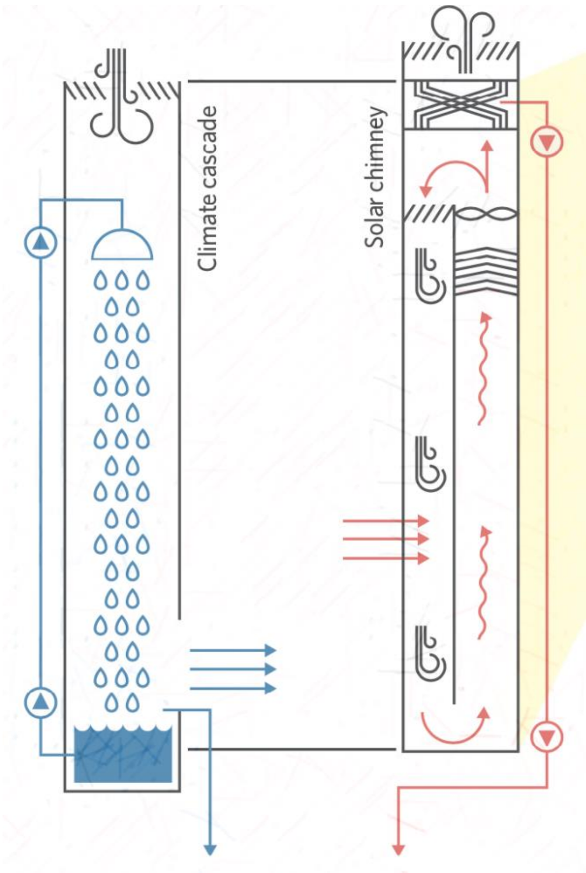
Refurbishment of an office building in the Netherlands using the Earth, Wind and Fire system.



Research Report

Building Technology Graduation Studio 2020-2021
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Abstract

The built environment is the largest energy consumer in the European Union in which the non-domestic sector accounts for 13% of the total energy consumption and the office buildings account for 50% of the energy consumption. The office buildings in the Netherlands exhibit poor energy performance and thermal comfort. There is an urgent need to rectify this problem by renovation or refurbishment by utilizing renewable sources of energy. Therefore, this research focuses on improving the energy consumption of an office building in the Netherlands by implementing the Earth, Wind and Fire system which utilizes the environmental energy of earth mass, wind and sun to generate and supply energy throughout the building by eliminating the use of HVAC systems. The research adopted basic and dynamic simulation models to evaluate the energy performance of the building with EWF system and ATG method to evaluate the Thermal comfort. The research concluded that the EWF system is an efficient way to reduce the energy performance of the Provinciehuis Utrecht building and by refurbishing the façade and adding PV panels, the energy consumption of the building can reduce further. The research was validated by using the BENG regulations and a proposal was designed to make the Provinciehuis Paris Proof.

Keywords: Earth, Wind and Fire system, Climate Cascade, Solar Chimney, Thermal Comfort, Energy Consumption, Office Buildings.

Acknowledgement

"Unity is strength....when there is teamwork and collaboration, wonderful things can be achieved."
- Mattie Stepanek

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Earth
Wind
Fire

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1. Introduction

The built environment is a central part of our life where we spend a large amount of our time. However, the built environment is the single largest energy consumer in the European Union (EU) and one of the largest carbon dioxide emitters. The building sector collectively constitutes for 40% of the energy consumption and 36% of greenhouse gas emissions (European Commission, 2020). As shown in Fig.1.1, the non-domestic or services sector accounts for 14.5% of the total energy consumption out of which 26% of the energy is consumed by the offices. However, the non-domestic sector accounts for a small percentage of the overall energy consumption, the energy consumed per square meter is about 40% more than the residential sector (National Energy Foundation, 2016).

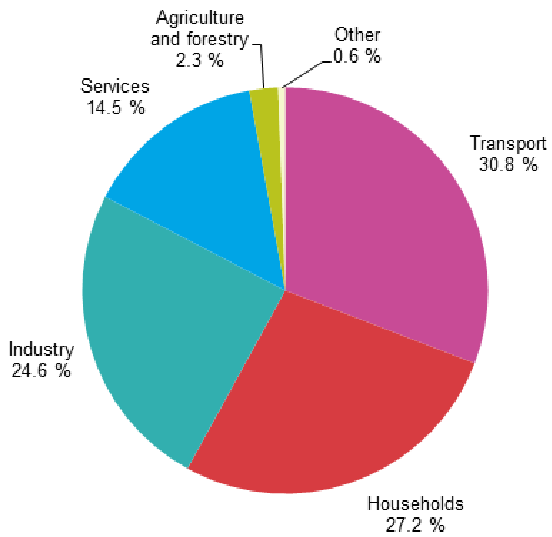


Figure 1.1: Final energy use by sector in 28 EU countries (Eurostat, 2017)

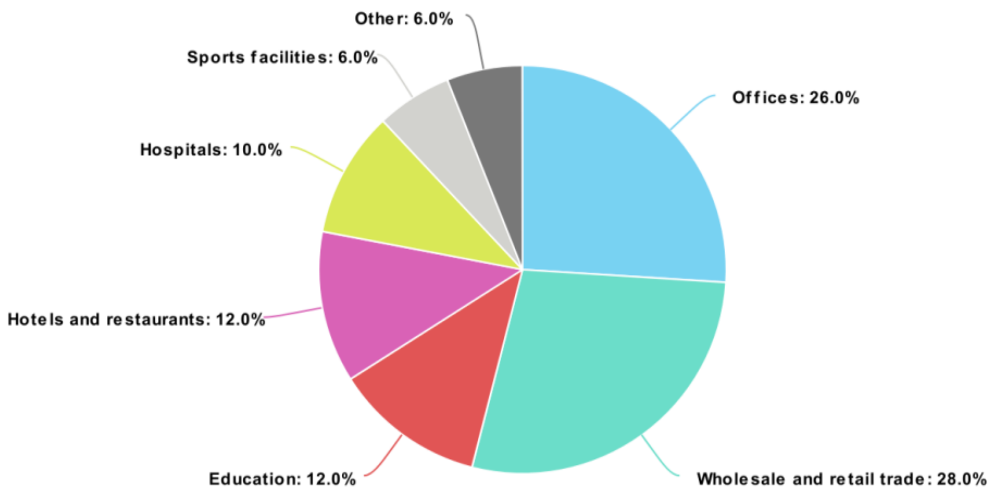


Figure 1.2: Energy breakdown in non-domestic buildings in 28 EU countries (National Energy Foundation, 2016)

According to a survey, around 85% of the 160 million buildings in the European Union show poor performance in terms of thermal comfort and energy consumption (Remøy et al., 2017). EU's total energy consumption can reduce by 5-6% and lower the carbon dioxide emissions by 5% through renovation, yet only 1% of the national building stock is being renovated every year (European Commission, 2020).

It is important to critically analyze the issues with the existing office buildings in the Netherlands. About 45% of the office stock in the Netherlands is older than 30 years which signifies that the façade and technical installations reach the end of their life (Vijverberg, 2002). Most technical installations have a life span of around 15-20 years and are often more fragile and expensive to maintain (Bronsema, 2013). Therefore, to improve the overall performance of the buildings, governments and global organizations aim at reducing the energy consumption through building refurbishments and renovations.

Office buildings ideally should provide a comfortable indoor environment which should not harm the occupants' health and contribute towards more productive work environment (Brink & Mobach, 2016). Thermal discomfort can lead to Sick Building Syndrome (SBS) or Building related illness (BRI) which can adversely affect the occupants' health (Pivac & Nižetić, 2017). A study conducted by Brink & Mobach on 182 office buildings in the Netherlands showed that the indoor temperature was the most significant indicator towards the study of thermal comfort. The study also concluded that most of the occupants were satisfied when the indoor air temperature was between 20°C - 22°C and anything more than this range might be too warm for the occupants during the winter months (Brink & Mobach, 2016).

Energy renovation is instrumental for reaching the EU and national 2020 goals and can reduce the overall energy demand by 50% (Saheb et al., 2015). The 2030 Communication published by the European Commission in July 2014 states that "the majority of the energy-saving potential is in the building sector" ("Energy, Climate change, Environment", 2020). The initial objective stated in the EPBD 11 Recast Directive 2010/31 / EU says that by December 31, 2020, the new buildings in the EU must be nearly zero energy building i.e. buildings with very high energy performance and this should be achieved using a considerable amount of renewable energy resources (Bronsema, 2013).

An important aspect to be tapped upon here is that existing research has not mentioned the lack of utilization of renewable energy resources despite mentioning increasing CO_2 emissions. In 2018, only 7.8% of the total final energy consumption use the energy generated from renewable sources. Environmental energy such as Solar, Wind, and geothermal energy have immense potential in energy generation and can play a key role

in contributing towards nZEB. The Earth, Wind and Fire concept (EWF) can play a key intervention to achieve the goals set by the European Union and National Governments. The concept is based on the phenomenon of using the driving forces of nature to control the indoor climate of the buildings. It utilizes the environmental energy of earth mass, wind and sun to generate and supply energy throughout the building by eliminating the use of HVAC systems, thereby minimizing the total energy consumption of the building and providing a healthy and productive working environment (Bronsema, 2013). The EWF system utilizes Earth mass through gravity that causes the water sprayed at the top of the Climate Cascade to fall down and Earth as a source for heating and cooling and for heat/cold storage. The system exploits wind through wind-driven natural ventilation utilizing the wind pressures for the movement. Climate Cascade provides the supply of ventilation air using the positive wind pressure whereas the air is extracted via the Solar Chimney utilizing the negative wind pressures. Fire is used as a metaphor for sun utilizing solar energy through active system in the form of Solar Chimney and solar facade and the use of PV foil on the Ventec roof (Bronsema, 2013).
As the EWF system incorporates natural ventilation systems such as wind and thermal buoyancy induced ventilation strategy where the driving force is the nature, the thermal comfort of the occupants can improve significantly.

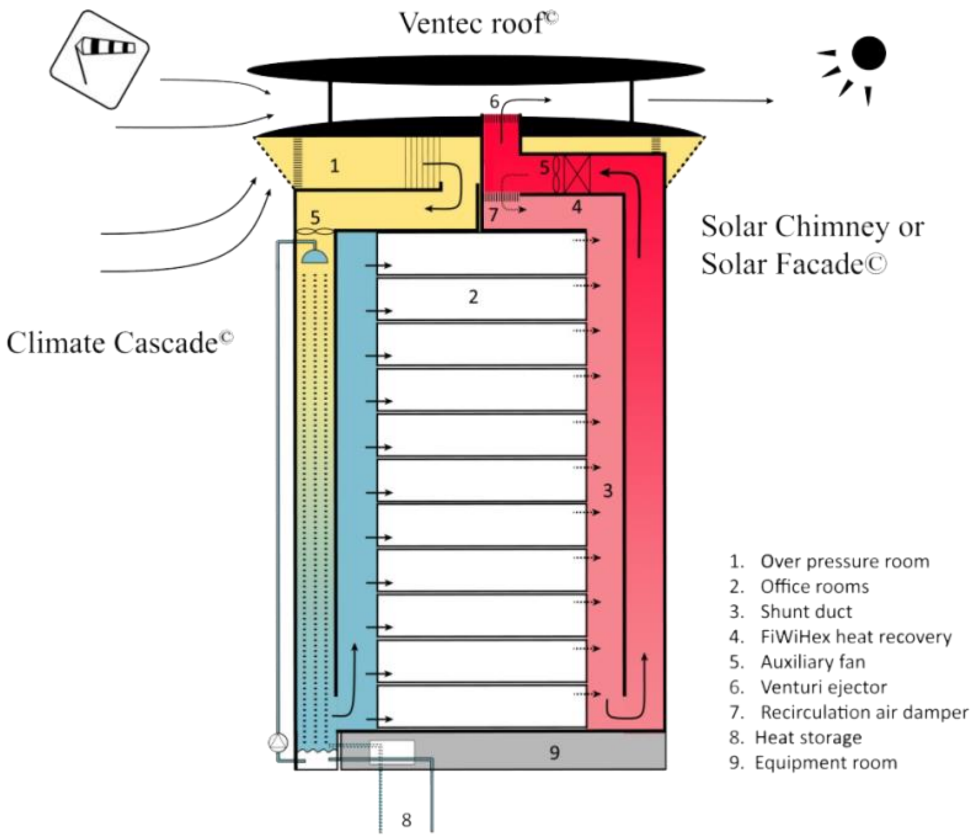


Figure 1.3: Earth, Wind and Fire Natural Air Conditioning system (Bronsema, 2013).

To solve the above mentioned issues related to poor energy performance and indoor work environment of office buildings, the main research question is formulated as follows:

> *How are the **design strategies** derived from the **Earth, Wind and Fire system**, implemented in the **refurbishment of an office building in the Netherlands** in order **to improve the energy performance**?*

The main objective of this research is to improve the energy performance of an office building using the EWF design strategies which will be developed in the literature study. The case study will showcase the elements of the EWF system, attempting to prove the efficiency of the system as a climate machine and approaching one step closer to the ambitious 2050 goals set by the EU commission. The conclusions drawn from this research will be applied to the chosen office building and will determine if the EWF system can reduce the energy consumption of the office building.

2. Office refurbishment

2.1. Energy consumption in offices

The energy consumption in office buildings of Europe varies from 100 kWh per m^2 to 1000 kWh per m^2 annually, depending on the site location, office equipment, building envelope, climate control strategies and systems and lighting (Burton, 2013). The highest amount of energy is consumed for heating, cooling and ventilation of the office building. In order to evaluate these parameters, 50 office buildings across Europe were selected and compared on the basis of energy consumption per country. As shown in Fig. 2.1, there are significant differences in the mean annual energy consumption per country which ranges between 170 kWh/m^2 in Greece and 438 kWh/m^2 in UK (Burton, 2013).

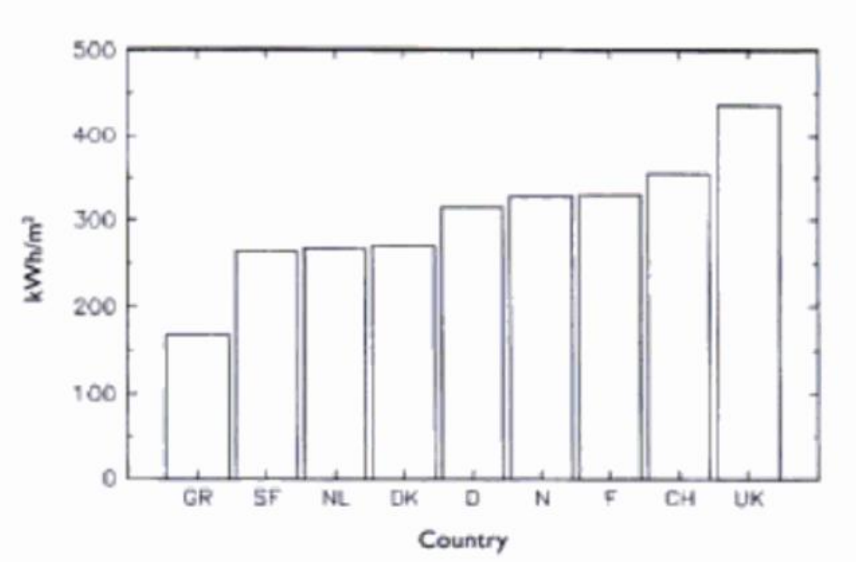


Figure 2.1: Mean annual energy consumption in office buildings per individual country (Burton, 2013).

A study was conducted by EU Building Stock Observatory in 2013 to evaluate the final Energy Use Intensities (EUI) (kWh/m^2) for different non-residential buildings for a selected number of European countries as shown in Fig.2.2 (Balaras et al., 2017). In case of Netherlands, the offices contribute to the highest EUI after hotels and restaurants, which is around 357 kWh/m^2.

Country	Offices	Wholesale & Retail	Hotels & Restaurants	Health care	Education	All NR (normal climate)
Austria						145.8 / -
Belgium						298.1 / -
Bulgaria		77.8 / -	96.5 / -	656.5 / -	219.3 / -	130.6 / -
Czech Republic						201.4 / -
Croatia						239.9 / -
Cyprus						291.3 / -
Denmark						201.6 / 182.0
Estonia		479.6 / -	70.7 / -	147.8 / -	217.4 / -	403.1 / -
Finland						292.6 / 273.5
France	- / 280.9	255.8 / 256.7	391.0 / 393.3	228.2 / 232.4	143.6 / 154.5	276.1 / 240.1
Germany	130.8 / 154.5	151.3 / 148.3	212.3 / 201.5	317.2 / 328.5	108.5 / 98.2	238.6 / 187.0
Greece						300.1 / -
Hungary						203.7 / -
Ireland						186.4 / -
Italy						652.5 / -
Latvia						302.7 / -
Lithuania						136.9 / -
Luxembourg						350.4 / -
Malta	234.9 / -	394.2 / -	302.1 / -			436.6 / -
Netherlands	356.8 / -	174.1 / -	380.8 / -	237.8 / -	127.8 / -	149.0 / -

Figure 2.2: Final energy use intensities (kWh/m^2) for Non-Residential buildings in European countries (Balaras et al., 2017)

The EUI can be further broken down for different end-uses namely space-heating, water heating, cooking, lighting and space cooling. The study shows that 61% of the total final EUI is consumed by space-heating followed by lighting (12.2%), cooking (12.0%), water heating (10.5%) and space cooling (4.2%) (Balaras et al., 2017). In case of Netherlands, space heating consumes the maximum amount of EUI which is around 150 kWh/m^2, followed by water heating, lighting, space cooling and cooking which consumes negligible amount of EUI. Thus, space heating is one of the major parameter which consumes maximum amount of energy.

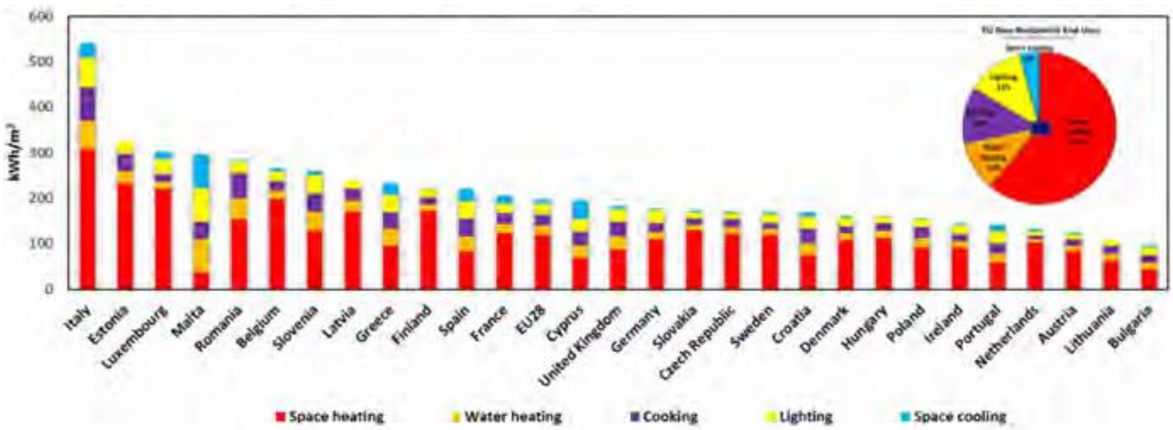


Figure 2.3: Breakdown of final energy use intensity (kWh/m2) for different end-uses in Europe (Balaras et al., 2017)

2.2. Energy efficient refurbishment

Energy efficient refurbishment means upgrading the energy performance of a building by improvements in the building envelope, energy systems and maximizing the use of renewable energy sources for energy production (Desideri & Asdrubali, 2019). While refurbishing a building, certain general objectives need to be considered. They are:

- To restore the original value of the existing building.
- To adapt to the new design layout and strategies.
- To improve the indoor climate.
- To reduce the energy consumption.

The first two objectives are the main driving forces for refurbishment while the last two objectives are generally achieved in order to eliminate the underlying issues of the existing poor performing office buildings. The following general strategies were established:

- To reduce energy demand for heating, cooling, lighting and ventilation.
- Energy supply and production should use passive methods like natural ventilation, solar heating, day lighting, stack effect, night cooling etc.
- Energy produced or released should be optimized by restoring it for future use or reuse it back to the energy cycle.

2.3. Physical factors affecting the comfort levels in offices

This research focuses on the physical factors of comfort as it is related to the biological responses to indoor quality, climate, noise and ergonomics (Remøy et al., 2017).

Thermal comfort

Thermal comfort is subjective and depends on 3 variables: Air temperature, relative humidity and relative air velocity (Remøy et al., 2017). It is practically not possible to be able to fulfill the comfort levels of every occupant in a particular space; hence it is important to set a thermal comfort range of occupants. In case of office buildings, thermal comfort can be measured by the number of occupant complaints. According to a study conducted by Lan et al. (2012), comfortable cool environment is beneficial for performance of office work by avoiding high temperatures in winters and in summers have significant benefits. The study shows that, for optimum performance the indoor air temperature should be increased from 23°C to 25.4°C in summers and reduced from 21.9°C to 19.7°C in winters (Lan et al., 2012). This study states that the indoor air temperature for occupants comfort has no impact on the energy efficiency of the building. Albeit air temperature, mean radiant temperature, temperature of neighboring surface are also important and need to be considered for refurbishment along with the radiant effects of ceilings, walls, thermal draughts and air movements.

Indoor Air Quality

To achieve a good IAQ, it is important to primarily reduce the amount of the indoor air pollutants and then design an efficient air circulation system which maintains the concentration of contaminants below the acceptable range. Records of office buildings in Europe have shown that the standards for IAQ are often not met despite air flow rates being higher than normal required standards (Burton, 2013). This is due to the building being the major contaminant in comparison with its occupants. With a judicious choice of building materials, fittings, equipment and finishes, this situation can be avoided. (Burton, 2013).

Acoustic Quality

Acoustic quality can be divided into 2 components: noise level and room acoustics. Noise levels are very significant in terms of designing an office building. Room acoustics is affected by the reverberation time. In office buildings, the reverberation time should be less than 1 second (Burton, 2013). This can be achieved by introducing sound absorbing materials, and these elements should be chosen on the basis of the effect of sound frequency on the reverberation time. If this condition varies significantly, reverberation time can increase and the room acoustics may lead to occupants' discomfort.

Lighting and Daylight

According to a study carried out by Santamouris et al. (1994) on 186 office buildings in Greece, use of daylight along with efficient lighting fixtures resulted in substantial amount of energy savings. From the study, Santamouris et al. (1994) concluded that 40% of lighting energy consumption can be reduced when daylight is allowed from one side of the façade and can reach up to 95% reduction when allowed from all four sides of the façade when fluorescent lamps are used along with daylight during the office working hours. By optimum utilization of Daylight, thermal loads in office buildings can be reduced as the use of artificial light is minimized. (Al-Ashwal & Hassan, 2017).

2.4. Space Heating

In case of new office buildings, the primary energy used for space heating is fairly less as compared to the energy used for ventilation, lighting and equipment (Burton, 2013). Some general strategies for space heating are formulated and are given below:

- Significantly decrease space heating demands by minimizing heat losses.
- Generate the heat to be supplied by means of passive solar technologies and heat recovery systems.
- If the heating demand is not met by the passive systems, efficient and controlled use of mechanical system can be applied.

To understand the effect of space heating in the overall energy consumption of the building, it is necessary to analyze the parameters which directly affect the need to have this system. These parameters and strategies are explained in the section.

Strategies for reducing space heating

In the case of refurbishment/renovation, building design, insulation and air tightness form the basic strategies.

Building Design

In case of buildings with less surface area and more volume i.e. buildings which are high-rise and compact, use less space heating energy as the exposed surface area is less and hence less heat is transmitted (Burton, 2013). In such cases, glass façades can have a significant impact, for example, glass covered atriums can be attached to the existing buildings which can be as high as the building and can help in providing better daylight, natural ventilation and insulating the building from the outside environment.

Layout

Thermal zoning of the floor plan of the existing building can also have a significant impact in reducing the heat losses. The building layout can be zoned on the basis of different spatial activities and building usage, HVAC requirements and temperature stratification (De Souza & Alsaadani, 2016).

Insulation

With better/increased insulation, occupant comfort can be improved considerably. Insulation of the building elements like walls, floors and roofs can help in reducing the thermal load on the building. Insulating the colder part of the building is preferred as it reduces thermal bridges, ensures that if any condensation occurs it is on the outer phase of the structure, internal thermal mass remains high and allows night ventilation cooling (Burton, 2013).

Windows

50% of the heat losses from the windows (window frame and glazing) can be reduced by adding 2-3 layers of glazing, i.e. double or triple glazing system (Burton, 2013). The cavity between the glass panes can be filled with a low conductivity gas and low emissive coatings can be used on the glass panes. Window frames should be made up of insulating materials like wood or thermal breaks should be included (Burton, 2013). It was concluded from a study in Norway where old double glazed windows were replaced by adding low-e coatings, that 50% of the energy consumption of the building was reduced by making the above changes along with reduction in air infiltration and contributed to almost 2/3rd of the energy savings (Burton, 2013). Another way of reducing heat losses is by adding a second skin to the façade which acts like a buffer between the outside and the skin of the building.

2.5. Ventilation

Indoor contaminant concentration can be controlled by segregating the sources in specific zones and extract the contaminants from these sources (Burton, 2013). Another way to tackle this issue is by primarily using natural ventilation system by maintaining the amount of fresh air supply and indoor air quality at an acceptable level.

Natural Ventilation

When Natural Ventilation system along with maintaining acceptable indoor air quality level is implemented during refurbishment, an energy-efficient and comfortable solution can be achieved. Natural ventilation can be categorized into wind-induced ventilation and buoyancy-induced ventilation (Wood & Salib, 2012).

Wind-induced and Buoyant-induced ventilation

The phenomenon of wind-induced ventilation is seen when pressure distribution is formed due to the wind, surrounding a structure, with respect to the atmospheric pressure. Buoyancy induced ventilation is seen occurring due to differences in density which is caused by changes in height and temperature when different zones in the building are taken into consideration. Buoyancy invoked pressure differences rely on the stack height and the difference in air density which is a function of temperature and moisture content (Wood & Salib, 2012).

Hybrid Ventilation

In cases where natural ventilation system cannot be used, hybrid or mix-mode ventilation strategy works well. In hybrid ventilation, the building utilizes both natural ventilation and mechanical ventilation system. This system is classified on the basis of the operation strategy, which zone of the building needs to be ventilated using which system, at what time or same time which system needs to operate etc. They are classified as contingency, zoned and complementary systems.

- Contingency: In this case, the building is designed primarily using mechanical systems but has the ability to switch to natural ventilation system or part of the building is reserved for future installations of mechanical equipment's (Wood & Salib, 2012).
- Zoned: In this case, both natural and mechanical systems operate in the building but have different zones of operation (Wood & Salib, 2012).
- Complementary: In this case, the mechanical and natural ventilation system works at the same time in the same space. The building has the ability to switch between mechanical ventilation and natural ventilation on a daily or seasonal basis according to the weather conditions. In some cases both the systems work simultaneously depending on the occupant comfort level and minimum energy consumption (Wood & Salib, 2012).

3. European and National level policies

Most of the European buildings follow certain government energy policies which help in improving the energy performance of the building. In this section, all the National and European energy standard and policies are described which will help in determining the energy goals to be achieved in this research.

3.1. The Paris Agreement

The Paris Agreement is a legally binding international climate change agreement adopted by 196 participating countries in 2015 (“Paris Agreement”, 2015). The aim of the agreement is to maintain the average temperature rise below 2°C, preferably below 1.5°C, and to reduce greenhouse gas emissions (“Paris Agreement”, 2015).

To ensure Paris Proof buildings, the Dutch Green Building Council (DGBC) stated that 2/3rd of the energy use in the Netherlands will have to be reduced as compared to the current energy situation (“Dutch Green Building Council”, n.d.). The DGBC conducted their research on predicting the total energy usage in 2050 assuming that all the energy generated and supplied will use renewable energy sources. Due to the assumption of using only renewable sources of energy, the buildings will consume considerably less energy as compared to the current energy reports (Veen, 2020). The DGBC established certain energy use limits for office buildings in the Netherlands to make it Paris Proof. According to their calculations, the maximum energy consumption of office buildings should not exceed 50 kWh/m^2/year (Veen, 2020). This includes both the building and user related energy consumption of the building. If the building needs to be considered Paris Proof only on the basis of building related energy use then the usage should not exceed more than 30-35 kWh/m^2/year (Veen, 2020). If this energy use limit exceeds, then the building will not be considered for 100% utilization of renewable sources of energy.

3.2. EPBD & EED

The Energy Performance of Buildings Directive (EPBD) and Energy Efficiency Directive (EED) are the two main legislative instruments in the European Union (EU) which aims at improving the energy performance of the buildings. According to the EPBD Directive 2010/31/EU and Directive 2012/27/EU on energy efficiency, by 2030, 40% of the greenhouse gas emissions should be eliminated in comparison with the year 1990 and an increase in the consumption of renewable sources of energy should be observed (“European Union”, 2018).

Under the directive, the overall EU energy consumption should not exceed 1483 million tonnes of oil equivalent (Mtoe) of primary energy (Fernbas, 2020). 1.5% reduction in national energy sales and at least 3% of the energy efficient renovation per year should be adopted throughout EU to achieve energy savings. By 2030, energy consumption should be no more than 1273 Mtoe of primary energy (Fernbas, 2020).

3.3. BENG

The current building standards that are EPC, EI and Energy Label are not compatible with the requirements of EPBD. Hence, a new building standard and determination method is established which is compatible with the EPBD regulations which is BENG and NTA 8800, effective from 1st January 2021 (Veen, 2020).

BENG consists of 3 indicators:

BENG 1: The maximum energy requirement in kWh per Usable Floor Area (UFA) per year.

BENG 2: The maximum primary energy consumption in kWh per UFA per year after netting.

BENG 3: The minimal share of renewable energy in percentages.

According to the EPBD regulations, BENG norms will also be affective on buildings with undergo major renovation or transformation. In accordance with this regulation, all offices which undergo renovation or transformation which change the surface of the building envelope more than 25% must abide by the BENG regulations (Veen, 2020). The BENG regulations for office buildings in the Netherlands are stated in Fig.3.1 with an overview of different versions of the norms.

	BENG 1 **Energy requirement** **[kWh/m².yr]**	**BENG 2** **Primary fossil energy consumption** **[kWh/m².yr]**	**BENG 3** **share renewable energy** **[%]**
2015 - NEN 7120	≤ 50	≤ 25	≥50
2018 - NTA 8800	A_{ls}/A_g ≤ 2,2 ->90 A_{ls}/A_g > 2,2 ->90 + 50 * (A_{ls}/A_g -2,2)	50	≥30
2019 - NTA 8800	A_{ls}/A_g ≤ 1,8 BENG 1 ≤ 90 A_{ls}/A_g > 1,8 BENG 1 ≤ 90 + 30 * (A_{ls}/A_g -1,8)	≤ 40	≥30

Figure 3.1: Overview of different versions of BENG norms for office buildings (Veen, 2020).

According to the current norms of 2019, all newly built office buildings and buildings undergoing major renovation should not consume more than 90kWh/m^2.yr of energy when the ratio between the surface area of the envelope and usable floor area is less than 1.8. When the ratio between the envelope surface and usable floor area is greater than 1.8, the energy consumption of the buildings should not exceed 90 kWh/m^2.yr + 30 * (A_{ls}/A_g -1.8) (Veen, 2020). The primary fossil energy consumption should be less than

40 kWh/m^2.yr and the use of renewable energy sources should be more than 30% of the total energy consumption of the building (Veen, 2020).

3.4. Thermal comfort guidelines in the Netherlands

In the 1970's, the Netherlands framed 3 methods under which guidelines were drafted for assessing thermal comfort. The temperature Overrun (TO) method and Predicted Mean Vote (PMV) were observed to be not effective for naturally ventilated buildings, therefore enabling the Adaptive Temperature Limit Value (ATG) method to be adopted (ISSO 74, 2019).

Temperature Overrun (TO)	Predicted Mean Vote (PMV) (NEN-EN-ISO 7730)	Adaptive Temperature Limit Value (ATG) (ISSO 74 / NEN-EN 15251)
The number of hours in a year that a room rises above a certain fixed temperature. For eg: the house may be above 25.5°C for a maximum of 300 hours per year. This is the method that the NOM Keur used in 2017 and 2018.	Percentage of people who are dissatisfied with the temperature in a room. A bandwidth is then designated as an objective. For eg: the PMV may fall below -0.5 or above 0.5 for a maximum of 2300 hours in a year.	The number of hours in a year that the temperature in a room exceeds a temperature that changes with the outside temperature. For eg: the hose may exceed class C for a maximum of 30 hours per year in accordance with the ATG as described in ISSO 74. This is the method described and used below.

Table 3.1: Three assessment methods for thermal comfort in the Netherlands (ISSO 74, 2019)

The ATG method helped categorizing and classifying buildings based on different parameters through which thermal comfort could be established. Within the ATG method, operative temperature is utilized for checking limits and buildings were analyzed depending on their categorization (Alpha/Beta) and class (A,B,C,D) as shown in Table 3.2. Figure 3.2 shows the relation between the comfort class limits and outdoor running mean temperature for both alpha and beta buildings. Buildings with operable windows with high level of user control and no active cooling falls under type Alpha and type Beta buildings can be considered when HVAC systems are used, facades are completely sealed and with little user control.

