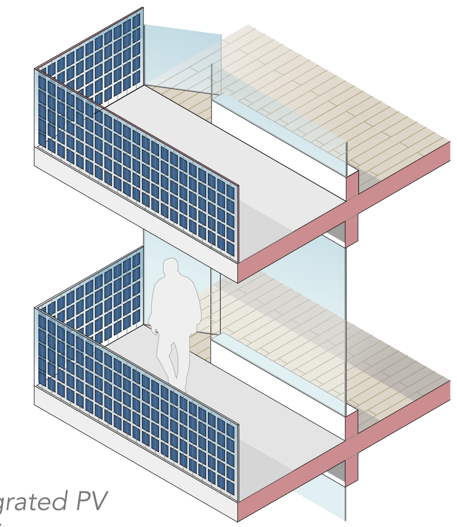


Figure 6.03.16: Integrated PV cells in balcony railing

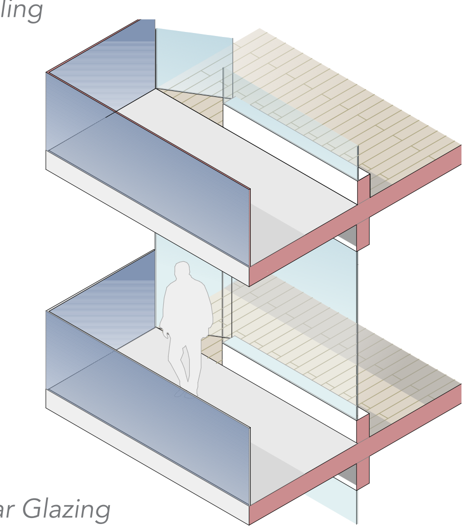


Figure 6.03.17: Solar Glazing as balcony railing

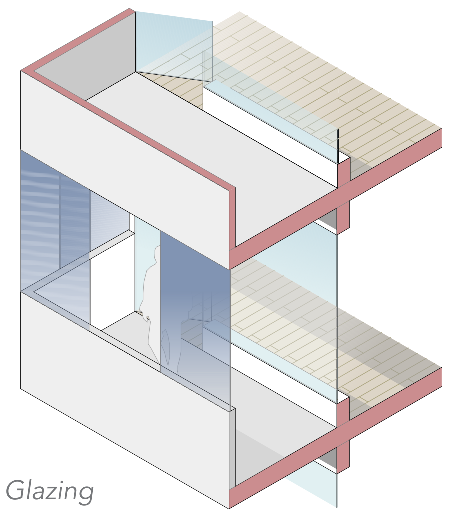


Figure 6.03.18: Solar Glazing as balcony shutters

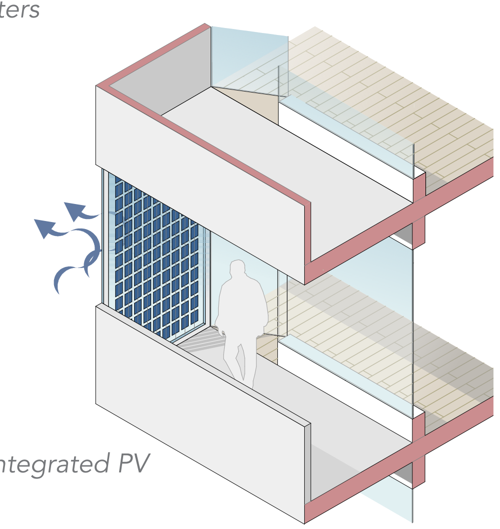


Figure 6.03.19: Integrated PV cells in sidewall

Energy Design Balcony	PV Area [m^2]	Efficiency [%]	Energy Output [kWh per year per floor]	[kWh/m^2 per year per floor]
BIPV Balcony	80%*78	20%	4256	5.7
Solar Balcony	78	7%	1862	2.5
Solar Shutters	100	7%	2363	3.2
BIPV Sidewalls	80%*68	20%	3687	4.9

Table 5.03.03: Output of Energy Generating Accessories

In order to improve the outdoor comfort on the balconies, these would need to be closed at higher levels, especially on the W facade. Several design options were analyzed with transparent solar glazing or with integrated PV cells in balcony railing and balcony shutters.

Combined with energy generating units, the last two design scenarios would be the most efficient if outdoor comfort conditions are taken into consideration, because increased protection is provided against wind. *Table 5.03.03* shows the energy produced with each design choice. The last design option will be taken into consideration for the redesign, because it is the second-best option in terms of generated energy while offering some protection against wind. The additional energy produced will be added to the energy produced on the facade and BENG 2* and BENG 3 will be recalculated for the chosen facade design.

06

Redesign

6.01

Redesign

In order to decide on the most beneficial facade parameter combination, all the results were ranked in terms of primary energy consumption (Beng 2*) and thermal comfort (*Figure 6.01.01*). It becomes obvious that thermal comfort has a conflicting influence over the total energy consumption. Therefore, it is impossible to achieve both objectives simultaneously. Subsequently, a design was chosen which has a balancing effect on fulfilling both comfort and performance.

The following facade design combination is proposed in order to improve the efficiency of the building to the targeted efficiency limits and provide acceptable indoor comfort conditions. A high WWR of 65% was chosen in combination with triple glazing, in order to make use of solar gains. Triple glazing with a high SHGC and VLT allows for incoming radiation while the low U-value helps to conserve the energy. A high insulation value of 6.0 m^2K/W additionally prevents heat losses.

In order to prevent overheating and keep cooling loads at a minimum, exterior shading is applied with integrated PV/T units. In addition, NV combined with vertical vegetation helps to induce cool air in summer at comfortable speeds and reduce the amount of MV. This NV strategy is the most effective at higher altitudes to draw air inside the building, because it can reduce wind speeds up to 50%, therefore maximizing the amount passive cooling, i.e. reduce active cooling.

PV/T units are mounted in front of the glazing to generate energy, while still allowing for some incoming daylight. The energy generated on the facade alone is insufficient to reach BENG 2*. Therefore, solar cells were integrated on the balcony sidewalls to increase the energy production while providing some protection against wind (*Chapter 6.03*). Taking into consideration the energy produced on the facade, the balconies and on the roof of the adjacent garage building, BENG 2* is achieved for 25m and lies slightly above the 50 kWh/m^2 limit at 130m. The total amount of primary energy produced is around 26 kWh/m^2 per year with BENG 3 reaching 25%, unable of reaching the 40% requirement with the energy production elements integrated on the facade alone.

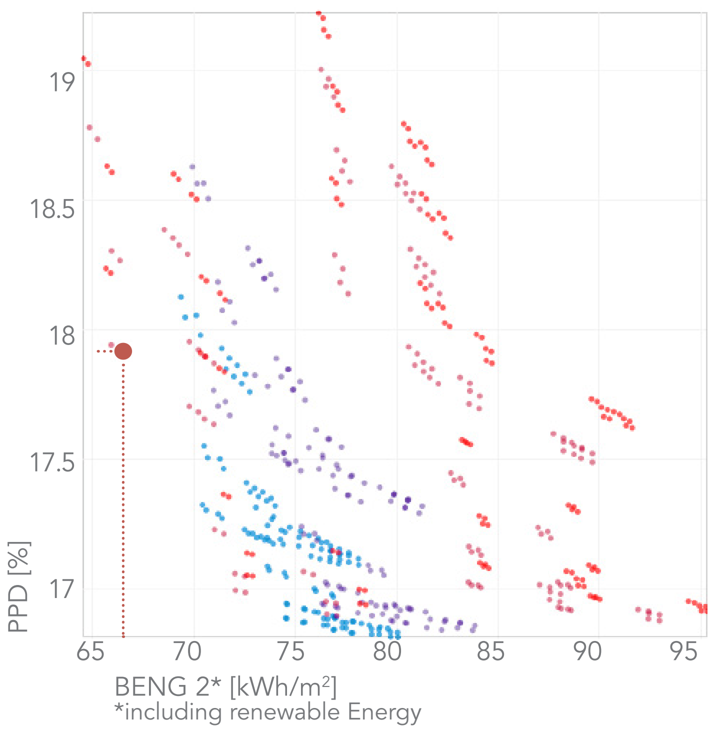


Figure 6.01.01: Ranking Results based on Primary Energy Need and Thermal Comfort

The average PMV per floor is within the +/- 0.5 limit, taking negative values because the toilet rooms, storage rooms, corridors and core area are not heated and therefore affect the overall result. People feel slightly cold in these rooms but the occupancy in these rooms is low and only for a short period of time. However, the PMV does not take occupancy into consideration.

The average PPD is above the target limit of 10%. Nevertheless, reaching a satisfaction rate of 90% is very difficult and most engineers aim for a PPD of 20%. That being said, the indoor comfort conditions can be assumed as being acceptable. However, the indoor comfort conditions cannot be reviewed based on the PMV and PPD values alone. Chapter 6.03 investigates the percentage of time comfortable per room in order to avoid possible overheating problems, given that the chosen WWR of 65% is quite high

Redesign Solution 25m / 130m

WWR : 65%
Glass : TripleG_0.9_0.6_0.8
Shade : Exterior Panels
NatVent : NatV1 (Veg. Layer)
Insul : Insul_6.0

Min_sDA_% : 46.43% of floor area
UGR 22.4 (>19)

Cooling : 0.1 / 0.2 kWh/m^2 per year
Heating : 51 / 56 kWh/m^2 per year
Fans : 1.7 / 1.8 kWh/m^2 per year
HotWater : 16.89 kWh/m^2 per year
Lighting : 13 / 13 kWh/m^2 per year
SolarGain : 42.8 / 42.9 kWh/m^2 per year
NatV : -15 / -9 kWh/m^2 per year
Infiltr : -36 / -39 kWh/m^2 per year

BENG1 : 51.3 / 56.2 kWh/m^2 per year
BENG2 : 76 / 79 kWh/m^2 per year
BENG2-BENG3* : 50 / 53 kWh/m^2 per year
BENG3*: 25.4% / 24.7%
* including energy production

PMV : - 0.27 / -0.26
PPD : 16% / 18%

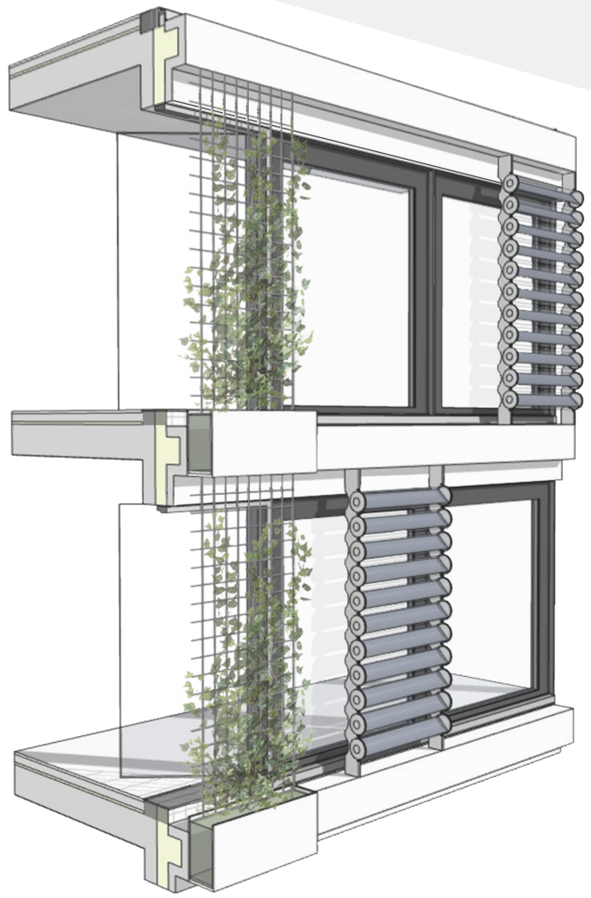


Figure 6.01.02: Redesign Proposal

Source: V8 Architects, n.d. (Redesigned)

25m

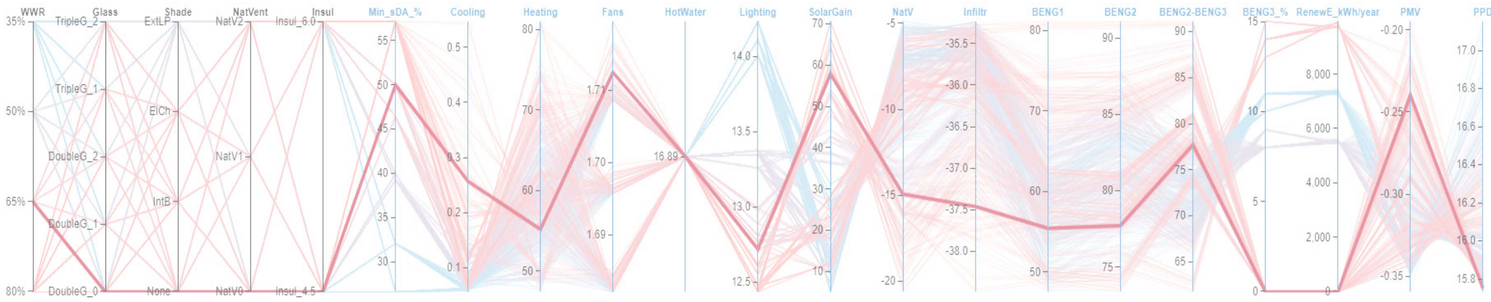


Figure 6.01.02: Current Performance 25m

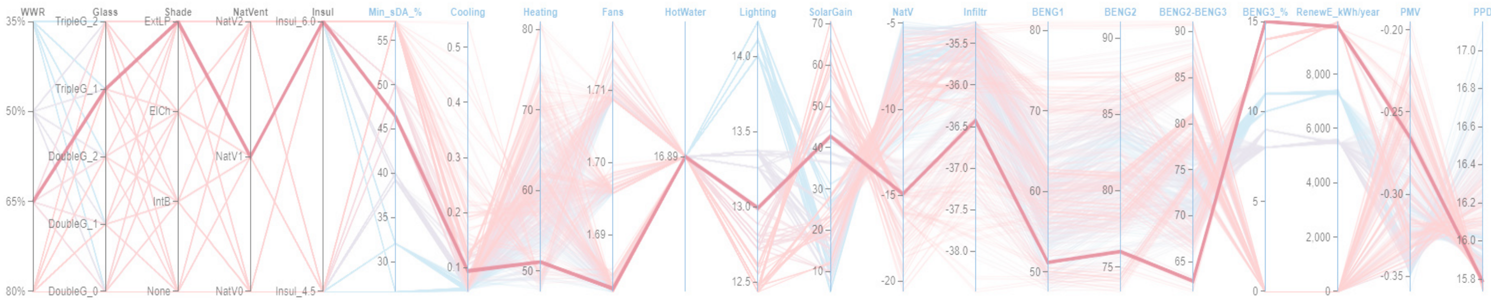


Figure 6.01.03: Performance Redesign 25m

	Daylight	Heating	Cooling	Lighting	Fans	70 kWh/m^2 BENG 1	50 kWh/m^2 BENG 2	40% BENG 3	Thermal Comf.
Redesign	46%	51	0.1	13	1.68	51	50	25%	16.3%
Now	50%	55	0.26	12.7	1.71	55	78	0%	16.6%

130m

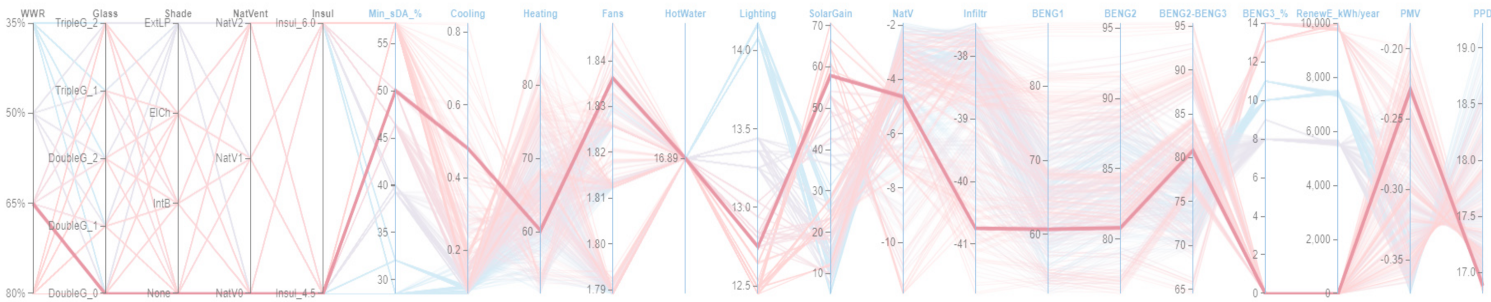


Figure 6.01.04: Current Performance 130m

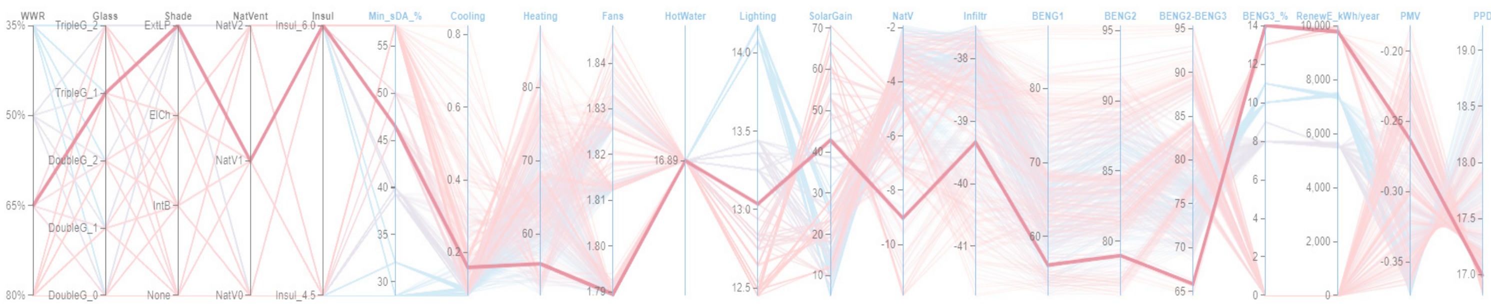


Figure 6.01.04: Performance Redesign 130m

	Daylight	Heating	Cooling	Lighting	Fans	70 kWh/m^2 BENG 1	50 kWh/m^2 BENG 2	40% BENG 3	Thermal Comf.
Redesign	46%	56	0.2	13.03	1.79	56	53	25%	17.9%
Now	50%	60	0.5	12.75	1.84	61	81	0%	18.5%

6.02
Energy Perfomance

For the chosen facade redesign proposal, the energy consumption was analyzed more in detail by looking at the amount of heating and cooling required for each room to reach the specified setpoints. As already mentioned in *Chapter 4.02.10*, a setpoint of 21°C for heating, respectively 28°C for cooling was specified.