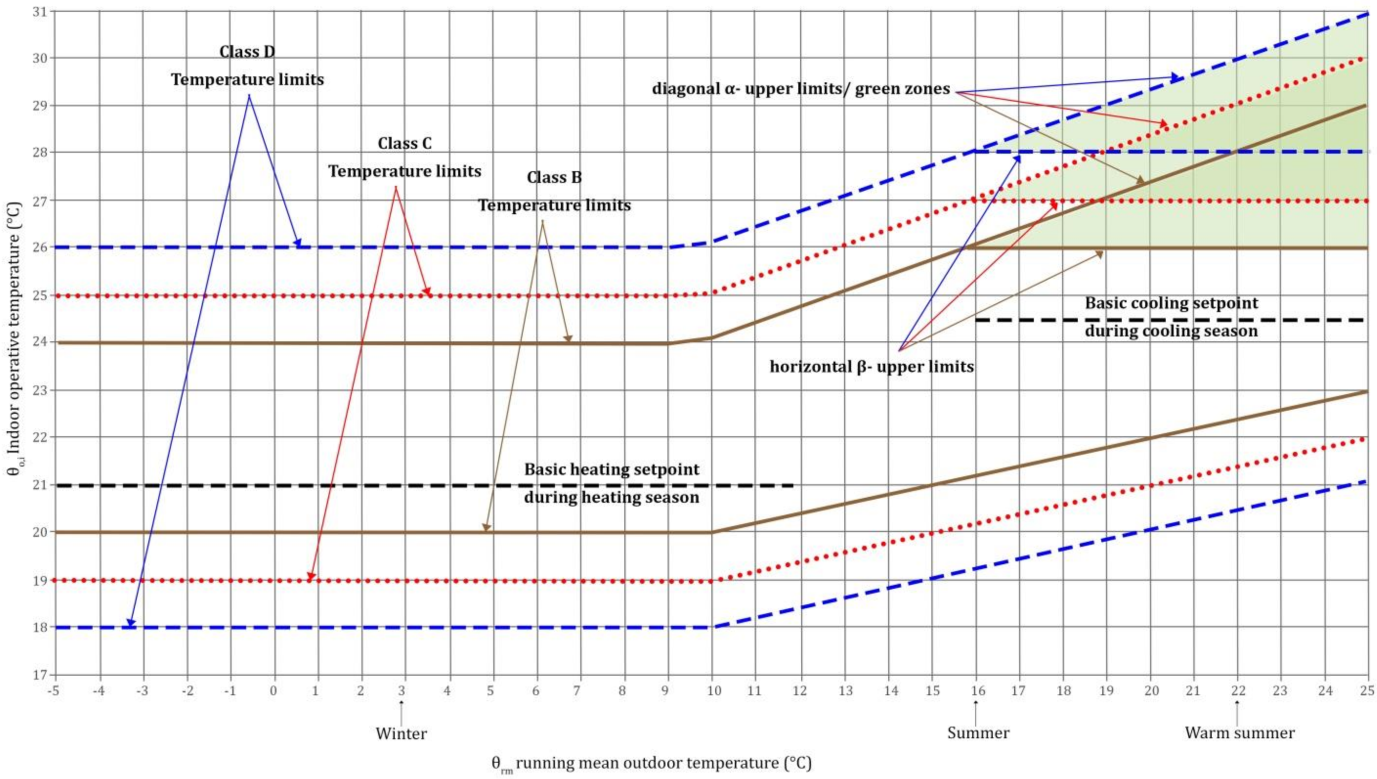


Figure 3.2: Relation of comfort for Alpha and Beta Buildings (ISSO 74, 2019)

		Operative temperature within [° C]		
		Winter	Mid-season	Summer
General	Setpoint line	21		24.5
Class A (PPD max. Approx. 5%)	Upper limit	See at class B (+ possibility to influence winter and summer)		
	Lower limit	See at class B (+ possibility to influence winter and summer)		
Class B +	Upper limit	See at class B (+ winter influencing option)		
	Lower limit	See at class B (+ winter influencing option)		
Class B (PPD max. Approx. 10%)	Upper limit	24 [1)]	18.8 + 0.33 θ rm + 2 [2)]	β: 26 [1)] , α: 18.8 + 0.33 rm + 2
	Lower limit	20 [1)]	20 + 0.2 (θ rm - 10) [3)]	
Class C (PPD max. Approx. 15%)	Upper limit	25 [1)]	18.8 + 0.33 rm + 3 [2)]	β: 27 [1)] , α: 18.8 + 0.33 θ rm + 3
	Lower limit	19 [1)]	19 + 0.2 (θ rm - 10) [3)]	
Class D (PPD max. Approx. 25%)	Upper limit	26 [4)]	18.8 + 0.33 θ rm + 4 [2)]	β: 28 [4)] , α: 18.8 + 0.33 rm + 4
	Lower limit	18 [4)]	18 + 0.2 (θ rm - 10) [3)]	

Table 3.2: Categorization of 4 classes within the ATG method (ISSO 74, 2019)

4. Earth, Wind and Fire system

Note: This section is written in collaboration with Yamini Patidar and Puji Nata Djaja.

4.1. Introduction

The Earth, Wind and Fire system is a concept which uses the driving forces of nature to control the indoor climate of the buildings. It utilizes the environmental energy of earth mass, wind and sun to generate and supply energy throughout the building by eliminating the use of HVAC systems, thereby minimizing the total energy consumption of the building and providing a healthy and productive working environment (Bronsema, 2013). This system eliminates the need of an air handling unit, the building functions as a “Climate Machine” with the help of 3 Responsive Building Elements (RBE): The Climate Cascade, Solar Chimney and Ventec roof (Bronsema et al., 2018). The application of the 3 elements will be explained in the following sections.

4.2. Utilization of environmental energy

Note: This chapter is written in collaboration with Yamini Patidar and Puji Nata Djaja.

Utilization of environmental energy is an essential strategy to reduce the operational energy consumption of the building and for achieving energy neutral goals. The Earth, Wind & Fire research focuses on passive, active and hybrid systems for the utilization of environmental energy in integrated building concepts (Bronsema, 2013). These elements which belong to each system are shown in Table 4.1.

Active Elements	Passive Elements	Hybrid Elements
Wind Turbines in the over pressure chamber	Ventec roof which generates positive and negative pressure for air circulation	Climate Cascade as the pump energy is used to feed cold water at the top of the cascade
PV Foil on the Ventec roof	Solar Chimney/Solar Façade which has an extraction system	
Solar Chimney/Solar façade which generates solar energy		

Table 4.1: Active, Passive and Hybrid elements used in the EWF system (Bronsema, 2013)

Theme Earth

The EWF system utilizes Earth mass through:

- Gravity that causes the water sprayed at the top of the Climate Cascade to fall down. The momentum of these drops is partially transferred to the air. The suspension of air and water creates a greater density of the air inside the Climate Cascade as compared to dry air.

- Earth as a source for heat/cold storage.

Theme Wind

The EWF system exploits wind through:

- Active energy generation using wind turbines installed in the overpressure chamber of the Ventec roof.
- Wind-driven natural ventilation utilizing the wind pressures for the movement. Climate Cascade provides the supply of Ventilation air using the positive wind pressure whereas the air is extracted via the Solar Chimney utilizing the negative wind pressures.

Theme Fire

In the Earth, Wind & Fire concept, Fire is used as a metaphor for sun utilizing solar energy through:

- Active system in the form of Solar Chimney and solar facade and the use of PV foil on the Ventec roof.

4.3. Application of Earth, Wind and Fire

The air is supplied throughout the building by the Climate Cascade. The air enters the building via an overpressure chamber and is supplied to the Climate Cascade. In the Climate Cascade, the cold water in the water sprinkler is sprayed on the incoming air at a temperature of 13°C (Bronsema et al., 2018). Due to the reduced temperature of the water droplets, the air is cooled down to approximately 18°C in the summers and the air is preheated to approximate 7-8°C in the winters (Bronsema et al., 2018). The cold water is supplied to the top of the Climate Cascade with the help of a Thermal Energy storage system located underground. The water droplets in the sprinkler form a heat exchanger with a large surface area which enables the system to generate temperature differences between water and air (Bronsema et al., 2018). This heat exchanger produces pressure at the base of the cascade which is used to supply the cooled/warm air throughout the building via the supply shaft.

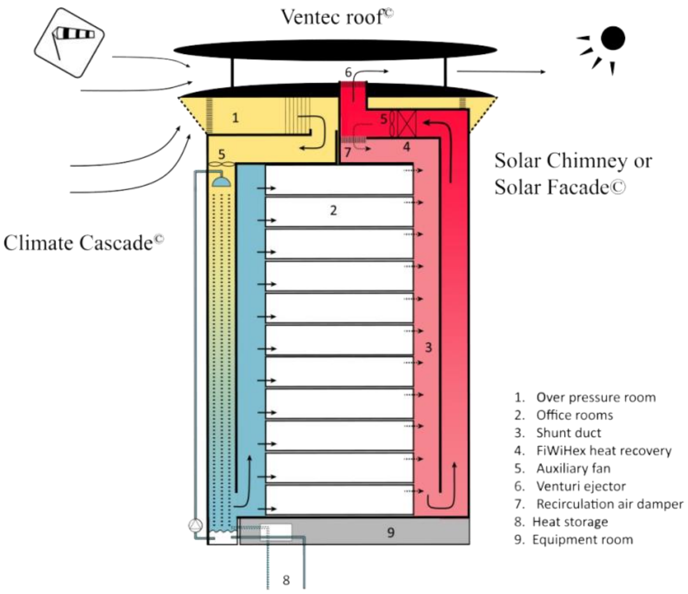


Figure 4.1: Earth, Wind and Fire Natural Air Conditioning system (Bronsema, 2013).

The used air from the building is extracted by a shunt/exhaust shaft which is connected to the Solar Chimney at the bottom. The Solar Chimney is a structural shaft which consists of solar panels and insulating glass facing the south in order to capture maximum solar radiation. The air in the Solar Chimney is heated up which pulls the air from the base of the exhaust shaft. The heat from the exhaust air is recovered at the top of the Solar Chimney by a heat recovery system. This heat is either supplied to the building or transported to the ground to restore the thermal balance and the used air is exhausted from the top (roof) (Bronsema et al., 2018). In order to maintain the air circulation, auxiliary fans are installed which operate on the basis of energy generated by the solar panels on the roof and in the façade of the Solar Chimney (Bronsema et al., 2018).

4.4. Climate Cascade

Note: This chapter is written in collaboration with Yamini Patidar and Puji Nata Djaja

The Climate cascade is the heart of the Earth, Wind & Fire system which utilizes gravity for cooling, heating, drying and humidifying the ventilation air, designed as an architectural shaft (Bronsema, 2013). In comparison to traditional cooling batteries, Climate Cascade offers various advantages as highlighted by Bronsema, such as:

- High heat transfer coefficient between falling water and air to be treated. The temperature difference between air and water can thus be minimal.
- The Climate Cascade not only cools or warms the air but is also suitable for air treatment in all seasons, such as humidification.
- Air filtering is not required.
- Through varying the spray spectrum, the cooling surface can be increased or decreased.
- No air-side resistance.

4.4.1. Thermal Comfort

The thermal comfort can be divided into ALPHA and BETA type with ALPHA type corresponding to naturally ventilated buildings and BETA type referring to air-conditioned buildings (Bronsema, 2013). ALPHA type stretches the comfort limits in order to save energy and hence is not an efficient design solution. The Climate Cascade is thus designed as a BETA type system since it emphasizes on increasing productivity and maintaining a good thermal comfort for the users. According to ASHRAE Standard 55-2002 (ASHRAE 2002), the upper limit of x (maximum moisture content) = 12 $g.kg^{-1}$ is specified corresponding to Relative Humidity (RH) value of maximum 60% for BETA type (Bronsema, 2013).

4.4.2. Climate cascade for diabatic cooling

In an adiabatic system, no heat is supplied or removed and the air enthalpy remains constant whereas for a diabetic change of state of a thermodynamic system, heat is exchanged with the environment. With the diabetic process in the Climate Cascade, the heat is removed by the supply of chilled water which absorbs heat and moisture from the air, causing the air to be dried and cooled and the water temperature to rise (Bronsema, 2013).

4.4.3. Temperature trajectory

A Climate Cascade can be considered as a direct flow heat exchanger where air and water are in direct contact such that not only heat transfer but also mass transfer can take place (Bronsema, 2013). With the diabetic process in the Climate cascade, the heat is absorbed from the air and transferred to the water, causing the air to be cooled down and rising the temperature of the water. At the inlet, the air is cooled by the cooling water of 13 ˚ C and dried to the outlet condition of 17 ˚ C with 90% RH. After absorbing the moisture in the room, the maximum room condition of 25 ˚ C at 60% RH is reached (Bronsema, 2013).

4.4.4. The water/air factor

The ratio of mass flow of water and air in the Climate Cascade is an important aspect to determine the energy use of the spray pump.

4.4.5. Basic modeling

The basic modeling of the Climate Cascade is done using the excel model developed during Ben's PhD. Before modeling and doing calculations, it is important to understand a few parameters and their formulas.

Climate cascade as a heat exchanger

The heat transfer is represented by the equation:

$$\Phi = h.A.(\theta_m - \theta_\infty)$$ (Bronsema, 2013)

Where,

Φ = Heat transfer from air to water which is equal to the required enthalpy change of air.

A= Active surface of the Climate Cascade determined by the cumulative area of the water droplets, product of the number of droplets formed per unit of time and its duration of stay.

h = Heat transfer coefficient

$\theta_m - \theta_\infty$= Temperature difference between water (θ_m)and air (θ_∞)

Note: Refer Appendix 2 for additional formulas related to the basic calculations of Climate cascade.

Pressure build-up in the Climate Cascade

The Climate Cascade not only ensures that the ventilation air is conditioned, but also shows a positive pressure difference for the air distribution in the connected building. This pressure difference is created by the generated aerodynamic draft, the hydraulic draft and the downward thermal draft (Bronsema, 2013).

The required spray spectrum is mainly determined by the required cooling performance. In higher buildings with a longer contact time between water and air, it is possible with a coarser spray spectrum. The heat transfer in a Climate Cascade is proportional to the heat transfer coefficient with the active surface and it increases with a finer spray spectrum with smaller drop. A choice should therefore be made in order to realize the greatest possible heat transfer for the finest possible spray spectrum (Bronsema, 2013).

4.5. Solar Chimney

Note: This chapter is written in collaboration with Yamini Patidar and Puji Nata Djaja

The Solar Chimney is an important architectural element of the EWF system. Utilizing the sun as a source of energy, the Solar Chimney helps in the extraction of ventilated air, thus contributing significantly towards the goal of natural air conditioning (Bronsema et al., 2018). The Solar Chimney absorbs the solar energy (thermal and electric) which is used to heat the buildings, restore the thermal equilibrium in the soil through the TES system and generate energy to run the power pumps and auxiliary fans. This element can significantly contribute towards achieving a nearly zero energy building (Bronsema et al., 2018).

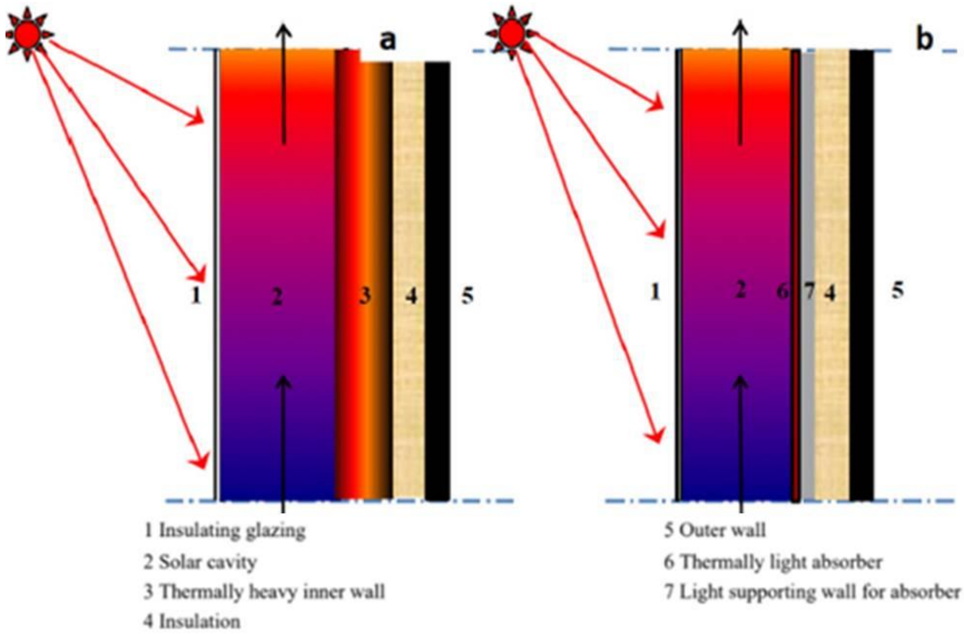


Figure 4.2: Principle of Solar Chimney (Bronsema, 2013).

Referring to the above figure, “a” is the more-common Solar Chimney with thermally heavy inner wall and “b” is Solar Chimney with light inner wall. A study conducted by Bronsema (2013) showed that the energy performance of the Solar Chimney with light inner wall was better in case of office buildings as solar radiation is directly transferred to the air as compared to heavy thermal wall which stores heat and can be used for night ventilation. Since offices do not require night ventilation, option b was chosen for the purpose of Earth, Wind and Fire system for office buildings.

4.5.1. Components of the Solar Chimney

Note: This section is written in collaboration with Yamini Patidar and Puji Nata Djaja

Glass wall

The glass wall of the Solar Chimney has been chosen such that it can yield the best energy performance: highest possible g-value for maximum transmission of the solar radiation and lowest possible U-value to limit the heat loss (Bronsema, 2013).

The absorber

The absorber in the inner wall should maximize the absorption of the solar radiation and minimize heat emission. These properties are expressed as the absorption factor α and the emission factor ε respectively (Bronsema, 2013). At equal wavelength λ:

$$\alpha_\lambda = \varepsilon_\lambda \quad \text{(Bronsema, 2013)}$$

Where,

α_λ= absorption factor at wavelength λ

ε_λ= emission factor at wavelength λ

A Solar Chimney is considered as a black body which will absorb all the radiation of the entire wavelength. This emittance of a black body at wavelength λ is calculated using Planck's law:

$$M_{\lambda.b} = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda kT} - 1}$$ (Bronsema, 2013)

Where,

$M_{\lambda.b}$ = emittance at wavelength λ [W.m^{-2}]

h = Planck's constant= 6.62 x 10^{-34} [J.s]

c = speed of light [ms^{-1}]

k = Boltzmann constant = 1.38 x 10^{-23} [JK^{-1}]

λ= wavelength of the radiation [µm]

Insulation

The inner walls of a Solar Chimney must be insulated to limit heat loss. The height of the Solar Chimney, the air flow and the width / depth ratio are important parameters to determine the thickness of the insulation (Bronsema, 2013).

Optimal orientation

In order to optimize the energy performance of the Solar Chimney, it is important to choose the orientation with the most solar radiation. In the Netherlands, south orientation is optimal, also partly due to the fact that winter solar radiation has a higher economic value than that in the summer (Bronsema, 2013).

Morphology

For a stable thermal draft in the cooling season, the average chimney temperature during operating hours should be above the outside temperature as much as possible. To ensure this, 4 types of morphology has been analyzed (Bronsema, 2013).

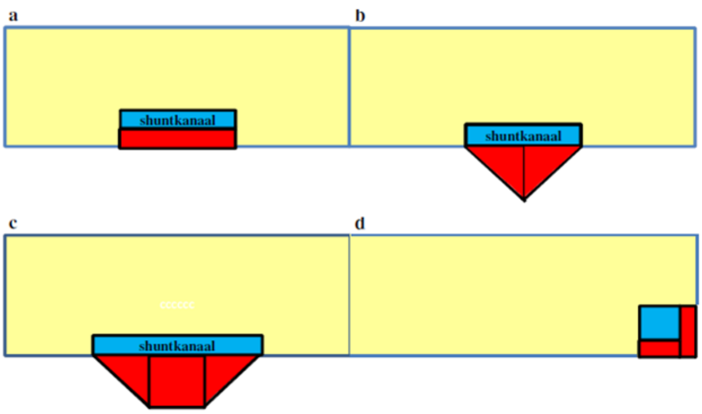


Figure 4.3: Architectural possibilities and morphology of Solar Chimney (Bronsema, 2013).

The façade model (a) is located inside the building with the glass wall oriented parallel to the building boundary. South orientation is the most preferred location. This option has high energy performance but due to one-sided orientation, the thermal draft is not stable during the day (Bronsema, 2013). The multiple SE / SW oriented pyramid model (b) is a simple and effective solution for the energy yield and stability of the thermal draft. In this configuration, two separate Solar Chimneys are connected in parallel to one shunt channel (Bronsema, 2013). The trapezoid model (c) is a variant of the pyramid model. By adding a south-facing surface, high radiation intensity is achieved. The angular model (d) can also collect solar radiation at multiple orientations (Bronsema, 2013). A SE / SW orientation provides reasonably stable solar radiation during the day. There are many other possibilities for the architectural integration of a Solar Chimney in buildings, including the combination with an (emergency) stairwell which will be explained in Section 4.8.

Solar facade

A solar façade is a Solar Chimney covering the façade, which mainly consists of windows that form a direct connection with the outside. The effective surface and the energy performance of the Solar Façade are determined by the size of the window openings (Bronsema, 2013). Several conflicting factors are in play e.g., daylight, cooling load, view, costs, and architectural expression. It is therefore an optimization issue based on various other variables that must be solved on a project basis.

Shunt channel

The thermal draft of a chimney is proportional to its height. If the extraction ducts on the floors would be connected directly to the Solar Chimney, the available draft for the higher floors will get smaller. To ensure that the negative pressure conditions for all floors are approximately the same, a shunt channel is required, shown in (a) below. It also allows for heating recovery to be used outside the operating channel, shown in (b) below (Bronsema, 2013).

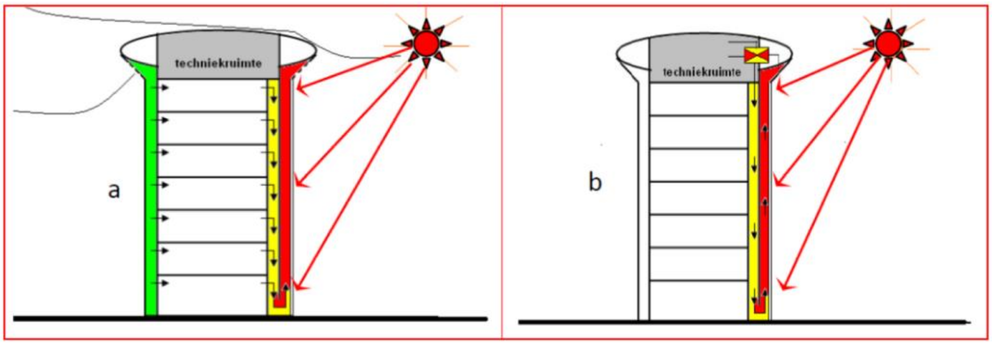


Figure 4.4: Principle of air extraction and recirculation via shunt channel (Bronsema, 2013)

4.5.2. Basic Modeling

A detailed analysis of heat transfer by convection and radiation is discussed in this section.

Convective heat transfer

It is represented by the equation:

$$\Phi_c = h_{c.m}.A.(\theta_w - \theta_\infty)$$ (Bronsema, 2013)

Where,

Φ_c = Convective heat flow [W]

$h_{c.m}$ = heat transfer coefficient [$Wm^{-2}K^{-1}$]

A = wall surface area [m^2]

θ_w = wall surface temperature [°C]

θ_∞ = air temperature in the main stream [°C]

Note: Refer Appendix 3 for additional formulas related to the basic calculations of Solar Chimney.

4.6. Ventec roof

Note: This section is written in collaboration with Yamini Patidar and Puji Nata Djaja

The Ventec roof utilizes positive wind pressures for the supply of ventilation air to the building via an overpressure chamber and the Climate Cascade. Negative wind pressures are used to extract used ventilation air from the building through the Solar Chimney and a Venturi ejector (Bronsema, 2013). Only the Overpressure chamber and venturi ejector are in scope of this research paper and rest of the elements of the Ventec roof are not considered in this research.

4.6.1. Overpressure chamber

On the windward side, using the roof overhangs ventilation air is collected and through the positive wind pressure air is transferred to the pressure chamber. The magnitude of the thrust is determined by the local wind speed and the wind pressure coefficient on the relevant facade section (Bronsema, 2013). Both normally have the highest value at the top of a building where the air quality is also optimal. The expected wind pressure coefficient at the edge of the roof is approximately 0.8. With a moderate wind of 3 - 4 Bft, wind speed 5 - 8 ms^{-1}, overpressures are to be expected at 12 - 32 Pa (Bronsema, 2013).

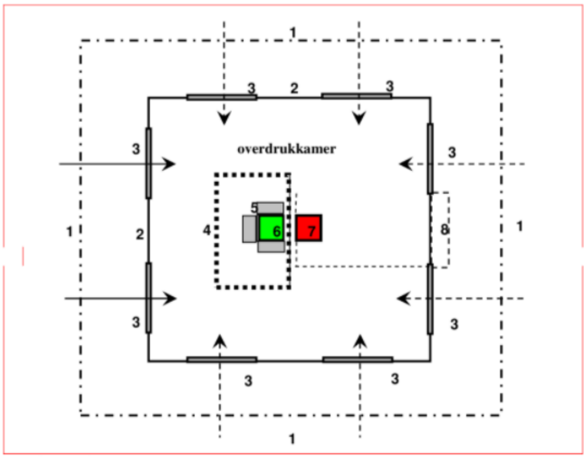


Figure 4.5: Schematic plan of overpressure chamber (Bronsema, 2013)

The figure above shows a schematic plan of the overpressure chamber with (1) roof over-cuttings, (2) building facade and air dampers, (3) A coarse filter, (4) keeps out insects and coarse dirt and also serves to protect any electrostatic filter, (5) Climate Cascade, (6) and mouth of the Solar Chimney (8) in the Venturi ejector (7).

4.6.2. Venturi ejector

The Venturi ejector is the outlet of the central extraction system in the Ventec roof and is also formed by the Solar Chimney and heat recovery system (Bronsema, 2013). The pressure loss of the extraction system must be compensated by the thermal draft of the Solar Chimney.

A Venturi is a setup for increasing the speed of fluid flow by constricting it in a tube which is cone shaped. In the restriction, the fluid must increase its velocity reducing its pressure and producing a partial vacuum. The Earth, Wind & Fire concept makes use of this principle to guide the wind through a constriction and to make use of the under pressure generated. Because the venturi is used in an open system, it is hereinafter referred to as pseudo venturi (Bronsema, 2013).

4.7. EWF system case study: The Four Elements Hotel, Amsterdam

Note: This section is written in collaboration with Yamini Patidar and Puji Nata Djaja

Initially named Breeze Hotel, this 11-story building with 198 'zero-energy rooms', 6 suites, and a total floor area of 9.343 m2, is the first building to implement the EWF system in the world. The building is developed by Amstelius/Dutch Green Company in association with Borghese Real Estate, with OZ architect as the project's architect. The 36 meters high building consists of the following main elements; a Solar Chimney, a Climate Cascade and a power façade (OZ Architect, 2019).

Figure 4.6: Left to right: View from IJmeer Lake, 2 Solar Chimneys on the south façade, huge balcony of the sky-bar on the north facade (OZ Architect, 2019)

The twin Solar Chimney on the south façade (each 0.65m deep, 3.5m wide) collects heat from the sun. As the air heats up, the weight decreases, causing the warm air that can reach 60°C, to ascend in the Solar Chimney. At the top, the air reaches a heat-recovery system to capture the heat from exiting air to be stored in the underground thermal energy storage. The annual thermal energy yield of the twin Solar Chimneys is estimated to be 101 MWh (Pearson, 2019).

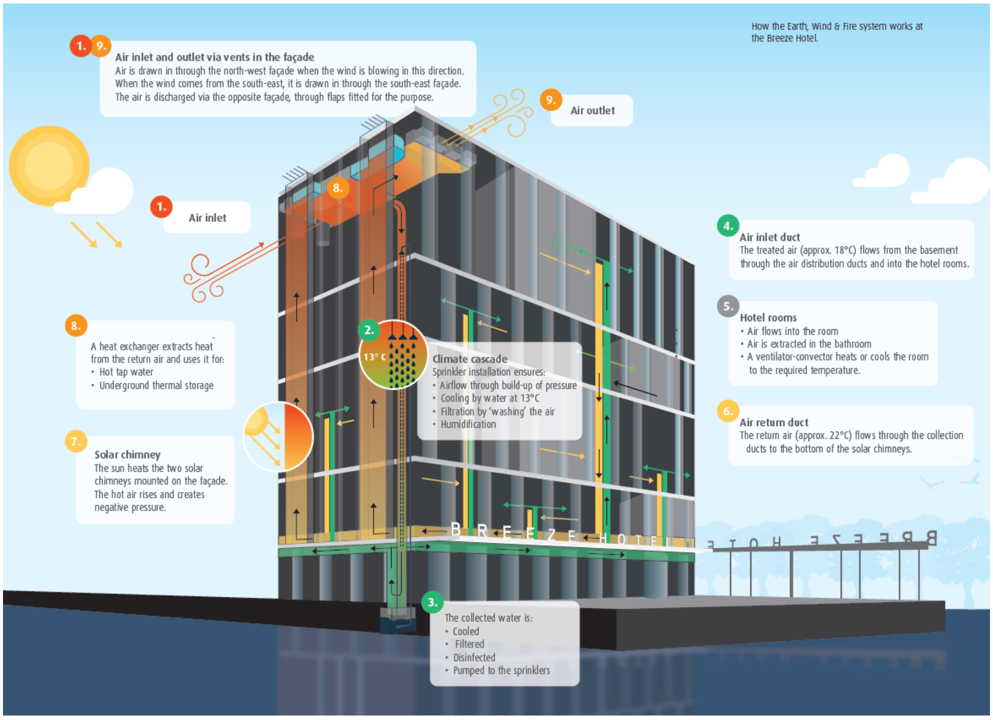


Figure 4.7: Application of EWF system in Breeze Hotel, Amsterdam (Heirbaut, 2019).

The captured heat stored in water underground can be used as pre-heated water to then be sent to a heat pump to raise its temperature for domestic hot water (DHW).
To replace the stale air that has been exhausted through the Solar Chimney, fresh outside air enters the building from the top of the Climate Cascade. Here, the air is cooled/heated and dried/ dehumidified depending on the season, by 9 water sprays

attached to the top of the shaft. The water is extracted from boreholes that extract water at a relatively constant temperature of 13°C throughout the year. In summer, the water sprays can cool outside air from 28°C (Relative Humidity 55%) to 18°C (Relative Humidity 60%), and can clean the air by scrubbing particulates from the air. The spray water is collected at the base of the Climate Cascade and pumped through a water-treatment installation for reuse. As the air cools down, the weight increases, causing it to sink to the bottom of the Climate Cascade, increasing the pressure. This causes the fresh air to move to the rooms. In winter a heater battery installed at the base of the cascade helps raise the temperature before being supplied to the rooms (Pearson, 2019).

This way, the supply and exhaust of ventilation air is happening naturally. However, both systems are fitted with axial fans to assist the airflow when necessary. As for temperature control, a fan coil unit enables guests to control the temperature and airflow rate in their room. The system is also designed to revert to energy-saving condition when guests leave their room (Pearson, 2019).

The Ventec roof for this project could not be realized due to unfeasible cost and were replaced by PV panels on the rooftop, façade, and at the rear of the Solar Chimney for energy production. The annual electricity production is 18,000kWh (Pearson, 2019).

4.8. EWF design strategies

To implement the EWF system in a case study, certain design strategies were established specifically for choosing the appropriate case study and EWF specific strategies for Climate cascade and Solar Chimney.

4.8.1. Building Assessment

The Building assessment strategies are assessed on the basis of 4 parameters which are based on the findings from Swier (2019) and they are described as follows:

Building Context

- The building should be higher than the surrounding buildings in order to incorporate the Ventec roof.
- The placement of the 3 elements of the EWF system should be assessed on the basis of the space available around the building, especially where the concentration of the buildings is very dense.
- In cases where the accumulation of buildings is very dense, placing the elements at a visible junction or which can enhance visual connection can have a positive impact on connecting people with this intervention.

Building shape

- The height of the building should be more than 15 m to generate the necessary pressure difference required for the functioning of the Climate cascade and Solar Chimney.

- In cases where the building has uneven corners or unused spaces, EWF elements could either occupy those niches or become an extension to the building by filling up the spaces and covering the projections.
- The free floor height of the building should be at least 2.6 m to fit in the air distribution ducts on the ceiling.
- Vertical shaft spaces should be enough to install all the EWF elements. If that is not enough, the ducts will become a part of the façade or the floor/ceiling. Introduction of atriums will be a good addition in such cases.

Façade

- The relation between the façade and the technical installations should be critically examined by the designer as it has an impact on the physical quality of the building for eg: Thermal bridges.
- The best option would be to strip down the façade completely (wherever possible) and a new façade should be designed which will be integrated with the EWF elements during the design stage.
- If the existing facade system does not include open able windows, then the façade needs to be changed in order to ventilate the building naturally as stated in the application of the EWF system.
- Flexibility of the building can be increased if small façade grids can be incorporated while designing the new façade.
- The entrances at the ground floor should be lined with revolving doors in order to reduce large temperature differences between the inside and the outside.
- Load bearing façade system will be a problem as they reduce the flexibility of the space and hinder the amount of daylight entering the space. This will not only eliminate the incorporation of EWF but also refurbishment.

Load bearing

- It is preferred if the connections between the building elements are demountable to increase flexibility and easy to disassemble.
- If the floors of the existing building have poured pipes or some other installations, it has to be replaced with the elements of the EWF system as it decreases the level of flexibility.
- The building should be able to withstand the load of adding additional floors in order to increase the building height (wherever necessary) for efficient performance of the EWF system.
- The load bearing structure of the existing building should be able to withstand the additional façade loads during the installation of the EWF elements.
- A building with a large column grid is preferred as it increases the possibilities to install all the EWF elements in the restricted space.
- Over dimensioning of the building is always preferred.

Climate study

- It is necessary to conduct a sun and wind path study to optimize the performance of the EWF elements.
- Thorough research should be conducted to analyze the possibilities of cold and heat storage. The WKO-tool developed by the Dutch government to examine whether the soil is suitable for energy storage.
- If heat and cold storage is not possible, other options like PCM can be explored.

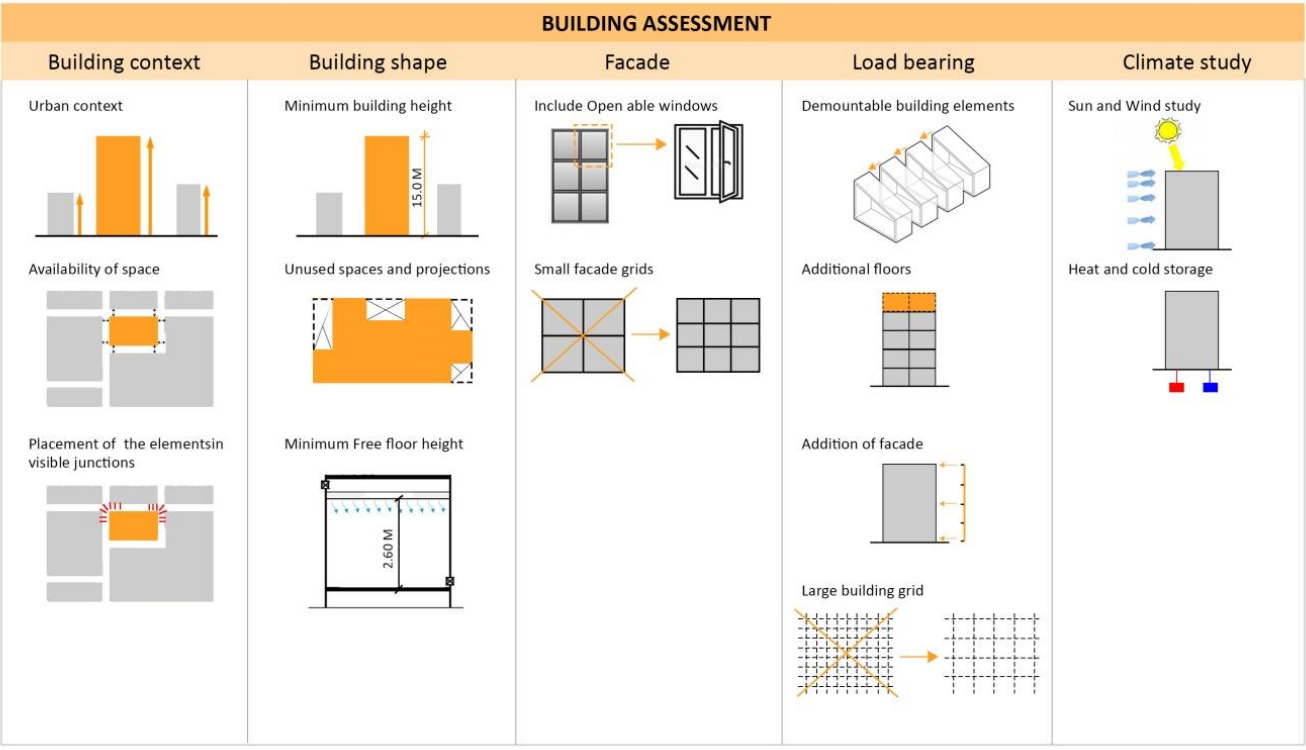


Figure 4.8: Building assessment criteria

Note: Refer Appendix 4 for clearer illustration of the Building assessment criteria.

4.8.2. EWF design criteria and possibilities

A database is generated for the implementation of Solar Chimney and Climate cascade. This database is extracted from 104 poster submissions by students of AE&T department, which explored the architectural possibilities of the elements of the EWF system along with the technical aspect of the EWF elements which were derived from Bronsema (2013).

104 poster submissions of EWF system

The 104 student submissions were part of the masters course Delft Seminars on Building Technology 2013-2015 Q1 & Q3. The posters were first analyzed if the design included all the 3 elements of the EWF system and only the posters with Climate Cascade and Solar Chimney were taken into consideration. Since the 104 posters only explored the architectural possibilities of the 3 EWF elements and the construction details, the database was developed using the same for different possibilities of the location, size and shape of the Climate Cascade and Solar Chimney, as shown in figure 4.10 and 4.11.

Figure 4.9: Examples of 104 student submissions on EWF system (Brightspace, 2020)
Note: Refer Appendix 15 for clear illustrations

General criteria

- The shafts/duct sizes in the EWF system are considerably larger than the traditional shafts for efficient distribution of air. It is important to consider the shafts/ducts as part of the building design strategy as it has a great impact on the climate design of the building.
- The air distribution system can have 2 solutions: Decentralized supply and centralized exhaust or centralized supply and decentralized exhaust.
- When the Indoor air quality is not in the acceptable range, only an electrostatic filter should be used as it yields in high performance with low air resistance.

Climate cascade

- The ventilation capacity of the Climate Cascade should be 6.5 dm/s/person as stated in the Dutch Building Decree for office buildings (Bouwbesluit Online, 2012).

- While designing a high rise building, the Climate Cascade should be placed at every 6th floor or multiple of it to increase its efficiency.
- To explore the architectural possibilities of the Climate Cascade, Fig.4.10 is illustrated below which was derived from the 104 student submissions. These interventions show that there is a huge scope for transparent Climate Cascade. This can be achieved if high level of insulation is used.

Solar Chimney

- The Solar Chimney/ façade gives optimum results when oriented towards South, South west or south east.
- A single big Solar Chimney gives better results than multiple small chimneys.
- The thermal performance and the energy efficiency of the Solar Chimney are important variables which must be assessed.
- The depth of the Solar Chimney should be min 0.65 m for maintenance purposes.
- Light thermal inner walls perform better than thick thermal inner walls depending on the use of the office space. This is true if the office space is not used during the nighttime.
- The glass panes should have a high g-value for maximum transmission of solar radiation and low U-value for reduction in the heat loss.
- The shunt channel should be connected to the Solar Chimney at the bottom and not the top to avoid lower thermal drafts at the top floors.
- The shunt channel does not necessarily need to be located adjacent to the Solar Chimney.
- The exhaust shaft should have direct access to the venturi ejector on the roof to throw the exhaust air out of the building.
- The heat from the exhaust air should be reused and stored which can be used for hot water supply in the building.
- In order to generate more energy and to achieve nearly zero-energy consumption, solar facades are a good solution. Building integrated PV and solar panels on the roof can contribute to high energy savings.
- To explore the architectural possibilities of the Solar Chimney, Fig.4.11 is illustrated below which was derived from the 104 student submissions.

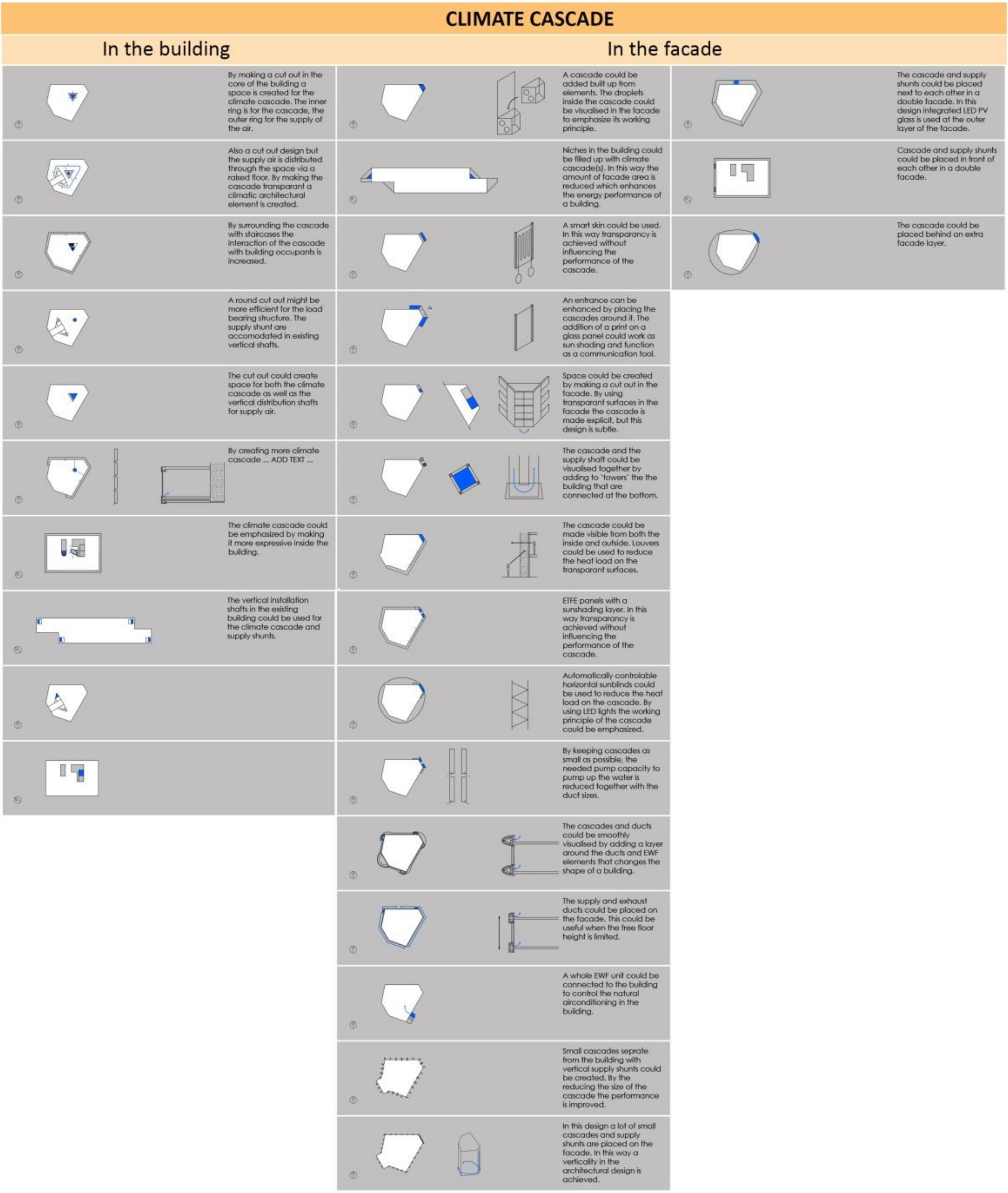


Figure 4.10: Architectural possibilities of Climate cascade (Swier, 2019)

Note: Refer Appendix 5 for clearer image.

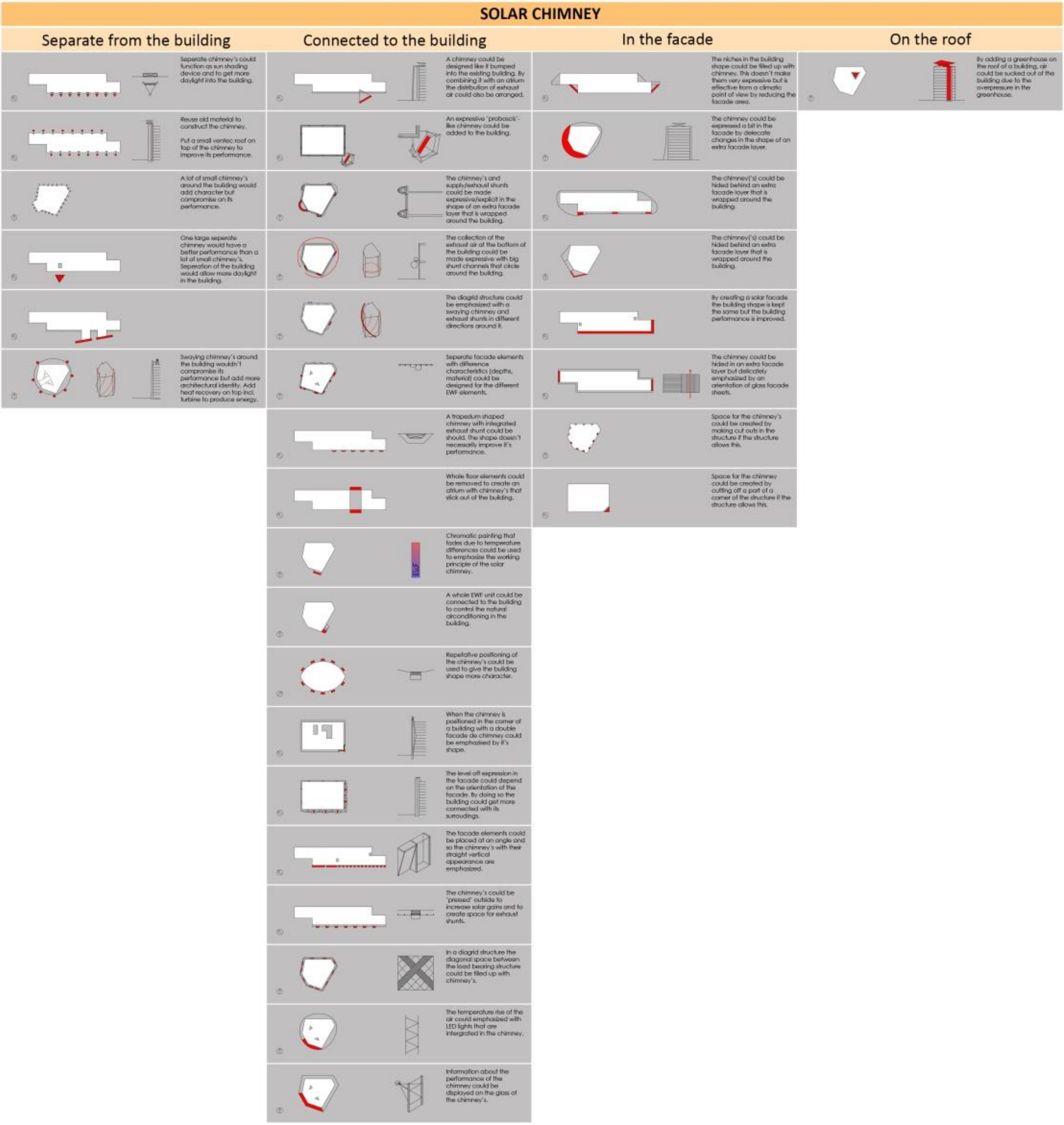


Figure 4.11: Architectural possibilities of Solar Chimney (Swier, 2019)

Note: Refer Appendix 5 for clearer image.

5. Summary of the Literature study

This section will discuss the conclusions from the literature study by answering the sub-research questions.

What are the influential parameters which correspond to office refurbishment?

The strategies related to the reduction of energy use for space heating can significantly reduce the total energy consumption in an office building. To improve the energy performance of the building, the primary focus of the research will be to improve the thermal comfort of the selected case study as it directly links to the elements of the EWF system like the Climate cascade. Refurbishment strategies should prioritize using renewable sources for energy generation and consumption and optimize the energy by restoring it for future use.

Which design variables, from the National and International regulations, are applicable for nZEB?

The BENG regulation and determination method NTA 8800 will replace the existing EPC norm and determination method NEN7120 as the existing norms are not compliant to the EPBD regulations. For this research, the operational energy consumption for offices mentioned in the BENG regulations will be followed as shown in Table 5.1.

<table>
<tr><th>Guideline/ Method</th><th>Building energy requirement ($kWh/m^2.yr$)</th><th>Primary fossil energy consumption ($kWh/m^2.yr$)</th><th>Share of renewable energy (%)</th><th>Building type and Building class</th><th>Thermal comfort range</th></tr>
<tr><td>BENG 1,2,3</td><td>If $A_{ls}/A_g \le 1.8$; BENG 1 ≤ 90</td><td>≤ 40</td><td>≥ 30</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">Adaptive Temperature Limit Value (ATG) (ISSO 74 / NEN-EN 15251)</td><td rowspan="3">-</td><td rowspan="3">-</td><td rowspan="3">-</td><td>Beta type, Class B</td><td>Percentage dissatisfied: max 10%</td></tr>
<tr><td>Acceptance- 80%</td><td rowspan="2">PMV bandwidth: - 0.5<PMV<+0.5</td></tr>
<tr><td>upper limit: $\theta_{oper} < (23.45 + 0.11\ \theta_{e,ref})$

lower limit: $\theta_{oper} > (19.45 + 0.11\ \theta_{e,ref})$</td></tr>
</table>

Table 5.1: Final energy guidelines with respect to EWF system

The choice of the thermal comfort range depends on the choice of the building type and the class. ISSO 74 suggests that all new buildings including renovations should fall under Class B category.

Which elements in the EWF system play a major role in improving the energy performance of the building?

From the 3 elements of the EWF system, Solar Chimney and Climate Cascade play a crucial role in shaping the building as a climate machine and maximum energy savings can be achieved when these elements are put to optimum use. The architectural intervention of these elements can have a huge impact on the energy performance of the system. Therefore, the implementation of the Ventec roof is excluded from this research as the scope of the research is limited within the given time frame and this subject is still undergoing research in order to make it more cost effective. This is also realized from the case study building Four Elements Hotel, as they also don't implement the Ventec roof due to high cost and limited scope.

What are the building assessment criteria's which needs to be considered while refurbishing an office building using EWF system?

From the 4 building assessment parameters described in the literature study, 3 boundary conditions can be defined. Firstly, the building has to be higher than its surroundings. If this is not considered, the required pressure will not be generated for the system to work. The building should not have a load bearing façade system as it reduces the flexibility and the ability to withstand additional loads on the façade. Finally, the possibility of using heat and cold storage system (ATES or other ground source systems) should be considered to increase the efficiency of the EWF system.

What are the design strategies under the EWF system?

All the EWF design strategies mentioned in section 4.8 need to be considered while implementing the elements in the case study. Although the general design strategies helped in choosing the case study building, the specific design strategies for Climate Cascade and Solar Chimney should be considered while establishing the design options. There is a possibility that the design strategies may contradict to the results while analyzing the EWF system, but all the design strategies are applicable during the initial design phase.

6. Methodology

To answer the research question, the research process is divided into 3 stages: case study selection, analysis and final design.

Selection of Case Study

2 case studies were selected to make a comparative analysis on the basis of the building assessment criteria listed in the design strategies. Out of 2 case study buildings, one office building will be selected to implement the design strategies.

Analysis

The chosen case study will be refurbished using the EWF system which will primarily focus on analyzing the performance of Solar Chimney, solar facade and Climate Cascade. Various permutations and combinations will be considered for the location, shape and material of the Climate Cascade and Solar Chimney. These systems will be simulated using the basic excel calculation models developed by Bronsema (2013) and his team, along with dynamic modeling using Design Builder software. The simulations will focus on energy consumed by the system and external factors affecting the annual energy performance of the building for every design option.

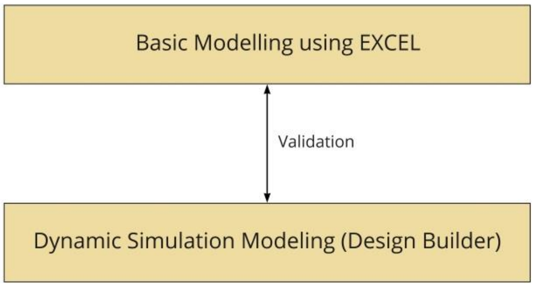


Figure 6.1: Calculation and Simulation process

The basic modeling process will include simple calculation models which will help in developing the first impressions of the feasibility and potential of the applied concept (Bronsema, 2013). The scientific and technical data required to perform these calculations will be derived from the MS Excel calculation developed by Bronsema (2013) and ABT B.V. The model consists of all the formulas derived from Installation Technology Manual (ISSO 2002), the Taschenbuch für Heizung + Klimatechnik, ASHRAE Handbooks Fundamentals (ASHRAE 2001) and HVAC Systems and Equipment (ASHRAE 2000) (Bronsema, 2013). The basic modeling will provide insight on the underlying phenomena of heat transfer and flow and how they work together. In order to validate the basic calculations, Design Builder software will be used. The excel calculations will be used for calculating and designing the Solar Chimney and Climate Cascade under stationary conditions. In order to study the dynamic behavior and annual estimates of the energy performance of the EWF system, dynamic simulation model Design Builder will be used.

Once the simulations are conducted for various design options, the option which gives the best results, according to the design conditions which will be established before the simulations, will be selected for dynamic simulations.

For the second part of the simulation, additional factors like façade, space heating and cooling and other parameters will be evaluated by analyzing its impact on the overall energy consumption. The simulations will also focus on developing strategies to generate energy within the building and check if the building can achieve nearly zero energy consumption.

Final design

After deriving the final design solution, these results will be compared to the results of the current energy performance of the building i.e. without the application of EWF system. This comparison will determine the efficiency of the EWF system and whether the system can improve the energy performance of the building. Additionally, the building will be assessed to determine if the energy demands are met entirely by renewable resources (Paris proof).

The final design solution will contain detailed drawings (plans, sections, and elevations), detailed calculations and simulations of the Climate Cascade and Solar Chimney on the chosen case study building.

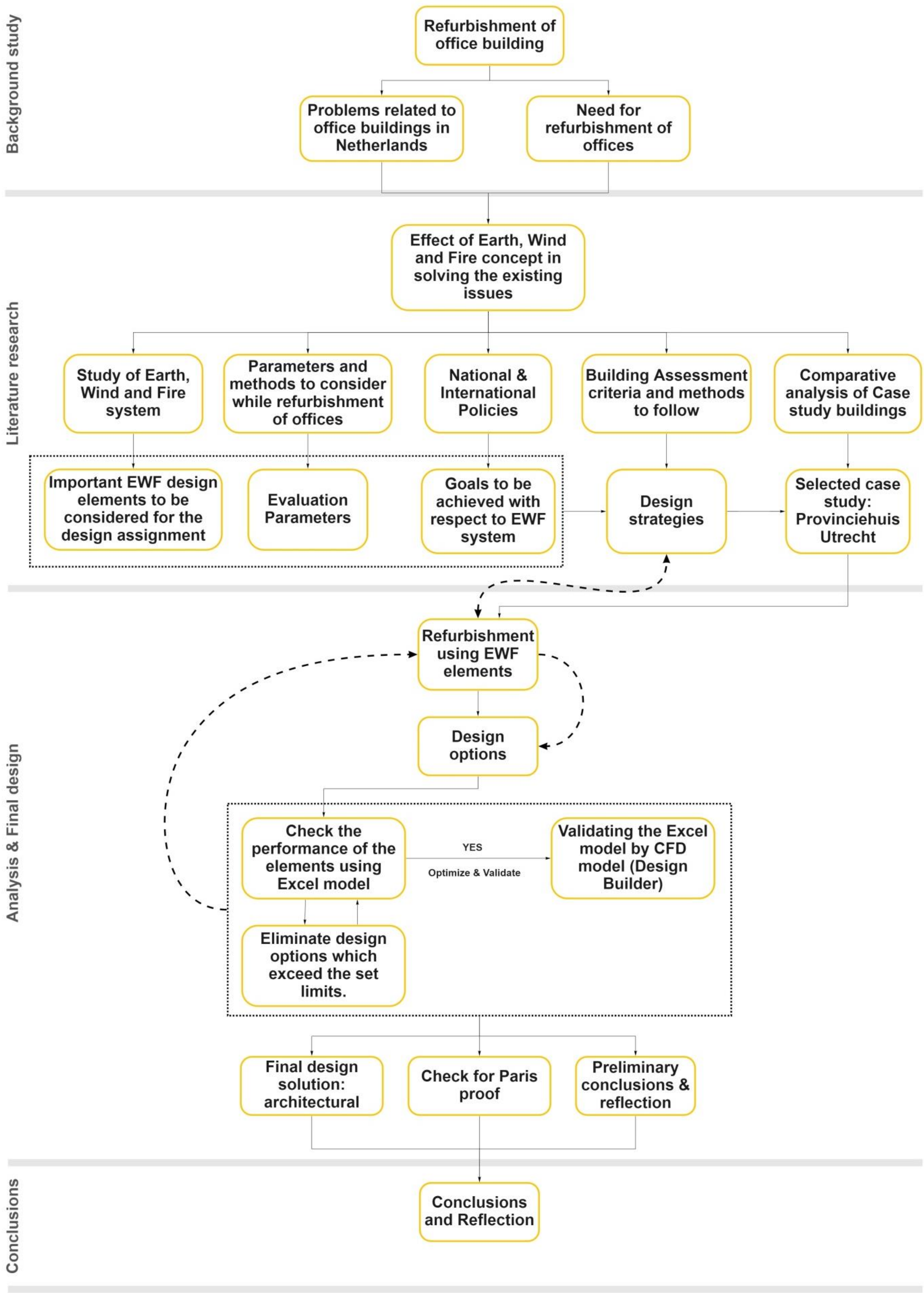


Figure 6.2: Basic methodology scheme

7. Selection of Case study

2 case study buildings namely, Provinciehuis Utrecht and Van Unnikgebouw, Utrecht, will be analyzed on the basis of the building assessment strategies established in the previous section. A comparative analysis will be conducted between the 2 case study buildings and one case study will be chosen for the implementation of the EWF system. Both the case study buildings are primarily used as Office function along with meeting function and educational function.

7.1. Case study 1: Provinciehuis Utrecht

The Provinciehuis (Provincial House) Utrecht, earlier called as VSB/Fortis Building, is an 85 m high office building dominating the skyline of east Utrecht. The construction of the VSB complex (earlier known) was executed by Van Mourik Vermeulen BV architects in the year 1995. The 20 storey high rise office building has a dimension of 15 x 98 x 85 m with a floor area of approximately 40,000 m^2 and 750 parking spaces (Drunen & Hendriks, 2017).

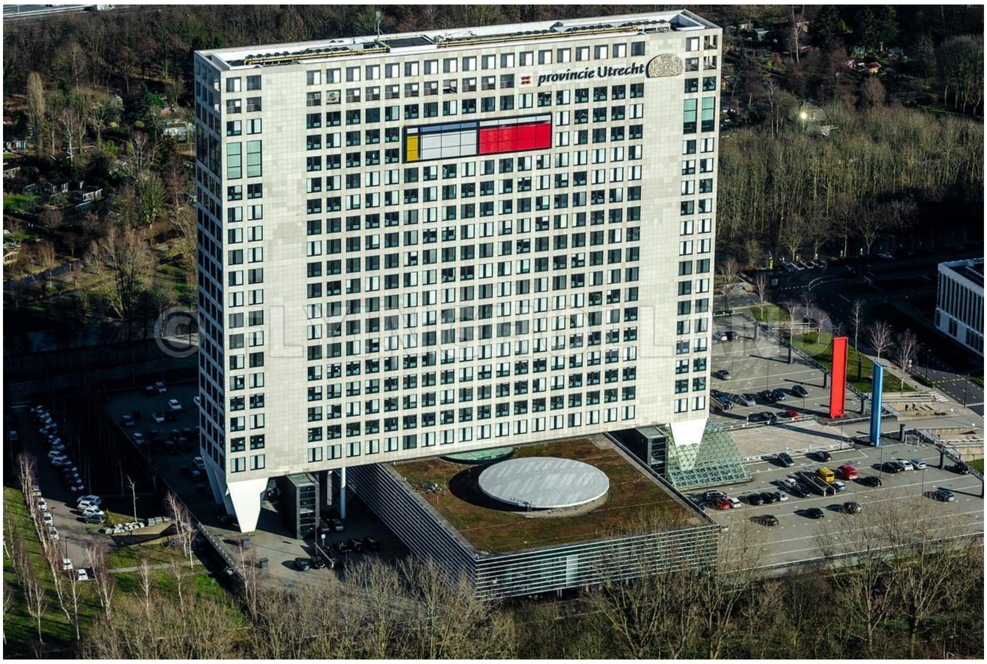


Figure 7.1: Provinciehuis Utrecht (flying holland.nl, n.d.)

Figure 7.2: Provinciehuis Utrecht (vvdmontfoort.nl, 2021)

Architectural Layout

The site is divided into 4 types of buildings namely: a. High rise office building, b. Low rise building with restaurants, c. Auditorium & d. Parking deck. The high rise comprises of a central core with 7 lifts and the emergency staircase is not attached to the external wall but placed inside leaving a corridor facing the exterior façade.

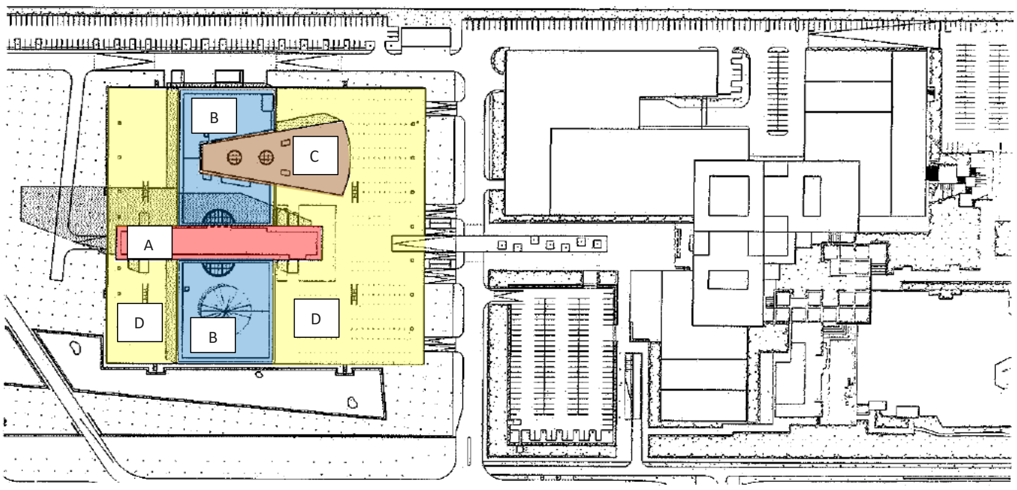


Figure 7.3: Site plan of the Provinciehuis Utrecht (Drunen & Hendriks, 2017).

Façade

The façade of the high rise building is cladded with white granite and is placed 2 m away from the building boundary on the 19^{th} and 20^{th} floor (technical floors) for maintenance purposes. The low rise is cladded with smoked glass and the auditorium with white aluminum plates. The façade elements of the high rise are 2.7 m wide and high infilled with glass panels consisting of aluminum frames. It comprises of double glazing and single glazing on the inside with a cavity between them. Venetian blinds are installed in the cavity space to block the solar radiation (Boer, 2020).

Structural design

Most of the structural elements are prefabricated elements. The high rise consists of 600 mm diameter prefab columns with a centre to centre distance of 7.2 m. In the transverse direction, hollow core slabs with pressure layer on top was constructed. In order to prevent vibration and noise nuisance, the installation layer on the nineteenth floor is completely isolated from the other constructions by neoprene supports (Drunen & Hendriks, 2017).

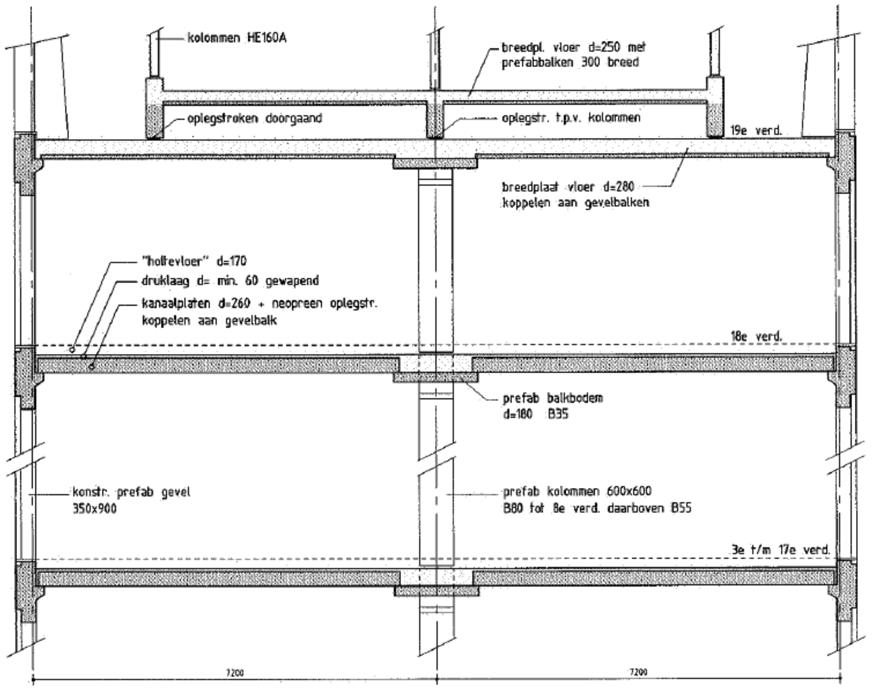


Figure 7.4: Principle section of high rise building (Drunen & Hendriks, 2017)

7.2. Case study 2: Van Unnikgebouw (Trans II), University Utrecht

The 20,000 m^2 gfa Willem C. van Unnik building is part of the Utrecht Science park and the tallest structure in the Utrecht University. The 75 m high office and educational building was contructed in 1969, one of the oldest buildings in the university (Willem C. van Unnikgebouw, 2020).

Figure 7.5: Southwest view of Van Unnik building (Pepijntje, 2008)

Construction

The office building was built due to the high demand of students and lack of space to fit in the incoming students. The building is made out of poured concrete using the jacblock system. Each floor was jacked up after puring the concrete through which the entire construction was completed in 2 years (Willem C. van Unnikgebouw, 2020).

Current situation

The 50 year old building is very old and outdated for the present situation and highly expensive to maintain with poor insulation. The presence of asbestos in the façade also has negative effects on the health of the users (Demontage laagbouw Van Unnik, 2020). Moreover, the thermal and energy performance of the building did not fit into the Utrecht University's ambitious goals to provide optimum occupant comfort and sustainable buildings. In order to fulfill the goals, the high-rise part of the building will undergo major renovation and the low-rise is currently being demolished (Demontage laagbouw Van Unnik, 2020). The building will be used as an education and office building under the control of Utrecht University.

7.3. Comparative Analysis

To implement the EWF system in a case study building, one case study will be chosen from the above mentioned buildings on the basis of a comparative analysis which corresponds to the building assessment criteria as shown in Table 7.1.

BUILDING	PROVINCIEHUIS UTRECHT	WILLEM C. VAN UNNIKGEBOUW
Typology	Office Building ✓	Education and Office building ✗
Higher than surrounding building	✓	✓
Building height	85m	75.5m
	✓	✓
Possibility to strip down the façade completely	✓	✓
Open able windows in the façade	✓	✓
Load bearing façade system	✗	✗
Easy disassembly	✓	✗
Poured pipes in the floor	✗	✗
Large column grid	✓	✓
Structural system can withstand additional façade loads	✓	✗
Possibility of cold and heat storage	✓	✓

Table 7.1: Comparative analysis of 2 Case Study buildings

The above table shows that the Van Unnik building does not satisfy the basic criteria of the typology of the building which has to be complete office use as it changes all the National and International regulations due to the change in the typology of the building. Moreover, the existing façade elements cannot be easily disassembled hence, the current proposals for this building need some amount of demolition of the building. If this building is considered for refurbishment with EWF system, the façade has to be stripped down completely which is possible for the high rise part, but the lower rise part has to be demolished and rebuilt completely due to structural instability. This means the structural system cannot bear the additional façade load of the EWF system without undergoing demolition and reconstruction.

In case of the Provinciehuis Utrecht building, it satisfies all the building assessment criteria's and is currently in need of energy efficient refurbishment. The owners of the building have an objective to reach energy-neutrality for all its real-estate properties by 2035. The high-rise building of the Provinciehuis is the highest contributor towards energy consumption. Incremental changes like replacing the lighting and optimizing cooling and ventilation will not change the energy performance significantly. Due to its height, orientation, high exposure to solar radiation due to many windows and improper use of sun shading, there is a huge energy demand on cooling & heating the structure leading to high energy consumption. Nevertheless, many of these challenges can to be tackled by the application of the EWF concept and help the Province to reach its objectives of energy-neutrality.

Although the Van Unnik building has more potential for the implementation of the EWF system as it gives the opportunity to redesign the structure along with the EWF system at the design stage and not after the building is constructed. In case of the Provinciehuis, the challenge will be to incorporate the EWF system in a building which is completely built and the possibility of completely stripping down the façade is not preferred. Since the main objective of this thesis is refurbishment and not major renovation/complete demolition, Provinciehuis Utrecht was chosen as the case study for this research.

8. Applying EWF system to the proposed design

After choosing the case study building (refer section 7.3), the next step is to analyze the existing energy performance of the building and implementing the EWF design strategies established in the literature research in the case study building. This section talks about how the design strategies were applied to the chosen building, the methodology followed, the design variables considered and finally the design option chosen for further consideration.

8.1. Energy performance of Provinciehuis Utrecht (Existing condition)

To check the efficiency of the EWF system, the first step is to analyze the energy performance of the existing systems in the building. The energy scan was performed in 2 parts: (1) an energy scan to map the total (fossil) energy use of the Provinciehuis and (2) provide insight into the measures that can be implemented in order to reduce energy consumption as much as possible by means of saving, reuse and/or own energy generation from renewable sources. All the data given below were extracted from the energy scan report conducted by DVTadvise BV in the year 2020.