The rooms presented with radiant floors for heating/cooling are the kitchens/living rooms, bedrooms and bathrooms. The figures below show the heating and cooling schedules for one room of each function. *Appendix B* provides an overview of the heating and cooling schedules for every room.

Due to the increased floor area and the limited amount of solar gains, the biggest amount of heating is needed for the kitchens/living rooms orientated towards the north. On the other hand, the bedrooms orientated towards the south barely require any heating. Then again, the bathrooms are heated very often in order to reach the 21°C target temperature. This indicates that a lower setpoint should have been applied for the bathrooms in order to avoid heating in summer or floor heating should have been not assigned to bathrooms. Nevertheless, the total amount of heating recorded in summer represents only 6% of the total heating loads and therefore does not affect the results.

The cooling loads are far lower than the heating loads. Due to the reduced floor area and the increased amount of solar gains, the biggest amount of cooling is needed for the bedrooms orientated towards the south, east and west. Then again, the bathrooms happen to be also cooled in summer in order to ensure a comfortable indoor temperature. In reality, this could be a problem because radiant floor cooling might turn on while taking a shower, due to the increased temperature inside the room. Therefore, radiant floor cooling should not be integrated in bathrooms. The total amount of cooling in the bathrooms represents only 5% of the total cooling loads and therefore does not affect the results.

Appendix B includes detailed information on the total amount of heating and cooling hours for each room as well as on the minimum and maximum temperature ranges.

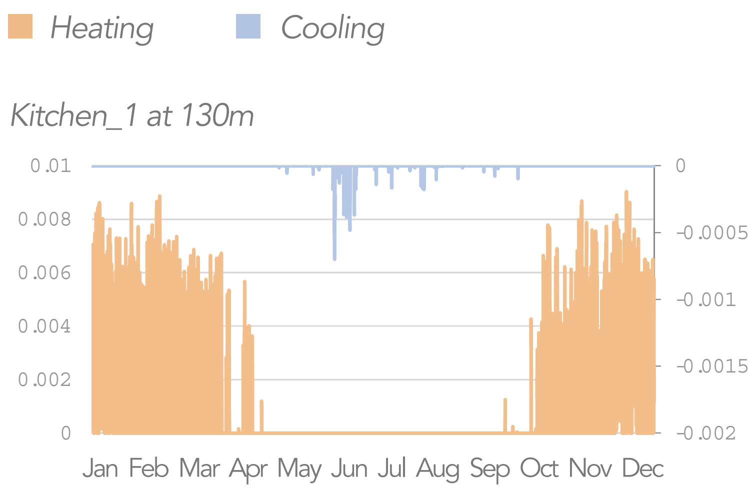


Figure 6.02.01: Heating/Cooling Schedule Kitchen_1

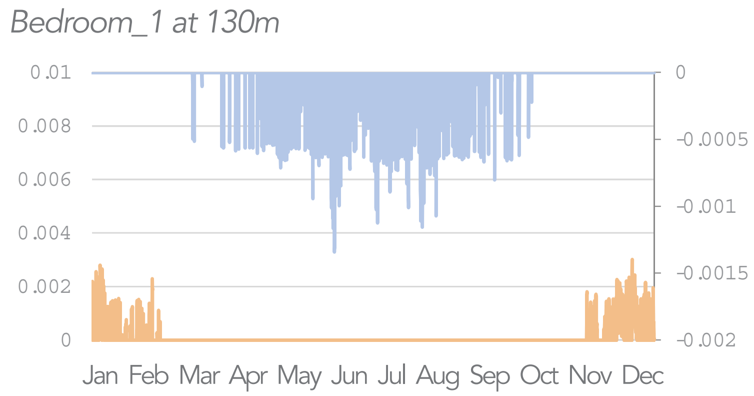


Figure 6.02.02: Heating/Cooling Schedule Bedroom_1

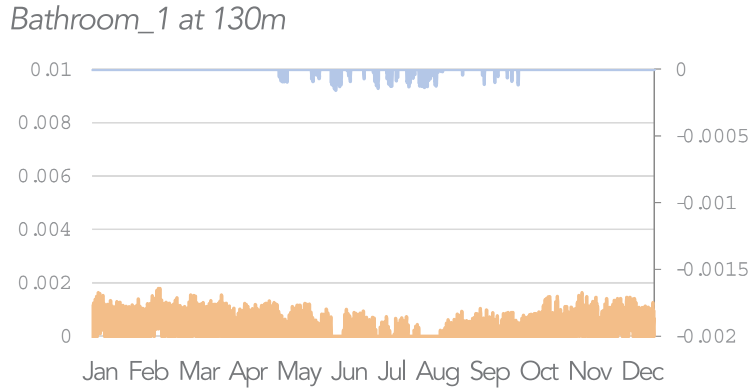


Figure 6.02.03: Heating/Cooling Schedule Bathroom_1

6.03
Thermal Comfort

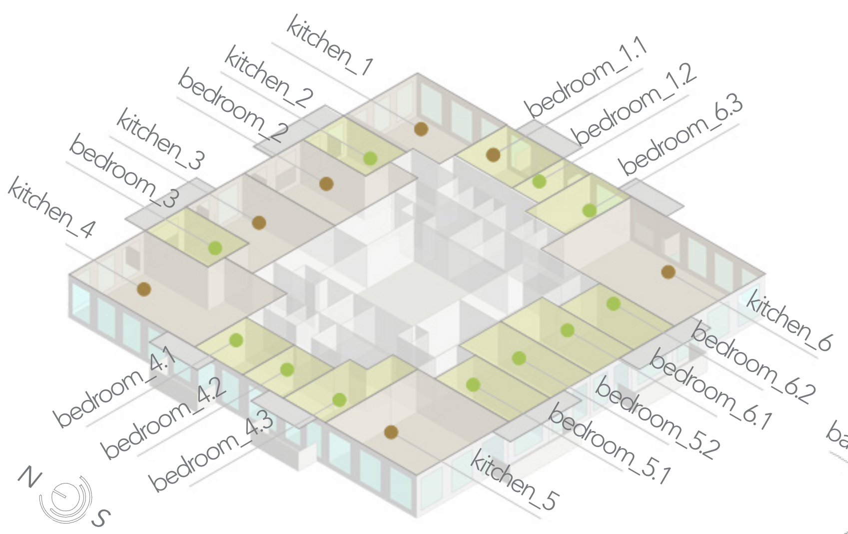
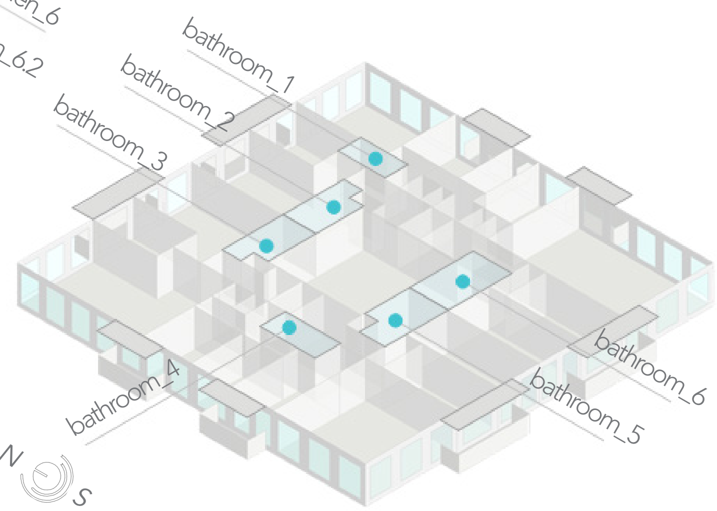


Figure 6.03.01: Location Kitchens/Living Rooms & Bedrooms

Figure 6.03.02: Location Bathrooms



This Chapter shows the percentage of time comfortable in each room with the proposed facade redesign. High WWRs have been found to lead to possible overheating problems in summer, respectively increased heat losses in winter and could therefore lead to uncomfortable indoor comfort conditions. The percentage of time comfortable was investigated for the zones provided with radiant floor heating/cooling - the kitchens/living rooms and bedrooms located at the facade and the bathrooms. As can be deduced from *Figure 6.03.03*, the percentage of time when the occupants feel too cold is below 8% and is therefore not so much a concern.

On the other hand, the percentage of time when the occupants feel too hot exceeds 10% in some rooms, reaching up to 19% in bedroom 5.2, as can be seen in *Figure 6.03.04*. The rooms which are more prone to overheating are the bedrooms between the balconies, orientated towards the east, south and west, which have not been equipped with any type of shading. It was assumed that the shadow projected by the balconies will prevent the rooms from overheating. However, this was not the case. For all the other rooms presented with exterior shading, the percentage of time feeling too hot is below 3%.

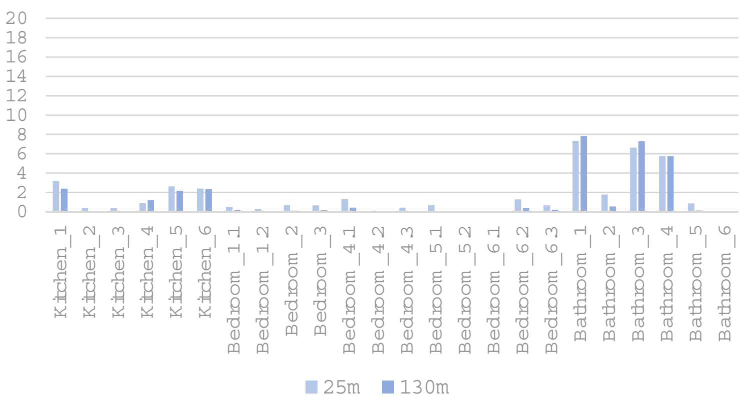


Figure 6.03.03: Percentage of Time Feeling Too Cold

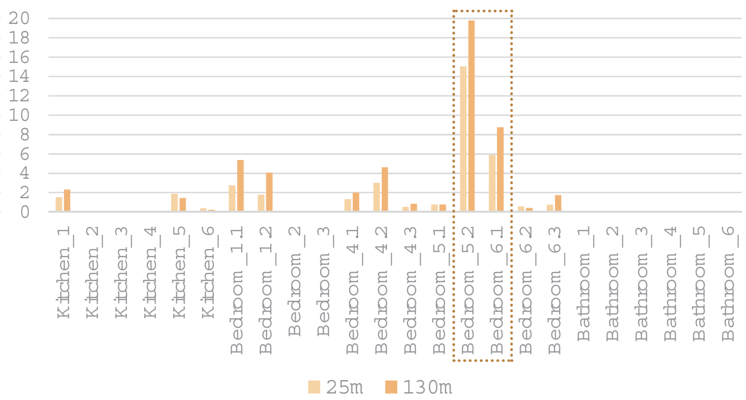
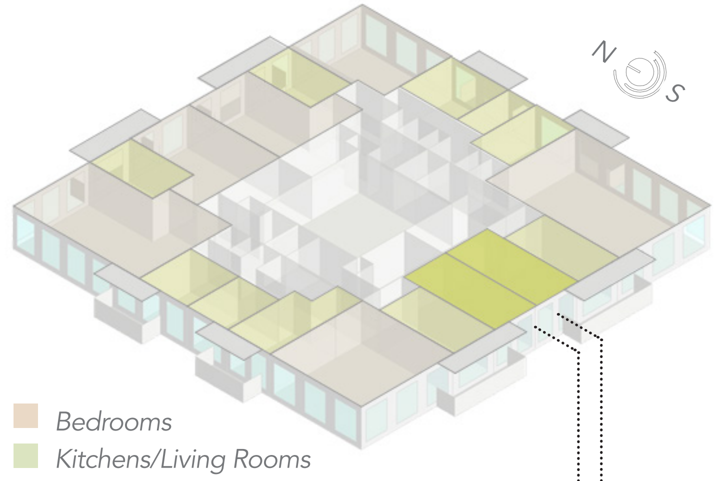


Figure 6.03.04: Percentage of Time Feeling Too Hot

In order to reduce the overheating period, the WWR was reduced to 50% and interior blinds were integrated for the concerning bedrooms - bedroom 5.2 and 6.1, orientated towards the south. *Figure 6.03.05* shows a reduction in 'percentage of time feeling too hot' from 20% to 8% for bedroom_5.2, respectively from 9% to 2% for bedroom_6.1. For all the other rooms, the chosen facade design combination is applied, as the percentage of time feeling too hot does not even exceed 6%. Now, the facade redesign proposal leads comfortable indoor conditions for the occupants for more than 90% of the time, as demonstrated in *Appendix B*.



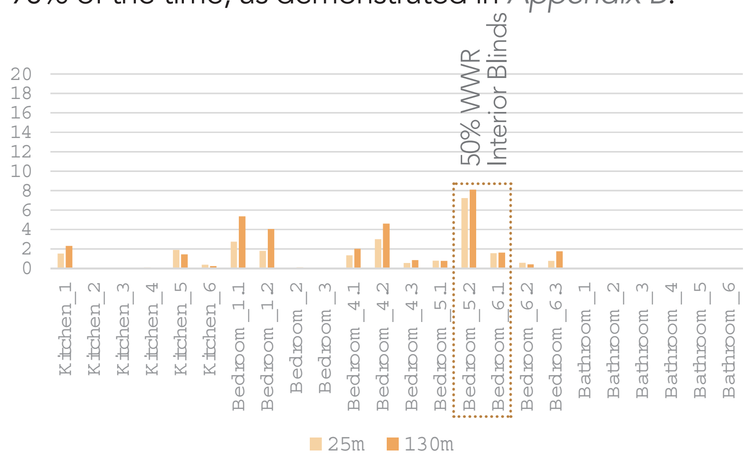
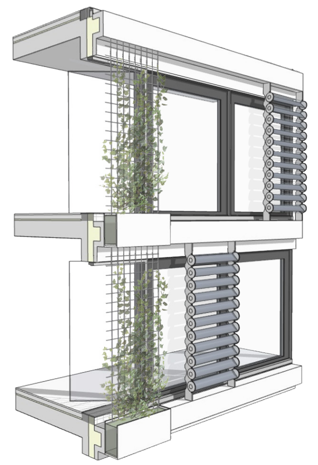
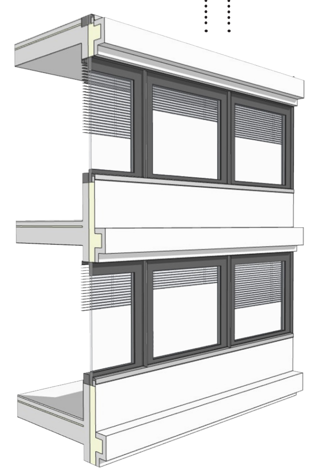


Figure 6.01.05: Percentage of Time Feeling Too Hot



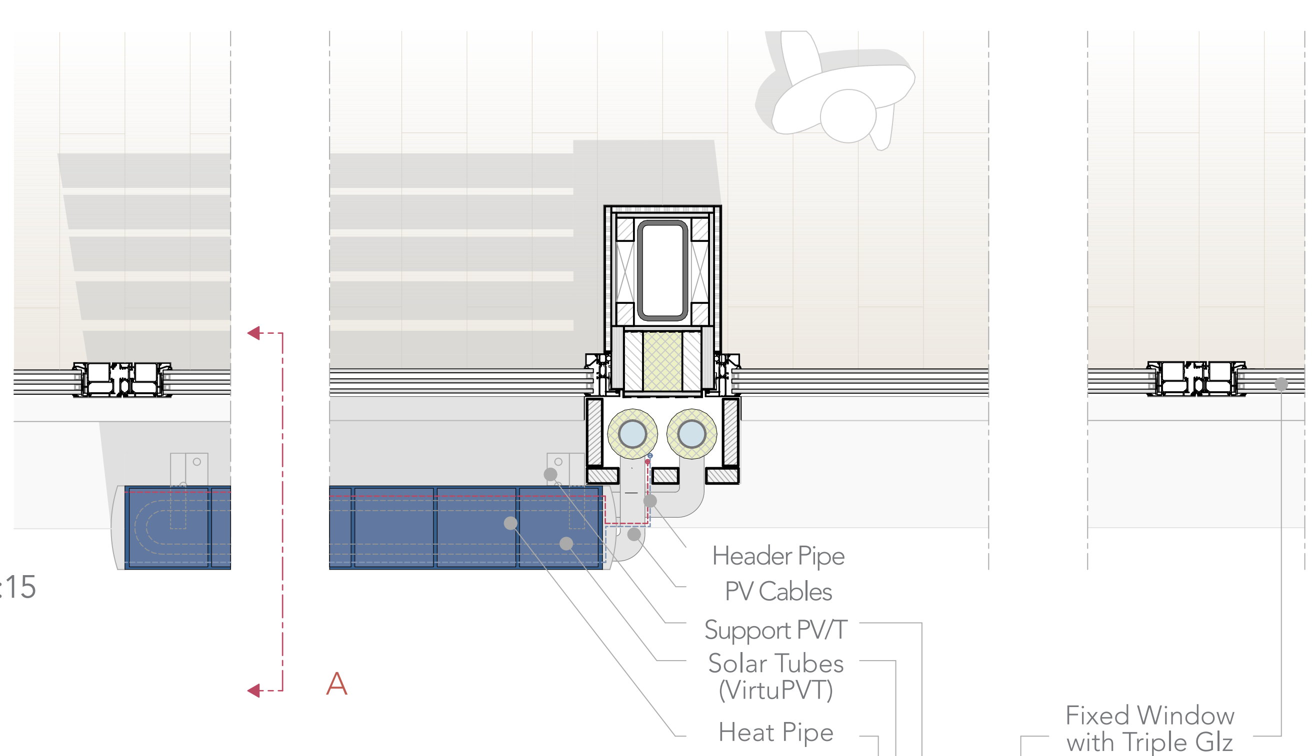
65% WWR, Triple Glazing, PV/T Shading, NV with Vegetation, 0.6 m²K/W



50% WWR, Triple Glazing, Interior Blinds, Tilting Windows, 0.6 m²K/W

6.04
TECHNICAL DETAILS

Figure 6.04.01: Horizontal Section Solar Tubes



The technical details were adapted to the redesign proposal as depicted in the horizontal and vertical sections M 1:15. The solar vacuum tube technology by *Naked Energy* was used as energy generating source on the facade. Unlike conventional PV/T panels, the hybrid solar tubes developed by *Naked Energy* can be installed on the facade at an angle. By inclining the PV/T units at 45 °, the annual energy production is 2.8 times higher compared to vertically mounted PV/T panels.

The diffuse reflector surface mounted between the tubes was removed in order to allow daylight to penetrate between the units. However, removing the reflector surface might reduce the efficiency of each PV/T unit. The proposed design includes 12 x 1m wide PV/T tubes with a visual field between the units of approx. 10cm. The larger the distance between the tubes, the more light can enter the room, i.e. the smaller the energy production area.

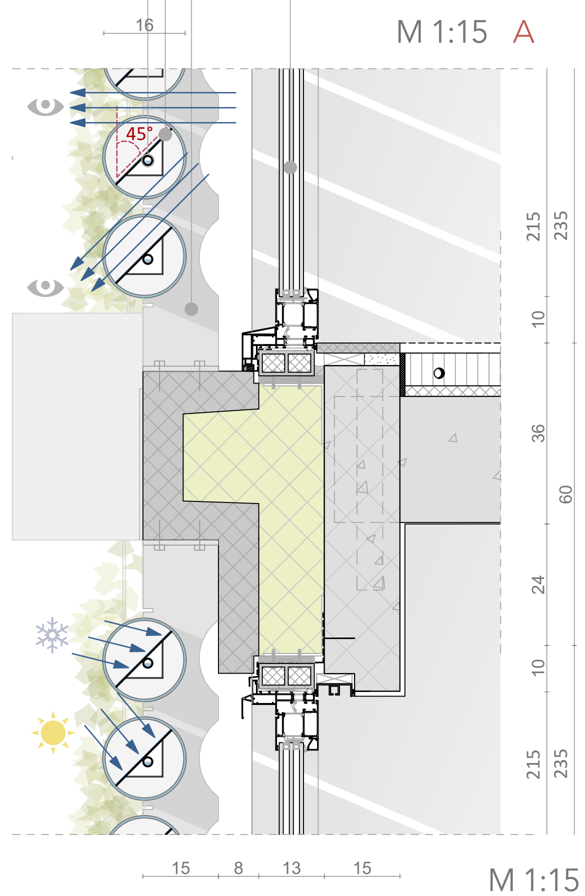
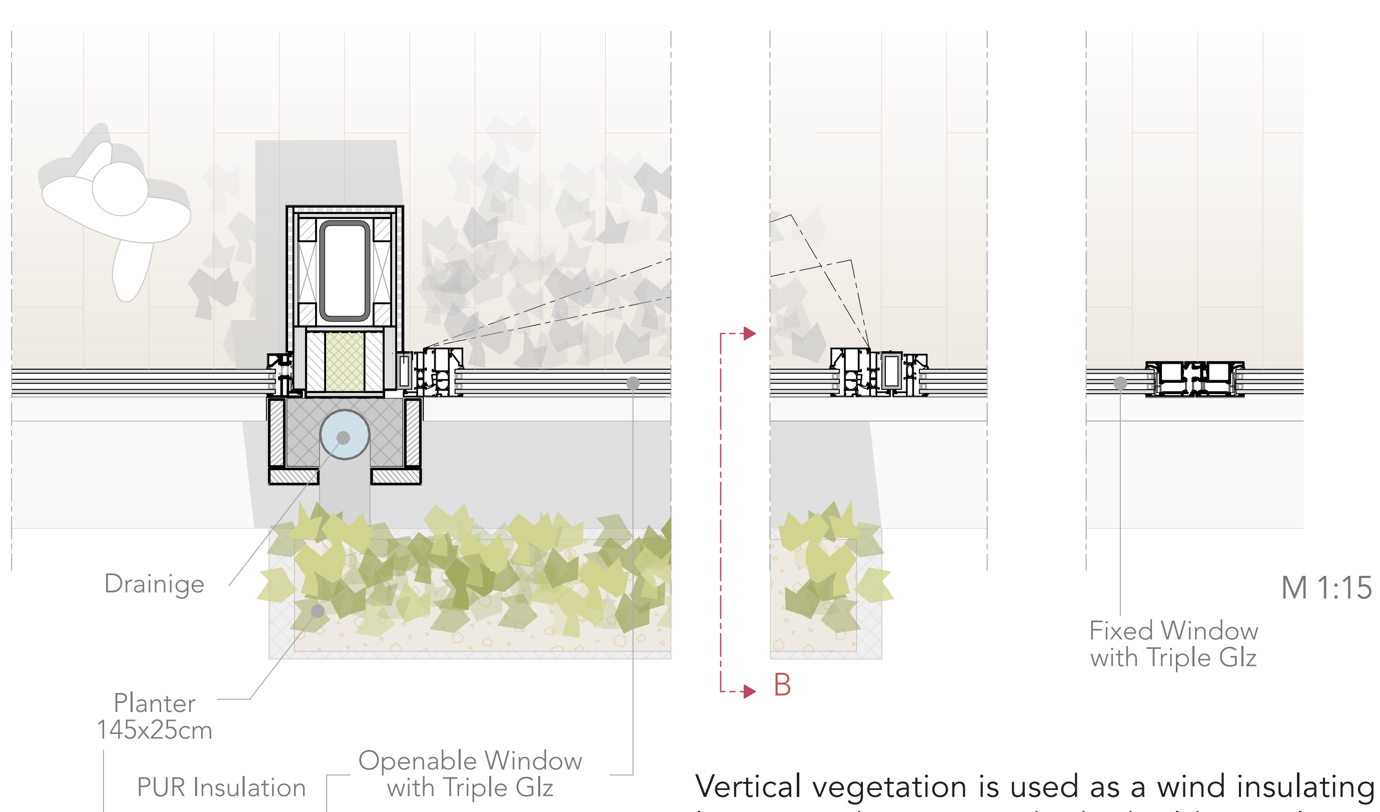


Figure 6.04.02: Vetical Section Solar Tubes
Source: Technical Details by V8 Architects (Redesigned)

Figure 6.04.03: Horizontal Section Planter



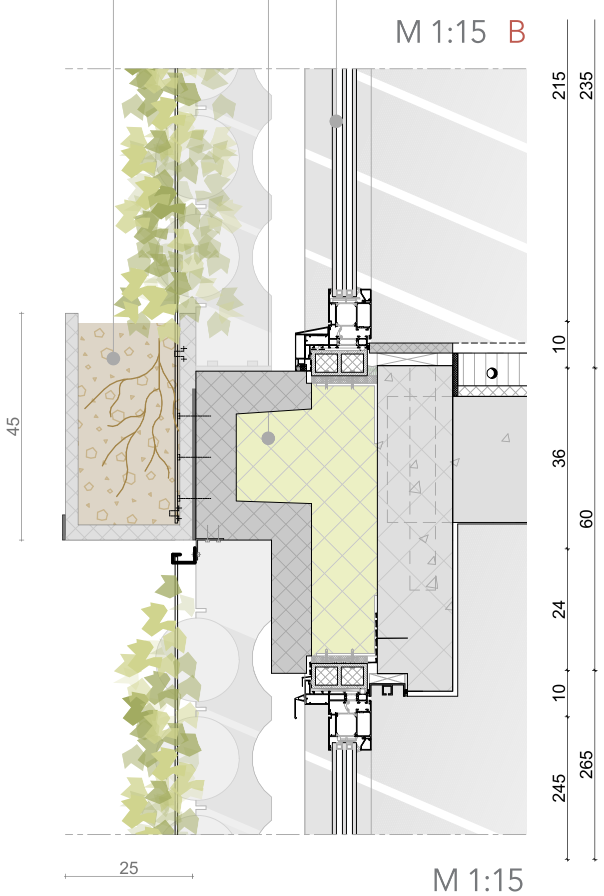


Figure 6.04.04: Vetical Section Planter
Source: Technical Details by V8 Architects (Redesigned)

Vertical vegetation is used as a wind insulating layer to induce air inside the building at lower wind speeds. The denser the foliage and the smaller the cavity between the window opening and the vegetation, the lower the induced wind speed. Moreover, it is important to grow plants which are evergreen and do not lose their foliage in winter. Ivy is one of such vine plants which stays green in winter. Because of its dense foliage, it provides good insulation against wind.

The proposed redesign integrates 45mm high and 25mm deep planter boxes on the facade, which are attached to the existing concrete structure. The planters are 1.3m wide and are located in front of the 1m wide openable windows. In combination with vertical greening, natural ventilation is possible for 1975 hours at 25m height and 1397 hours at 130m height. This is significantly more compared to the current situation, where incoming air is induced through tilting windows, allowing for 1260 hours of natural ventilation at 25m and only 410 hours at 130m.

01 PV/T Units

The Vacuum Solar Tubes are mounted at a distance between each other, leaving 10cm space between each unit for some indirect sunlight to enter the rooms. The individual tubes are mounted on a metal support and held in place by metal wires. Each PV/T unit is 1000mm wide and integrates 6 PV cells mounted on top of an absorber plate.

The absorbed heat is transferred to the water pipe running under the absorber. The pipes for cold water supply and hot water production, as well as the PV wiring are hidden at the facade behind a lightweight stone cladding provided with outlet holes for the piping. The PV/T units will be used in combination with the heat pump to generate enough heat for low temperature heating through radiant floors.

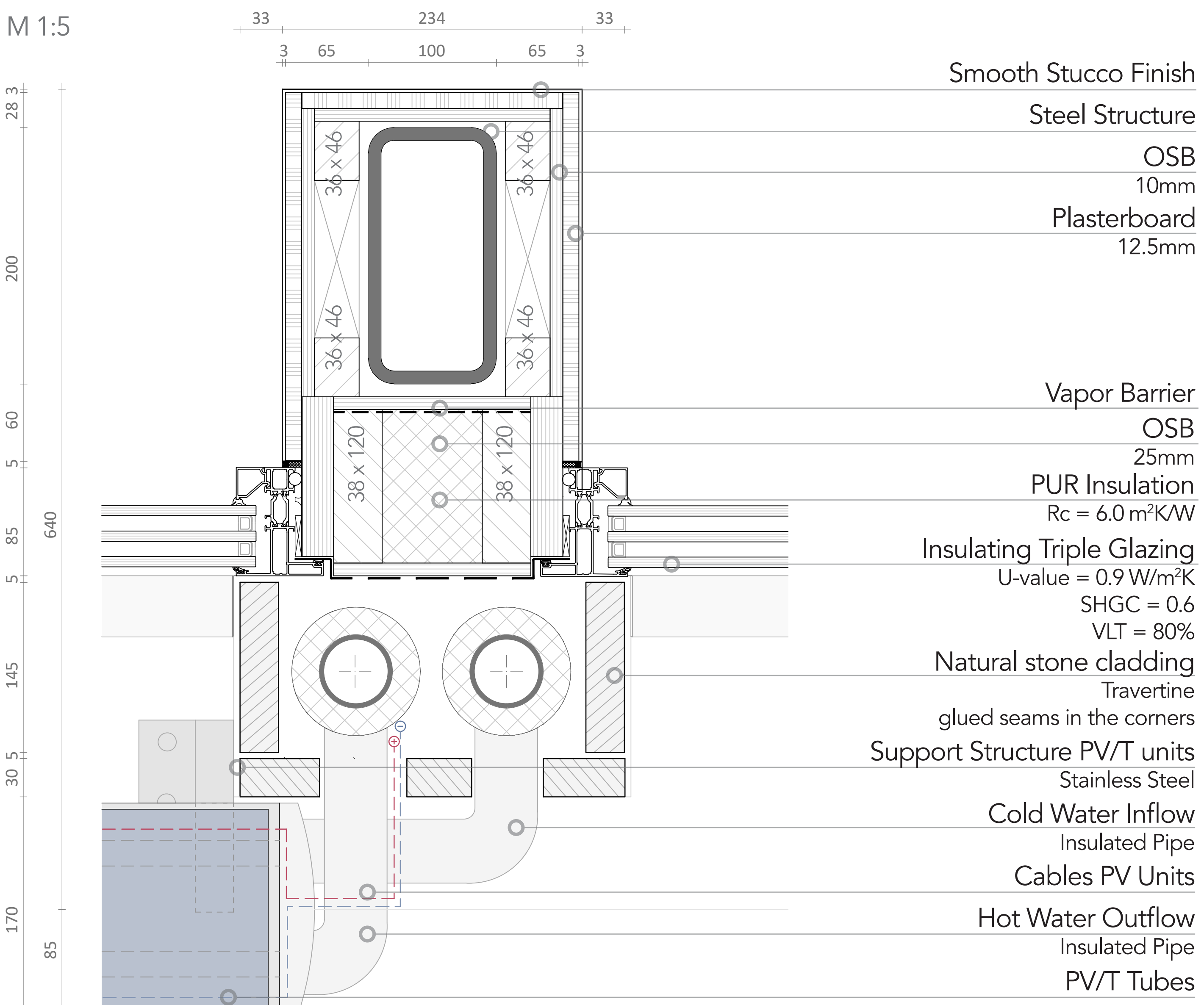


Figure 6.04.05: Detail PV/T Solar Tubes

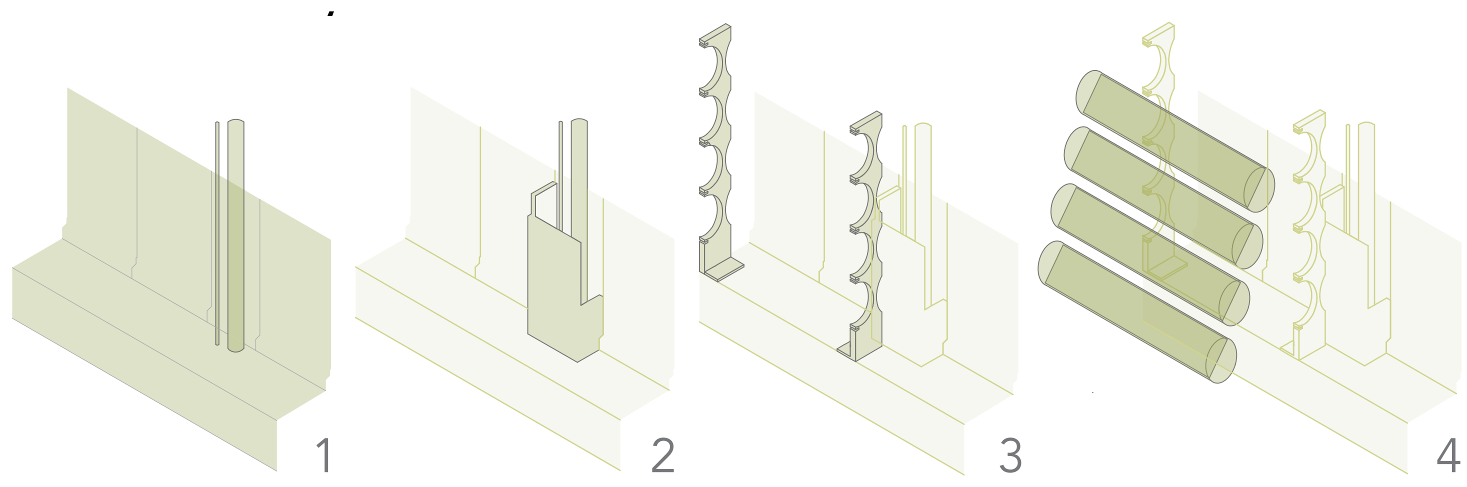


Figure 6.04.06: Assembley Sequence

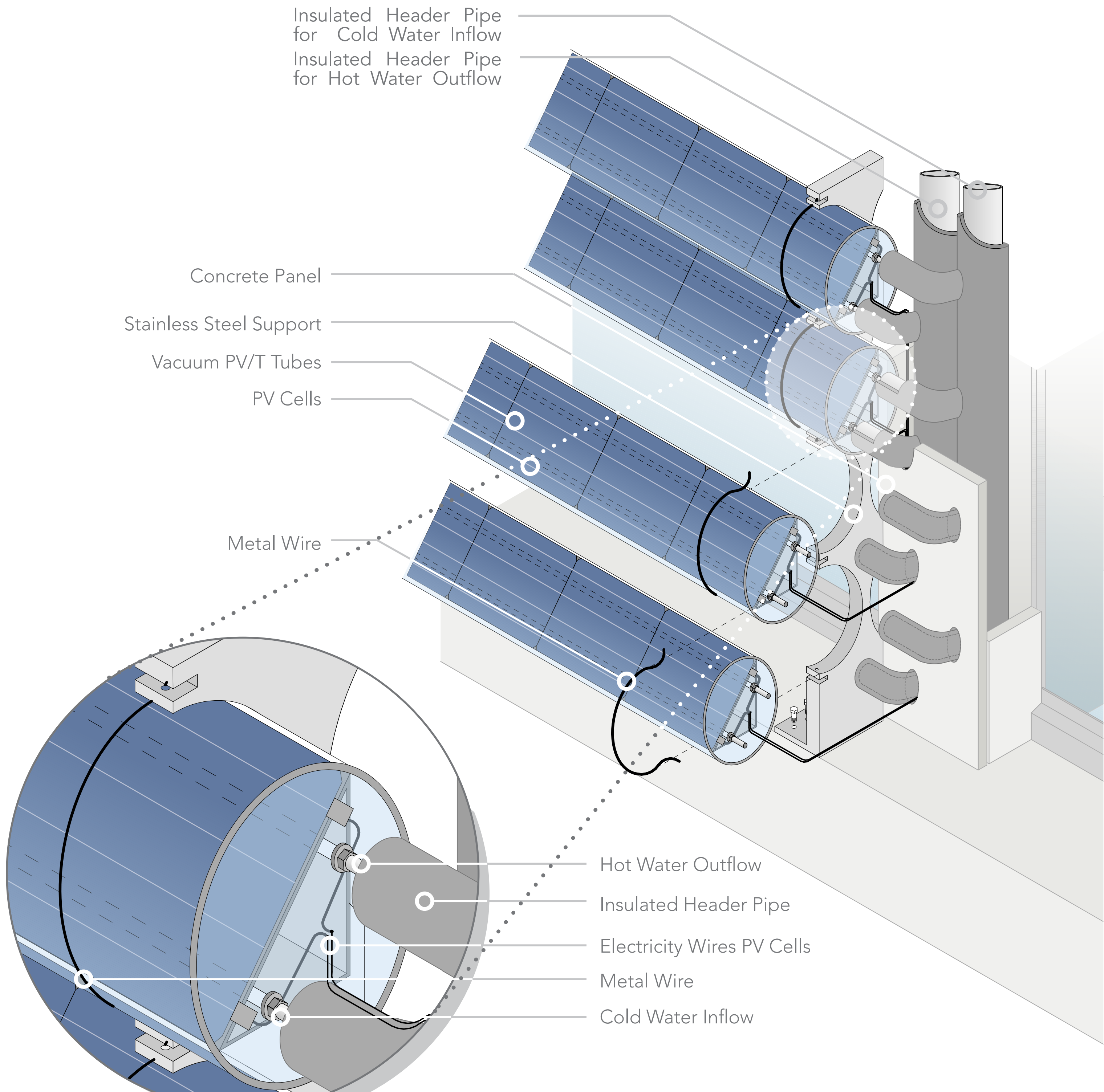


Figure 6.04.07: Assembley Detail PV/T Solar Tubes

02 Planter Boxes

The 1000x25x45 mm planter boxes are resting on L-shaped metal profiles which are anchored to the existing concrete facade structure. The metal planter boxes are die forged, with the profile of the supports pressed into the final shape of the planter. Afterwards, the boxes will be screwed from the inside of the tray into the metal supports and to the existing concrete structure.