8.1.1. Building characteristics

General Building data

Construction period	: 1992-2012
Number of floors	: 18 floors (19th and 20th floors are technical spaces)
Size	: 53953 m^2 GFA/ 29096 m^2 GO
Parking area	: 18270 m^2 GFA
Function	: predominantly office with meeting function
Working hours	: 8:00 am – 8:00 pm (Mon-Fri)

Architectural data

Roof	: R_c= 2.0 m^2 K/W
Façade	: R_c= 2.0 m^2 K/W
Floor	: R_c= 1.5 m^2 K/W
Façade fragment with Glass	: U= 1.5 W/ m^2 K
Double glazed window	: U=1.2 W/ m^2 K (13cm cavity)
Solar factor	: 30%
Light transmission	: 80%
Sun protection outside	: only on low rise as fixed sun blinds
Sun protection inside	: electrically operated intermediate blinds

Technical data

Heat generation	: district heat network Utrecht-Nieuwegein (ŋ= 150%)
Heat distribution 1	: ventilation air (transport medium air with 18°C)
Heat distribution 2	: VAV boxes (transport medium water)
Heat distribution 3	: under floor heating (only on the ground floor)
Space heating control 1	: room thermostats
Space heating control 2	: demand driven CO_2 presence thermostats
Cold generation	: air/water compression refrigerators
Cold distribution	: ventilation air (transport medium air with 7°C)
Ventilation	: mechanical exhaust and supply
Domestic Hot Water	: TSA on district heating network and electric boilers
Specific lighting power	: 9 Watt/m2
Humidification	: adiabatic humidification
Heat recovery low-rise	: twin coil unit
Heat recovery high rise	: heat wheels

8.1.2. Energy calculations

This building accounts for more than 90% of the total energy consumption, a detailed energy balance can be seen in Table 8.1. The calculations are based on the energy consumption on the basis of the year 2018-2019. The electricity consumption of this building for the selected reference year is 154 kWh/m^2 GO, heat consumption is 0.3 GJ/m^2 GO ≈ 97 kWh/m^2 and the CO_2 emissions is 249 kWh/m^2.

Energy consumption reference year 2018-2019				
	Electricity (kWh/ year)	Heat (GJ/year)	Primary energy (kWh)	Primary energy (kWh/m2)
Space Heating	-	9,734	2,703,808	93
DHW	-	209	57,998	2
DHW electric	83,020	-	83,020	3
Cooling	1,208,722	-	1,208,722	42
Ventilation	1,420,012	-	1,420,012	49
Production equipment	135,350	-	135,350	5
Lighting	675,146	-	675,146	23
Electric charging stations	250,390	-	250,390	9
Sprinkler and fire alarm equipment	260	-	260	0
Other electricity	500,679	-	500,679	17
Total	**4,326,355**	**9,943**	**7,088,161**	**244**

Table 8.1: Energy balance (reference year 2018-2019)

Figure 8.1 shows that heating and ventilation are the largest energy consumers, followed by cooling, lighting and other electricity. The number of charging stations and fire extinguishing system is neglected in this calculation. Since the largest energy contributor is heating, improving the building envelope will be beneficial as 75% of the existing façade is glazed causing high amount of heat gain inside the building. In addition to the implementation of the EWF system, on-site energy generative strategies will help in further reduction of the primary energy consumption of the building thereby increasing the percentage of the renewable sources of energy.

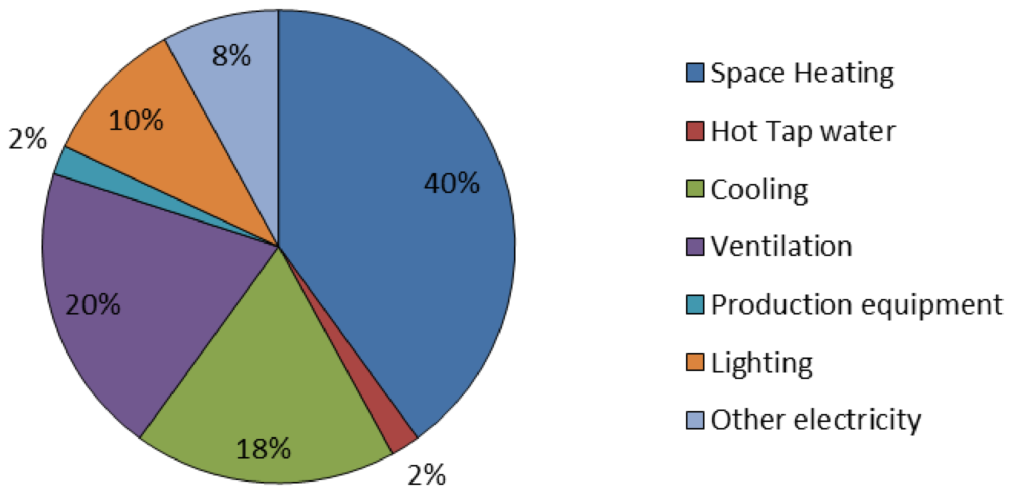


Figure 8.1: Distribution of total primary energy consumption for the reference year 2018-2019

8.2. Application of EWF strategies in the Case study building

8.2.1. Calculation methodology

In order to check which parameters to consider for the basic calculations and dynamic calculations (design builder), a methodology was designed. For the basic calculations, the fan energy consumed by supply and exhaust air, additional heating for supply air and water pump energy for supply air was considered as shown in Figure 8.2 and 8.7. For the dynamic calculations, the energy consumed by domestic hot water supply, space heating, space cooling, heat pumps and façade were considered. The total energy consumed will be the sum of the energy consumed in the basic calculations and the dynamic calculations.

A detailed methodology is explained below to understand which parameters were considered at which step and how these parameters led to the final results.

STEP 1: 4 different design options were realized, each having different locations, sizes and number of EWF elements.

STEP 2: Design conditions were defined. This is an important step as the calculations will depend on the values defined in the design conditions as they represent the desired output values.

STEP 3: For the basic excel calculation (refer section 6), the first step is to determine the ventilation capacity required for the building corresponding to the number of occupants (see table 8.2). The percentage of occupants was defined according to an estimate of the number of occupants using the space at that particular hour. The Provinciehuis office hours are from 8:00 am to 8:00 pm during the weekdays and only the meeting rooms are open till 10:00 pm. Therefore, not all the users will use the office spaces throughout the day, the ventilation capacity will differ according to the amount of users occupying the space per 3 hours. For the offices, around 85-90% of users are considered during the office hours and after the office hours, the amount of users will reduce gradually. Since the meeting rooms in the offices are open till 22:00, the amount of users at night is not considered as 0% but 5-10% of the total ventilation amount. The occupancy scheme does not consider extreme conditions where 100% users or 0% users are occupying the space as it is an estimated value of the user occupancy and the system does not operate on 100% capacity or switched off during the night.

Ventilation Capacity											
	Max. amount of air needed per function (m3/h)	No. of occupants per function	Occupancy % per 3 hours								
			0:00	3:00	6:00	9:00	12:00	15:00	18:00	21:00	0:00
Offices	40,000	800	10%	5%	5%	85%	90%	85%	30%	15%	10%
Ground floor (Restaurant)	5,000	100	5%	5%	15%	85%	90%	85%	70%	30%	5%
First floor (Meeting rooms + Common areas)	5,000	100	5%	5%	10%	60%	85%	60%	70%	30%	10%
Required ventilation capacity according to occupant %	**50,000**	**1000**	**4500**	**2500**	**3250**	**41250**	**44750**	**41250**	**19000**	**9000**	**4750**
Required Pressure (Pa)	**150**		**32**	**24**	**27**	**96**	**100**	**96**	**65**	**45**	**33**

Table 8.2: Ventilation capacity corresponding to the number of occupants

STEP 4: Different variables for Climate Cascade and Solar Chimney were derived and comparisons were made with different input values to achieve the desired output value as shown in Fig 8.7. These comparative scenarios concluded which input parameters were considered and determined the input values which need to be applied for further analysis.

STEP 5: These values of the input parameters were applied to the 4 design options. Each option was evaluated on the basis of the amount of energy consumed by fan, pump energy, additional heating energy and heat recovery as shown in Fig 8.7. The design option which gave optimum results was chosen to be evaluated further for dynamic simulations.

STEP 6: For the dynamic calculations using Design Builder, the workflow adopted is shown in Figure 8.2. The first step is to choose an appropriate HVAC system from the library and change the settings accordingly as per EWF specifications. Since the EWF system has a constant air supply 18°C, CAV Reheat system was chosen. To avoid reheating the air before entering the zone, the reheating coil was removed and replaced with CAV No reheat coil (see Fig 8.3). To supply air at constant 18°C, irrespective of the outside temperature, the schedule in the air loop set point manager within the HVAC system was set to supply 18°C always as shown in Fig 8.4. To check if the HVAC system is supplying 18°C air temperature, Design Builder results viewer was used and the air loop supply side outlet was checked as shown in Fig 8.5.

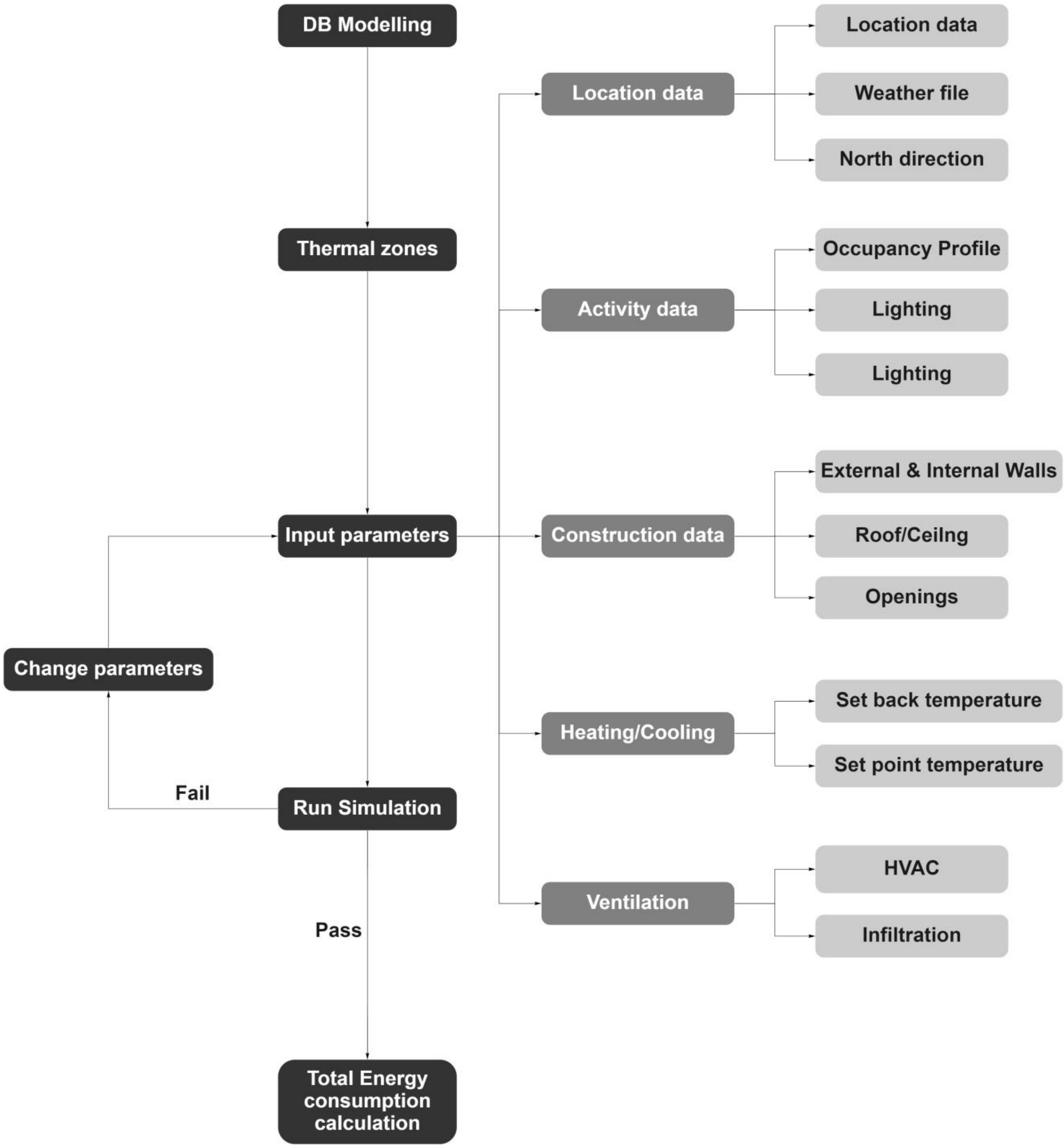


Figure 8.1: Workflow diagram for Dynamic simulation using Design Builder.

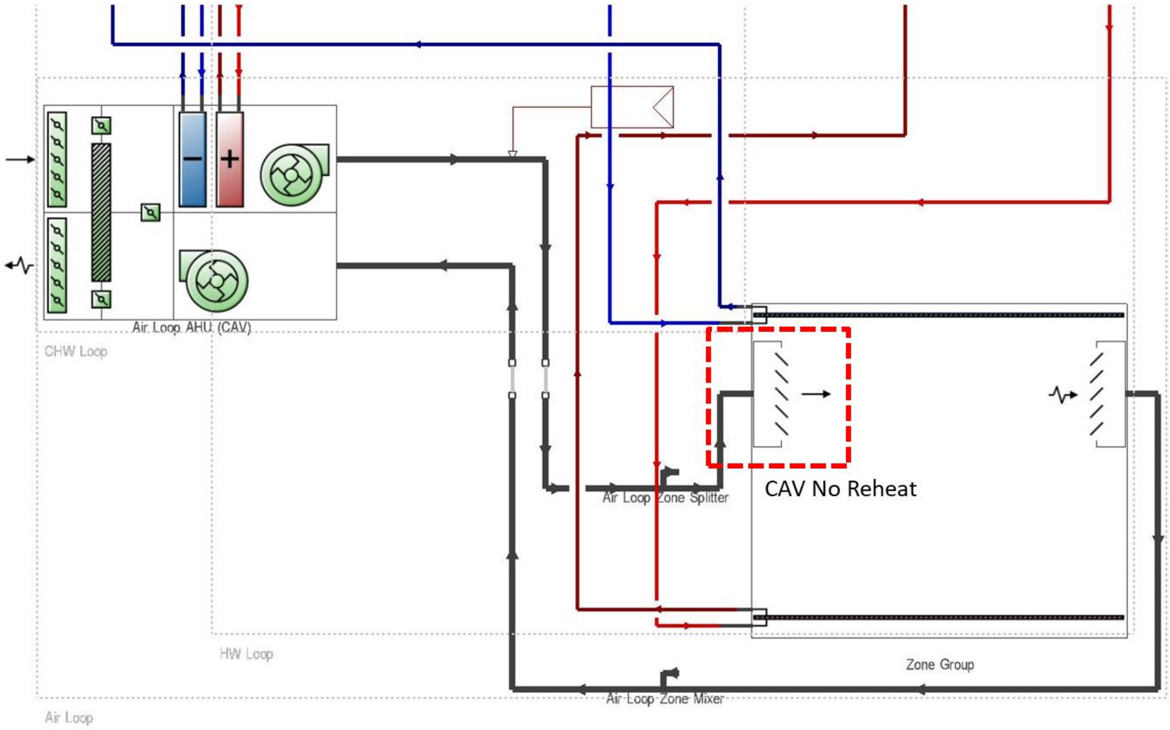


Figure 8.2: CAV No Reheat system

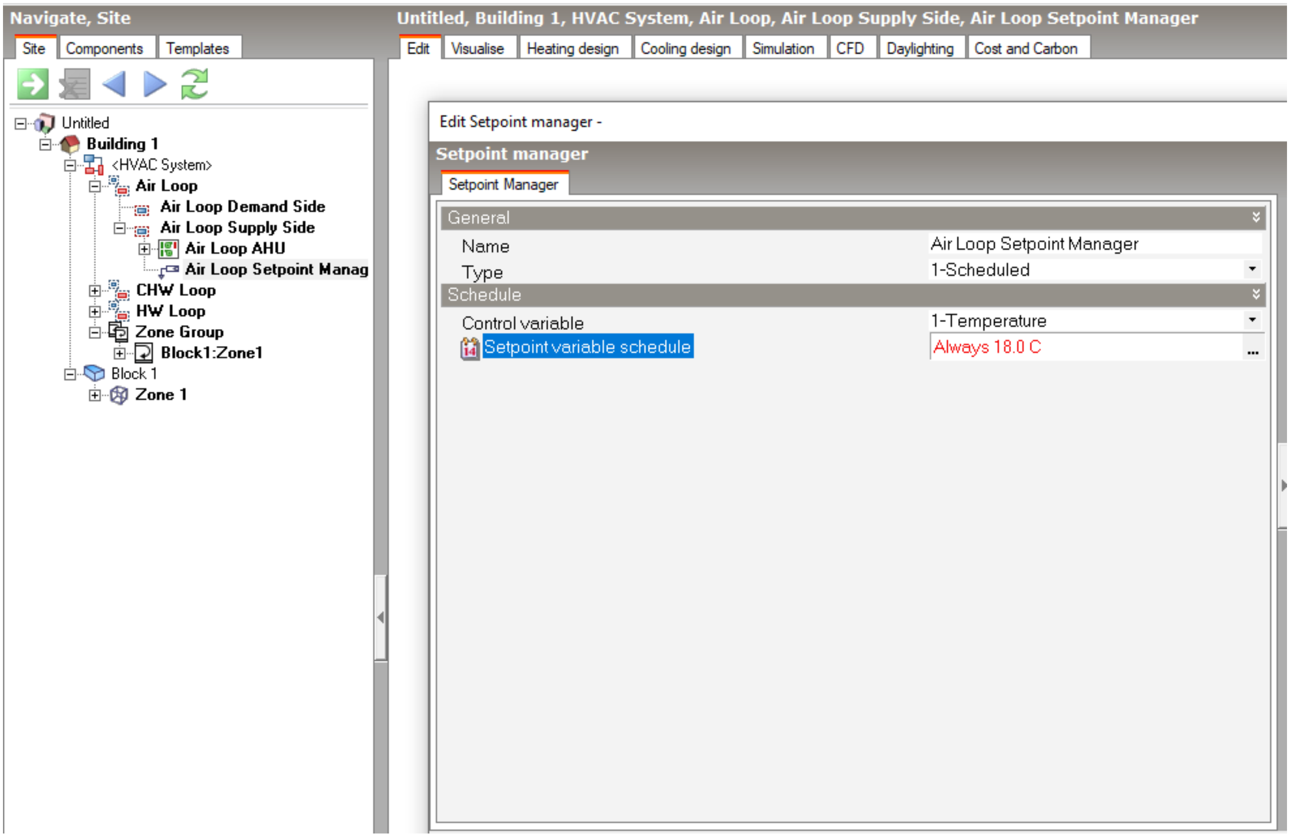


Figure 8.3: Setting the air loop set point schedule

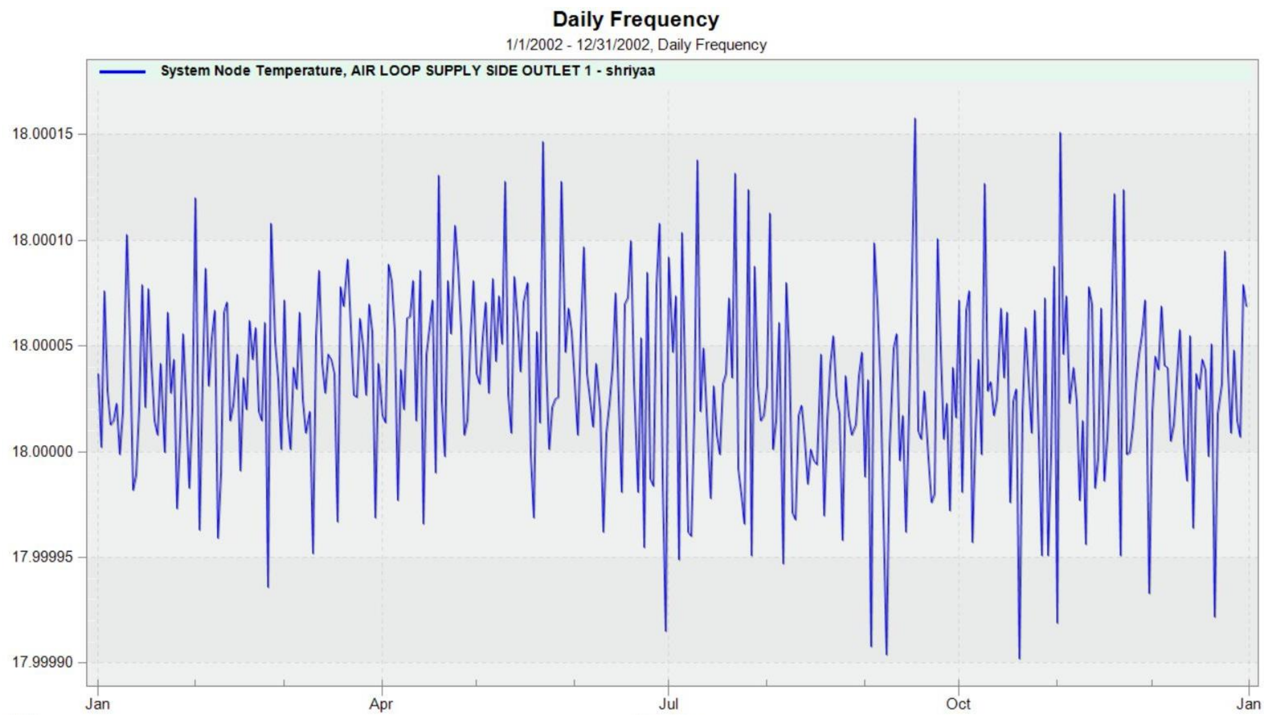


Figure 8.4: Supply air supply temperature of the HVAC system

STEP 7: Once the HVAC system is set up, the next step is to determine the construction, building materials, openings in the façade and lighting (refer appendix 14). One important step is to determine the HVAC, heating and cooling schedule and the occupancy density. The results will change drastically if appropriate schedule is not chosen for the type of the building.

	Schedule
Heating schedule	• Always on during the weekdays only for the heating season. • Always off during weekends and holidays. • Always off on all days during the cooling season.
Cooling schedule	• Always on during the weekdays only for the cooling season. • Always off during weekends and holidays. • Always off on all days during the heating season.
Ventilation schedule	• Always on during the weekdays 24/7, 365 days according to the occupancy density (see table 4.2). • Always off during weekends and holidays.

Table 8.3: Schedule adopted in the dynamic simulation

STEP 8: The next step is to add the zone heating and cooling system to the mechanical loop. Since the EWF HVAC system in the design builder does not consider centralized heating and cooling according to varying outdoor temperature, it is important to add heating and cooling system in the loop. For this research, chilled ceiling and heated floor system was chosen as shown in Fig 8.6.

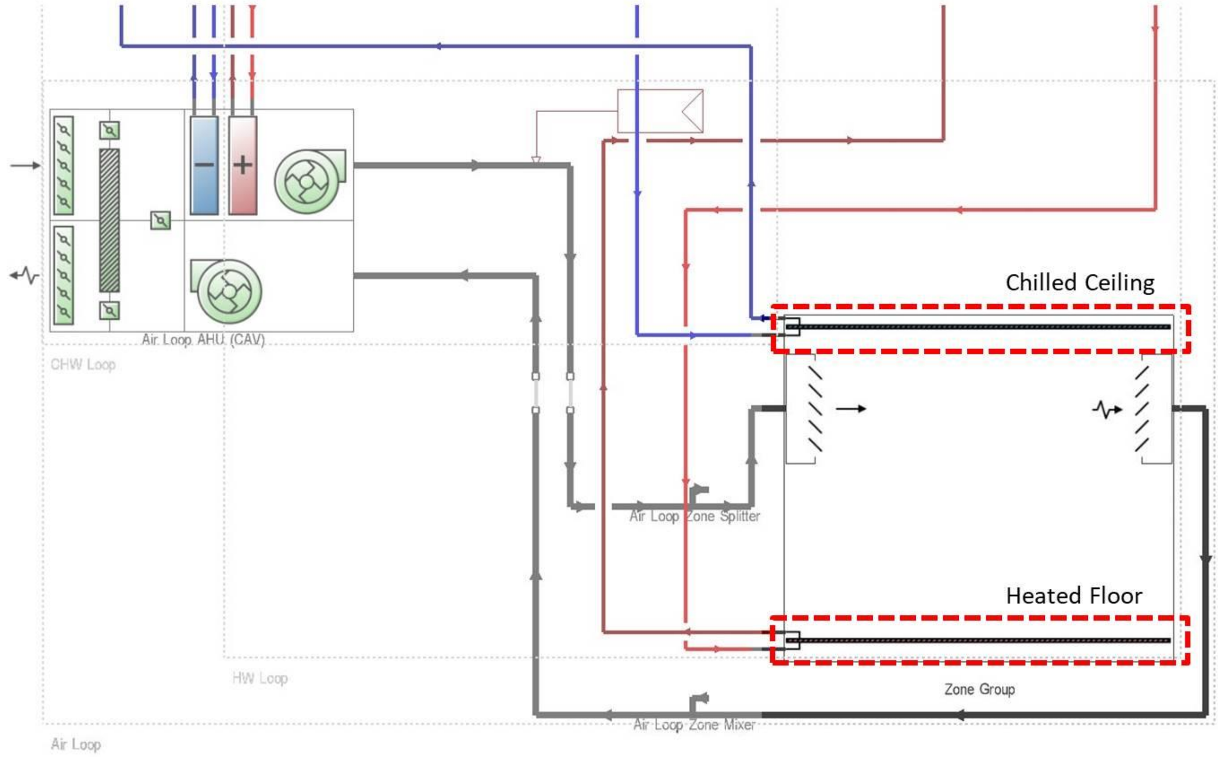


Figure 8.5: Mechanical ventilation loop showing heated floor and chilled ceiling in Design Builder.

STEP 9: Run the simulation and obtain the results. The energy calculation for the zone heating and cooling were derived from the design builder results and the energy consumed by the EWF system were derived from the excel model. The final result is the summation of the basic and dynamic model.

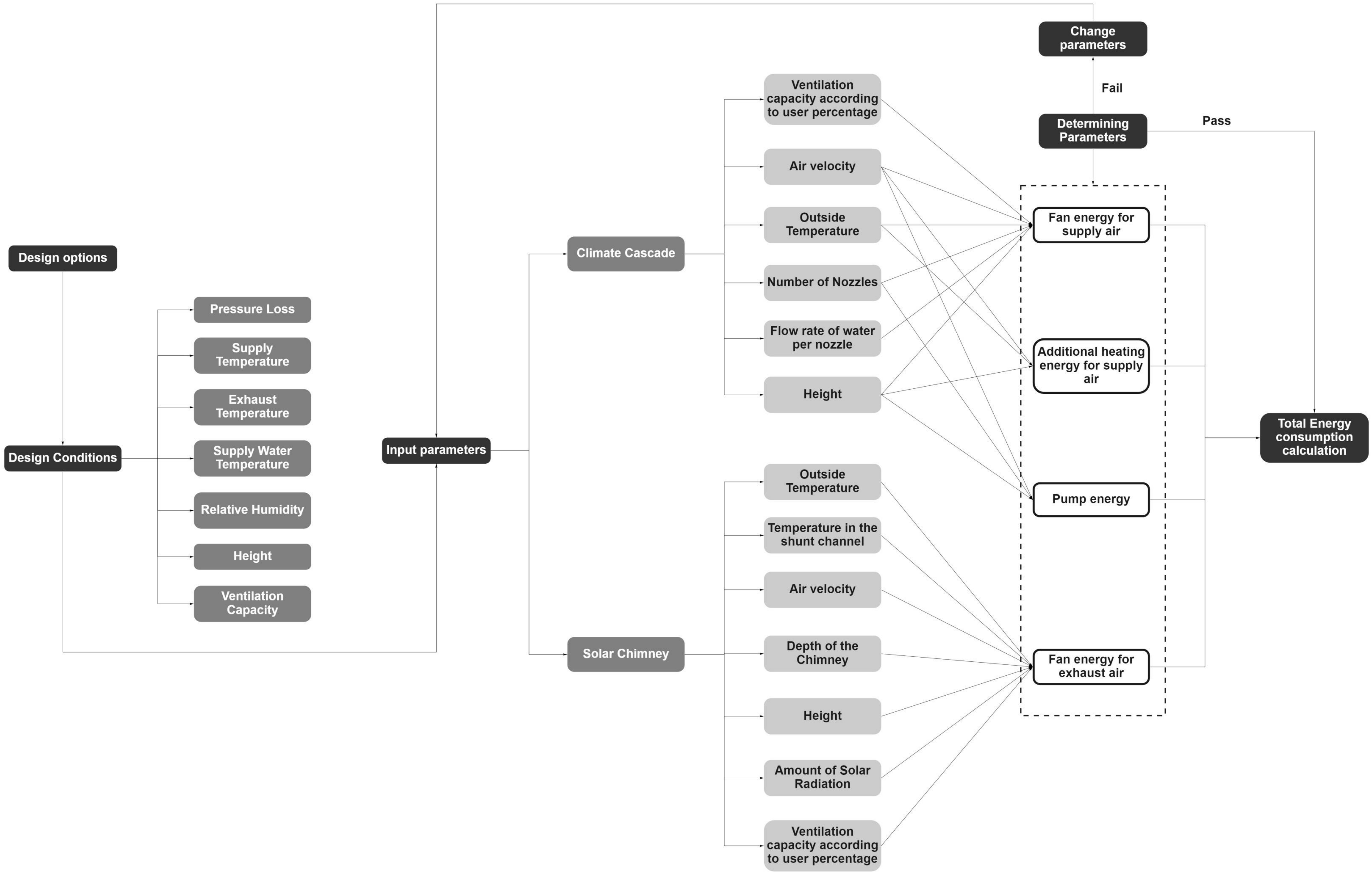


Figure 8.6: Calculation Methodology for Basic excel modelling

8.2.2. Design options

To evaluate the performance of the Climate Cascade and Solar Chimney, 4 design options were produced. Each design option varies with respect to the location, size, number of Climate Cascades and Solar Chimneys, and type of supply and exhaust. A comparative analysis was conducted to check which option gives optimum results on the basis of the set design conditions which will be discussed in section 9.1.

Case 1: In this design option, 1 Climate Cascade and 1 Solar Chimney were considered with decentralized supply and centralized exhaust. With 1 Climate Cascade and 1 Solar Chimney, the size also increases, especially for Solar Chimney, which can be considered as a solar façade in this case.

Case 1: 1 Climate Cascade, 1 Solar Chimney
(Decentralized supply, Centralized exhaust)

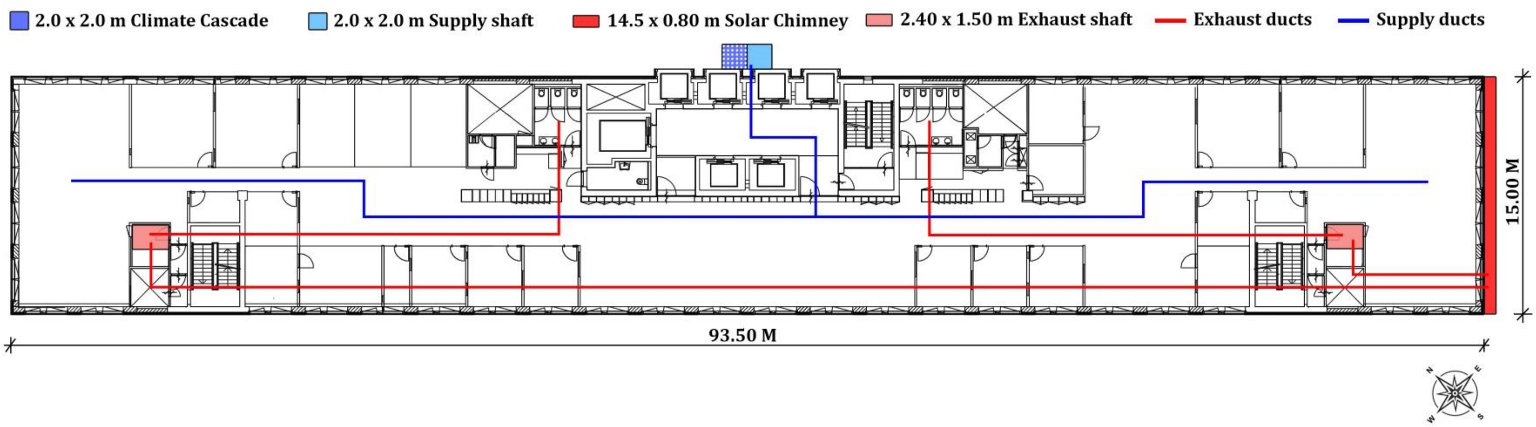


Figure 8.7: Design option 1 with 1 Climate cascade and 1 Solar Chimney

Case 2: In this design option 2 sub options were produced. In option 2a, 2 Climate Cascades and 2 Solar Chimneys were considered with decentralized supply and decentralized exhaust. In option 2b same number of Climate Cascades and Solar Chimneys were considered with decentralized supply and centralized exhaust and the Climate Cascade is placed within the building envelope. With 2 Climate Cascades and 2 Solar Chimneys, the length of the supply and the exhaust duct reduces as 2 units of each element are considered which divides the building into 2 parts.