A mesh screen is connected to the planter boxes which serves as a support for the climbing plants. The planter boxes are provided with an inlet hole for the drainpipes at the bottom of each tray. A controlled water supply is ensured by an irrigation system. The drainpipe as well as the irrigation pipes are hidden at the facade behind lightweight stone cladding.

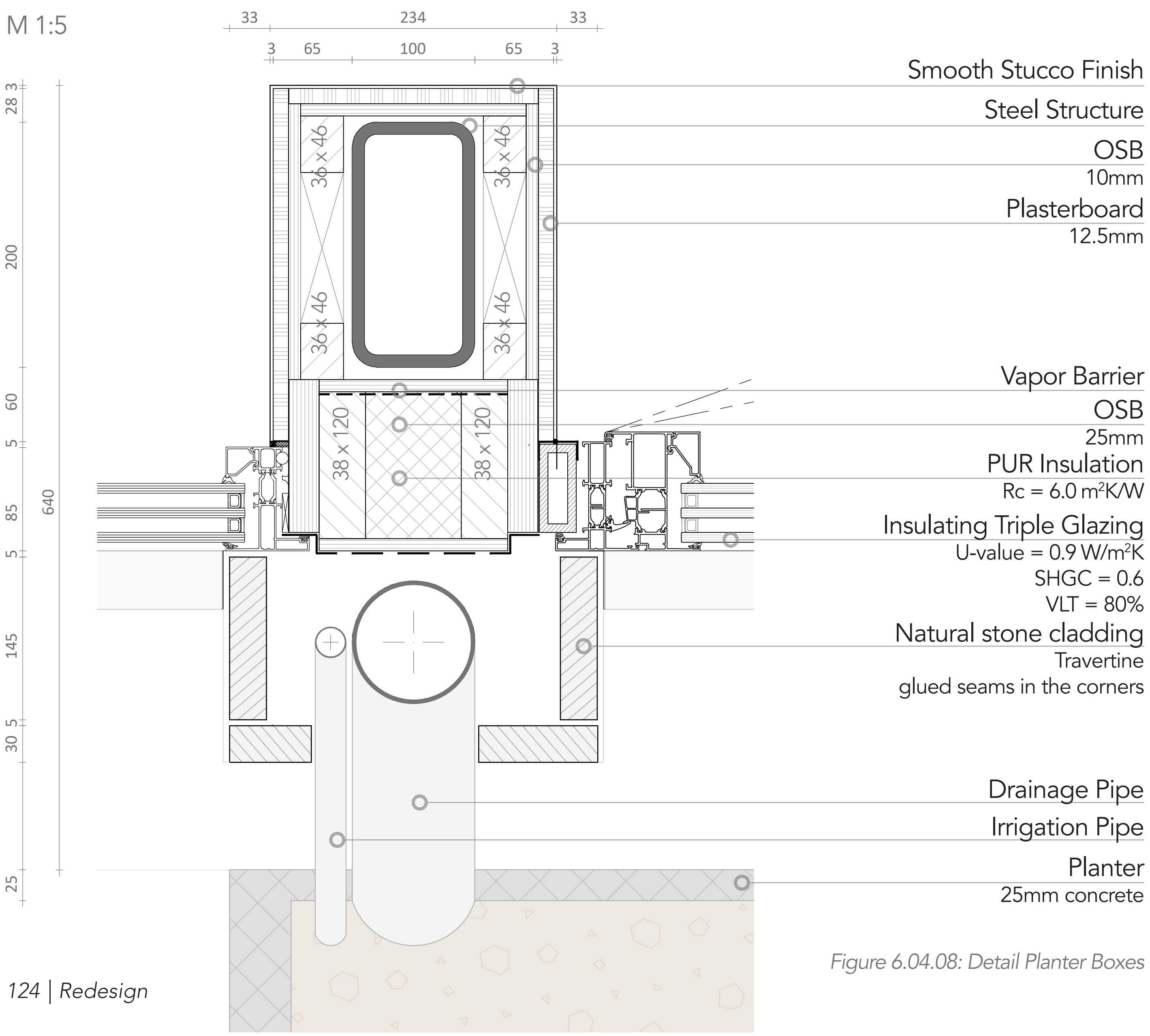


Figure 6.04.08: Detail Planter Boxes

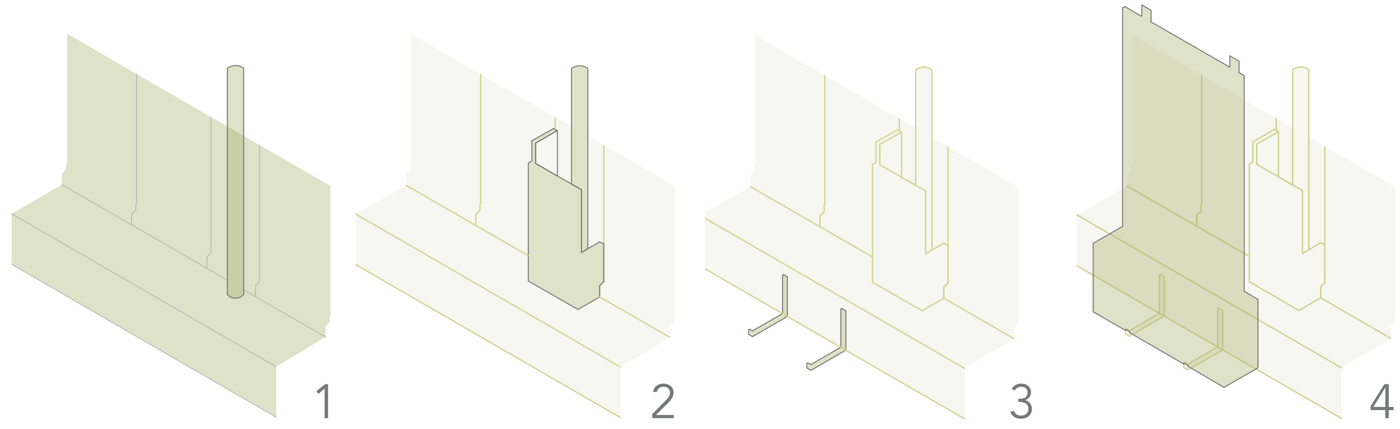


Figure 6.04.09: Assembley Sequence

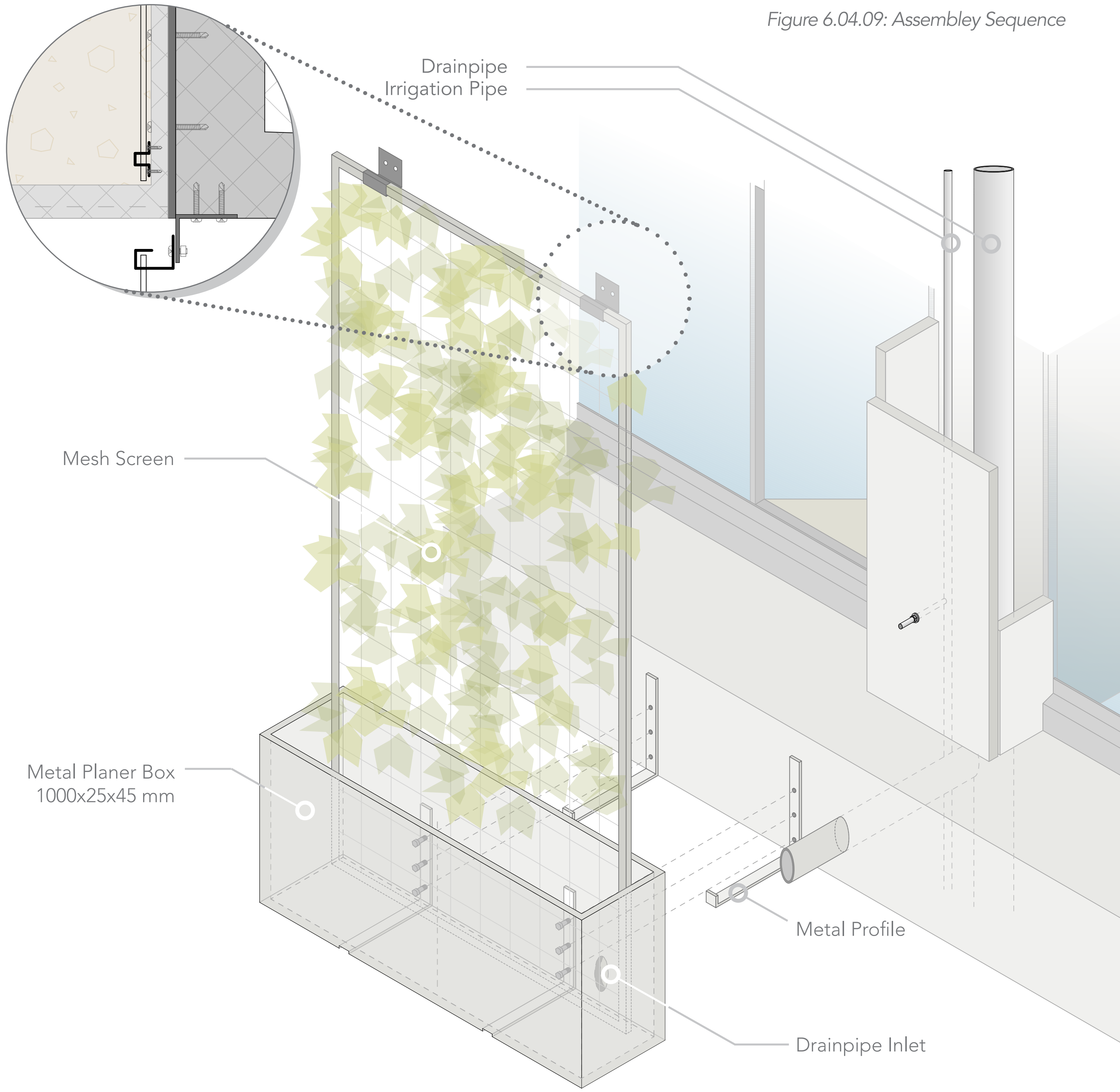
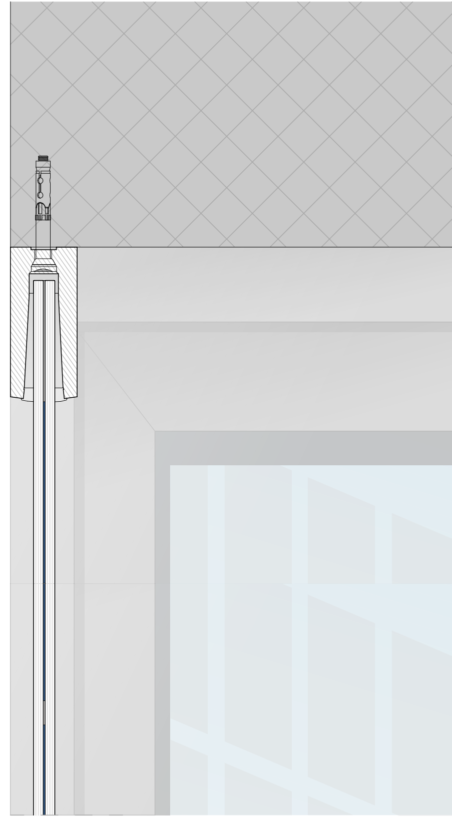


Figure 6.04.10: Assembley Detail Planter Boxes

03 Balconies

Partially closing up the balconies would also offer some sun and wind protection in order to increase the outdoor comfort level. Therefore, the balconies are closed on the sides with solar glazing at both altitudes.

The sidewalls are made of two tempered glass panes in between which solar cells are arranged, leaving space between the cells for sun to shine through. The solar glass walls will be inserted in a stainless steel construction which is mounted at the edges of the balcony and fixed to the main concrete structure at the bottom and at the top.



The energy generated on the facade alone is insufficient to reach BENG 2* even with energy generating systems integrated onto the facade. In order to reach the 50 kWh/m² target limit, solar glazing with a PV coverage of 80% is mounted on the sides of each balcony. Taking into consideration the energy production on the facade and on the balconies, 50 kWh/m² was achieved for the 25m level and 53 kWh/m² at 130m for BENG 2*. The total energy generated on the facade alone adds up to 25% renewable energy (BENG 3).

Source	[m²]	[kWh/floor per year]	[kWh/m² per year]	
PV/T Facade per floor	43	9739.6	13.05	
BIPV Balcony per floor	68	7890.8	10.57	
PV on Garage Building	141	792.1	2.27	
			25.89	[kWh/m² per year]

Table 6.04.01: Energy Production on the Facade and Neighboring Garage Building Roof
** Gross Floor Area = 746.6 m²*

2.27

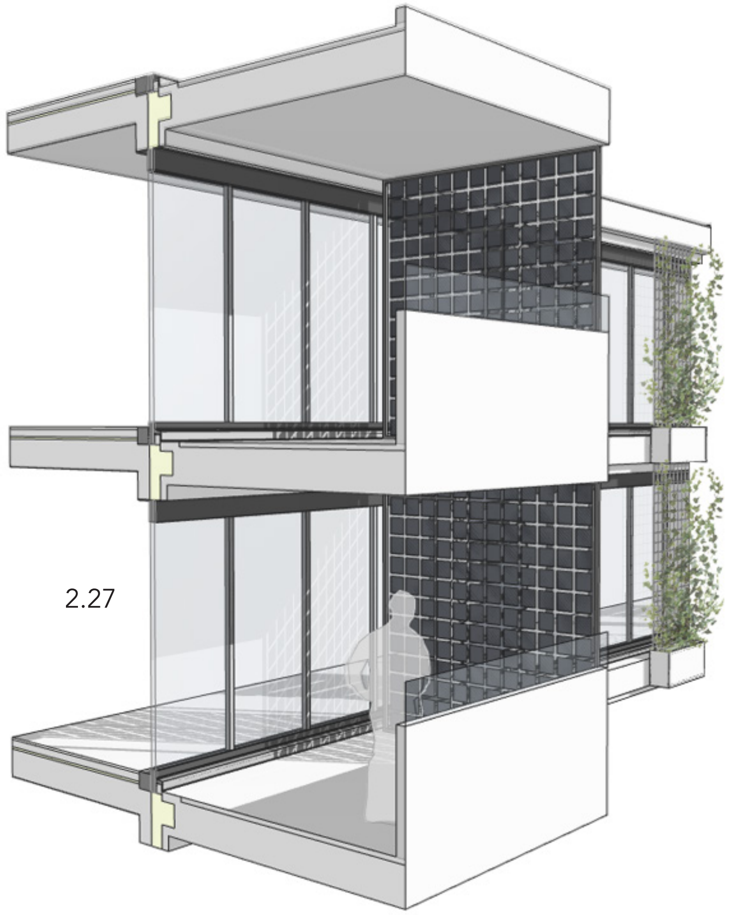
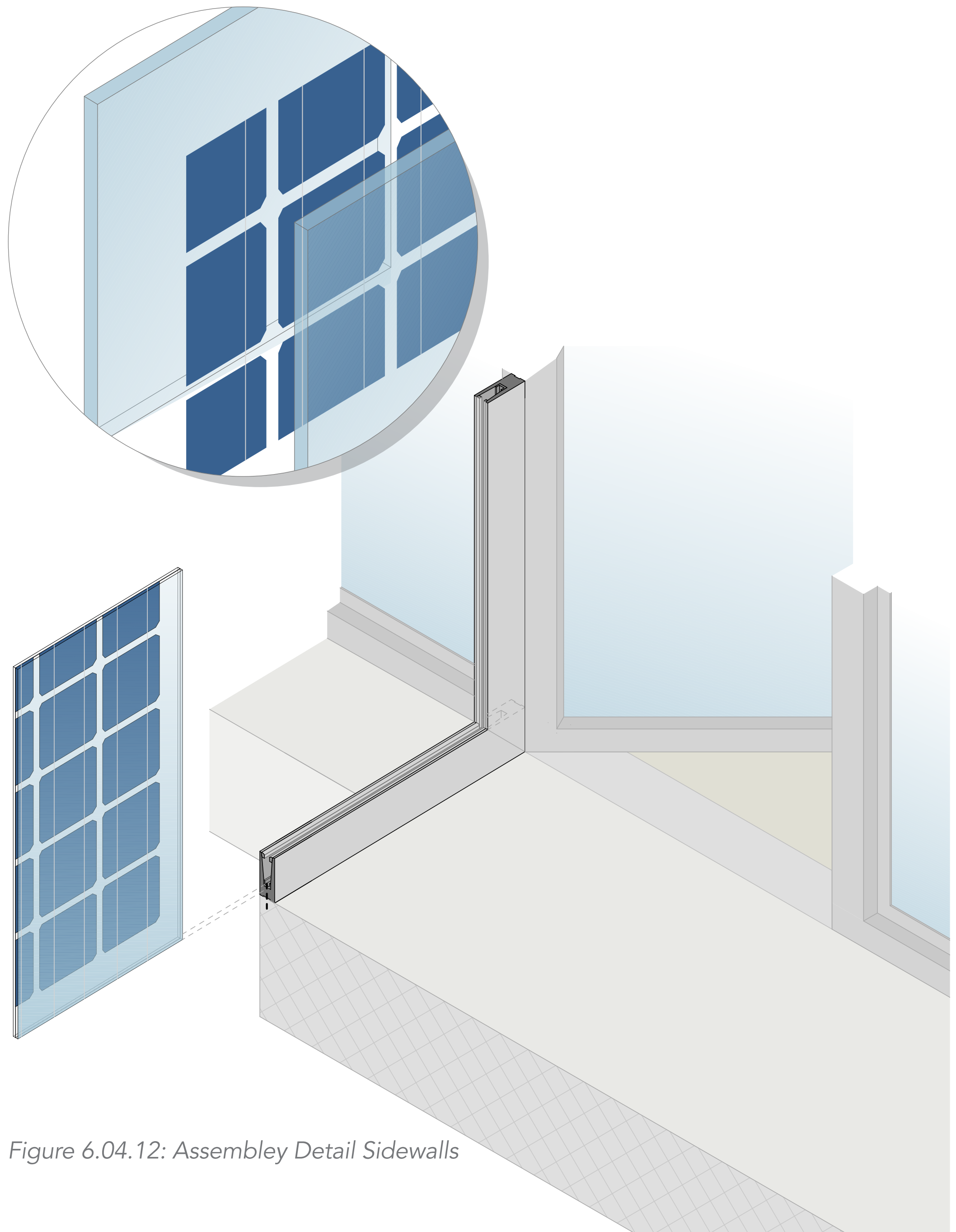


Figure 6.04.11: Balcony Design Proposal



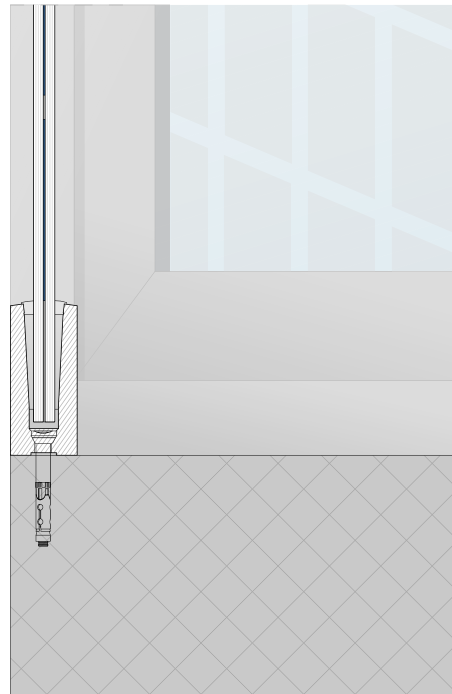


Figure 6.04.12: Assembley Detail Sidewalls

07

Discussion

7.01

Discussion

This study shows the potential of an optimized facade design in residential high-rise buildings in a temperate climate. The aim of this research paper was to answer the following question:

> *'What is the impact of facade design on energy, daylight and thermal comfort, to achieve a nearly zero-energy residential high-rise building in a temperate climate?'*

In order to answer this main research question, an iterative optimization process was adopted using Grasshopper and Colibri, which made it possible to simulate the performance of a large number of design combinations and compare them easily in Design Explorer. Through the literature review, the most influential facade design parameters were filtered out, which served as variables in the optimization process - window to wall ratio (WWR), glazing type, shading elements, natural ventilation (NV) strategy, insulation and energy generating systems.

Through the optimization process, the following aspects have become apparent: the WWR, glazing type and shading system have the highest impact on reducing the overall energy efficiency of the building. The window ratio determines the electricity demand and the area for electricity production and it defines the operable glazing area available for natural ventilation. If the window ratio is high, the R-value of the thermal insulation is less influential because heat is mainly lost through the glazing. This implies that triple glazing should be used in order to avoid heat losses. Triple glazing with a high SHGC and a high VLT helps to conserve solar gains by reducing heat losses in winter. To prevent overheating in summer, Architects and Engineers should consider employing exterior shading elements together with an efficient natural ventilation strategy which enable users to open the windows even at higher altitudes, without causing unpleasant wind draughts.

The impact of the different facade design parameters was assessed using the Cooltoren building in Rotterdam by V8 architects as a case study. The building incorporates quite efficient active systems in order to cope with the high energy demand. The presence of these active systems overshadowed the passive design optimization in terms of cooling. Due to the high COP of 15, the impact of the parameters on the cooling loads is less visible in this case. Nevertheless, all the different design parameters described in *Chapter 5* are believed to have similar benefits also in other types of buildings, with a more significant impact on cooling if less efficient active systems are used.

The study was conducted considering radiant floors for low temperature heating/cooling in the kitchens/living rooms, bedrooms and in the bathrooms, with a setpoint of 21°C for heating, respectively 28°C for cooling. After the simulation was performed, it has been noticed that the bathrooms are sometimes heated or cooled in summer in order to reach the specified temperature limits. This indicates that a lower setpoint should have been applied for floor heating in order to avoid heating in summer or floor heating should have been not assigned to bathrooms. Radiant floor cooling should also not be assigned to bathrooms because it might turn on while taking a shower, due to the increased temperature inside the room. Nevertheless, the total amount of heating and cooling recorded in summer represents only 6% of the total heating and cooling loads and therefore do not affect the results and conclusions of this research paper.

It is also worth mentioning that for this study a distinction has not been made between the heating setpoint during the day and during the night.

7.01.01 Guidelines

There is no precise recipe for the most optimal facade design. As this study has shown, energy performance and thermal comfort are two contradicting objectives and depending on what the higher priority is, the facade parameters should be determined accordingly. In most cases, Architects and Engineers try to balance out these two factors. The impact of the individual facade parameters on the energy performance, daylight and thermal comfort was described in detail in Chapter 5. The presented guidelines are intended to help Architects and Engineers to make preliminary design choices. However, by combining these facade parameters, the overall impact can be different, as demonstrated with the proposed redesign. A high WWR does not necessarily lead to a reduced energy performance if used in combination with triple glazing, exterior shading and an efficient natural ventilation strategy. On the other hand, WWRs higher than 65% should be avoided because of reduced indoor comfort conditions due to overheating problems in summer and increased heat losses in winter. Consequently, this study shows the importance of a multi-objective optimization process to filter out the most effective passive design strategies towards designing nearly zero energy high-rises.

Out of the 480 analyzed design options, the following solutions were found to have a balancing effect on the energy performance and thermal comfort. As already mentioned, the energy generated on the facade alone is insufficient to reach BENG 2* and BENG 3 and therefore additional energy production units would need to be integrated for example on balconies. These facade parameter combinations are advised to be used in future residential high-rise buildings in temperate climates in order to come one step closer to zero energy.

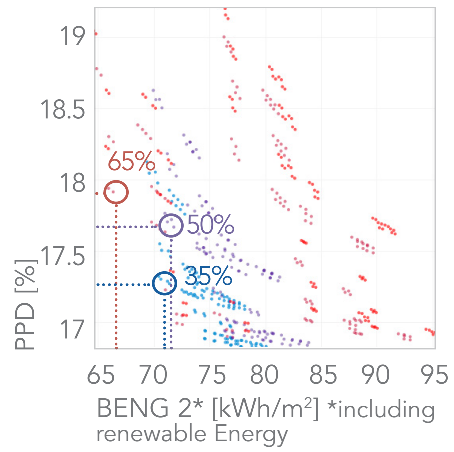


Figure 7.01.01: Results Ranking

sDA: 29%
BENG 1: 54 kWh/m²
BENG 2: 71 kWh/m²
BENG 3: 11 %
PPD: 17.5 %

WWR: 35%

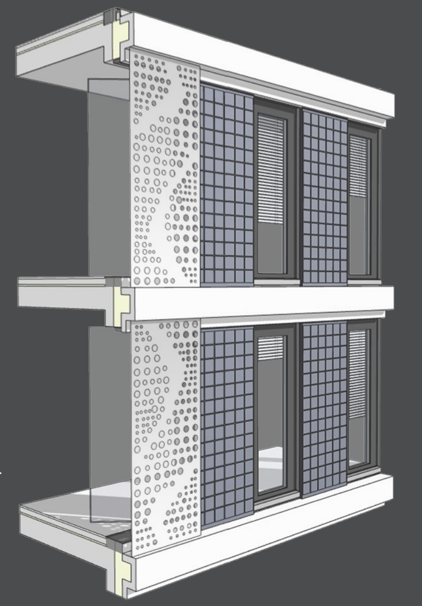
Gazing: Triple

Shading: None / Interior Blinds

Insulation: 6.0 m²K/W

Nat.Vent.: Openable W. + Vegetation/ Perf. Screens

Energy: BIPV/T



sDA: 39%
BENG 1: 55 kWh/m²
BENG 2: 72 kWh/m²
BENG 3: 9 %
PPD: 18 %

WWR: 50%

Gazing: Triple

Shading: Interior Blinds

Insulation: 4.5/6.0 m²K/W

Nat.Vent.: Openable W. + Vegetation/ Perf. Screens

Energy: BIPV/T

sDA: 46%
BENG 1: 57 kWh/m²
BENG 2: 66 kWh/m²
BENG 3: 14 %
PPD: 18 %

WWR: 65%

Gazing: Triple

Shading: PV/T Shading

Insulation: 4.5/6.0 m²K/W

Nat.Vent.: Openable W. + Vegetation/ Perf. Screens

Energy: PV/T Shading

7.01.02 Sustainability Review

Life cycle energy

Operational Energy vs Embodied Energy

Considering the presented results of the optimization, it hs been demonstrated that an optimized facade design can save up 30 kWh/m² of the primary energy consumption, improve the daylight and indoor comfort conditions and significantly increase the renewable energy production with energy generating systems integrated on the facade.

However, the energy performance alone does not yet define a building as sustainable. The total life cycle energy of a building is defined by the operational energy, as well as the total embodied energy consumed during the production, maintenance and demolition phase. The environmental impact of buildings is mostly dominated by the use phase, i.e. the energy demand for operation, which accounts for 80-90% of the total life cycle energy. The other 10-20% of the total life cycle energy depends on the embodied energy. By reducing the operating energy through passive and active technologies, the total life cycle energy comes down significantly while the embodied energy of the building will increase just slightly. *Ramesh, Prakash, Shukla (2010)* evaluated the relation between the embodied energy and operating energy for 73 office and residential buildings.

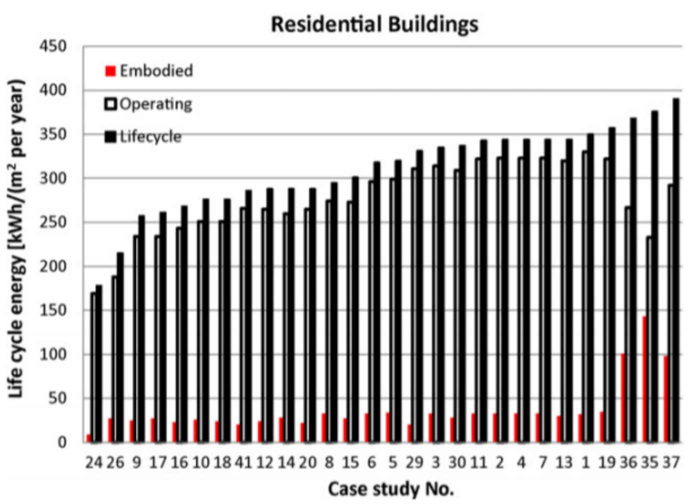


Figure 7.01.02: Normalized life cycle energy for conventional residential buildings (primary)
Source: El-Haggar, 2007

But even though the share of the embodied energy is far lower than that of the operating energy, the impact of construction materials is nowadays also gaining more focus, due to strict regulations concerning climate change. With the construction sector growing more and more every year, so does construction and demolition waste. Approximately 40% of the total waste in the Netherlands involves construction and demolition waste. To change this, the Netherlands is aiming to develop a Circular Economy by 2050, with a main focus on processing construction waste more efficiently.

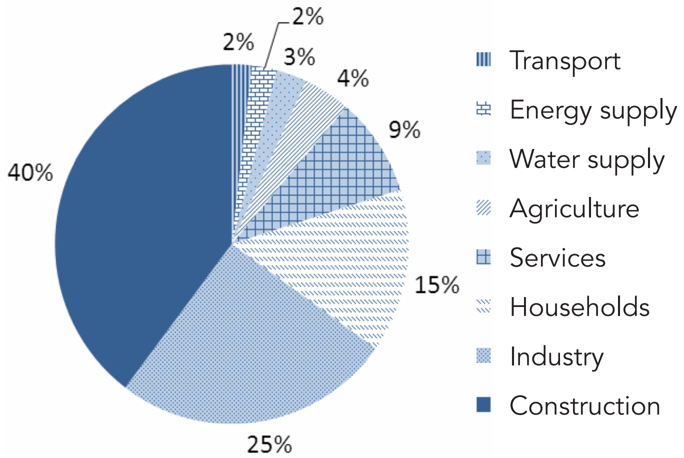


Figure 7.01.03: Source of waste in the Netherlands 2010
Source: CBS, PBL, Wageningen UR, 2012a

High rises in particular, require bigger amounts of materials, larger in size compared to low-rise buildings. Moreover, they tend to consume more energy/m² with height, so that more technical installations need to be integrated in order to compensate for the higher demand. The overall embodied energy is therefore higher compared to low-rise buildings. More detailed study needs to be conducted to see how much the embodied energy of high-rises increases, by reducing the operational energy. In this case, the embodied energy would vary depending on the quantity and quality of the materials used.

The conclusion that can be drawn at this stage is that significant consideration needs to be given to the high-rise typology in the future, not only concerning energy savings during the operational phase, but also material waste streams during the production and demolition phase, given the enormous landfills that have emerged in the last decades due to construction waste.

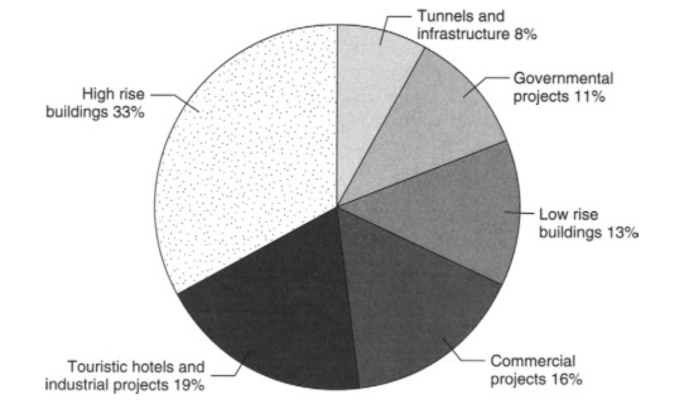


Figure 7.01.04: Cumulative percentages of projects generating construction waste in Egypt
Source: El-Haggar, 2007

Material Waste Streams

Glass

A big part of the proposed building envelope includes insulating glazing. The amount and type of glazing is very important, as it can improve the efficiency of the building considerably by making use of incoming daylight and solar gains while conserving energy. Glass uses significant amounts of energy during the manufacturing and recycling process. Recycling glass can only save up 5% of the total energy required for producing a new product *(Achintha, 2016)*. Dismantling the glazing from the frame, crushing the glass, cleaning, treating it and melting the cullet into a new product requires a substantial amount of energy. Another reason why glass used in building construction is not recycled is because of the difficult separation of the coatings which are usually applied to the glazing during the manufacturing process, on the float glass line.

Since the glazing from windows is hard to be recycled/downcycled, it is important that the glass waste is reused. Window glazing can be reused by consuming less energy, mainly by mixing the cleaned glass chips with other materials to produce new products.

Figure 7.01.05: WasteBasedBrick
Source: Stonecycling, n.d.

Concrete

Although concrete has a smaller embodied energy per m² than glass, the fact that it is used in much larger quantities has a significant impact on the overall embodied energy of any building. In addition, concrete is also the largest contributor to construction and demolition waste.

More than 80% of the CDW is concrete and stony waste *(European Commission, Sep 2015)*. An alternative would be to use a lightweight building construction which would reduce the amount of material used and implicitly the embodied energy of the building. However, a heavy concrete construction offers better stability in high-rise buildings and is a good thermal mass. In heating dominated climates, such as the Netherlands, greater thermal mass can significantly reduce the operating energy, which has a higher impact on the overall life cycle energy.

Another important measure is to reduce the quantities of waste on landfills. In the Netherlands, 95% of concrete waste from construction and demolition sites is crushed and downcycled into lower grade concrete building components *(Xicotencatl, 27 Jan 2019)*. The additional transport, sorting and crushing process will increase the embodied energy of the recycled aggregates, but it reduces the need for primary extraction.

Metal

Metal has a high embodied energy per m² and is therefore another big contributor to the embodied energy of a building. Aluminum is one of the easiest metals to recycle. In facade design, it is usually used as wall cladding, for window frames or interior blind slats. But the highest amount of metal can be found in the supporting structure of the building, either as reinforcement for the concrete or as structural elements.

Metal from construction and demolition sites can be recycled to 100% by sorting out and remelting the metal components. Depending on the type of metal and the metal product, metal recycling can save up 60-95% of energy compared to the primary production *(Revuelta, 2018)*.

Insulation

Thermal insulation is an important parameter to reduce the need for fossil fuels and improve the comfort in buildings. The efficiency of thermal insulation materials is defined by the thermal resistance, also known as the R-value. The higher the R-value, the better the thermal performance of the material is. As insulation material, PUR was selected due to its high thermal performance for thickness.

The sustainability of PUR as an organic insulation material might be questionable given the fact that it is derived from oil. However, its high insulation performance helps Architects to better insulate buildings for less thickness, which reduces the consumption of gas and electricity otherwise needed to heat and cool them.

Because PURs are petrochemical-based polymers, the lifetime of the product is long so that PUR products can be recycled afterwards. There are different ways to recycle PUR, either through mechanical or chemical processes. Common recycling processes are regrinding pieces of foam or reusing insulation blocks. The lifespan of PUR insulations is often longer than that of the building. The insulation value is hardly or not at all affected by moisture or other influences so after demolition insulation boards can be easily reused. If PUR is neither recycled, nor reuse, another option is energy recovery. Polyurethane contains the same amount of energy as coal which makes it useful for energy generation. With all these options, PUR insulation should not be disposed on landfills *(Polyurethanes, n.d.)*.

PV/T Systems

In order to be able to reach future energy regulations, energy generating systems need to be included in the facade design of future buildings. Photovoltaic Systems are the most common on the market. Their efficiency generally ranges from 5-22%. However, the efficiency of the PV cells decreases with increasing cell temperature. Photovoltaic Thermal Systems (PV/T) combine a PV module with a solar thermal collector to produce electrical and thermal energy. By harvesting the excess heat, thermal energy is produced while increasing the cell efficiency due to the decrease in cell temperature. By combining these two technologies in one module, less space is needed for more energy production. The amount of material used is also reduced, as well as the installation time required.

Current research has been conducted on how to make PV and PV/T systems more efficient, but the process involved for retrieving and dismantling waste panels should also be considered. Solar-panels include valuable metals such as silver, indium, gallium and germanium. Recycling these metals is very difficult due to the release of solvent emissions during the recycling process.