Case 2a: 2 Climate Cascade, 2 Solar Chimney
(Decentralized supply, Decentralized exhaust)

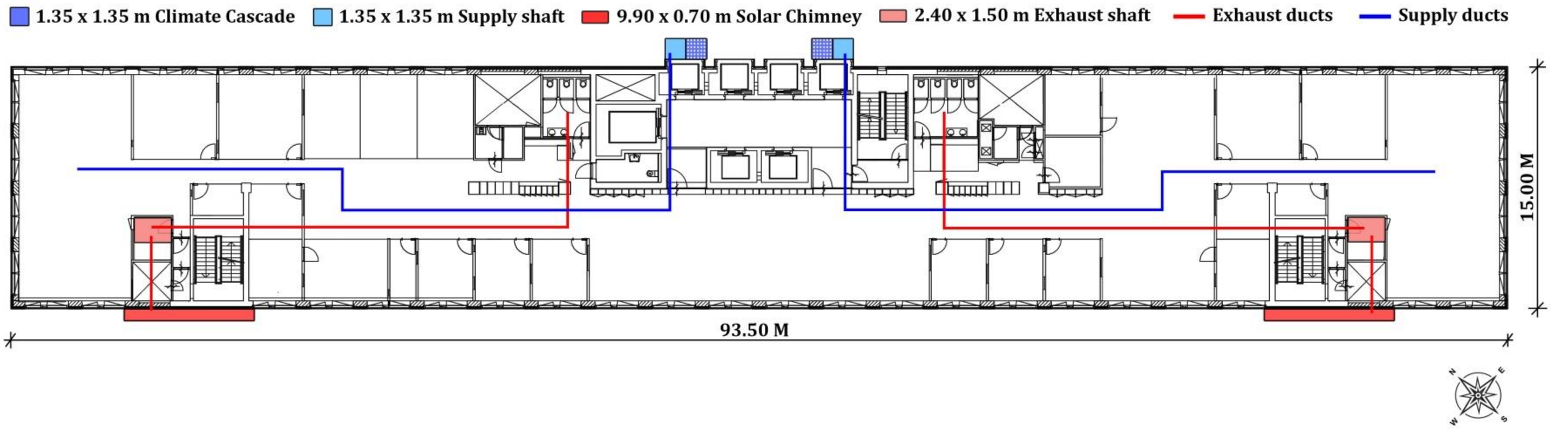


Figure 8.8: Design option 2a with 2 Climate cascades and 2 Solar Chimneys

Case 2b: 2 Climate Cascade, 2 Solar Chimney
(Decentralized supply, Centralized exhaust)

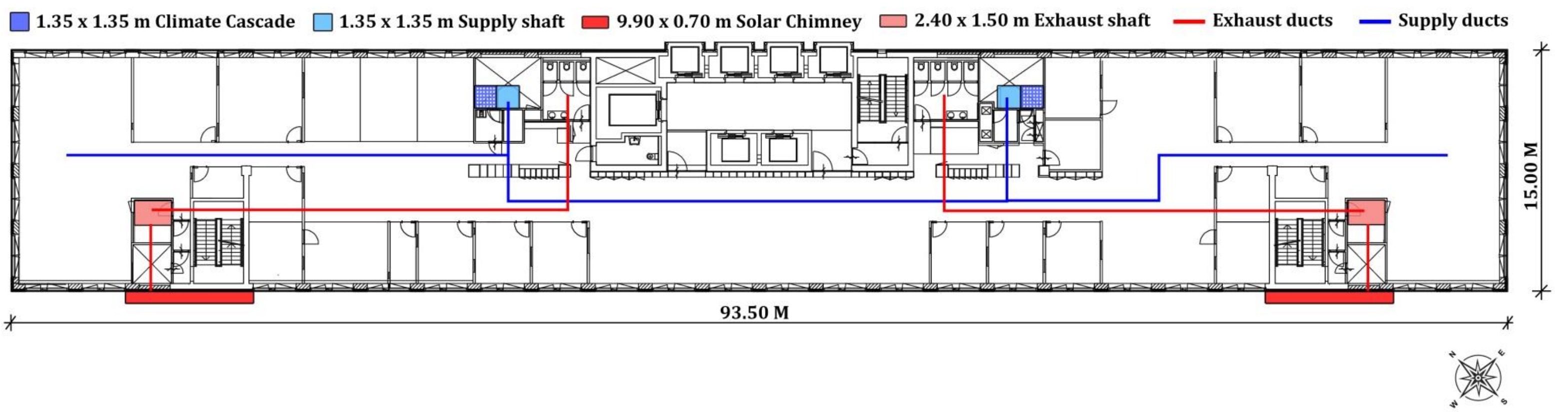


Figure 8.9: Design option 2b with 2 Climate cascades and 2 Solar Chimneys

Case 3: In this design option, 1 Climate Cascade and 2 Solar Chimneys were considered with decentralized supply and centralized exhaust.

Case 3: 1 Climate Cascade, 2 Solar Chimney
(Decentralized supply, Centralized exhaust)

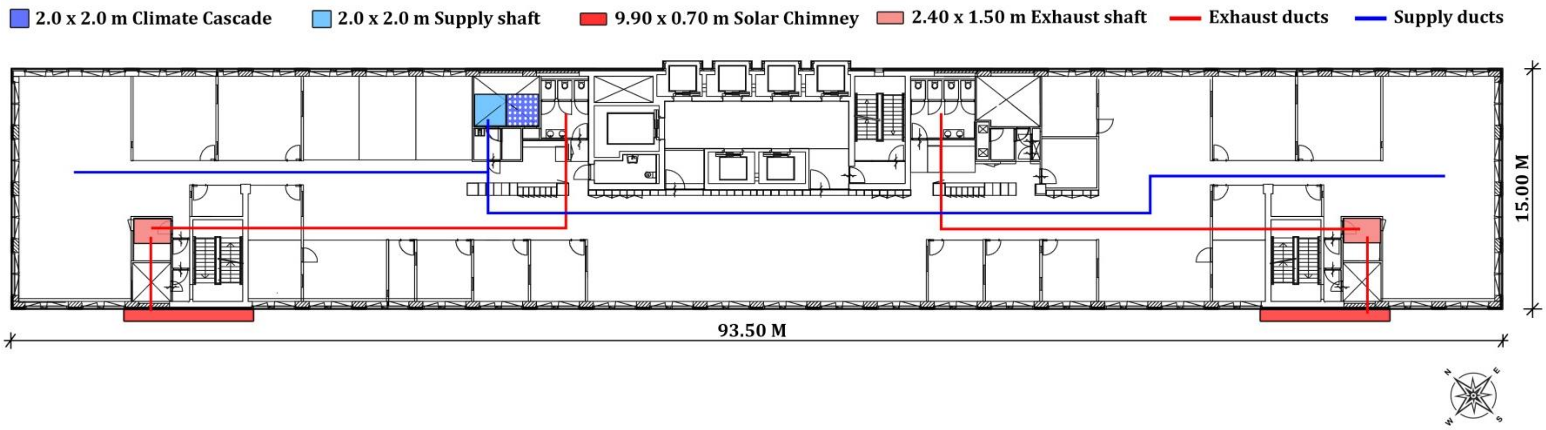


Figure 8.10: Design option 3 with 1 Climate cascade and 2 Solar Chimneys

Case 4: In this design option, 2 Climate Cascades and 1 Solar Chimney were considered with decentralized supply and centralized exhaust.

Case 4: 2 Climate Cascade, 1 Solar Chimney
(Decentralized supply, Centralized exhaust)

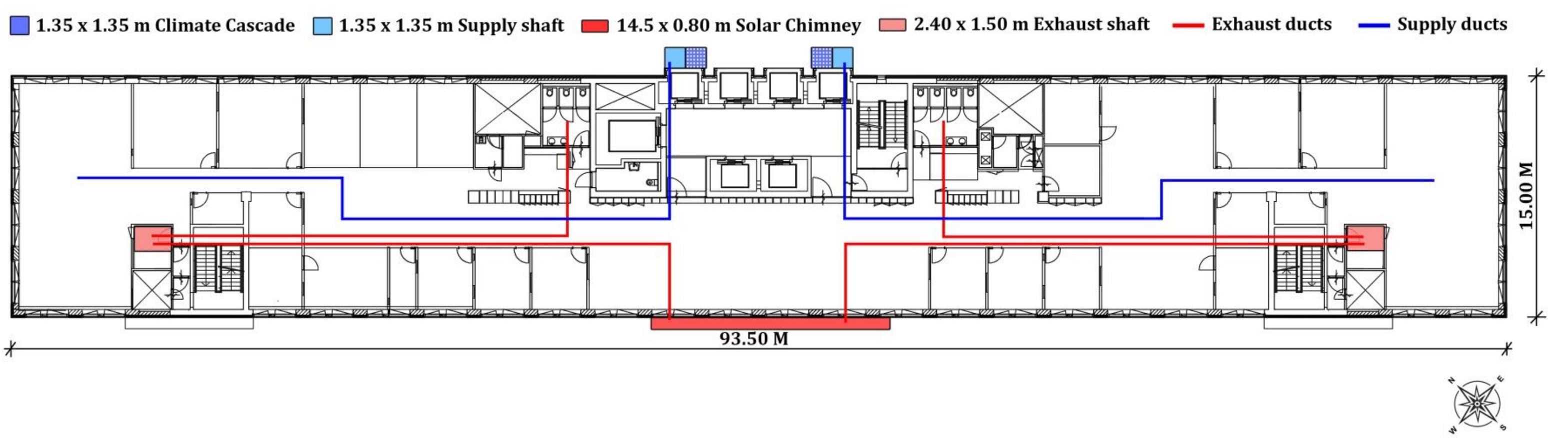


Figure 8.11: Design option 4 with 2 Climate cascades and 1 Solar Chimney

8.2.3. Design conditions

In order to evaluate the design options, it was important to establish the desired output values. In case of the Climate cascade, the total pressure loss for the entire system, irrespective of the number of Climate Cascades, was considered as 150 Pa after consulting Dr.Ben Bronsema. Supply air temperature of 18°C in the rooms and supply water temperature of 13°C for the sprinkler in the Climate Cascade were considered with a relative humidity of 55% when the outside temperature is 28°C. In case of the Solar

Chimney, the total pressure loss for the entire system, irrespective of the number of Solar Chimneys, was considered as 50 Pa after consulting Dr.Ben Bronsema. Exhaust air temperature of 22°C in the exhaust shunt channel was considered.

Before calculating the performance of the EWF elements for each design option, the first step is to calculate the total ventilation capacity required to cater to the total number of users in the building. Considering 1000 people, the total ventilation capacity required per person was estimated to be 50 m^3/h/person which will be 50,000 m^3/h for 1000 people.

DESIGN CONDITIONS								
		Constants						
		Total Pressure loss (Pa)	Supply temperature (°C)	Exhaust temperature (°C)	Supply water temperature (°C)	Relative humidity	Height (m)	Ventilation capacity (m3/h)
1	Climate cascade	150	18	-	13	55%	80	50000
2	Solar chimney	50	-	22	-	-	80	50000

Table 8.4: Design conditions for Solar Chimney and Climate cascade

8.2.4. Determining variables

The excel model is the starting point for all the calculations and the determining variables. To understand the different variables for Climate Cascade and Solar Chimney, a detailed analysis was conducted to realize the relationship between these variables and how they affect the end result.

Climate Cascade

The number of nozzles, outside temperature, velocity of air, ventilation capacity, height of the building and spray spectrum directly affect the supply temperature of air and the pressure difference at the bottom of the Climate Cascade. To understand how to choose the number of nozzles and the corresponding air velocity to achieve the desired temperature and pressure, different situations were made to check which value gives the best results for single or double Climate Cascade. The following situations were evaluated only when the outside temperature is 28°C.

Spray Spectrum: The selection of the spray spectrum is dependent on the number of nozzles, velocity of air and outside temperature. Figure 8.13 shows the performance of the spray spectrum with respect to the desired temperature and pressure. In this case, outside temperature of 28°C was considered with 9 nozzles and air velocity of 3.2 m/s. It was observed that the supply air temperature decreases when the number of spray spectrum increases. When the spray spectrum is 6, the desired temperature of 18°C and pressure of

150Pa is reached as compared to the other values. Therefore, spray spectrum 6 was chosen for all the design options for Climate Cascade.

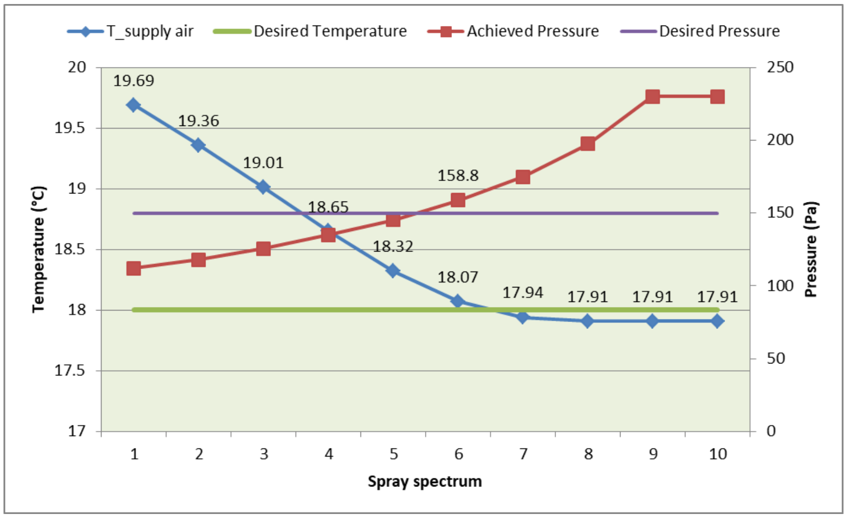


Figure 8.12: Performance of the spray spectrum when outside temperature is 28°C.

Number of nozzles, air velocity, supply air temperature and pressure difference: 3 cases with varying velocities, for single and double cascade, were evaluated to understand which values need to be selected for further calculations corresponding to the design options.

For single Climate Cascade:

As shown in in figure 8.14, when the velocity of air is 2 m/s and outside temperature is 28°C, with 9 nozzles, the desired temperature of 18°C is achieved but the achieved pressure is lower than the desired pressure. In order to achieve the desired pressure, more number of nozzles will be required which leads to higher temperatures. Therefore, this case is eliminated.

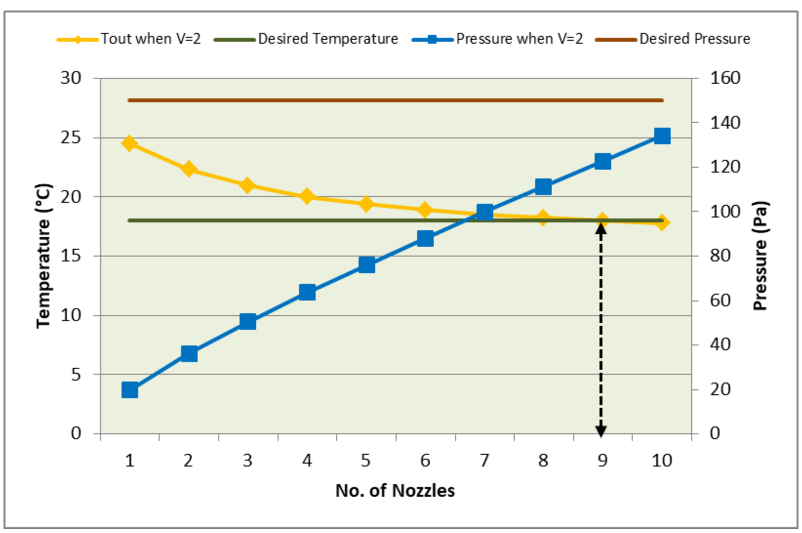


Figure 8.13: Air velocity=2m/s : Number of Nozzles

As shown in in figure 8.15, when the velocity of air is 3 m/s and outside temperature is 28°C, with 9 nozzles, the desired temperature and the desired pressure are achieved. Therefore, this case can be considered for further calculations.

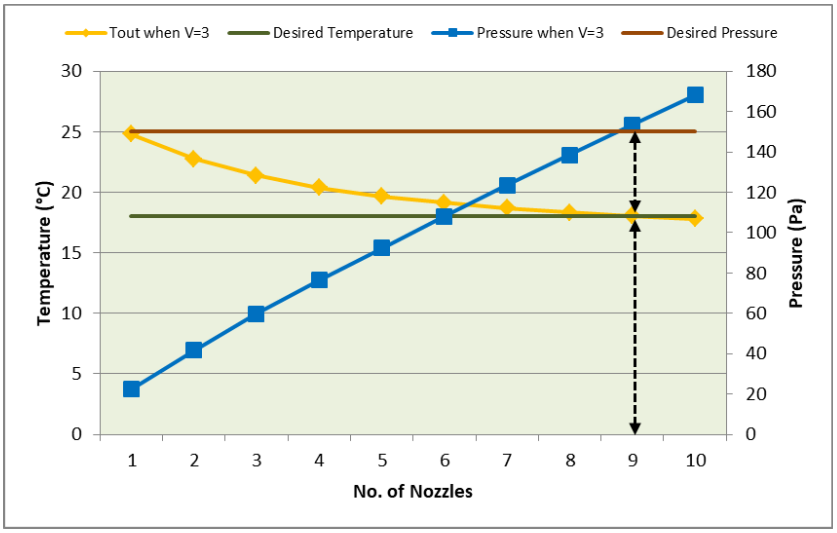


Figure 8.14: Air velocity= 3m/s : Number of Nozzles

As shown in in figure 8.16, when the velocity of air is 3.8 m/s and outside temperature is 28°C, with 9 nozzles, the desired temperature is achieved but the desired pressure is higher than required.

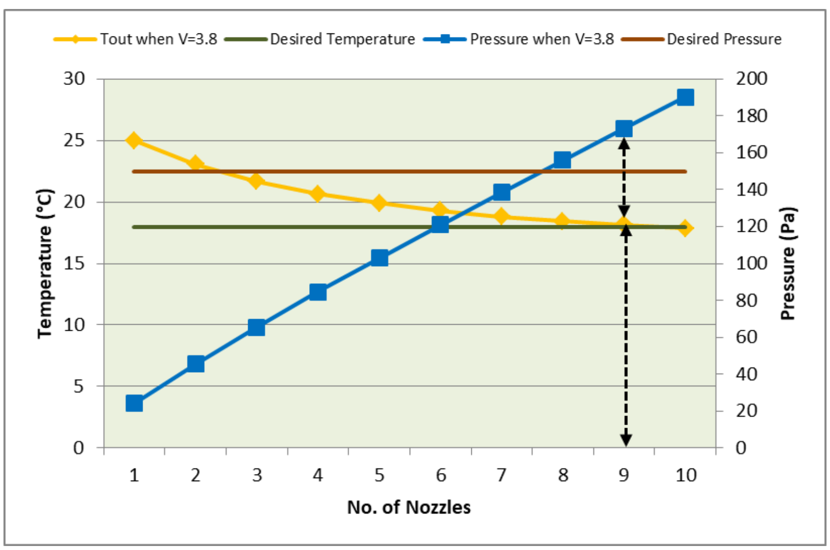


Figure 8.15: Air velocity= 3.8 m/s : Number of Nozzles

From the 3 cases, it can be concluded that the second case gives optimum results. Hence, when 1 Climate Cascade is designed, an air velocity of 3m/s with 9 nozzles will be used which will require 6.30 kg/s of water.

For Double Climate Cascade:

As shown in in figure 8.17, when the velocity of air is 2.5 m/s and outside temperature is 28°C, with 5 nozzles, the desired temperature and the desired pressure are achieved. Therefore, this case can be considered for further calculations.

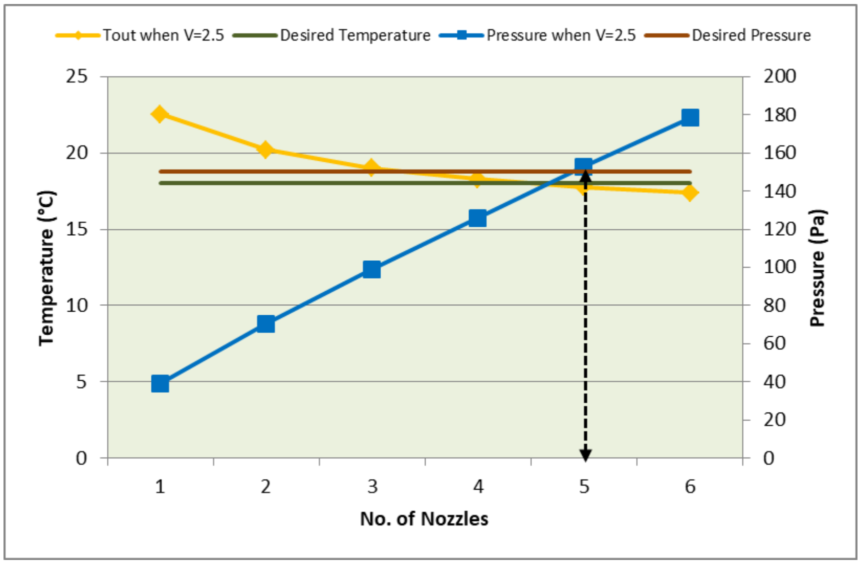


Figure 8.16: Air velocity= 2.5 m/s : Number of Nozzles

As shown in in figure 8.18, when the velocity of air is 3.5 m/s and outside temperature is 28°C, with 4 nozzles, the desired temperature and the desired pressure are achieved. Therefore, with less number of nozzles as compared to the earlier case, the desired results can be achieved.

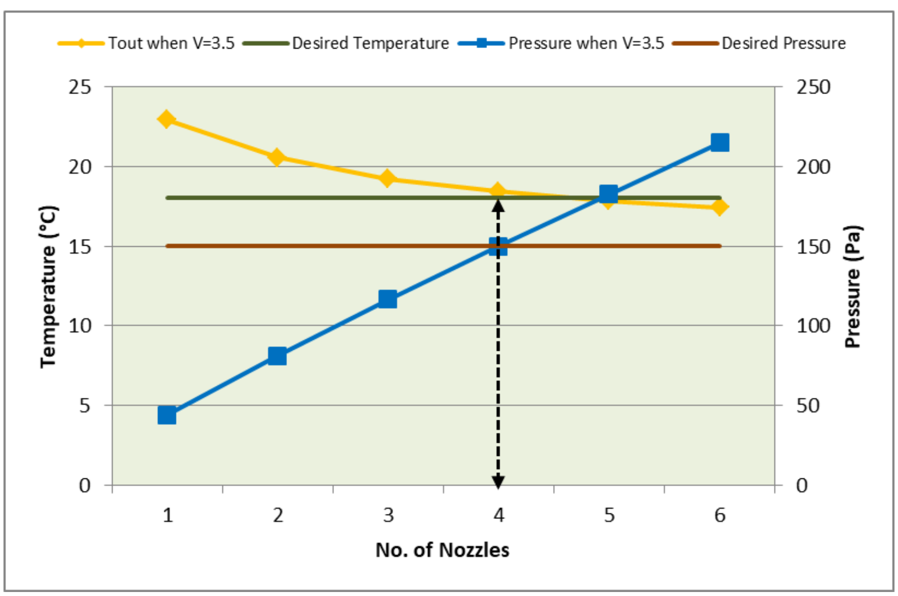


Figure 8.17: Air velocity= 3.5 m/s : Number of Nozzles

As shown in in figure 8.19, when the velocity of air is 3.8 m/s and outside temperature is 28°C, with 5 nozzles, the desired temperature is achieved but the desired pressure is higher than required.

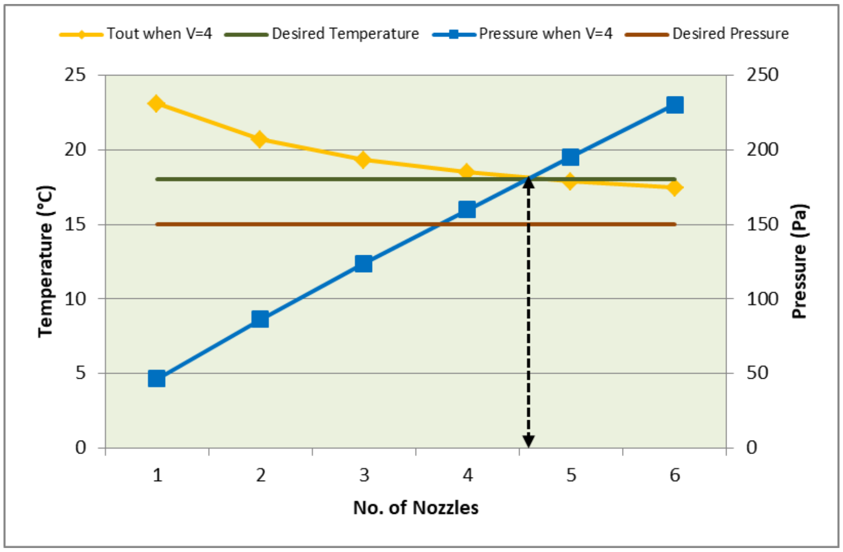


Figure 8.18: Air velocity= 4.0 m/s : Number of Nozzles

From the 3 cases, it can be concluded that the second case gives optimum results. Hence, when 2 Climate Cascades are designed, an air velocity of 3.5 m/s with 4 nozzles will be used which will require 2.80 kg/s of water.

Solar Chimney

The outside temperature, velocity of air, depth of the chimney, height of the building and total pressure loss directly affects the temperature of air at the top of the chimney and the thermal draught. To understand how to choose the depth and the corresponding air velocity to achieve the desired temperature and thermal draught, different situations were made to check which value gives the best results for single Solar Chimney. The following situations were evaluated only when the outside temperature is 28°C.

Depth of chimney, thermal draught, pressure loss and air velocity: 3 cases with varying depths of the chimney were evaluated to understand which values need to be selected for further calculations corresponding to the design options.

As shown in figure 8.19, when depth of the chimney is 0.65m, the thermal draft is higher when the velocity is lower as compared to the other two cases, but the corresponding size of the chimney is huge which is practically not possible. With higher velocity, the size of the chimney reduces marginally covering a large part of the façade.

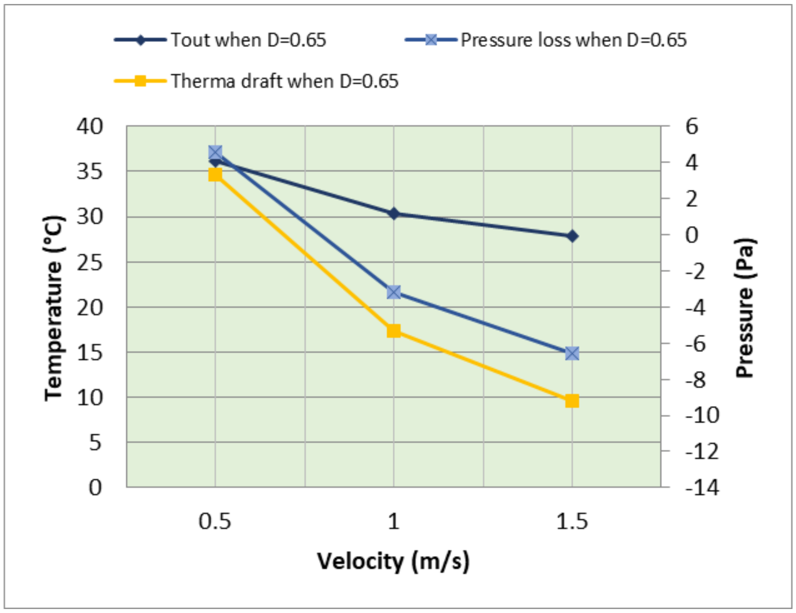


Figure 8.19: Depth= 0.65m : Air velocity

When depth is 0.80m, the thermal draft is low when the velocity is high and higher when the velocity is lower and so is the pressure loss. Although, the temperature at the top of the chimney in this case is lower than the T_{out} when the depth is 0.65m, it can be considered as the size of the chimney reduces considerably.

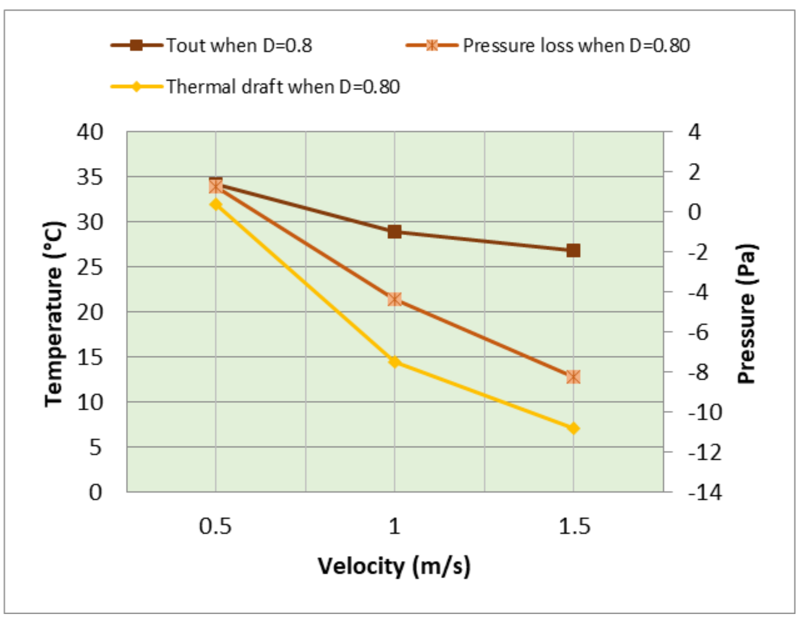


Figure 8.20: Depth= 0.80m : Air velocity

When depth is 1m, thermal draft is lower and the temperature at the top of the chimney is also lower than the other 2 cases. Therefore, the heat to be restored by the heat exchanger will be less as compared to the other 2 cases.

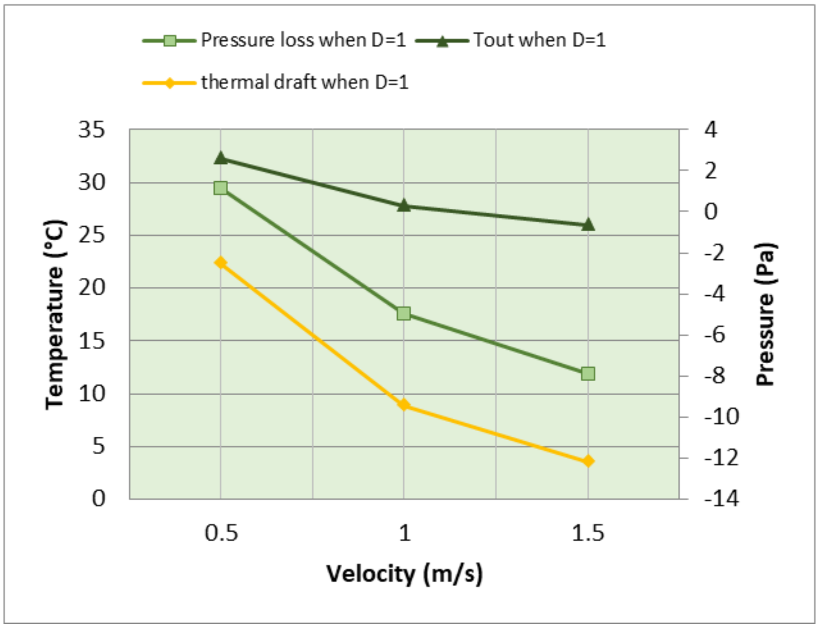


Figure 8.21: Depth= 1.0 m : Air velocity

From the 3 cases, it can be concluded that the second case gives optimum results as (1) The chimney size will reduce as compared to case 1, (2) The thermal draft is higher than case 3 but lower than case 1 which is acceptable as smaller depth of the chimney will increase the size of the chimney, (3) Although depth of 1m will have the smallest chimney size, but fan energy will be high as thermal draft is lower than 0 (negative values) (4) Higher temperatures can be achieved at the top of the chimney, so more amount of heat can be recovered.

Hence, when 1 Solar Chimney is designed, an air velocity of 1 m/s with depth of 0.80 m will be used.

9. Energy and Thermal comfort calculations

9.1. Results from Basic excel modeling

The design variables established in section 8.2.4 form the basis for performing a detailed analysis for each design case. The values of the variables will be used to calculate the total energy consumed by fan, water pump and additional heating energy in case of the Climate Cascade and fan energy in case of the Solar Chimney.

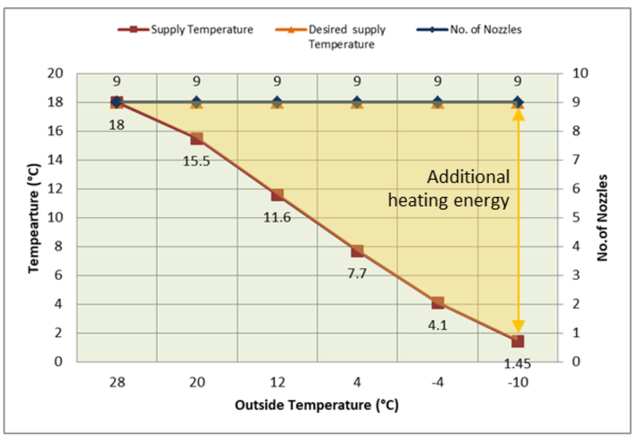
9.1.1. Energy Comparison between the design options for Climate Cascade

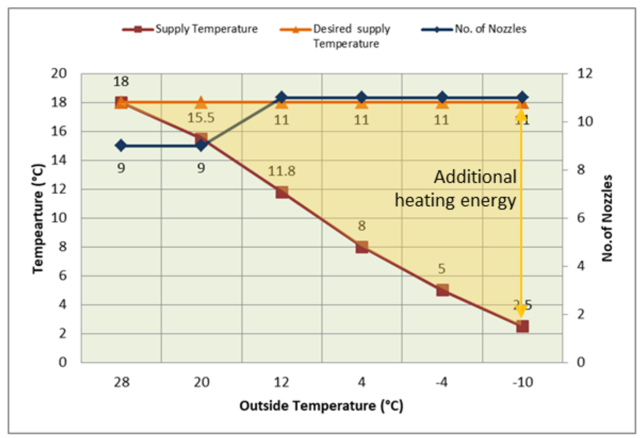
Table 9.1 shows the results from the excel model of a single Climate Cascade when the air velocity is 3.2 m/s, spray spectrum 6 and number of nozzles is 9. In case 1, the desired supply air temperature is achieved when the outside temperature is 28°C and reduces considerably as the outside temperature reduces. This indicates that more energy will be consumed to heat the air in order to reach the desired temperature. According to NEN-IS0 7730 annex D, the relative humidity inside the usable spaces should be between 30-70%. In this case, it is observed that the relative humidity achieved in the rooms is within the desired range except when the outside temperature is -10°C.

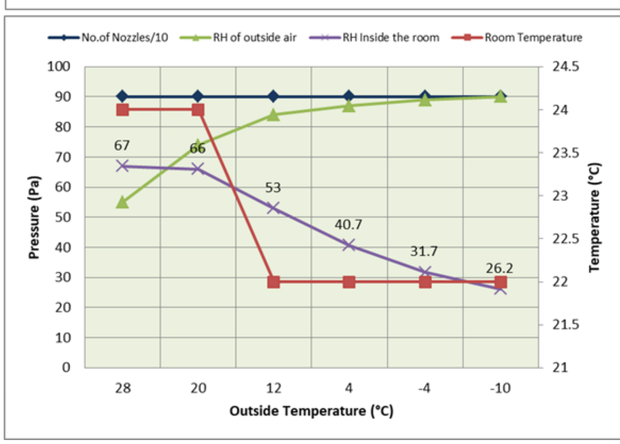
In case 3, the number of nozzles is not constant but it is increased to 11 nozzles when the outside temperature is more than 18°C. Therefore, it is observed that the supply air temperatures are higher during the winter months as compared to case 1 which will lead to lower heating energy. The relative humidity inside the rooms, for this case, is slightly higher than case 1 and fits within the desired range except when the outside temperature is -10°C.

CLIMATE CASCADE: Single Cascade

CASE 1= 1 Climate Cascade & 1 Solar Chimney	CASE 3= 1 Climate Cascade & 2 Solar Chimneys







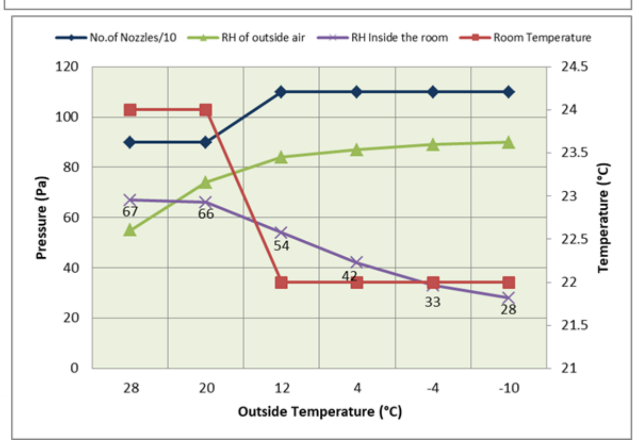


Table 9.1: Comparing the design variables for design case 1 & 3
Note: Refer Appendix 9 for clear illustrations

Table 9.2 shows the results from the excel model of double Climate Cascades when the air velocity is 3.8 m/s, spray spectrum 6 and number of nozzles is 4. Similar results were observed as compared to case 1 & 3. In case 2 & 4, the supply air temperatures are lower than case 1 & 3 but the relative humidity achieved inside the rooms is similar. Though the heating energy will be higher than case 1 & 3, pump energy will be reduced drastically as lower number of nozzles is used.

CLIMATE CASCADE: Double Cascade	
CASE 2= 2 Climate Cascades & 2 Solar Chimneys	CASE 4= 2 Climate Cascades & 1 Solar Chimney

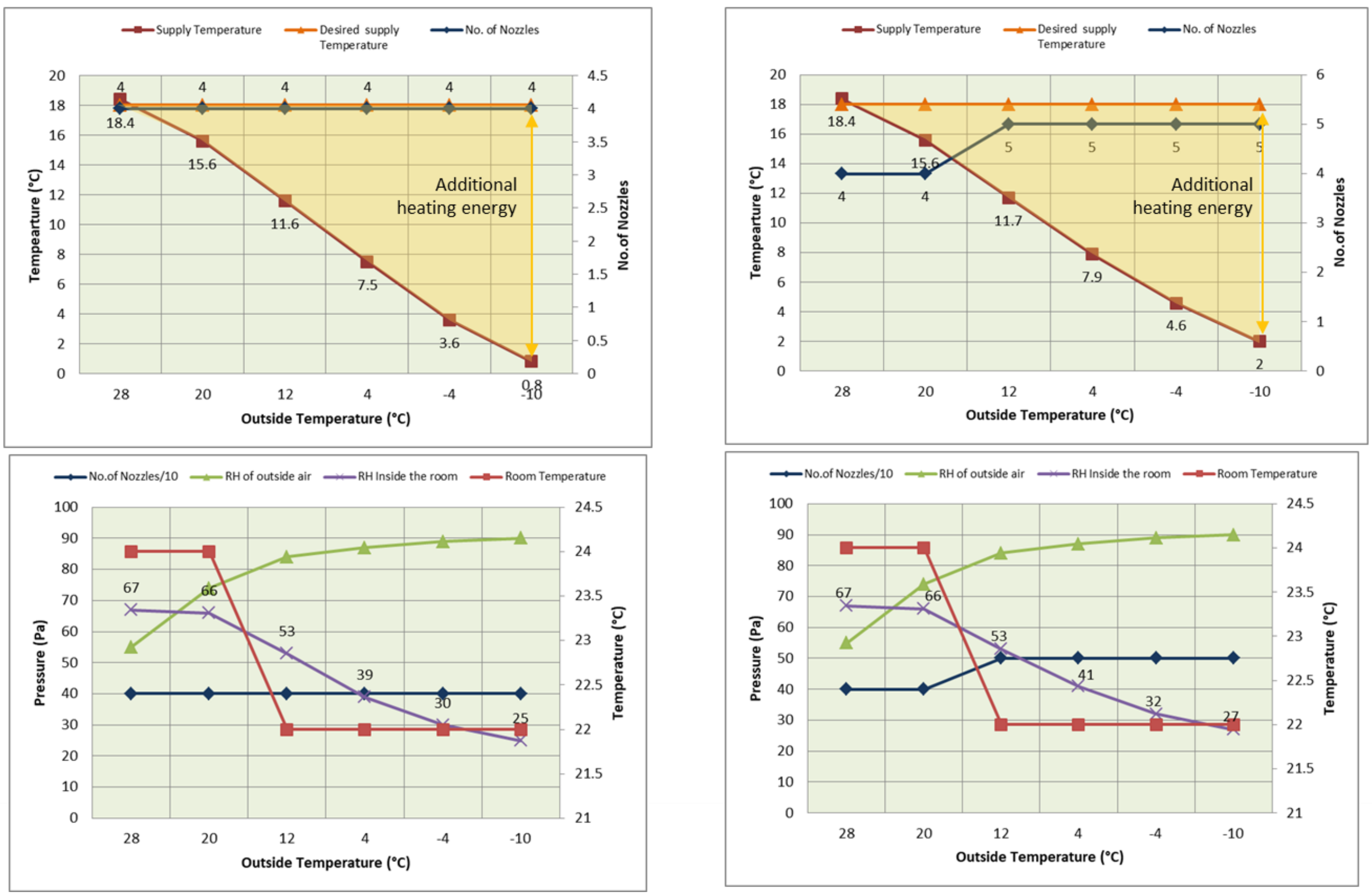


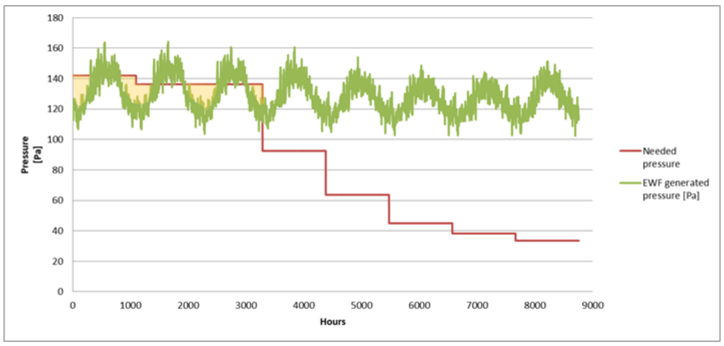
Table 9.2: Comparing the design variables for design case 2 & 4

Note: Refer Appendix 10 for clear illustrations

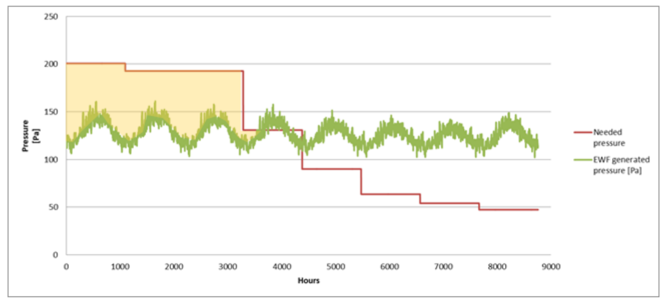
To evaluate the pressure generated at the bottom of the Climate Cascade for every design case, Table 9.3 can be referred. In case 1, the generated pressure is more than the desired pressure at most times of the year except at extremely low temperatures giving rise to lower fan energy. In case 2, the generated pressure is lower than the desired pressure, hence the fan energy is more than case 1. This is due to the presence of 2 Climate Cascade and each cascade will require its own auxiliary fan. In case 3, as the number of nozzles are increased during the winter months, the generated pressure is higher leading to nearly zero fan energy. In case 4, as the number of nozzles are increased during the winter months, the generated pressure is higher as compared to case 2 but still needs fan energy to achieve the desired pressure.

CLIMATE CASCADE: GENERATED PRESSURE

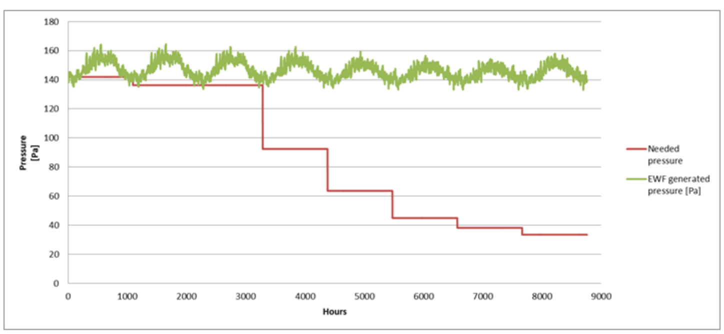
CASE 1= 1 Climate Cascade & 1 Solar Chimney



CASE 2= 2 Climate Cascades & 2 Solar Chimneys



CASE 3= 1 Climate Cascade & 2 Solar Chimneys



CASE 4= 2 Climate Cascades & 1 Solar Chimney

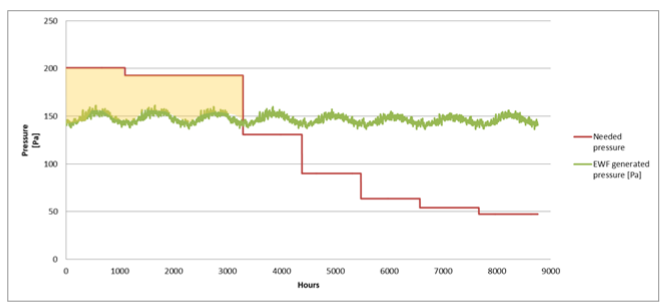


Table 9.3: Comparison of fan energy for all cases
Note: Refer Appendix 11 for clear illustrations

To summarize all the 4 cases as shown in Table 9.4, Case 2 has comparatively lower pump energy due to lower number of nozzles and can achieve enough pressure at the bottom of the Climate cascade with minimum fan energy. In case 1, the fan energy is low due to higher number of nozzles which leads to higher pressure. With higher number of nozzles, the pump energy also increases significantly. Moreover, the pressure losses in the supply ducts will be higher if one cascade has to serve for the entire floor. It is wise to have 2 Climate Cascades to reduce pressure losses in the supply ducts with reduced pump energy and minimum amount of fan energy to cater the pressure difference.

Hence, Case 2 with 2 Climate cascades of size 1.35 m x 1.35 m was chosen.

CLIMATE CASCADE											
			Evaluation Parameters								
	Design Options	Supply/ Exhaust	Size (m)	Generated pressure (Pa)	Tout of CC (°C)	No. of Nozzles	Velocity of air (m/s)	Water/ Air Ratio (kg/kg)	Pump energy (kWh/ year)	Fan Energy (kWh/ year)	Additional heating energy (kWh/m2)
1	1 Climate cascade 1 Solar chimney	Decentralized supply, Centralized Exhaust	2.0 x 2.0	160 Pa (T_supply= 28°C; RH= 55%)	18.0°C (RH= 98%)	9	3.2 m/s	0.37	61650 kWh	200 kWh	13
2	2 Climate cascade 2 Solar chimney	Decentralized supply, Decentralized exhaust	1.35 x 1.35	156 Pa (T_supply= 28°C; RH= 55%)	18.4°C (RH= 96%)	4	3.8 m/s	0.33	54800 kWh	6700 kWh	12.7
3	1 Climate cascade 2 solar chimney	Decentralized supply, Centralized exhaust	2.0 x 2.0	160 Pa (T_supply= 28°C; RH= 55%)	18.0°C (RH= 98%)	Winter = 11 Summer= 9	3.2 m/s	Winter= 0.46 Summer = 0.37	73000 kWh	0.3 kWh	12
4	2 Climate cascade 1 Solar chimney	Decentralized supply, Centralized exhaust	1.35 x 1.35	156 Pa (T_supply= 28°C; RH= 55%)	18.4°C (RH= 96%)	Winter = 5 Summer= 4	3.8 m/s	Winter= 0.42 Summer = 0.33	66200 kWh	5000 kWh	12

Table 9.4: Summary of all 4 cases with the corresponding design variables.

9.1.2. Energy Comparison between the design options for Solar Chimney

In case of the Solar Chimney, the thermal draught has to be higher than the total pressure loss and the temperature of air at the top of the chimney should be higher than the outside temperature. In case 1, with 1 chimney and air velocity 1.2m/s, the thermal draught is higher than the pressure loss when the outside temperature is less than 8°C. In case 2, with air velocity 1 m/s, the thermal draught is higher than the pressure loss only when the outside temperature is less than 6°C. In both these cases, the supply temperature was considered as 22 °C constant.

When the supply temperature is changed to 22°C in winter and 24°C in summer, which is applied in case 3 & 4, the thermal draught is higher during the extreme summers which saves a lot of fan energy.

SOLAR CHIMNEY: Thermal draught, Pressure loss and Tout

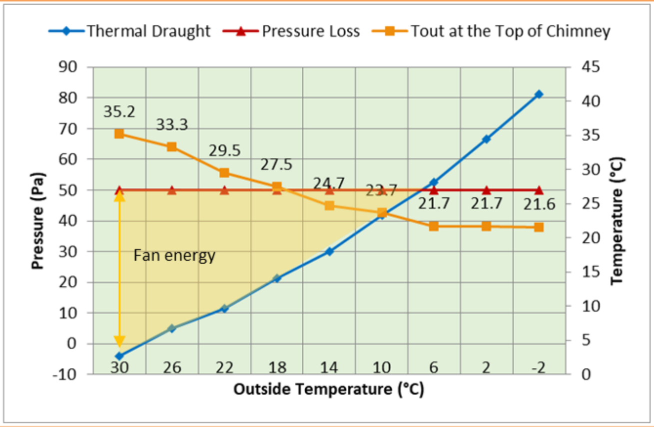
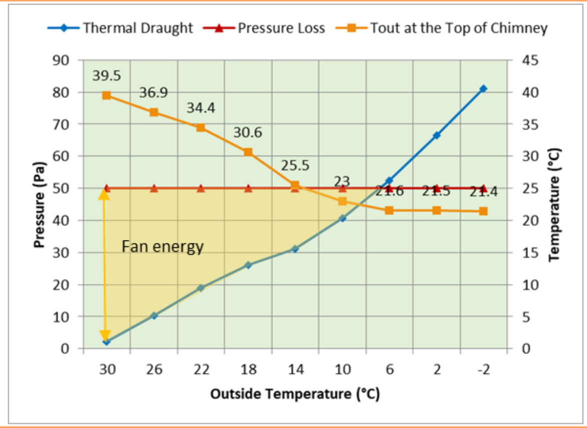
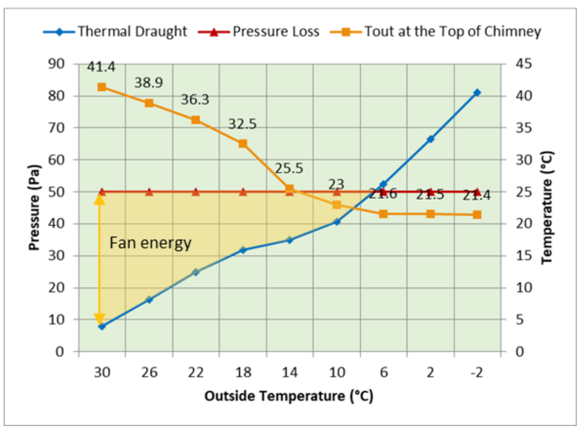
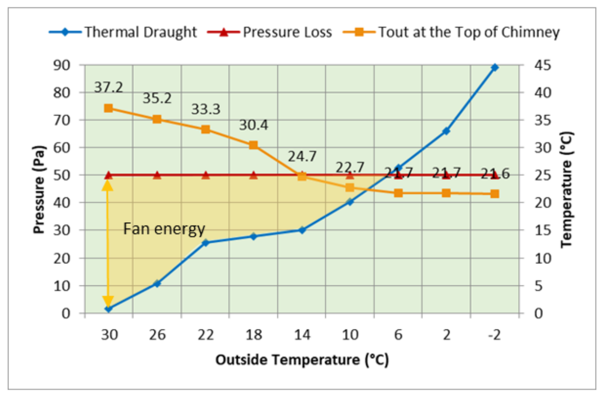
CASE 1= Single Chimney	CASE 2= Double Chimney
	
CASE 3 = Double Chimney	**CASE 4= Single Chimney**
	

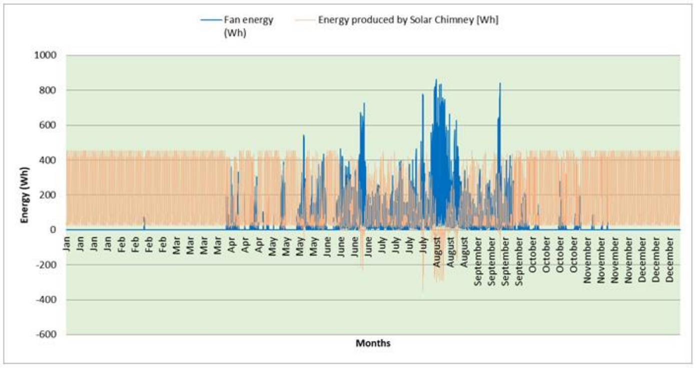
Table 9.5: Comparing the design variables for all 4 design cases

Note: Refer Appendix 12 for clear illustrations

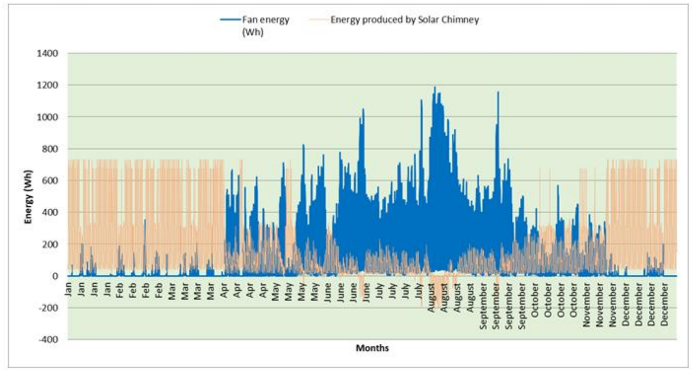
To evaluate the fan energy used for every design case, Table 9.6 can be referred. It is observed that a single Solar Chimney has lower fan energy compared to 2 Solar Chimneys. When the supply temperature is varied (in case 3 & 4), the fan energy reduces further. Having a single chimney leads to increase in its size, almost occupying half of the façade.

SOLAR CHIMNEY: Fan energy

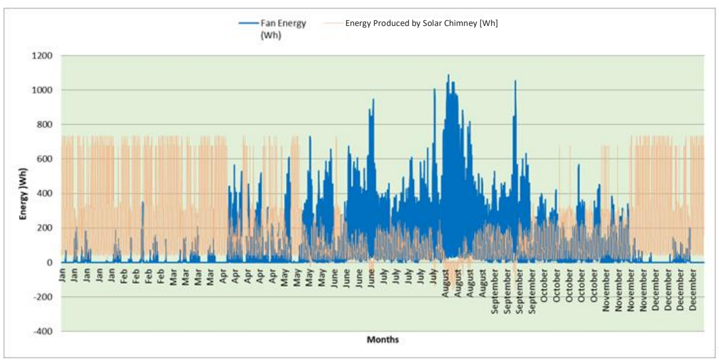
CASE 1= Single Chimney



CASE 2= Double Chimney



CASE 3 = Double Chimney



CASE 4= Single Chimney

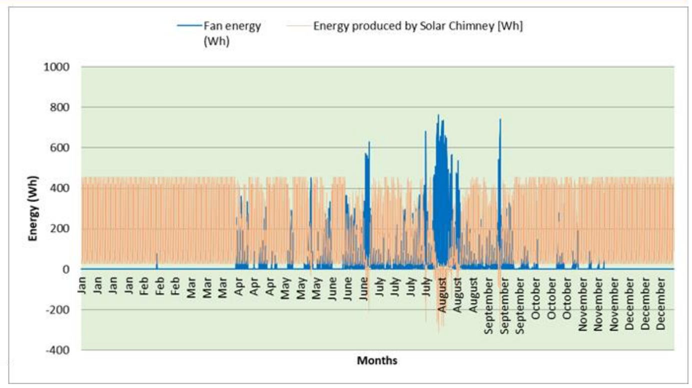


Table 9.6: Fan energy consumed for all 4 design cases

Note: Refer Appendix 13 for clear illustrations

To summarize all 4 cases, it is observed that in case 1 & 4, the size of the chimney is larger with lower fan energy and the achieved air temperature at the top of the chimney is lesser as compared to case 2 & 3. As the air temperatures are lower, the heat recovered by the heat exchanger at the top of the chimney will also be less.

Comparing the four cases, case 3 was chosen which has 2 Solar Chimneys with varying supply temperatures. As higher temperatures are achieved at the top of the chimney which leads to higher amount heat energy recovery and reduced size.

Case 3 with 2 Solar Chimneys of size 10.0 x 0.7 m was chosen.

SOLAR CHIMNEY									
			Evaluation Parameters						
	Design Options	Supply/ Exhaust	Total Pressure loss (Pa)	Thermal Draught (Pa)	Velocity of air (m/s)	Tout at the top of chimney (°C)	Size (m)	Fan Energy (kWh)	Recovered Heat energy (kWh)
1	1 Climate cascade 1 Solar chimney	Decentralized supply, Centralized Exhaust	25.6 Pa	-12.5 Pa (T_supply= 22°C & T_out= 30°C)	1.2 m/s	29.7 °C	14.5 x 0.8	400 kWh	435000
2	2 Climate cascade 2 Solar chimney	Decentralized supply, Decentralized exhaust	36.8 Pa	-8 Pa (T_supply= 22°C & T_out= 28°C)	1.0 m/s	32.7°C	9.9 x 0.7	760 kWh	444000
3	1 Climate cascade 2 solar chimney	Decentralized supply, Centralized exhaust	36.8 Pa	-2.6 Pa (T_supply= 24°C & T_out= 28°C)	1.0 m/s	34.2°C	9.9 x 0.7	600 kWh	480800
4	2 Climate cascade 1 Solar chimney	Decentralized supply, Centralized exhaust	26.2 Pa	-6.2 Pa (T_supply= 24°C & T_out= 28°C)	1.2 m/s	31.8°C	14.5 x 0.8	250 kWh	467000

Table 9.7: Summary of all 4 cases with the corresponding design variables.

9.1.3. Chosen design option

The chosen option has 2 Climate Cascades and 2 Solar Chimneys with decentralized supply and centralized exhaust. The Climate Cascade will have a constant number of 4 nozzles with an air velocity of 3.8 m/s and the Solar Chimney will have a varying supply temperature, which is 22°C in winters and 24°C in summers, with an air velocity of 1m/s.

CHOSEN OPTION

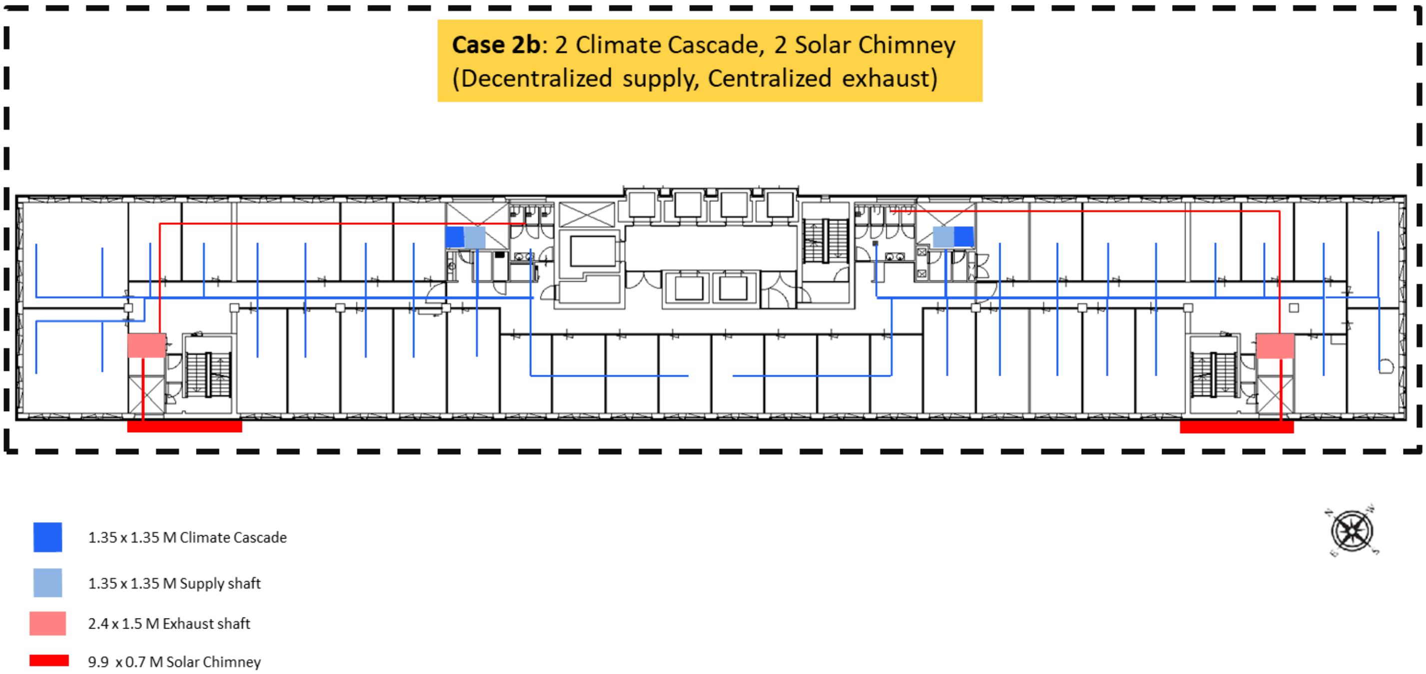


Figure 9.1: Chosen design option for further optimization

9.2. Results from Dynamic calculations

The chosen design option established in section 9.1.3 formed the basis for analyzing the energy consumption of the Provinciehuis case study with respect to the parameters realized in Fig 8.2. All the simulations were conducted for the year 2020 and the weather file used in the software is for the location DeBilt.

9.2.1. Energy calculations for existing system configuration without EWF

The existing conditions of the Provinciehuis Utrecht building was simulated in Design Builder. The results are only calculated for the occupied office zone as shown in Fig 9.2. The building uses a VAV Air cooled chiller unit with centralized mechanical heating and cooling using district heating and air/water compression refrigerators. The source of the heat for Domestic hot water (DHW) is from the boilers. The schedule for the ventilation, heating and cooling was selected from the Design builder library for office occupancy schedule and heating and cooling schedule for general open office area.

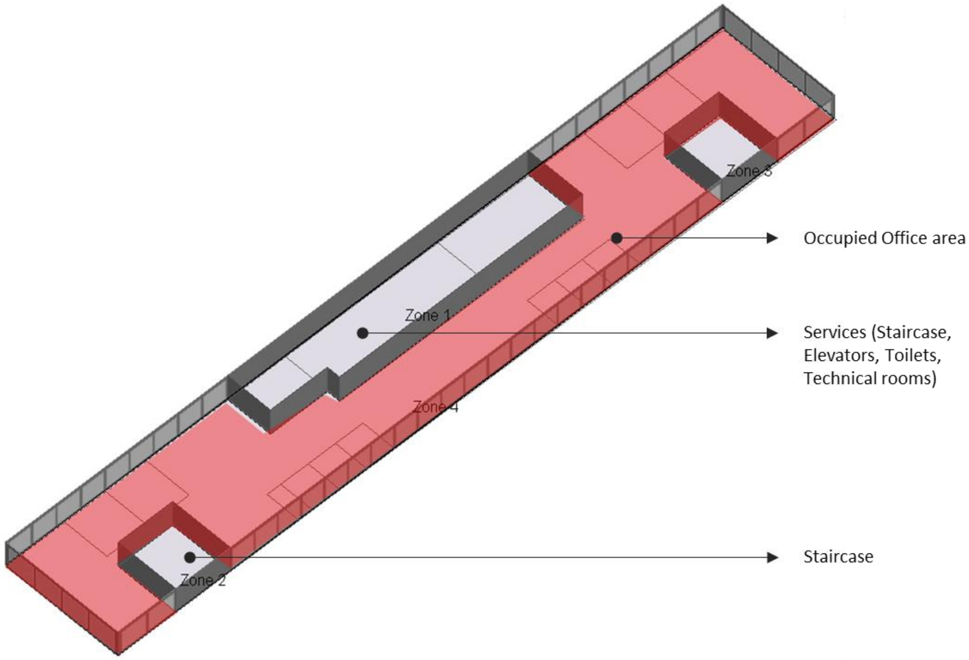


Figure 9.2: Determining the zones in the dynamic simulation model.

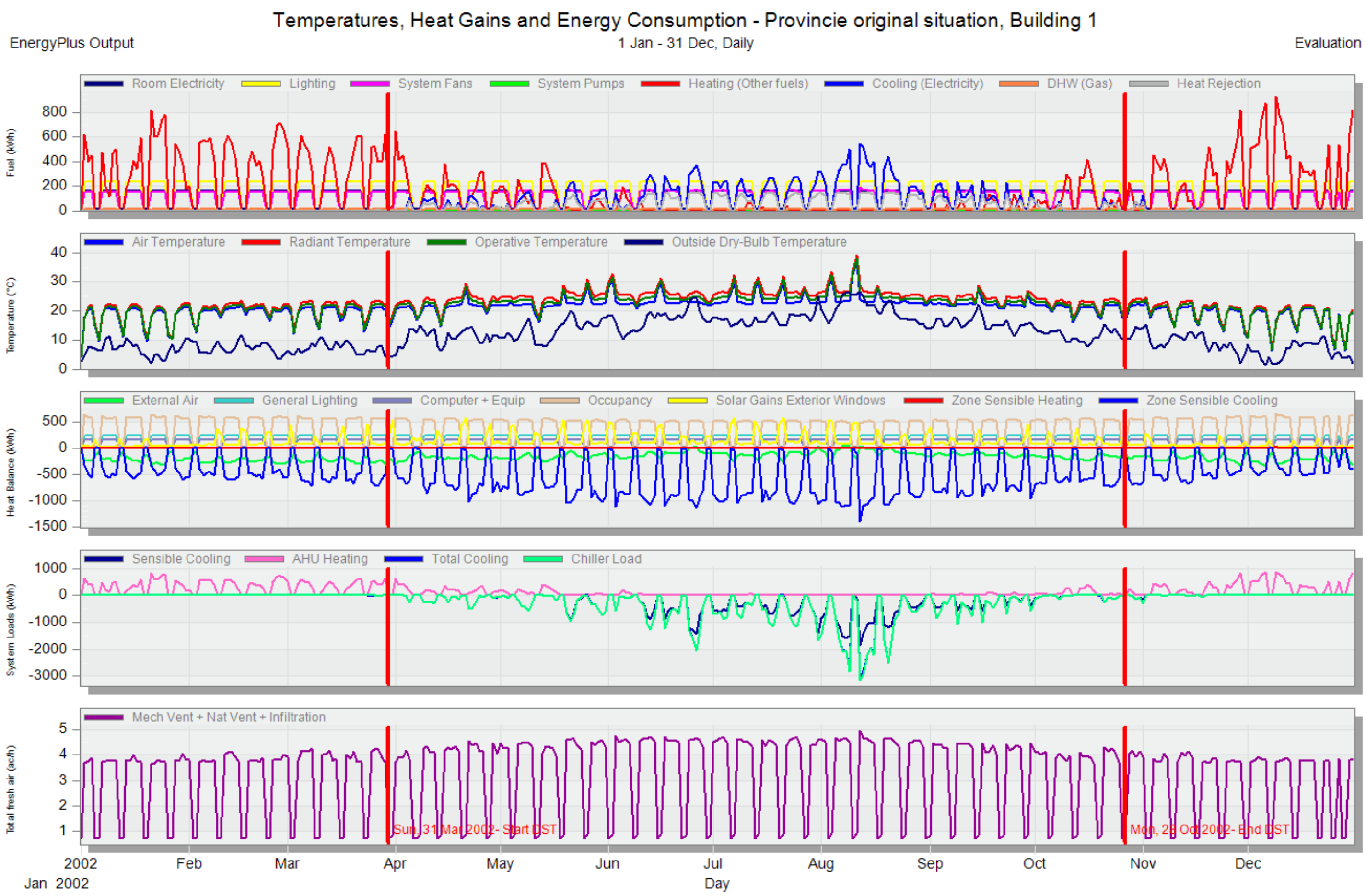


Figure 9.3: Results for the Provinciehuis with the existing system.

ENERGY CONSUMPTION: Without EWF				
		Energy Consumption without EWF		
		Area (m2)	Primary Energy (kWh/year)	Primary energy (kWh/m2/year)
	Usable Floor area	17,640		
1	Space Heating		1,640,520	93
2	DHW		35,280	2
3	Cooling		740,880	42
4	Ventilation		864,360	49
5	Production Equipment		88,200	5
6	Lighting		405,720	23
	Total		**3,774,960**	**214**

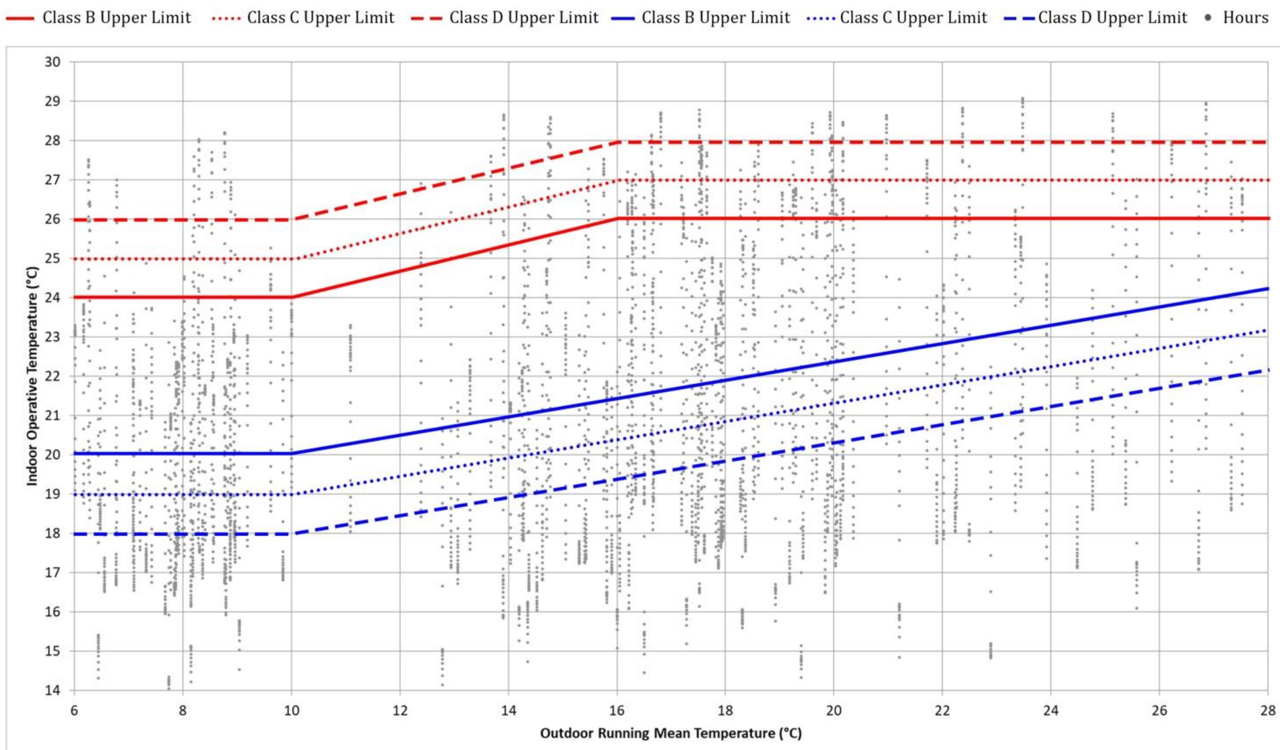
Table 9.8: Energy consumption without EWF

As shown in Fig 9.3, it is observed that the heating load is quite high due to the high amount of glazing in the façade contributing to 75% of the wall-window ratio. Moreover, the HVAC system use high amount of auxiliary energy leading to high energy consumption. There is also under floor heating in the building in the low-rise part where the floor is adjacent to the outside air of the unheated parking space. Due to this, heat losses occur which explains the high heat consumption. In terms of the operative temperature, the temperatures are higher during the peak summer months and reaches 30°C in mid-August. The results from Table 9.8 show that the highest amount of energy is consumed by heating followed by ventilation, cooling, lighting, equipment and DHW.