To date, relatively little research has been conducted on the environmental impact of PV/T systems. *Good (2015)* evaluated several studies on the environmental assessment of PV/T systems using LCA (Life Cycle Assessment) methods. It was found that the Energy Payback Time (EPBT) is most of the time between 1-4 years and the Greenhouse Gas Payback Time (GPBT) ranges between 0.8-4 years. PV/T systems have a product warranty of 5-10 years and a performance warranty of 20-25 years. Taking these aspects into consideration, it can be concluded that the environmental impact of PV/T systems is small compared to the high total renewable energy output during their lifetime.

Operational Energy vs Embodied Energy

In order to deal with the inevitable effects of global warming, the world needs to reduce its concrete production. But this will not be possible without building longer-lasting structures. In order to achieve this, the first step is to reduce the operating energy consumption, as it is responsible for the biggest part of the total life cycle energy of the building. The proposed design solution proved that assessing the performance of the building from an early design stage and finding the most optimal passive design strategy can save up to 30 kWh/m^2 of the primary energy consumption. By reducing the operating energy, the total life cycle energy comes down significantly while the embodied energy of the building increases just slightly. However, more detailed study needs to be conducted in order to see how much the embodied energy of high-rises increases when reducing the operational energy through active and passive design strategies.

The embodied energy of any building can be reduced either by using less material more efficiently and/or recycling. By assessing the life cycle of different materials used for this design, it can be concluded that a significant part of the components can be reused, recycled or downcycled. The energy intensity of the recycling process is small compared to the extremely high improvement of the energy performance. Reprocessing the materials after their lifetime would also reduce the need for primary extraction and prevent demolition waste disposal.

To conclude, the proposed facade design can be considered as a fairly sustainable system. The new facade design includes a higher amount of materials compared to the initial design, but it shows a considerable improvement in terms of energy performance.

7.01.03 LIMITATIONS

The most important limitation of an iterative optimization process as such is the substantial amount of computational time involved in relation to the number of variables selected and the complexity of the simulation workflow. This study analyses the impact of only a few variables which were identified as having the most significant influence based on reference projects described in literature. Nevertheless, the selected variables still lead to a high number of 480 different facade combinations.

In addition, simplifications were necessary to be made in terms of geometry by slightly simplifying the floor plan and dividing concave rooms by 'air walls'. This was necessary because the solar distribution cannot be calculated for concave/L-shaped rooms with Open Studio.

This study uses as reference existing systems on the market to produce energy on the facade. However, PV/T panels, i.e. PV/T solar tubes are still in experimental phase and their capabilities have not been investigated on high-rises at higher altitudes.

7.01.04 FURTHER RESEARCH

This study could serve as a starting point for further studies. This could entail broadening the variable spectrum of this study and analyze different aspects of residential high-rise buildings. This study makes evident that the following aspects have room for improvement:

- Add the building shape, building orientation and variations in heating/ cooling setpoints to the presented methodology process.
- Assess the impact of the selected facade design parameters in office high-rises, which are a rather cooling dominated typology.
- Investigate the performance of passive facade design strategies without the use of a heat pump.
- Simulate the impact of facades in terms of energy performance and thermal comfort with full user control.
- Analyze the performance and indoor comfort difference for super-tall high-rises (300-600m) at a low and high altitude, taking into consideration also the decrease in usable floor area with height.
- Investigate whether a change in facade with height is beneficial if the high-rise building is located in a much denser urban context.
- Investigate the performance of PV/T systems on high-rises at high altitudes.
- Perform the same facade optimization workflow under different climatic conditions.
- Calculate the embodied energy of the building with the new facade.

These are just a few topics which need to be investigated in order to come one step closer to designing sustainable zero-energy high-rises.

7.02 CONCLUSION

As an overall conclusion about the future design of nearly zero-energy high-rise buildings, it can be concluded that the facade design plays an important role to reduce the energy demand, produce energy and improve the indoor comfort conditions. While the facade design contributes considerably to the efficiency of the building, its performance decreases with altitude due to the harsh environmental conditions. For this study only a slight increase of 4.5-7.4 kWh/m^2 (8-9%) was recorded at 130m compared to the performance at 25m. However, looking at super-tall high-rises reaching above 600m this difference increases to 24.9-39.3 kWh/m^2 (33-34%) and the impact on the energy performance becomes more significant from one design to another, considering that the difference in performance between the best and worst performing design choice is 30 kWh/m^2 at 25m and 50 kWh/m^2 at 600m. Nevertheless, a variation in facade with height would not lead to a better performance in residential high-rises, considering that the facade design combinations which perform best at 600m are also the same ones which perform best at 25m. On the other hand, a variation in facade with orientation is important.

Due to time constraints, this study has not investigated the performance of the different facade parameters with respect to orientation. However, based on the results, the following conclusions can be drawn. It has been demonstrated that rooms orientated towards the south can overheat in summer if high window ratios are used. Therefore, a 50% WWR in combination with interior or exterior shading and triple glazing should be used for the south orientated rooms in order to prevent possible overheating while still making use of increased solar gains in winter. Due to the fact that the solar gains are low for the north orientated rooms, lower WWRs can be applied in order to avoid heat losses. For the comer rooms and the ones orientated towards east and west, a 65% WWR in combination with triple glazing and shading has been found to be the best option to reduce heating loads while still ensuring comfortable indoor conditions. However, this variation of facade with orientation would need to be investigated more in depth in order to define how much the energy performance and indoor comfort conditions can be improved.

Based on the results of the optimization process, the primary energy demand of a residential high-rise building located in a temperate climate can be reduced with approximately 30kWh/m^2 with an optimized facade design alone. It has been demonstrated that energy generating units are an indispensable facade element in high-rises if energy generating targets are to be met. However, facade integrated energy systems also affect the overall aesthetics of the building, and aesthetics has always played an important role in the built environment. But high-rises in particular tend to consume more energy/m^2 with height, so their environmental impact is higher than that of low-rise buildings. For this reason, designing high-rises which comply to future energy-efficiency targets will be quite challenging in the near future. This will only be possible if Architects and Engineers make compromises in terms of architectural design for the sake of a better performance.

08

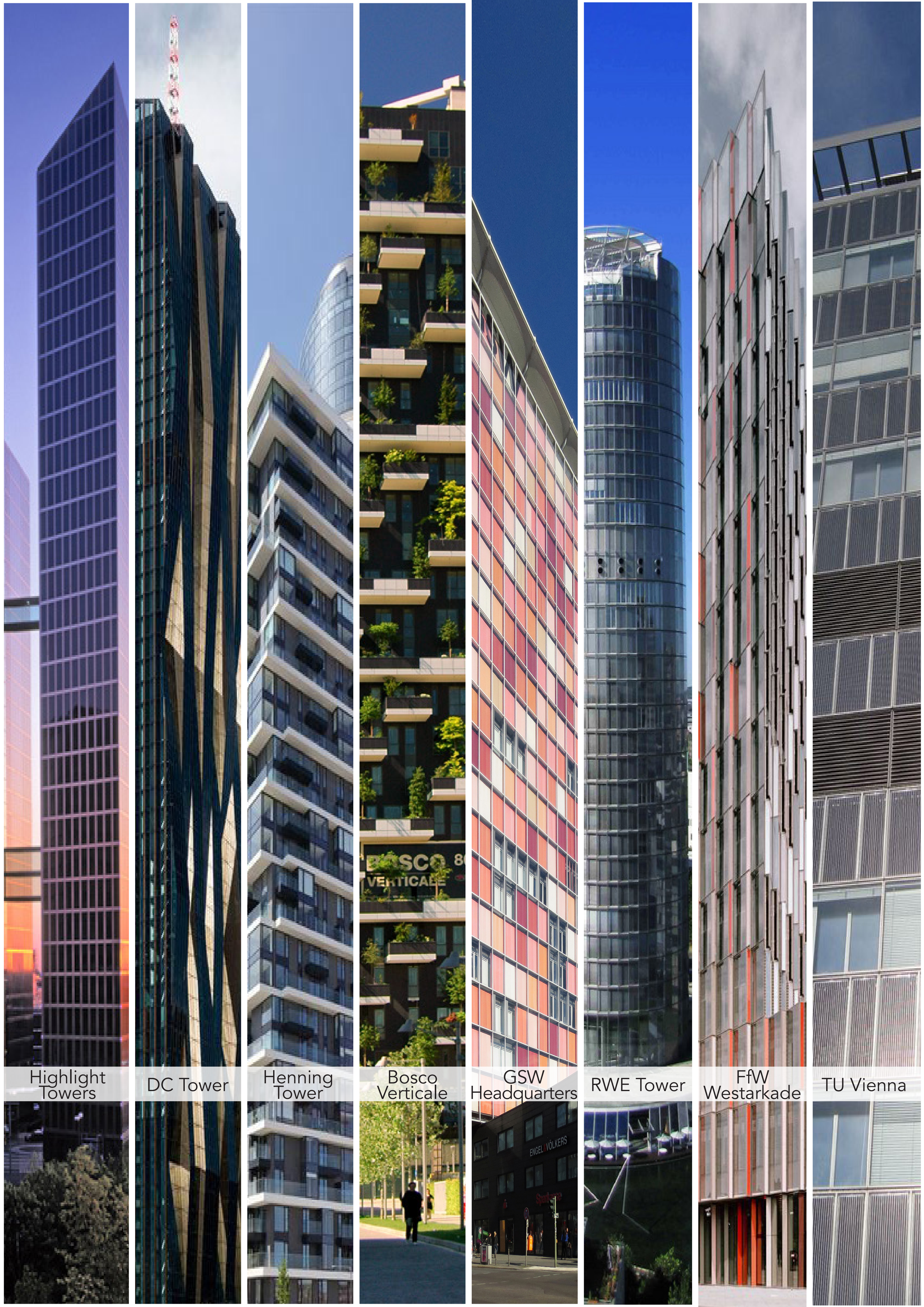
Appendix A: Examples of Sustainable High-rises

4.01
Examples

The following section analyses precedent examples of nearly zero-energy high-rise buildings. Examples were chosen which present innovative solutions with regard to energy efficient facade design principles. The strengths and flaws of each facade design strategy will be highlighted, with emphasis on the facade parameters which influence on the overall energy performance the most. The aim is to get an idea of the multiple passive design strategies and their effectiveness in terms of energy efficiency.

For the selection process of the chosen examples, some initial selection criteria were set. Only buildings located in temperate climates were considered. Buildings which include atria, vertical gardens, present an optimized plan layout for ventilation or have an aerodynamic shape, were excluded. This research focuses on the potential of facade design principles and the aforementioned parameters are beyond the focus of this study.

High-rise buildings like the Highlight Towers, the DC Tower, Henninger Tower, GSW Headquarters, RWE Tower, KfW Westarkade, Bosco Verticale, and the TU Vienna Energy-Plus office building were considered as significant examples to be analyzed in this chapter.



Source: Rainer Viertlböck, n.d.
Source: Domus Web, n.d.
Source: Conne van d Grachten, 12 Sept. 2018.
Source: The Skyscraper Center, n.d.
Source: Wiki Arquitectura, n.d.
Source: ImgCop, n.d.
Source: Brigida Gonzalez, n.d.
Source: David Alexander, n.d.

4.02.01 Single Skin

Highlight Towers

Frankfurt puts a lot of value on the energy efficiency for high-rise buildings. It is the town with the most energy efficient high-rises in Germany. The Highlight Towers are one example.

Unlike many other high-rise buildings, the Highlight Towers make use of natural ventilation through a high performing single skin facade. The single skin facade consists of a 950mm fixed triple glazed panel and a 400mm hinged double glazed window panel. The hinged windows are protected by a perforated stainless steel exterior panel, which serves as a noise, wind and rain protection when the hinged windows are opened for ventilation. The windows can be operated electronically by the occupants *(Wood & Salib, 2013)*.

Nevertheless, opening the windows can cause uncomfortable wind drafts during extreme outdoor conditions. Therefore, the building also relies on a decentralized heating and cooling system by feeding preheated/-cooled air through fan coil units integrated into the raised floor. As hot air raises due to the convection principle, the warm air is exhausted at the ceiling level, whereas fresh air is supplied at floor level. Water pipes are embedded into the concrete floors to provide additional heating and cooling.

In order to avoid overheating, the highly insulating triple glazing unit includes a highly reflective coating and the hinged window panel consists of a double pane unit with tinted glazing. The outside perforated steel panels and the venetian blinds mounted on the inside offer additional sun protection.

The benefit of using a single skin facade instead of a double skin lies in the material savings, lower costs and increased usable floor area. However, double skin facades are more effective for natural ventilation in high-rises as they can moderate increased wind velocities in high located floors, thus avoiding uncomfortable wind drafts. Moreover, they make use of the warm air trapped inside the cavity to preheat the building.

Location
Frankfurt, Germany

Design Architects
Murphy/Jahn

Building Function
Office

Project Data:
2004
113m & 126m
27 & 32 stories
74.148 m²

Rectangular Shape
8m Depth

Ventilation:
- Mixed-Mode
  Wind-driven
  Mechanical
  Control: BMS & User

Facade:
- Single Skin
- Glazing
  fixed refl. 3 glazing
  openable tinted 2 glazing

Shading:
- Perforated Steel
- Vertical Blinds
  Control: BMS & User

Energy Production:
-

(Wood & Salib, 2013)

Annual % of NV
Unpublished
Annual Savings:
69% (< AC)
Annual Consumption:
100 kWh/m²

Source: Werner Sobek, n.d.
Source: Apleona R&M Ausbau, n.d.

High performance compact single skin facade with consideration to sun, wind and rain.

4.02.02 Single Skin

DC Tower

The DC Tower in the Donau City is the first tower out of the three towers as part of the DC Project. It is currently the tallest and most prominent tower in Vienna. The tower stands out due to its outstanding folding facade, resembling the flow of the Danube river. But aesthetics was not the only focus point. The high-rise was designed following the sustainability requirements of the EU Commission for a 'green building' certificate and attained the Platinum LEED certificate *(CTBUH, January 2015)*.

The south facade consists of a fully glazed folding curtain wall system with coated solar control glass, which allows for 51% direct light transmission *(Guardian Glass, n.d.)*. The other three facades present a similar facade system as the one of the Highlight Towers in Frankfurt. 10.000m^2 of specially imprinted glazing panels alternate with the fully glazed, solar coated units and narrow window units which can be opened towards the inside to provide natural ventilation. A perforated steel panel, mounted on the outside of the pivoting panels, serves as safety protection. *(Glassolutions Austria, 2018)*

However, the building mostly relies on the air conditioning system with combined air inlet and outlet devices including heat recovery. Cooling is spread through: concrete core cooling, ventilation systems, cooling ceilings and ventilation convectors. Heating is spread through: underfloor heating, radiators, convectors, ventilation systems and ventilation convectors *(Caverion, n.d.)*. Moreover, the project includes an outside rainwater pool with a 20 m³ tank volume and a water treatment plant which recycles the water from the adjacent Danube River and uses it for heating/cooling *(CTBUH, January 2015)*.

Location
Vienna, Austria

Design Architects
Dominique Perrault

Building Function
Residential, Hotel, Office

Project Data:
2013
250m
60 stories
93,600 m^2

Rectangular Shape
Depth unknown

Ventilation:
- Mixed-Mode
  Wind-driven
  Mechanical
  Control: BMS & User

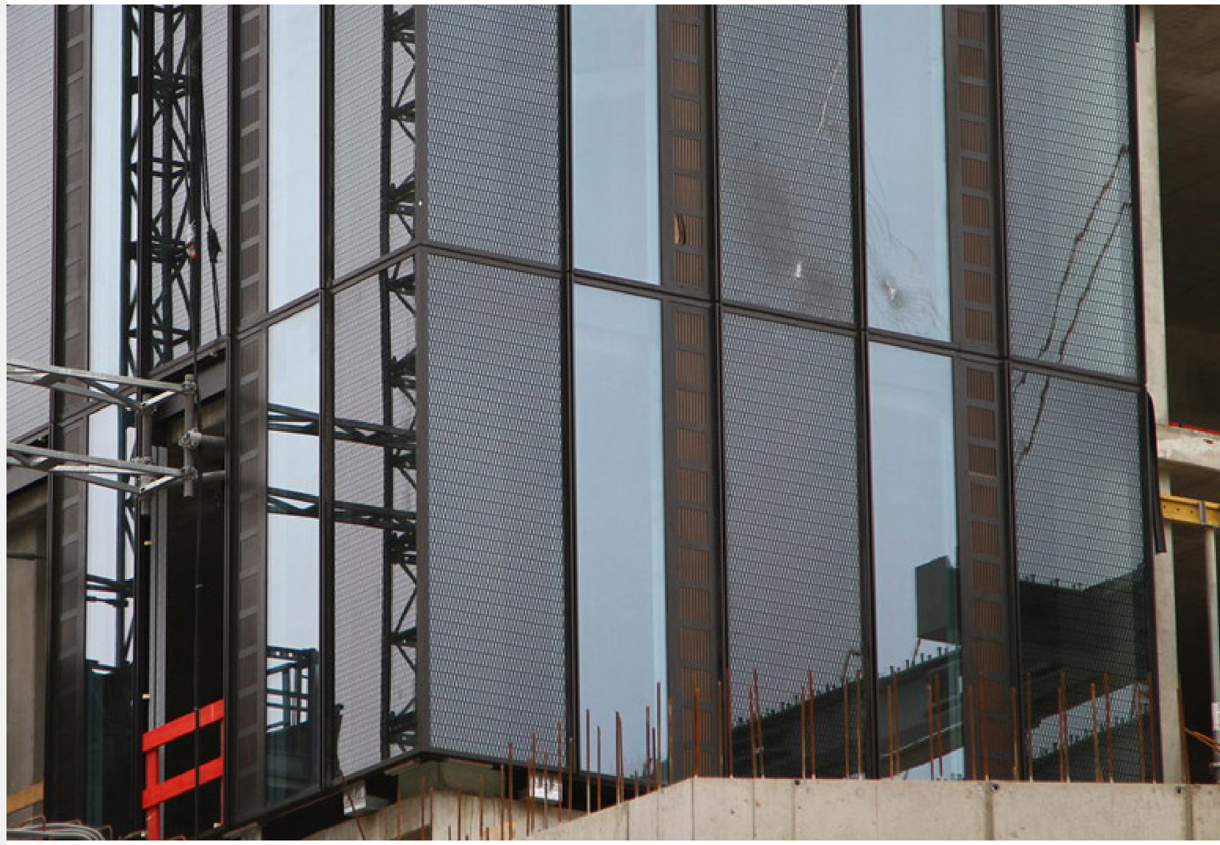
Facade:
- Single Skin
- Glazing
  coated solar control glass

Shading:
- Vertical Blinds
  Control: BMS

Energy Production:
-

(CTBUH, Jan. 2015)

Annual % of NV
Unpublished
Annual Savings:
Unpublished
Annual Consumption:
28kWh/m^2



Source: Afasiaarchzine, n.d.
Source: Peter Freyka, n.d.