9.2.2. Thermal comfort of existing system configuration without EWF

To access the thermal comfort of the occupied zone in the Provinciehuis without the EWF system, ATG method was followed as mentioned in section 3.4. The Dutch adaptive thermal comfort model (ATG) indicate the percentage of comfortable hours a space should satisfy according to the classes A, B, C and D (ISSO74). Since the chosen strategy includes active cooling, Beta type building category was chosen to plot the ATG graph.
According to ISSO 74, EN 15251, the occupied office spaces should have an expectation level of Class B which only allows for 10% of discomfort hours. As shown in Fig 9.4, 35% of the occupied hours fall under Class B and 64.5% of the hours exceed Class B. Thus, the

space cannot fall into this category. 63% of the occupied hours fall under Class C and 38% of the hours exceed Class C. Thus, the space cannot be considered as Class C. 82% of the occupied hours fall under Class D and 17% of the hours exceed Class D. Thus, the space is considered as bad as it falls under Class D (<25%).



Building	Provinciehuis Utrecht
Space	1 Office floor
Building type	Beta
Temperature type	Operative
Analysis Period	Jan-Sept
Occupied Hours	8049
Thermal Performance	Bad
Class	Class D

Comfort Bandwidth	No. of Hours	% of Time
Class B	2858	35.51
Class C	2231	27.72
Class D	1567	19.47
Above Class D	1393	17.31

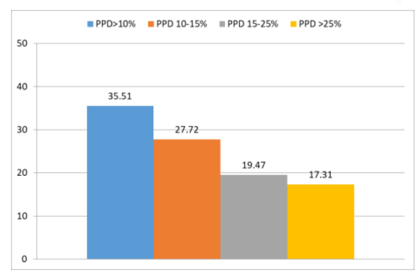


Figure 9.4: ATG graph for the occupied zone in Provinciehuis building without EWF.

To improve the thermal comfort within the offices, reducing the amount of glazing in the façade will be an effective solution along with implementing the EWF system. By refurbishing the façade, the heat load within the occupied spaces can reduce drastically, thereby improving the thermal comfort.

9.2.3. Energy calculations for new system configuration with EWF

The new configuration of the Provinciehuis Utrecht building was simulated on Design Builder. The results are only calculated for the occupied office zone as shown in Fig 9.2. The building uses a CAV No Reheat system with floor heating and chilled ceiling with a constant air supply of 18°C throughout the year as explained in section 8.2.1.

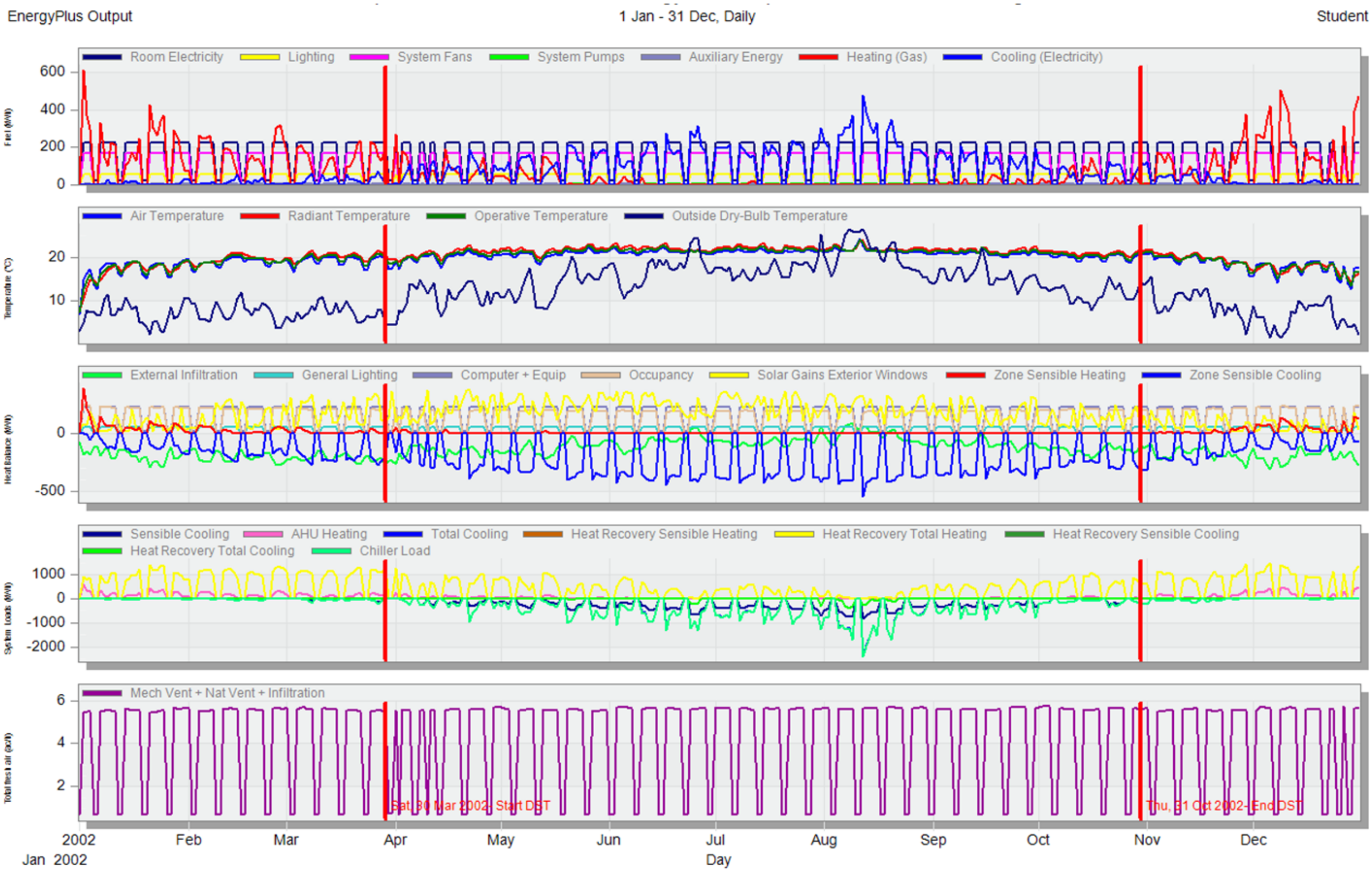


Figure 9.5: Results for the Provinciehuis with EWF system.

As shown in Fig 9.5, it is observed that the operative temperatures maintain constant temperatures between 18°C-24°C due to the change in the supply air temperature except for a few weeks in the winter months where the operative temperatures go below 15°C. There is a dip in the operative temperature and mechanical ventilation at certain intervals due to the adopted schedule, where the system is off during the weekends and holidays and adapts to the setback temperature during the non-working hours of the week. Since the façade has not been refurbished, the solar gain from the windows is high leading to higher cooling energy. The air change rate of the system is around 5 ac/h as the ventilation capacity per person has been considered as 50 m^3/hr. Since the ventilation capacity per person is double the capacity than required (25 m^3/hr), the indoor air quality is considered to be good.

To check the energy performance of the EWF, a comparison was made between the systems without EWF and with EWF as shown in Table 9.9. It is observed that the heating load is reduced by 72% as compared to the original configuration as EWF system requires less heating energy to supply constant air temperature of 18°C throughout the year. Moreover, the cooling load is reduced by 36% and energy consumed by ventilation is reduced by 62%. The energy consumed by DHW, lighting and production equipment remains the same as no alterations were made for the same. This reduction in the energy consumption led to an overall reduction by 53% as compared to the existing configuration. The primary energy consumed per m^2 reduces by 50% which shows the efficiency of the EWF system.

ENERGY COMPARISON							
		Energy Consumption without EWF			Energy consumption with EWF		
		Area (m2)	Primary Energy (kWh)	Primary energy (kWh/m2)	Primary Energy (kWh)	Primary energy (kWh/m2)	Reduction %
	Usable Floor area	17,640					
1	Space Heating		1,640,520	93	447,660	25.3	72%
2	DHW		35,280	2	35,280	2	-
3	Cooling		740,880	42	469,404	26.6	36%
4	Ventilation		864,360	49	322,400	18.3	62.7%
5	Production Equipment		88,200	5	88,200	5	-
6	Lighting		405,720	23	405,720	23	-
	Total		**3,774,960**	**214**	**1,768,664**	**100.3**	**53.1%**

Table 9.9: Energy consumption comparison with and without EWF

9.2.4. Energy consumed by EWF ventilation system

After analyzing the results from section 9.2.3, it is important to check the energy consumed by the EWF system itself without the additional energy contributors of the entire system (see Table 9.10). The energy consumed by the EWF system depends on the energy consumed by the pump, fan and additional heating energy for the Climate Cascade and Solar Chimney, as shown in Table 9.10. These values were derived from the excel calculation model for the chosen design case 2b (see table 9.4 & 9.7).

From the Table 9.10, it was observed that the EWF system without using the heat recovery system has high fan energy, heating energy and pump energy for the Climate cascade as it uses the outside air directly in the system without pre-heating the air. When the heat from the heat recovery system at the top of the Solar Chimney is used to pre-heat the incoming air during the winters in the Climate Cascade, it was observed that the outside air is heated from 2°C to 12°C. Due to the increase in the air temperature, less amount of water will be used to heat/ cool the air up to 18°C and the pressure at the bottom of the Climate Cascade is able to achieve 150 Pa without using auxiliary fans. Therefore, the overall energy consumption is reduced by 25%.

	EWF Ventilation Energy without Heat recovery		**EWF Ventilation Energy with Heat recovery**	
	Primary Energy (kWh/year)	**Primary Energy (kWh/m2)**	**Primary Energy (kWh/year)**	**Primary Energy (kWh/m2)**
Climate Cascade				
Pump energy	54,800	-	25800	
Fan energy	6,700	-	0	
Additional Heating energy	368,000	12.7	294,800	10.2
Solar Chimney				
Fan energy	1800	-	1800	
Total	**431,300**		**322,400**	

Table 9.10: Energy consumed by EWF system for Provinciehuis Utrecht

Although the input temperatures (air temperature coming from the room to the exhaust shaft) for the Solar Chimney was assumed to be 22°C in the winter months and 24°C in the summer months, the actual temperatures in the room vary on an hourly basis. These temperatures were derived from the design builder simulations and were applied to the excel model of the Solar Chimney. This change in the input air temperature has an effect on the fan energy of the exhaust air and the total energy consumed by the EWF system as shown in Table 9.11. The overall energy consumed by the EWF system increases marginally by 700 KWh.

EWF Ventilation Energy		
	Primary Energy (kWh/year)	**Primary Energy (kWh/m2)**
Climate Cascade		
Pump energy	25800	-
Fan energy	0	-
Additional Heating energy	294,800	12.7
Solar Chimney		
Fan energy (22°C constant Incoming air)	1800	-
Fan energy (Varying temperatures according to dynamic simulations)	**2500**	-
Total	**323,100**	

Table 9.11: Energy consumed by EWF when operative temperatures from Design Builder is fed into the excel calculation

Heat Recovery

The Solar Chimney consists of an air-air heat exchanger which recovers the heat from the air inside the Solar Chimney during the winters and the summers. During the winters, the heat recovered will be used to heat up the outside air entering the climate cascade before reaching the sprayers. This amount of heat recovered during the winters was calculated in the excel model setting 2 boundary conditions:

(1) The air temperature at the top of the Solar Chimney should be more than the outside temperature,

(2) The temperature difference between the outside air and the air at the top of the Solar Chimney should be 5°C.

Only when these 2 conditions are met, the heat will be recovered by the heat exchanger. During the summers, all the heat recovered at the top of the Solar Chimney will be used to recharge the ATES system and to heat the water for DHW via an air-water heat exchanger with an additional heating provided by booster heat pumps.

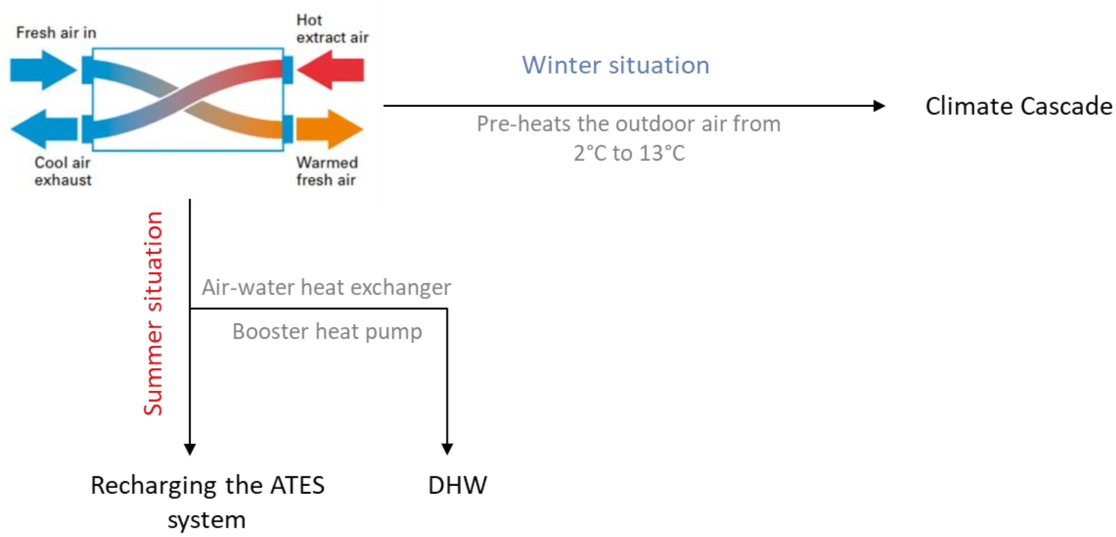
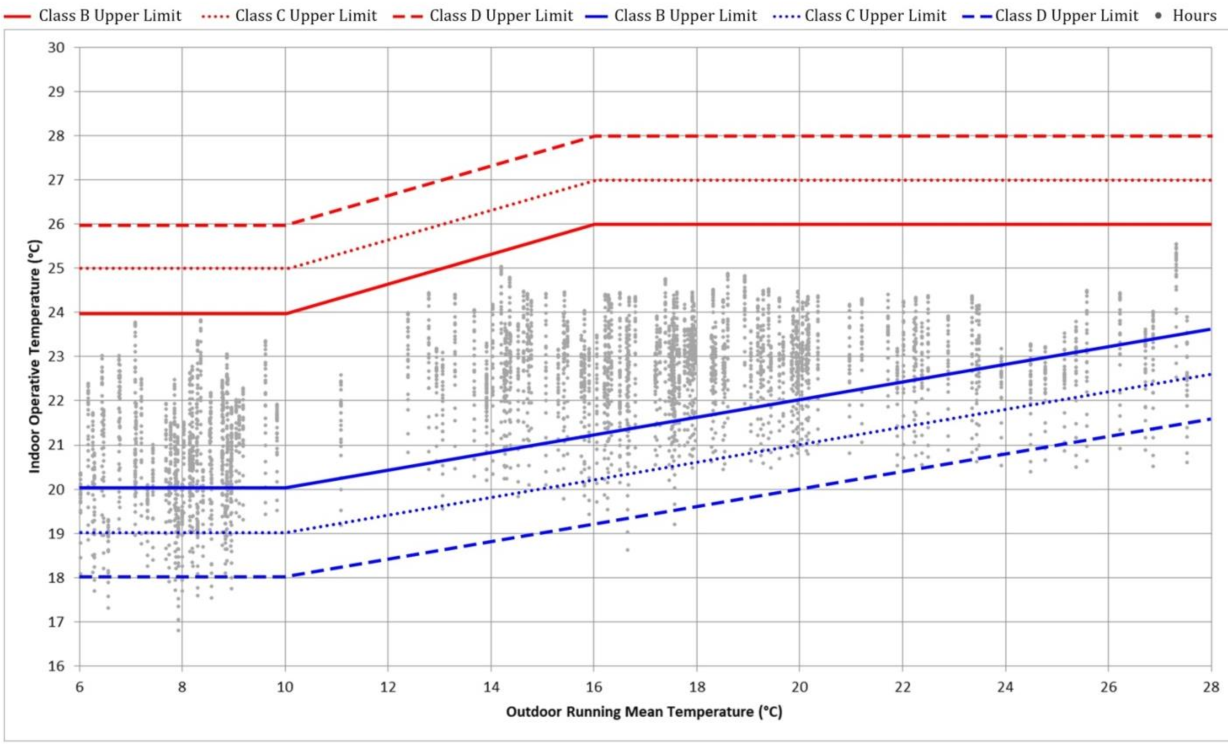


Figure 9.6: Summer and winter situation for the use of the Heat recovery system in the Solar Chimney

9.2.5. Thermal Comfort of new system configuration with EWF

To access the thermal comfort of the occupied zone in the Provinciehuis with the EWF system, ATG method was followed. According to ISSO 74, EN 15251, the occupied office spaces should have an expectation level of Class B which only allows for 10% of discomfort hours. As shown in Fig 9.7, 73% of the occupied hours fall under Class B and 26.8% of the hours exceed Class B. Thus, the space cannot fall into this category. 95.6% of the occupied hours fall under Class C and only 4.3% of the hours exceed Class C. Thus, the space can be considered as acceptable.



Building	Provinciehuis Utrecht
Space	1 Office floor
Building type	Beta
Temperature type	Operative
Analysis Period	Jan-Sept
Occupied Hours	1367
Thermal Performance	Acceptable
Class	Class C

Comfort Bandwidth	No. of Hours	% of Time
Class B	1000	73.1
Class C	308	22.5
Class D	59	4.3

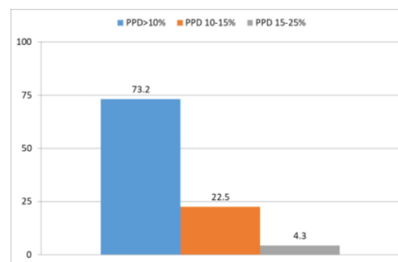


Figure 9.7: ATG graph for the occupied zone in Provinciehuis building.

9.2.6. Improvement in the energy calculations with EWF system

The energy calculations in section 9.2.3 were based on the ventilation, heating and cooling schedule where the system was off during the weekend and holidays. To improve the thermal comfort during the heating season within the occupied zones, the ventilation and heating schedule were modified to operate on the setback temperature during the weekends. This increased the operative temperature in the occupied zones which were dropping below 15°C in the earlier simulation.

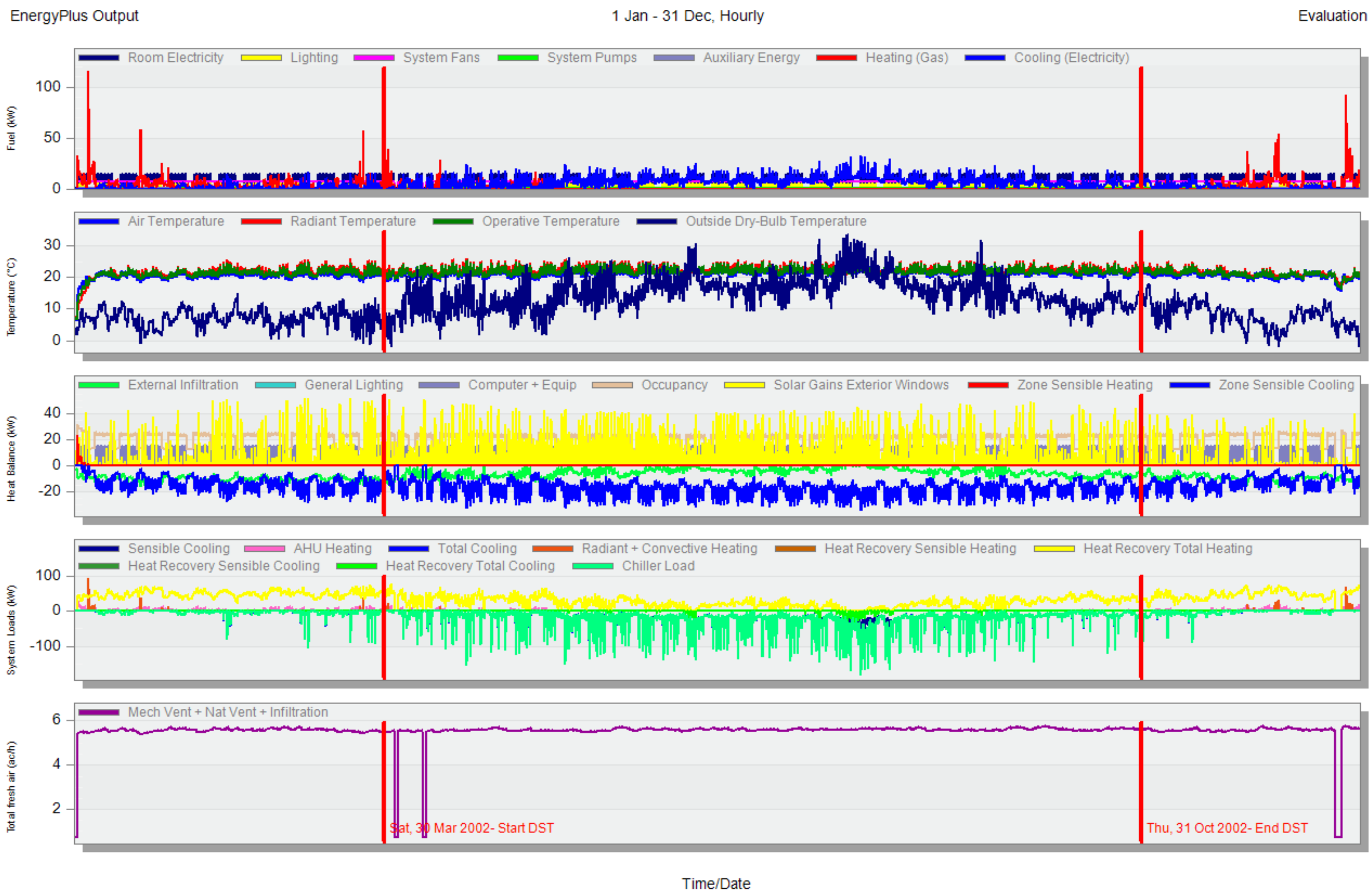


Figure 9.8: Results for the Provinciehuis with improved EWF system.

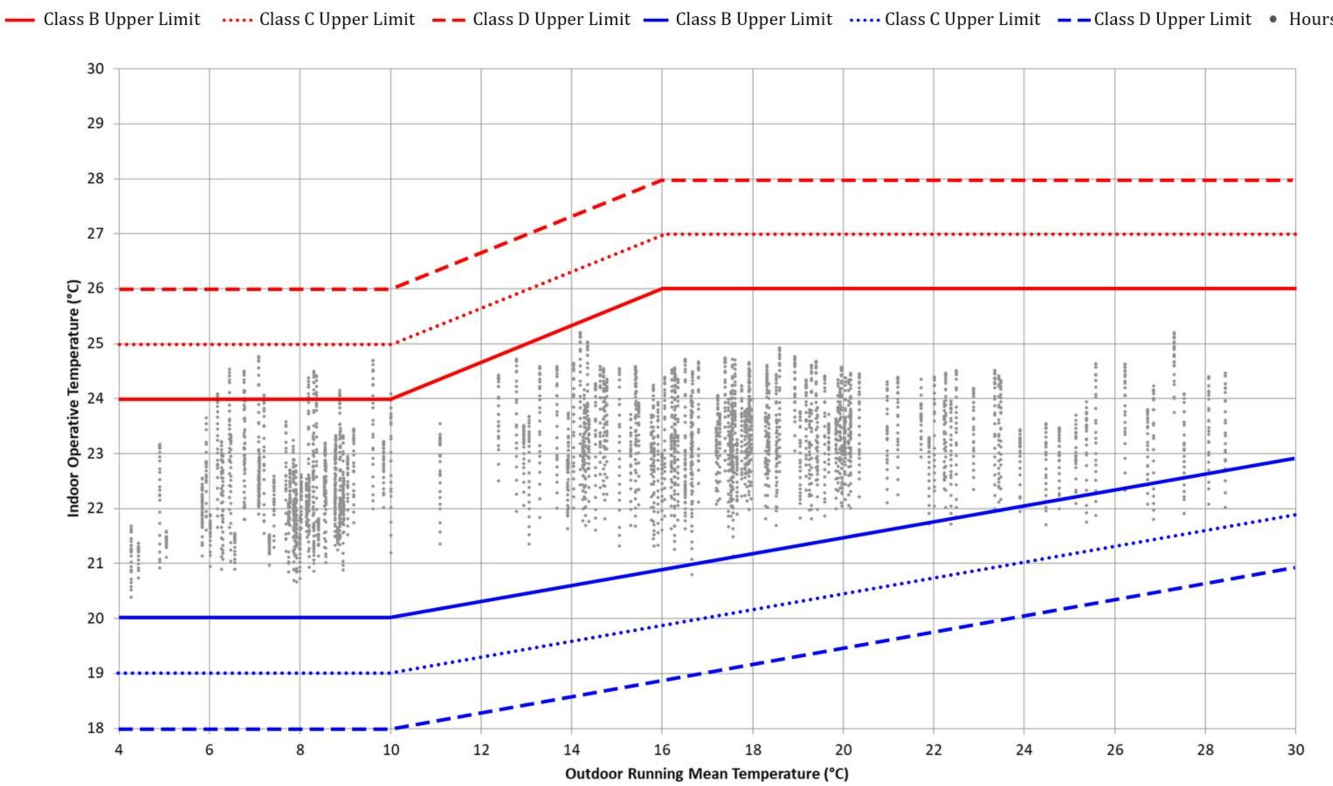
From Fig 9.8, it is observed that the operative temperatures remain constant between 18°C to 24°C. The operative temperatures during the heating season have improved as compared to the previous simulation, thereby improving the thermal comfort in the occupied zone. Since the system is running during the weekends, the energy consumption will be higher as shown in Table 9.12. Although the cooling energy reduces by 18% as compared to the previous simulation, the heating energy has increased by 22%. There is no change in the ventilation, DHW, Lighting and production equipment energy as they have not been changed. The total energy consumption is decreased by 52% to the existing condition and increased by 2% as compared to the previous simulation.

ENERGY COMPARISON: Improved EWF system							
		Energy Consumption without EWF			Energy consumption with Improved EWF		
		Area (m2)	Primary Energy (kWh)	Primary energy (kWh/m2)	Primary Energy (kWh)	Primary energy (kWh/m2)	Reduction %
	Usable Floor area	17,640					
1	Space Heating		1,640,520	93	574,524	32.6	64%
2	DHW		35,280	2	35,280	2	-
3	Cooling		740,880	42	385,290	21.8	48%
4	Ventilation		864,360	49	323,100	18.3	62.7%
5	Production Equipment		88,200	5	88,200	5	-
6	Lighting		405,720	23	405,720	23	-
	Total		**3,774,960**	**214**	**1,809,414**	**102.6**	**52%**

Table 9.12: Energy consumed by improved EWF system

9.2.7. Improvement in the Thermal Comfort with EWF system

The thermal comfort of the occupied zone has improved significantly as shown in Fig 9.9. 91% of the occupied hours fall under Class B and only 9% of the hours exceed Class B. Thus, the space can be considered as good as the exceeded hours are within the 10% limit.



Building	Provinciehuis Utrecht
Space	1 Office floor
Building type	Beta
Temperature type	Operative
Analysis Period	Jan-Sept
Occupied Hours	255
Thermal Performance	Good
Class	Class B

Comfort Bandwidth	No. of Hours	% of Time
Class B	232	90.98
Class C	23	9.02
Class D	0	0

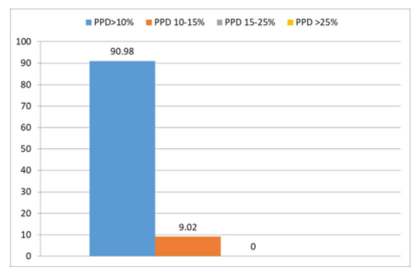


Figure 9.9: ATG graph of the occupied zone for the improved EWF system.

9.3. Conclusion

The EWF system is an efficient system to reduce the energy consumption of the building as the ventilation energy reduces significantly compared to the existing system. Since the space heating and cooling is added as a separate system in the zone, the heating energy required for the EWF ventilation system to maintain the 18°C supply air temperature is very low. Moreover, the building with EWF system is more comfortable, with respect to the operative temperature, than the existing system. With further improvements in the EWF system, the building is observed to be more comfortable as it falls under the Class B category as recommended by ISSO 74. Although the thermal performance increases by changing the system schedule, the energy consumption also increases as the operating hours of the zone heating system is increased. Since the main objective of this research is to reduce the energy consumption of the building, the simulation without improvements in the EWF system, which consumes less energy with an acceptable level of thermal comfort, will be chosen for further optimization.

10. Refurbishment of the Façade

The existing façade of the Provinciehuis has 75% glazing with a window size of 2.70 x 2.70 m. Although the windows have a ventilated cavity (climate windows), due to the presence of large amount of glazed surface on the façade, the heat gain inside the occupied spaces is high. Thus, improving the building envelope will directly impact the energy consumption of the building. As shown in Fig 10.1, 10.3, 10.5, 3 façade options have been proposed to check the potential of energy generation and reduction and how they will contribute towards reducing the total energy consumption of the building.

10.1. Façade option 1: Building Integrated Photovoltaic

In this option, the existing façade panel, comprised of granite stone and insulation, between the lintel level of the window and the floor level above is replaced with prefab sandwich panel with insulated aluminium and building integrated PV (BIPV) in the South, South-West and South-East façade. The heat gain inside the occupied zone is unaltered as the existing window and the sun shading remains the same (see Fig 10.1, 10.2).

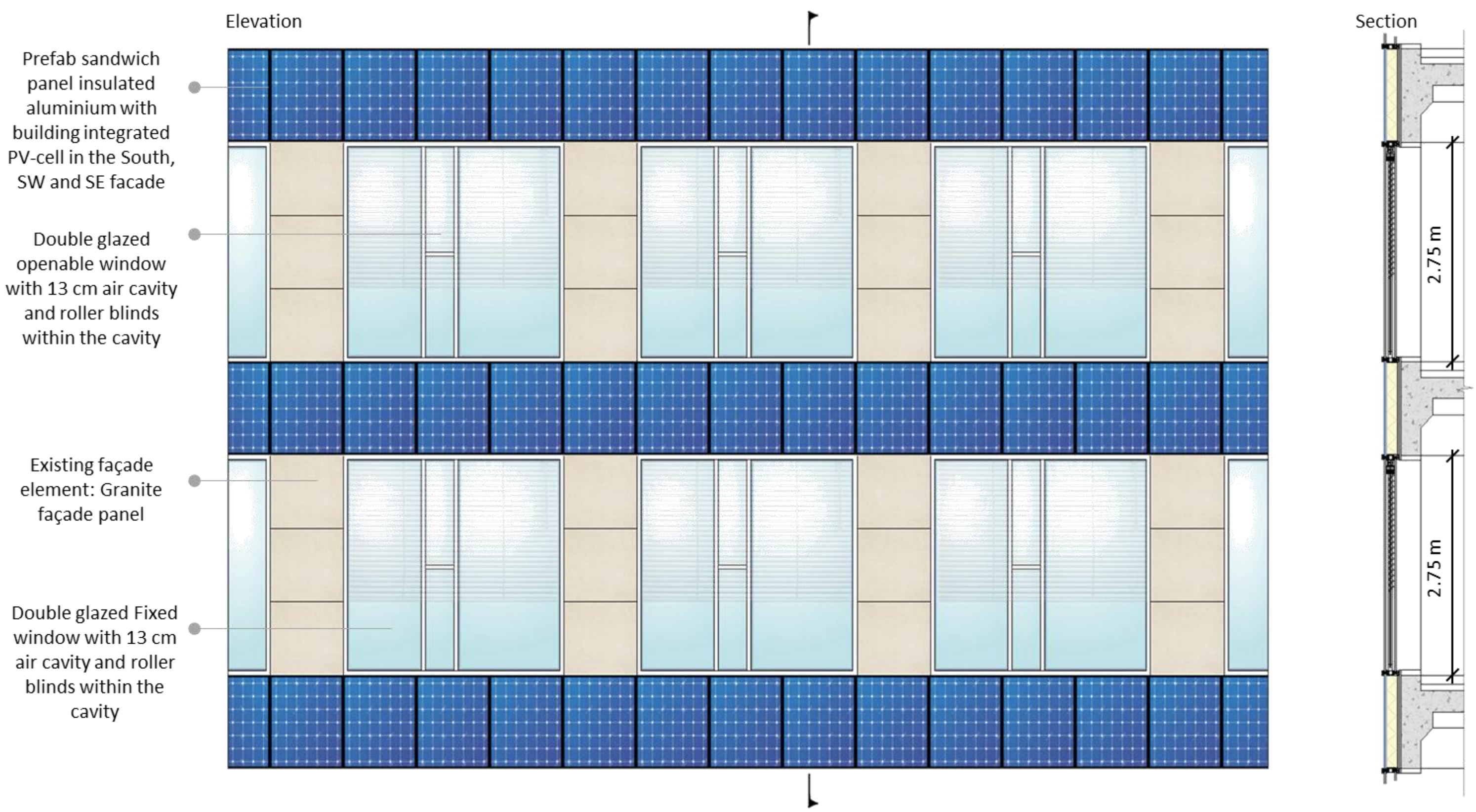


Figure 10.1: Refurbished facade with Building Integrated PV

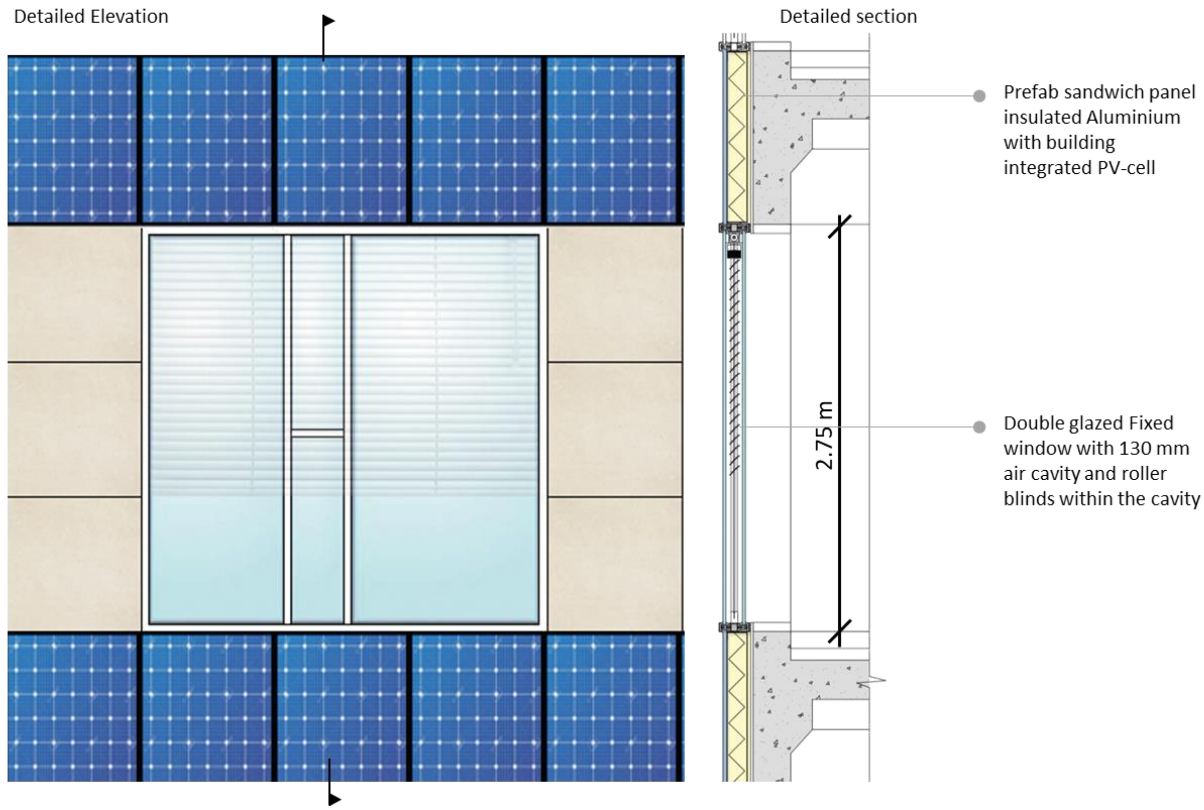


Figure 10.2: Detailed facade with Building Integrated PV

Due to the addition of BIPV, the annual PV energy generated will reduce the total energy consumption of the building without any change in the heating load. Table 10.1 shows the PV yield calculations when the panel is placed parallel to the façade (90° PV angle). The PV yield calculations were done by using grasshopper and ladybug software. It is observed that the energy produced by the BIPV can reduce the total energy consumption of the building by 12%.