Fully glazed single skin facade with coated solar control glazing units, imprinted glazing panels and pivoting narrow window units.

4.02.03 Single Skin

Henninger Tower

The Henninger Tower was initially built by Henninger-Bräu AG in 1950 as one of the world's tallest grain storage silos of more than 120m high. Later, the tower became a landmark in Frankfurt due to the two rotating restaurants and an observation deck in the barrel-shaped tip of the tower *(Bazula, 25 July 2018)*. Today, the tower hosts 210 luxury apartments, with four lofts, a restaurant and a viewing platform in the 'barrel'.

Like many other high-rises in Frankfurt, this particular building stands out due to its energy efficient design. The 'pixel facade' results from the alternating punch windows and the facade elements of the exterior winter gardens. The facade consists of unitized glass-aluminum units with electrically driven parallel vent windows with triple glazing. The glazing units achieved an U-value of 0.9 W/m²K thanks to the high performance thermally insulated aluminum composite profiles. Internal sun shading screens were integrated to prevent overheating in summer. *(WICONA finder, n.d.)*.

The ventilation mainly happens through the parallel outward opening sash windows. However, when the weather conditions are not favorable to open the windows, a very efficient ventilation system based on heat recovery and geothermal energy is maintaining a comfortable indoor temperature *(WICONA finder, n.d.)*.

Location
Frankfurt, Germany

Design Architects
Meixner Schlüter
Wendt Architects

Building Function
Residential

Project Data:
2017
140m
33 stories
77,000 m^2

Cubic Shape
Depth unknown

Ventilation:

- Mixed-Mode
  Wind-driven
  Mechanical
  Control: User

Facade:

- Single Skin
- Glazing
  3 Glazing

Shading:

- Internal Screens
  Control: User

Energy Production:

- Geothermal Energy System

(WICONA finder, n.d.)

Annual % of NV
Unpublished
Annual Savings:
Unpublished
Annual Consumption:
38kWh/m^2

Source: Conne van d Grachten, 12 Sept. 2018.
Source: App Fassaden aus Metall + Glas, 12 Sept. 2018.

'Pixel Facade' generated from alternating punch windows and exterior winter gardens.

4.02.04 Single Skin

Bosco Verticale

The two residential towers in Milano gained a lot of international attention in the last years, due to the impressive use of vertical greenery. The irregularly arranged balconies host around 20.000 trees, shrubs and covering plants, thus creating a vertical forest, bosco verticale, as its name already suggests.

The choice of plant species and the plant distribution is different on each floor, depending on the orientation of the facade and the facade height. The plants contribute to the indoor climate design by providing shade in summer, thus minimizing the cooling needs. In winter, when the branches are bare, they allow the warm sun to warm the apartments, thus reducing the heating requirements.

The main goal of the 'vertical forest' was to create a noise barrier, purify the air by absorbing CO_2, provide shade and generate a microclimate environment around the building by cooling the air temperature due to the evapotranspiratory effect of the plants. However, the trees are only one part of the project's climatic strategy. While tilt and turn windows allow for natural ventilation during mild conditions, an air conditioning system based on fan coil units, and radiant floors help to balance the annual heating and cooling demand. The fan coil units exchange heat and cold from an underground aquifer, which serves as a heat and cold source for the underfloor heating/cooling. The plants are watered automatically through a centralized system that reuses water extracted also from the aquifer.

The plants also help to reduce heat losses by creating a micro-climate environment of approximately 2°C temperature difference. However, is mainly because of the innovative use of heat pump technology that the heating and cooling costs are reduced for the tenants. Nevertheless, even though the low energy consumption is not mainly dependent on the plants, the 'vertical forest' also contributes to the reduction of the heat island effect, purifies the air by absorbing CO_2 and producing O_2, hosts several bird species and has a positive impact on the psychological comfort of the occupants *(Designing Buildings Wiki, 07 Apr. 2017)*.

Location
Milan, Italy

Design Architects
Boeri Studio

Building Function
Residential

Project Data:
2014
85m & 116m
27 & 19 stories
9.417 m² & 21,528 m²

Rectangular Shape
8m Depth

Ventilation:
- Mixed-Mode
  Wind-driven
  Mechanical
  Control: User

Facade:
- Single Skin
- Glazing
  insul. 2 Glazing

Shading:
- Vertical Greenery
- Vertical Blinds
  Control: User

Energy Production:
- PV Roof 500m²
  Total: 26 kWp
- 4 Geothermic heat pumps

(Greenroofs, n.d)

Annual % of NV
Unpublished
Annual Savings:
Unpublished
Annual Consumption:
Unpublished

Source: Paolo Rosseli, n.d.

> The plants contribute to the indoor climate - they create a noise barrier, purify the air, provide shade and greate a microclimate environment around the building.

4.03.01 Double Skin

GSW Headquarters

The building was designed in 1999 as an extension and renovation of the GSW residential and commercial Headquarter. The building stands out with its intelligent facade design. Louvre systems and a double-skin facade add an interesting complexity to the outside appearance, while effectively contributing to the passive climate control strategy.

The GSW Headquarters makes use of two different strategies to induce natural ventilation into the building. The eastern double skin facade provides wind-driven natural ventilation, whereas the western double-skin facade relies on the stack effect to draw fresh air from the double skin facade cavity into the rooms.

The eastern facade consists of a double skin facade with a single skin outer layer and a double skin inner layer. Fixed louvres are alternating with the single glazed windows on the outer skin, which is responsible for the air supply inside the cavity. By opening the pivoting panel, mounted on the inner skin behind the louvres, fresh air trapped inside the cavity can flow into the room. As fresh air enters the building from the eastern facade, stale air is exhausted on the western facade by enhancing cross- and stack-ventilation.

It is worth noticing that the ventilation strategy is highly dependent on external weather conditions and might not be effective if there is no sun to facilitate the stack effect inside the cavity of the western facade. Moreover, naturally ventilating the space at higher levels can lead to excessive drafts and cause user discomfort due to the increased wind speeds with altitude. The air velocity could be regulated by optimizing the size or the profile of the passive ventilation elements at higher levels.

Location
Berlin, Germany

Design Architects
Sauerbruch Hutton

Building Function
Office

Project Data:
1999
82m
23 stories
48,000 m^2

Rectangular Shape
7.2-11m Depth

Ventilation:
- Mixed-Mode
  east: Wind-driven
  west: Stack-ventilation
  Mechanical
  Control: BMS & User

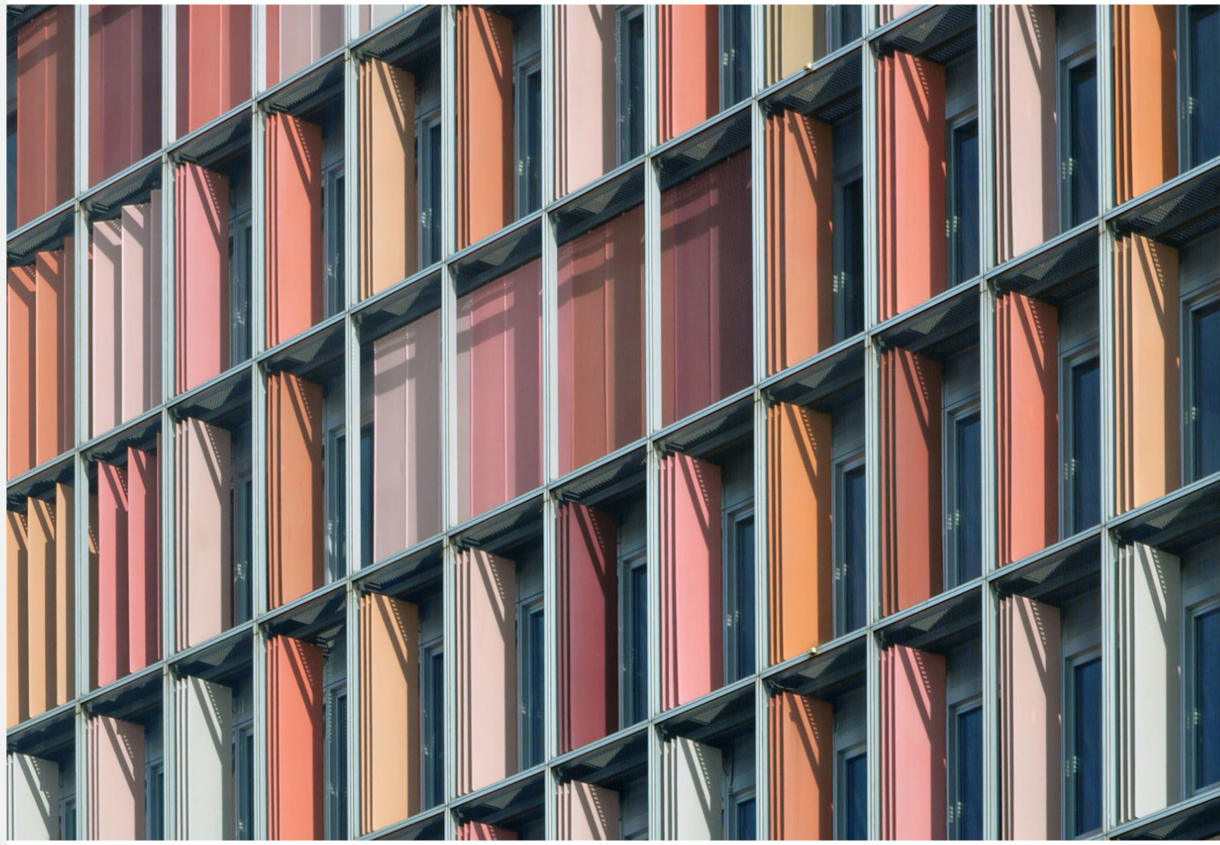
Facade:
- Double Skin
  Cavity east: 200mm
  Cavity west: 1000mm
- Glazing
  Outer Skin: 1 Glazing
  Inner Window: 2 Glazing

Shading:
- Vertical Blinds
east: Integrated Louvres
west: Perforated
Aluminium Shutters
Control: BMS & User

Energy Production:
-

(Wood & Salib, 2013)

Annual % of NV
70%
Annual Savings:
53% < typical office
Annual Consumption:
150kWh/m^2



Source: Annette Kisling, n.d.
Source: Baunetz Wissen, n.d.

The GSW Headquarters makes use of two different strategies - wind driven cross ventilation and stack ventilation.

4.03.02 Double Skin

RWE Tower

The RWE Tower in Essen is the first ecologically orientated high-rise building in Germany *(Ingenhoven Architects, n.d)*. It is a 127m high, circular tower with a GFA of 36,000m^2 finalized in 1997 in Essen, Germany.

The tower was designed with a particular focus on the natural ventilation strategy. It's aerodynamic circular shape not only encourages wind flow around the building, but it also minimizes the envelopes surface area, thus reducing heat gains and losses through the building skin.

The building is ventilated naturally throughout 75% of the year through a double skin facade *(Wood & Salib, 2013)*. The most significant feature of the facade is the Fish Mouth inlet device integrated in between the glazing unit. The Fish Mouth device regulates the changing wind speeds with respect to height and keeps a constant air flow rate in between the cavity, thus avoiding uncomfortable wind drafts even at high altitudes. The inner skin of the facade consists of floor to ceiling sash windows which can be opened by the users to ventilate the room.

In case of extreme weather conditions, an integrated Building Management System (BMS) automatically closes the Fish Mouth ventilation openings and activates the mechanical ventilation. The BMS also controls the amount of daylight entering the rooms by adjusting the vertical blinds integrated in the cavity.

A negative aspect of the facade design is the vertical segmentation of the cavity with glass fins. The segmentation hinders the airflow around the building and gives rise to different air flow rates for differently orientated rooms.

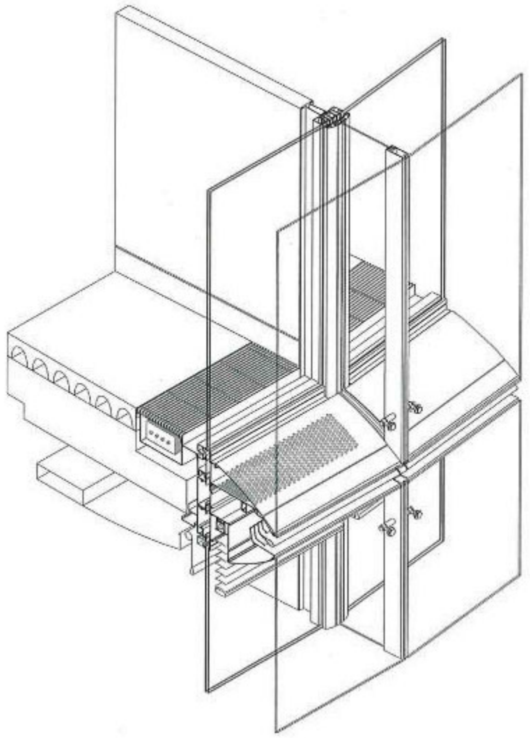


Figure 4.02.02: Isometric drawing of the double-skin facade showing the Fish Mouth inlet device.
Source: Ingenhoven Architects, n.d.

Location
Essen, Germany

Design Architects
Ingenhoven Architects

Building Function
Office

Project Data:
1994 - 1996
127m
31stories
36,000 m^2

Circular Shape
8m Depth

Ventilation:
- Mixed-Mode
  Wind-driven
  Mechanical
  Control: BMS & User

Facade:
- Double-Skin
  Cavity: 500mm
  Horiz. Continuity: 2m
  Vert. Continuity: 3.5m
- Extra-Clear Glazing
  Outer Skin:
  toughened safety glass
  Inner Sash Window:
  laminated safety glass

Shading:
- Vertical Blinds
  Control: BMS

Energy Production:
-

(Wood & Salib, 2013)

Annual % of NV
75%
Annual Savings:
Unpublished
Annual Consumption:
Unpublished

Source: Architizer, n.d.

The Fish Mouth device regulates the changing wind speeds with respect to height.

4.03.03 Double Skin

KfW Westarkade

The KfW Westarkade is another sustainable high-rise building in Frankfurt and one of the most energy efficient buildings in the world. The energy concept relies to a large extend on the highly innovative wind-pressurized facade design and its aerodynamic shape which both facilitate the natural ventilation inside the building.

The envelope of the building consists of a double skin facade with a sawtooth shaped fixed outer skin and a inner layer alternating between fixed and movable glazing units. The colored sawtooth profile is alternating between the fixed outside glazing and can be opened 90° to the side in order to allow fresh air into the cavity. The flap openings are sensor-controlled in order to maintain a constant air pressure (<6m/s) inside the cavity, with consideration to outside temperature, solar radiation and wind pressure on the windward and leeward sides of the building *(CTBUH, December 2011)*.

The inner facade layer consists of fixed and openable argon-filled double-glazed windows with a low-e coating, which can be fully operated by the users to naturally ventilate the building. The air travels across the rooms, into the core, where the air is naturally driven upwards and exhausted through roof shafts. Due to the highly-efficient ventilation strategy, the building can be naturally ventilated for 8 months of the year. Water pipes embedded into the slabs provide the building with additional heating and cooling.

The venetian blinds are protected from outdoor conditions by being incorporated into the cavity. They are fully operated by the BMS, depending on the amount of solar radiation.

Location
Frankfurt, Germany

Design Architects
Ingenhoven Architects

Building Function
Office

Project Data:
2010
56m
14 stories
22,300 m^2

Aerodynamic Shape
6.3m Depth

Ventilation:
- Mixed-Mode
  Wind-driven
  Mechanical
  Control: BMS & User

Facade:
- Double Skin
  Cavity: 700mm
  Vert. Continuity: 3.7m
- Glazing
  Outer Skin: Acoustic Insulating Glazing
  Inner Window: 2 Glazing with low-E coating

Shading:
- Vertical Blinds
  Control: BMS

Energy Production:
-

(Wood & Salib, 2013)

Annual % of NV
60%
Annual Savings:
84% < typical office
Annual Consumption:
50kWh/m^2

Source: Domus Web, n.d.

> Due to the highly-efficient ventilation strategy, the building can be naturally ventilated for 8 months of the year.

4.04.01 Energy Generating Facade

TU Vienna

The TU Vienna building at the 'Getreidemerkt' is one of the eight buildings renovated or rebuilt as part of the TU University 2015 project. The former high-rise building from the 70s had an energy consumption of around 803 kWh/m²BGF.a and has been renovated in 2014 into an plus-energy building with the largest Building Integrated Photovoltaic System in Austria *(Univercity, n.d)*.

In order to achieve a plus-energy standard, an extreme reduction of the energy consumption was necessary. Therefore, 9300 building components were assessed and optimized. The optimization process lead to the design of an intelligent building envelope, the integration of highly performing building services and the use of more energy efficient computers.

The coverage of the primary energy demand is mainly achieved through the significant amount of PV panels on the roof and the BIPV cells incorporated into the south and south-east facades. The facade modules of the outer skin were divided in three sections, the Photovoltaic cells being located at the top and at the bottom part of each module, whereas the fixed and openable triple glazing windows are located in the middle section.

The Photovoltaic cells with an efficiency of 19% are integrated in between two glass panes and are distanced from the building insulation layer by a 150mm cavity for ventilation. In continuation of the Photovoltaic panels, a second skin glazing layer is covering the window area and protects the integrated blinds from high wind speeds. The ventilation of the double skin cavity is separated from the ventilation of the PV modules.

By opening the internal windows, fresh air is drawn from the cavity into the building. Nevertheless, during the day, the building mostly relies on the ultra-efficient mechanical ventilation system with heat and moisture recovery. An integrated Building Monitoring System (BMS) opens the windows automatically at night to cool the building in summer. The BMS also controls the vertical blinds depending on the weather. The energy demand for heating is mostly covered by the waste heat recovered by the servers.

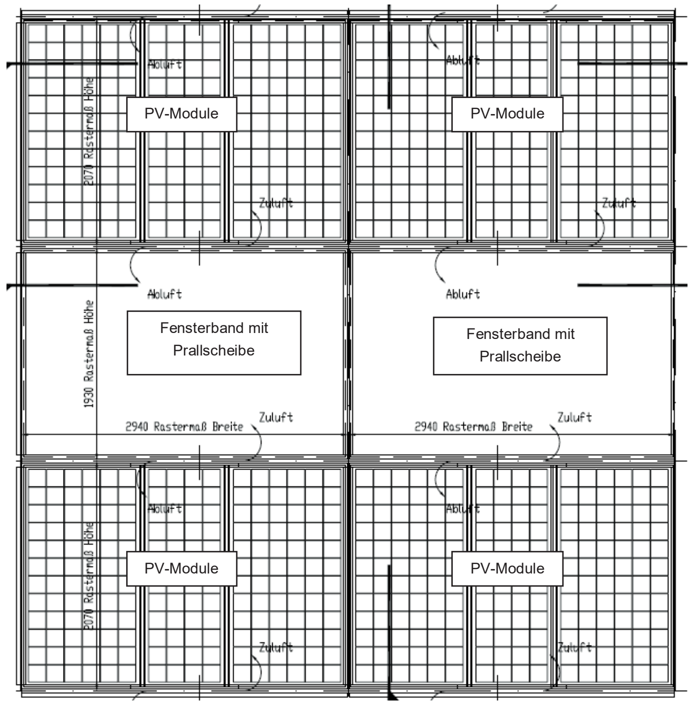


Figure 4.02.03: PV Panel Distribution of South Facade System
Source: Schöberl et al., n.d.

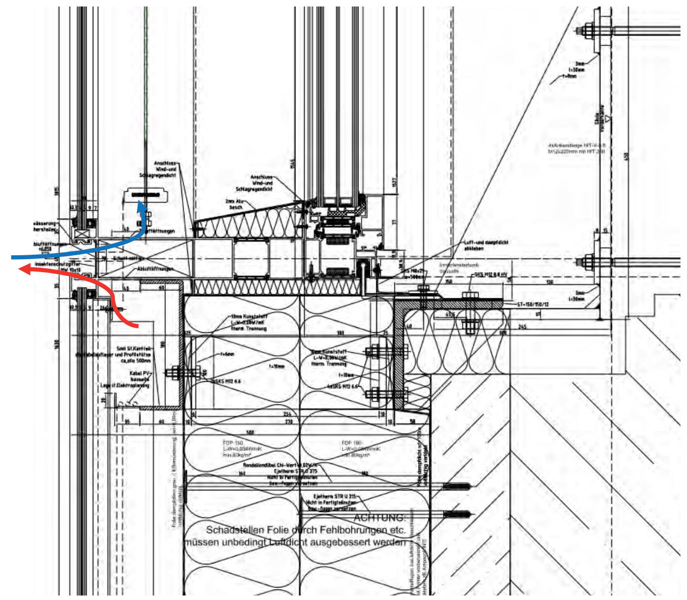


Figure 4.02.04: Facade Vetilation Strategy
Source: Schöberl et al., n.d.

Location
Vienna, Austria

Design Architects
ARGE Architekten
Hiesmayr, Gallister,
Kratochwil

Building Function
Office

Project Data:
2014
55m
11stories
8,000 m²

Rectangular Shape
8m Depth

Ventilation:
- Mixed-Mode
  Wind-driven
  Mechanical
  Control: BMS & User

Facade:
- Box windows
  Cavity: 150mm
- Solar Glazing
  Outer Skin: 2 Glazing
  Inner Window: 3 Glazing

Shading:
- Vertical Blinds
  Control: BMS

Energy Production:
- PV Roof & Facade
  Roof: 618m²
  97.8 kWp
  Facade: 1581m²
  230.6 kWp
  Total: 248.8 kWh/yr
- Waste Heat Recovery
- Energy Recovery Lifts

(Univercity, n.d)

Annual % of NV
Unpublished
Annual Savings:
87.5% < typical
Annual Production:
+5kWh/m²

Source: TU Wien, n.d.

Plus-energy building with with the largest Building-Integrated Photovoltaic System (BIPV) in Austria.

09

Appendix B: Schedules and Detailed Results

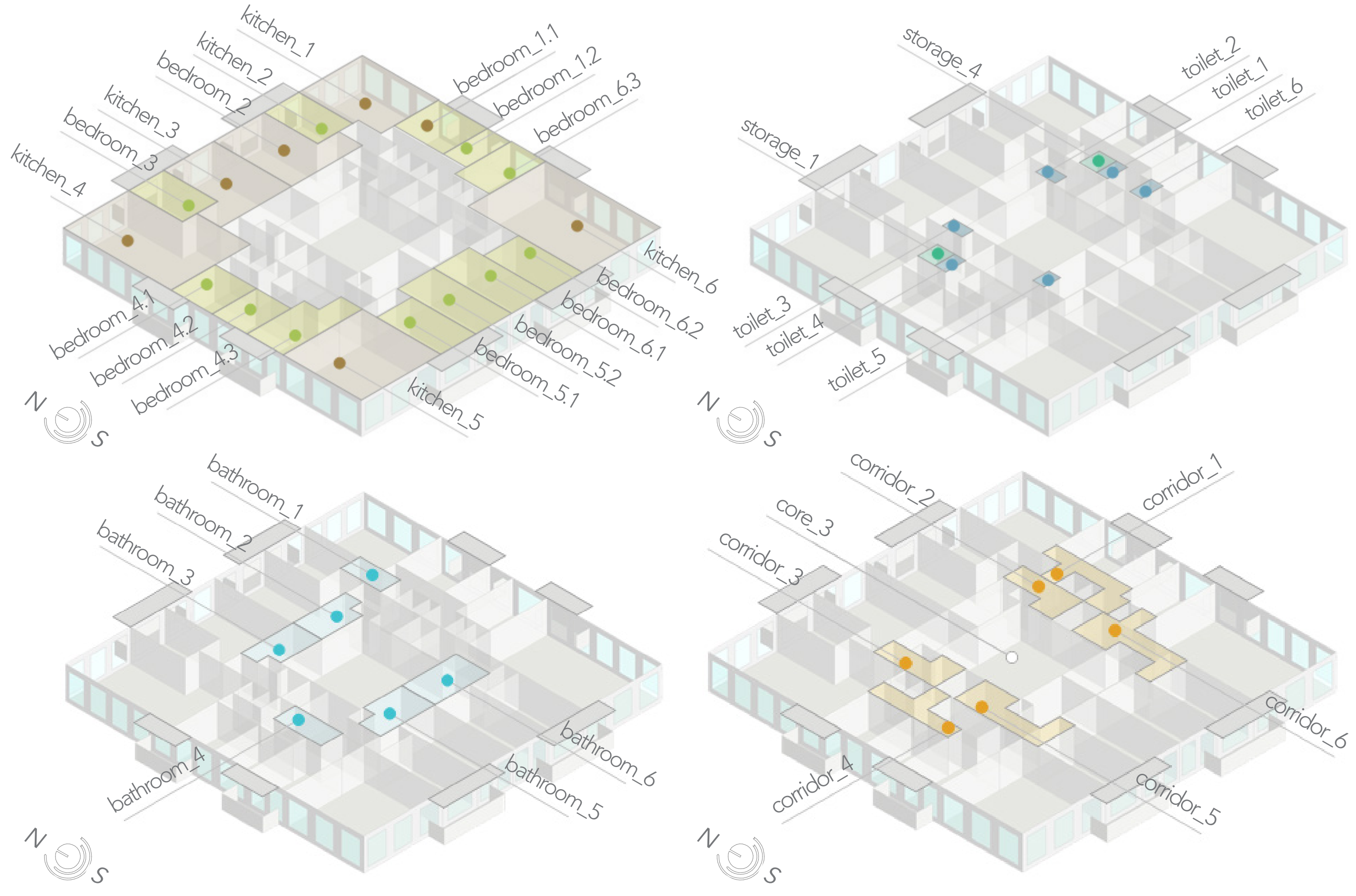
Occupancy Schedules

	Kitchens/Living		Bedrooms		Bathrooms	
Hour	Week days	Weekend	Week days	Weekend	Week days	Weekend
0	0.1	0.1	1	1	0	0
1	0.1	0.1	1	1	0	0
2	0.1	0.1	1	1	0	0
3	0.1	0.1	1	1	0	0
4	0.1	0.1	1	1	0	0
5	0.2	0.2	1	1	0	0
6	0.8	0.2	1	1	1	0.1
7	1	0.5	0.85	0.85	0.8	0.2
8	0.5	0.8	0.39	0.39	0.5	0.8
9	0.5	1	0.25	0.25	0.1	0.5
10	0.1	0.5	0.25	0.25	0	0
11	0.1	0.8	0.25	0.25	0.1	0.1
12	0.25	1	0.25	0.25	0	0
13	0.5	0.5	0.25	0.25	0.1	0.1
14	0.25	0.5	0.25	0.25	0	0
15	0.1	0.25	0.25	0.25	0	0
16	0.1	0.25	0.3	0.3	0	0.1
17	0.25	0.5	0.52	0.52	0.5	0.5
18	0.8	0.5	0.87	0.87	0.2	0.5
19	1	0.5	0.87	0.87	0	0
20	1	0.5	0.87	0.87	0	0
21	0.8	0.5	1	1	0.2	0.2
22	0.5	0.5	1	1	0	0
23	0.25	0.25	1	1	0	0

	Toilets		Storages		Corridors/Core	
Hour	Week days	Weekend	Week days	Weekend	Week days	Weekend
0	0	0	0	0	0	0
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0.1	0.1	0	0	0.1	0.1
7	0.1	0.1	0	0.25	0.1	0.1
8	0.1	0.1	0	0.1	0.1	0.1
9	0	0	0	0.1	0.05	0.05
10	0	0	0	0.25	0.05	0.05
11	0.1	0.1	0	0	0.05	0.05
12	0	0	0	0	0.1	0.1
13	0.1	0.1	0	0	0.1	0.1
14	0	0	0	0	0.05	0.05
15	0	0	0	0	0.05	0.05
16	0	0	0	0	0.05	0.05
17	0.1	0.1	0	0	0.05	0.05
18	0.1	0.1	0	0	0.1	0.1
19	0	0	0	0	0.1	0.1
20	0	0	0	0	0.05	0.05
21	0.1	0.1	0	0	0.1	0.1
22	0	0	0	0	0.05	0.05
23	0	0	0	0	0	0

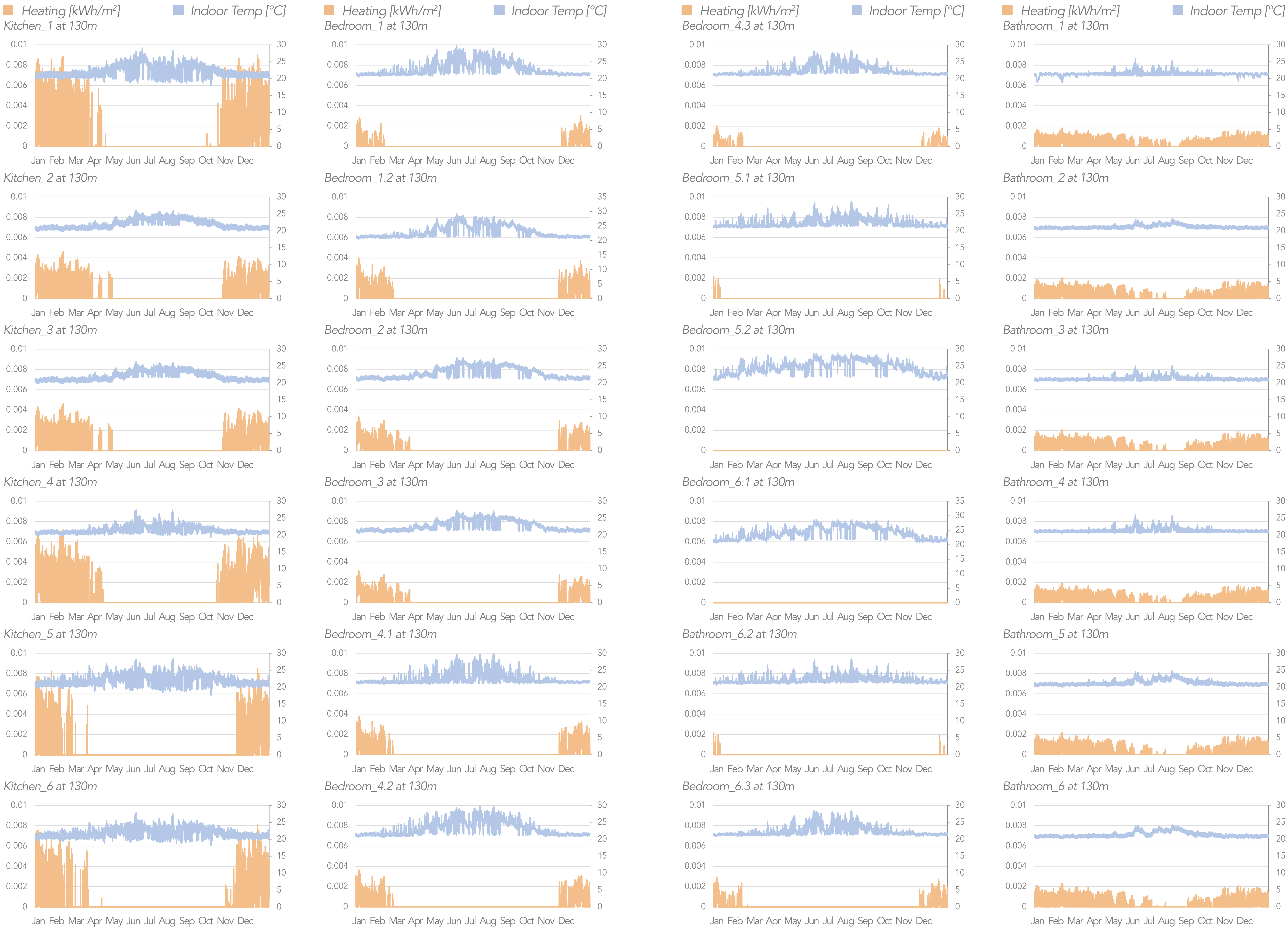
Equipment

	Kitchens/Living		Storage	
Hour	Week days	Weekend	Week days	Weekend
0	0.05	0.05	0	0
1	0.05	0.05	0	0
2	0.05	0.05	0	0
3	0.05	0.05	0	0
4	0.05	0.05	0	0
5	0.05	0.05	0	0
6	0.1	0.05	0	0
7	0.2	0.1	0	0
8	0.1	0.2	0	1
9	0.05	0.2	0	1
10	0.05	0.05	0	0
11	0.1	0.1	0	0
12	0.2	0.2	0	0
13	0.1	0.2	0	0
14	0.05	0.1	0	0
15	0.05	0.05	0	0
16	0.05	0.05	0	0
17	0.05	0.1	0	0
18	0.1	0.1	0	0
19	0.2	0.2	0	0
20	0.1	0.1	0	0
21	0.05	0.05	0	0
22	0.05	0.05	0	0
23	0.05	0.05	0	0



Room 130m	Heating Hours		Cooling Hours		Percentage of Time Comfortable		Minimum Indoor Temp		Maximum Indoor Temp	
Kitchen_1	2923	hours	166	hours	95	%	18	°C	29	°C
Kitchen_2	2745	hours	394	hours	100	%	20	°C	26	°C
Kitchen_3	2749	hours	394	hours	100	%	20	°C	26	°C
Kitchen_4	3218	hours	133	hours	99	%	19	°C	27	°C
Kitchen_5	1718	hours	195	hours	96	%	18	°C	28	°C
Kitchen_6	2002	hours	120	hours	97	%	18	°C	28	°C
Bedroom_1.1	1023	hours	1239	hours	94	%	21	°C	30	°C
Bedroom_1.2	1697	hours	983	hours	96	%	20	°C	29	°C
Bedroom_2	2095	hours	775	hours	100	%	20	°C	28	°C
Bedroom_3	2093	hours	750	hours	100	%	20	°C	27	°C
Bedroom_4.1	1489	hours	991	hours	98	%	21	°C	30	°C
Bedroom_4.2	1505	hours	972	hours	95	%	21	°C	30	°C
Bedroom_4.3	950	hours	870	hours	99	%	21	°C	28	°C
Bedroom_5.1	129	hours	1672	hours	99	%	21	°C	29	°C
Bedroom_5.2	0	hours	1998	hours	92	%	21	°C	29	°C
Bedroom_6.1	0	hours	2046	hours	98	%	21	°C	29	°C
Bedroom_6.2	129	hours	1663	hours	99	%	21	°C	28	°C
Bedroom_6.3	1008	hours	1255	hours	98	%	21	°C	28	°C
Bathroom_1	5517	hours	570	hours	92	%	19	°C	26	°C
Bathroom_2	5003	hours	570	hours	99	%	20	°C	24	°C
Bathroom_3	5003	hours	570	hours	93	%	20	°C	25	°C
Bathroom_4	5230	hours	570	hours	94	%	20	°C	26	°C
Bathroom_5	4855	hours	570	hours	100	%	20	°C	25	°C
Bathroom_6	4800	hours	570	hours	100	%	20	°C	24	°C


Heating [kWh/m²]
Cooling [kWh/m²]
Kitchen_1 at 130m
Bedroom_1 at 130m
Bedroom_4.3 at 130m
Bathroom_1 at 130m
Kitchen_2 at 130m
Bedroom_1.2 at 130m
Bedroom_5.1 at 130m
Bathroom_2 at 130m
Kitchen_3 at 130m
Bedroom_2 at 130m
Bedroom_5.2 at 130m
Bathroom_3 at 130m
Kitchen_4 at 130m
Bedroom_3 at 130m
Bedroom_6.1 at 130m
Bathroom_4 at 130m
Kitchen_5 at 130m
Bedroom_4.1 at 130m
Bathroom_6.2 at 130m
Bathroom_5 at 130m
Kitchen_6 at 130m
Bedroom_4.2 at 130m
Bedroom_6.3 at 130m
Bathroom_6 at 130m
0.01
0.008
0.006
0.004
0.002
0
0
-0.0005
-0.001
-0.0015
-0.002
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


Heating [kWh/m2]
Indoor Temp [°C]
Kitchen_1 at 130m
Kitchen_2 at 130m
Kitchen_3 at 130m
Kitchen_4 at 130m
Kitchen_5 at 130m
Kitchen_6 at 130m
Bedroom_1 at 130m
Bedroom_1.2 at 130m
Bedroom_2 at 130m
Bedroom_3 at 130m
Bedroom_4.1 at 130m
Bedroom_4.2 at 130m
Bedroom_4.3 at 130m
Bedroom_5.1 at 130m
Bedroom_5.2 at 130m
Bedroom_6.1 at 130m
Bathroom_6.2 at 130m
Bedroom_6.3 at 130m
Bathroom_1 at 130m
Bathroom_2 at 130m
Bathroom_3 at 130m
Bathroom_4 at 130m
Bathroom_5 at 130m
Bathroom_6 at 130m
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

10

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8.01

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