PV Yield Calculations		
Location	South, SW, SE	
Total Surface area available to install PV (m2)	4350	
PV Panel power (WP)	300	
PV size/panel (m2)	1.5	
Angle ?	35°	
System size (kW)	400	
Module material	c-Si	
Module efficiency	15%	
PV Annual energy (kWh)	**224076**	
Energy Consumption: Façade Option 1		
	Primary Energy (kWh)	Reduction Factor
Energy Consumed by EWF	**1,768,664**	-
PV Yield from Facade option 2	224076	-
Energy Reduction	**1,544,588**	**12%**

Table 10.1: Energy consumption after refurbishing the facade with prefab sandwich panel with BIPV

10.2. Façade option 2: Sun-shading with PV

In this option, a sun-shading system comprised of 35° fixed module with horizontal louvre glass glades with PV panel is attached to the existing windows in the South, South-West and South-East façade. PV panel tilted at around 35° with the horizontal plane to the south is highly efficient for the region of Netherlands. Since the south-west and south east façade have the same PV angle, the PV yield will be less as compared to the PV in the south façade. Each sun-shading module has 5 horizontal louvers with PV cells thereby covering a large percentage of the exposed glazed façade.

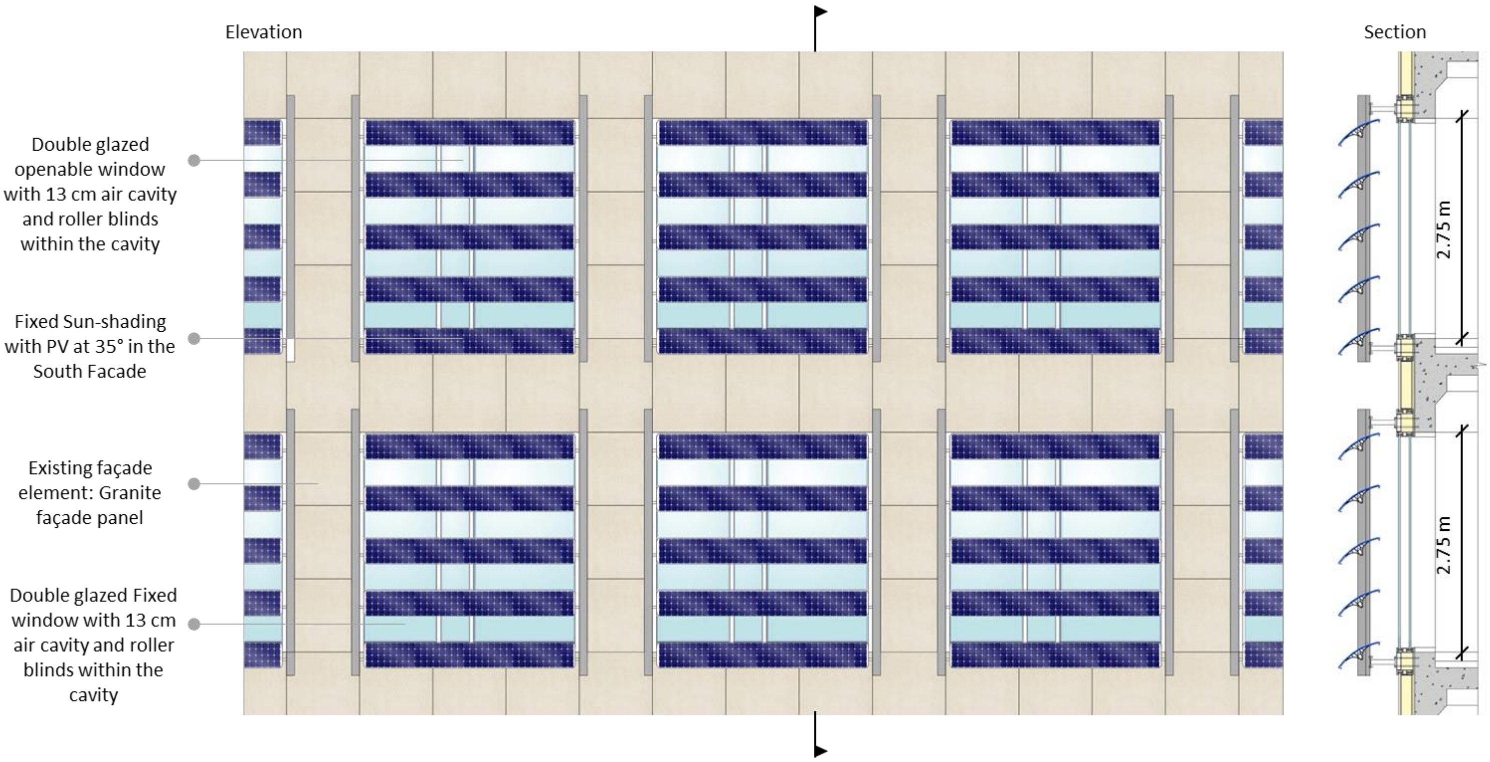


Figure 10.3: Refurbished facade with PV sun-shading

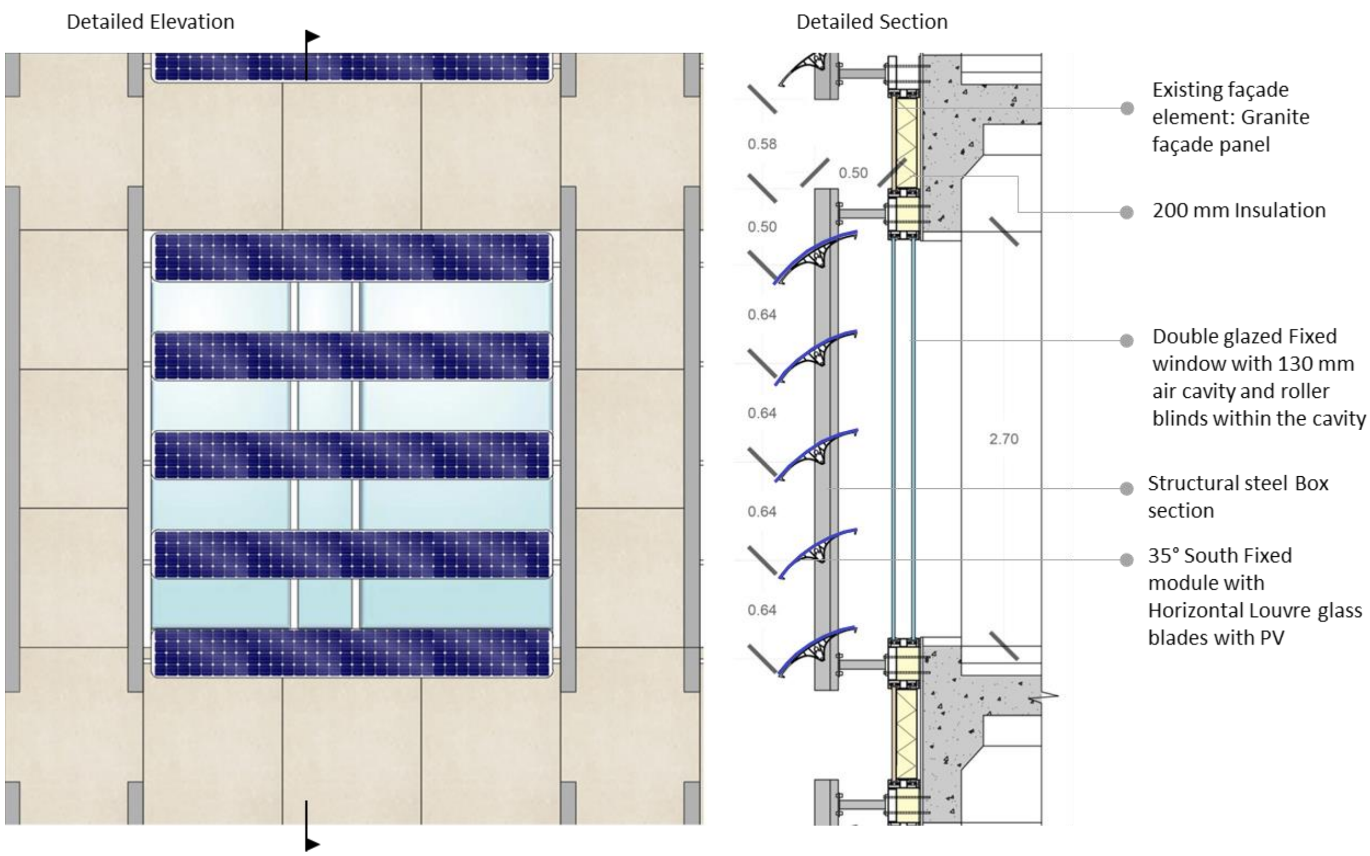


Figure 10.4: Detailed facade with PV sun-shading

Due to the addition of the PV panel in the sun shading system, the annual PV energy generated will reduce the total energy consumption of the building. Table 10.2 shows the PV yield calculations when the panel is tilted at 35° angle. Due to the presence of external sun-shading, the solar gain from the external windows was reduced by 50%. The effect of the sun-shading and the energy produced by the PV-cells cumulatively reduce the net energy consumption of the building by 13%.

PV Yield Calculations		
Location	South, SW, SE	
Total Surface area available to install PV (m2)	4350	
PV Panel power (WP)	300	
PV size/panel (m2)	1.5	
Angle □	35°	
System size (kW)	400	
Module material	c-Si	
Module efficiency	15%	
PV Annual energy (kWh)	**150237**	
Energy Consumption: Façade Option 2		
	Primary Energy (kWh)	Reduction Factor
Energy Consumed by EWF	**1,768,664**	-
Energy Consumed by EWF: after refurbished façade	**1,684,820**	
PV Yield from Facade option 2	150237	-
Energy Reduction	**1,534,583**	**13%**

Table 10.2: Energy consumption after refurbishing the facade with PV sun-shading

10.3. Façade option 3: Living Wall system with BIPV

In this option, the entire façade along with the window module will be refurbished. The wall-window ratio is reduced from 75% glazing to 30% glazing. The opaque part in the new window module comprises of a living wall system. PV panels are incorporated in the façade in a similar way as described in section 10.1. The layers of the double glazed window are the same as the existing condition thereby only changing the size of the glazed unit. Due to the change in the construction of the façade, there will be an effect on the R-value of the façade and the solar gains from the windows (see Table 10.3).

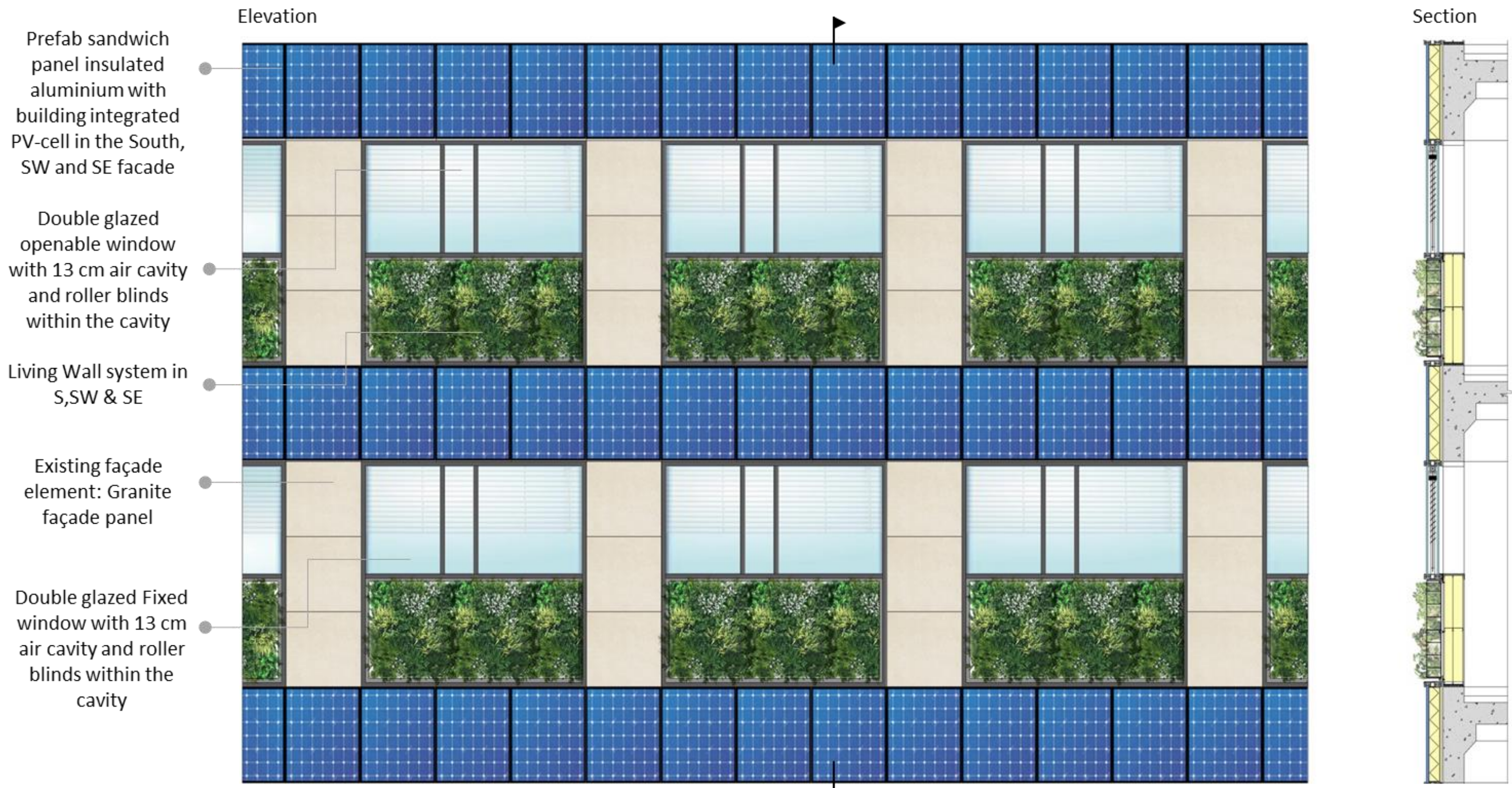


Figure 10.5: Refurbished facade with Living Wall System and BIPV

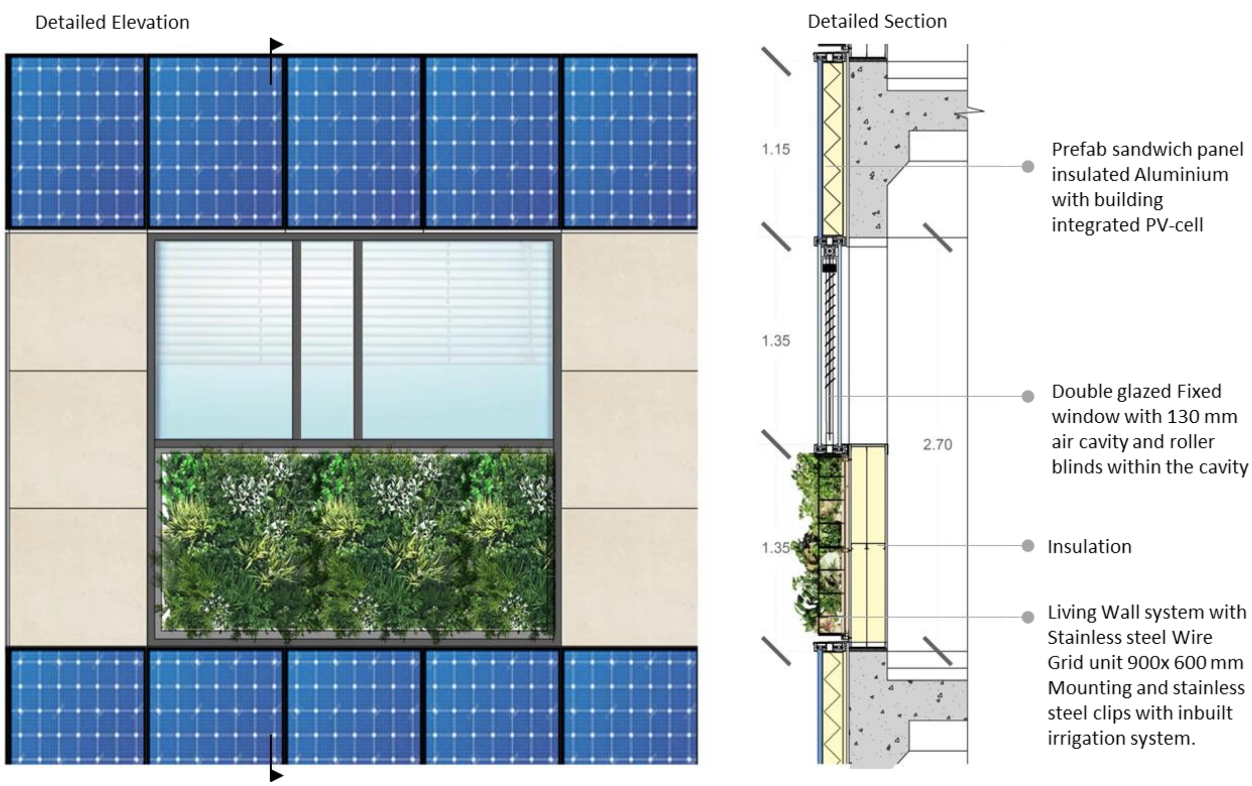


Figure 10.6: Detailed facade with Living Wall System and BIPV

Table 10.3 shows the PV yield calculations as explained in section 10.1. Due to the changes in the façade construction and glazing percentage, the solar gain from the external windows was reduced by 84%. It is observed that the refurbished facade reduces the net energy consumption of the building by 19%. With the addition of the Living Wall system and reduction of the window size, the achieved R-value significantly improves the energy performance of the building.

Thermal Insulation Improvements					
R-Value				**Wall-Window Ratio**	
Existing Façade-Opaque part (m2K/W)	Existing Façade-complete unit (m2K/W)	Refurbished Façade-Opaque part (m2K/W)	Refurbished Façade-complete unit (m2K/W)	Wall-Window Ratio: Existing	Wall-Window Ratio: Refurbihed
4.2	2	**5.9**	**3.6**	75%	**30%**
Energy Consumption: Façade Option 3					
				Primary Energy (kWh)	Reduction Factor
Energy Consumed by EWF: before refurbished facade				**1,768,664**	-
Energy Consumed by EWF: after refurbished façade				**1,654,616**	-
PV Yield from Facade option 3				224076	-
Energy Reduction				**1,430,540**	**19%**

Table 10.3: Energy consumption after refurbishing the facade with PV sun-shading

10.4. Energy Comparison of the 3 façade options

In order to improve the energy consumption of the building with the EWF system further, the building envelope plays a major role in increasing or decreasing the building energy. 3 façade options were analyzed individually in the previous section. To assess which façade refurbishment option will further reduce the building energy consumption and energy generation with PV, a comparative analysis has been conducted as shown in Table 10.4.

The comparison has been made on the basis of 4 parameters: the R-value of the façade, % reduction in the solar gains from the windows, PV energy produced and % reduction in the total energy consumption of the building. It is observed that, façade option 3 gives the highest amount of energy reduction as the entire façade has been refurbished by reducing the glazing % from 75% to 30% thereby reducing the solar gains significantly. Due to the addition of the Living Wall system, the R-value of the façade has also increased, thus, decreasing the infiltration rate. In façade option 1 and 2, the window construction remains the same and the PV panel and the sun-shading system has been added to the façade. This addition will not require major changes in the façade as compared to option 3 where the entire façade has to undergo major renovation.

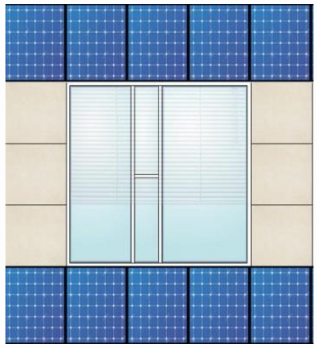
Changed parameters	Façade option 1: BIPV	Façade option 2: Sun-shading with PV	Façade option 3: Living Wall System with BIPV
			
R-value	4.2 m^2K/W	No change	5.9 m^2K/W
% Reduction in solar gain from windows	No change	50%	84%
PV yield	224 MWh/year	150 MWh/year	224 MWh/year
% Reduction in the total energy consumption of the building	12%	13%	19%

Table 10.4: Comparative analysis of 3 facade refurbishment options

10.5. Conclusion

The comparative analysis gives a clear picture of the 3 façade options and how they affect the total energy consumption of the building. As mentioned in Bronsema's (2013) research and also in the design strategies established in the literature study of this research, EWF system performs the best when the building envelope is completely stripped down and a new façade is installed. Moreover, if the building has to comply with the new BENG regulations, façade option 3 gives optimum results as least amount of energy is consumed by the building along with maximum amount of energy generation and improved thermal comfort as solar gains are reduced significantly.

11. Final Design

The section comprises of the final design solution for the Provinciehuis Utrecht building whilst using the EWF system. The system comprises of 2 Climate cascades and 2 Solar Chimneys where the supply is decentralized and the exhaust is centralized except for the toilet areas as shown in Fig 11.1.

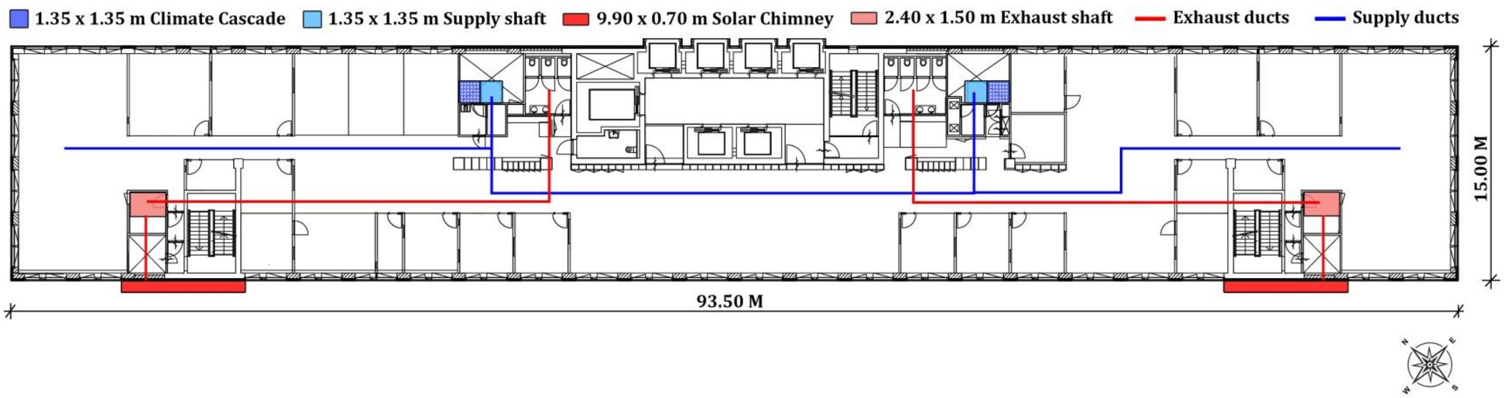


Figure 11.1: Plan of Provinciehuis Utrecht with EWF system

11.1. Working principle

As shown in Fig 11.2, the air enters the Climate Cascade from the top, through the 4 way air flaps present at the top. Since a detailed analysis was not conducted for the external wind factor, it is assumed that the air will enter the Climate Cascade via the air flaps. The incoming air will be heated up by the heat exchanger in the summers before reaching the sprayers. This air to air heat exchanger is connected to the heat exchanger in the Solar Chimney which recovers the heat from the exhaust air before flushing the air out of the chimney. The heated incoming air will pass through the sprayers thereby increasing the air temperature to 18°C (when outside temperature is 28°C). The twin coil unit at the bottom of the Climate Cascade will provide additional heating to the supply air (heating up to 18°C) which is connected to the supply shunt channel. The shunt channel distributes the supply air to every office floor using the supply ducts. The air in the room is supplied by ventilation grills at the ceiling level which is connected to the main supply duct. The exhaust air from the room is extracted by the exhaust shunt channel which is connected to the Solar Chimney at the bottom. When the necessary pressure is not generated to supply and exhaust the air, the auxiliary fans will be used.

The 19th and the 20th floor are technical floors which will have equipment space for maintenance of the heat exchanger and the duct connection between the two heat exchangers. Since the terrace of the building is accessible, the Climate Cascade and Solar Chimney are raised by 2m to avoid exhaust air infiltrating the terrace.

At the bottom of the Climate Cascade, the water is collect in the water basin which is connected to the water tank and the filtration tank in the basement. The water tank is connected to the Aquifer thermal energy storage system (ATES) underground which heats up/cools down the water to 13°C before supplying it back to the filtration unit. The water is pumped to the sprayers at the top thereby completing the loop.

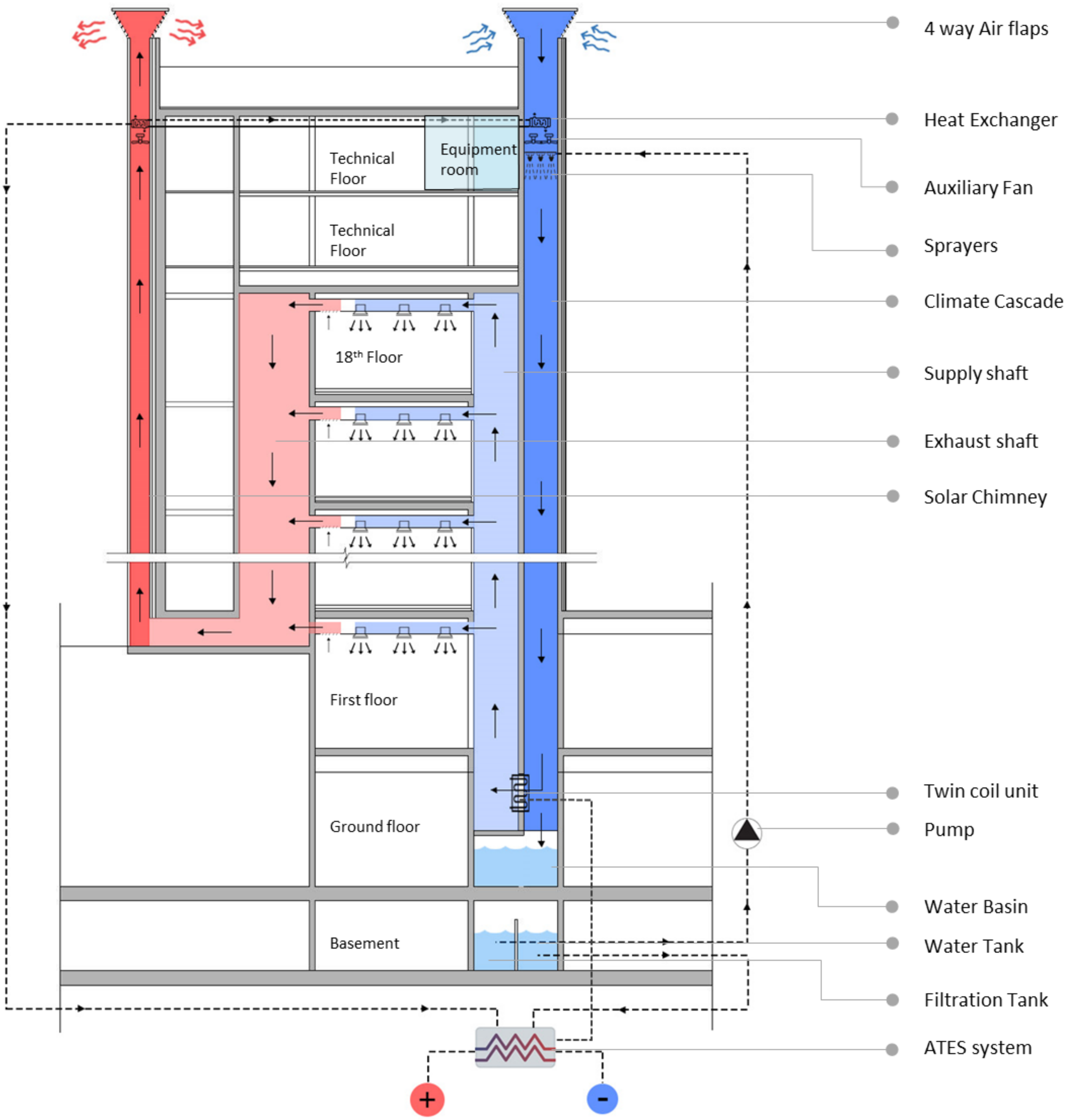


Figure 11.2: Schematic working of the EWF system in the Provinciehuis Utrecht building.

11.2. Ventilation, Heating and Cooling System

In section 10.5, the façade option with Living Wall System and PV was selected along with the EWF system. In the earlier simulations (refer section 9.2.3), the mechanical loop in the Design Builder did not consider ATES as the source for heating and cooling but only considered a constant supply of 18°C air temperature. Since the EWF system along with ATES system could be very efficient as the COP for heating and cooling is high for an ATES system, the mechanical loop for heating (boiler) and cooling (chiller) was replaced with heat pump heating and heat pump cooling which is connect to a Ground Source Heat Pump (GSHP) as shown in Fig 11.3. The heating, cooling and mechanical ventilation schedule remain the same as the earlier simulation, that is, on during the weekdays 24/7 and off during the weekends and holidays. To reduce the cooling load, natural ventilation was introduced only during the summer months (weekdays).

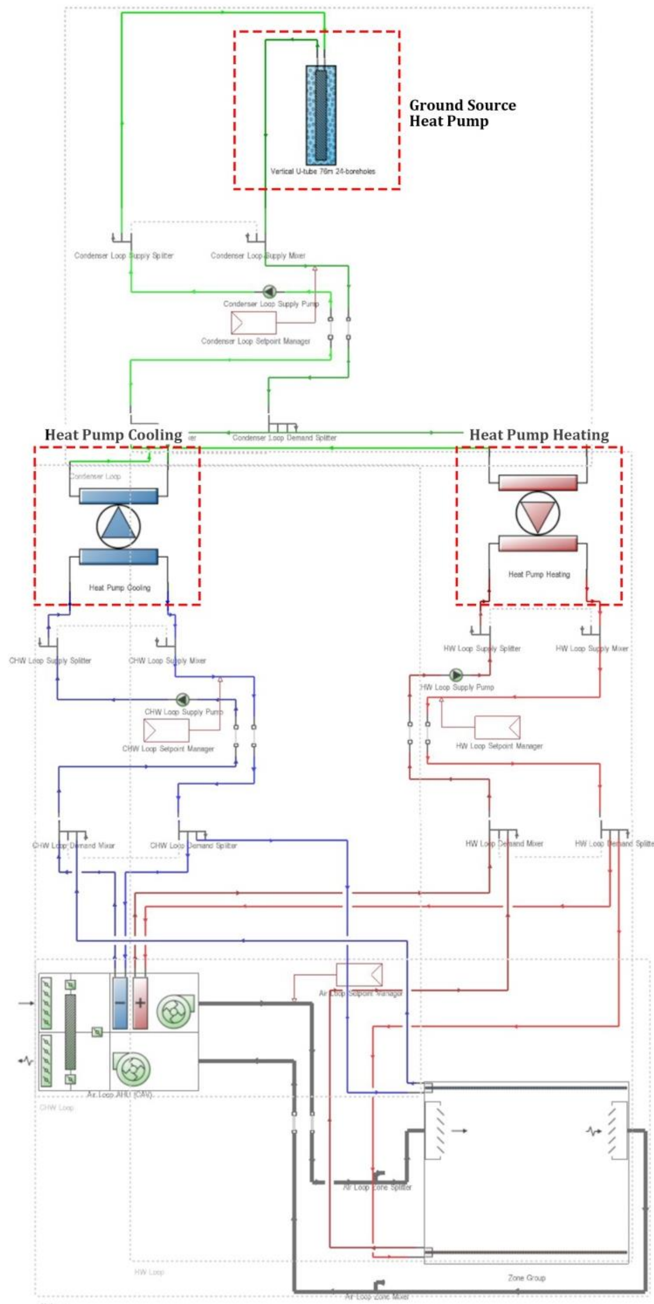


Figure 11.3: EWF Ventilation system with Ground Source Heat Pump for heating and cooling

From the Design Builder simulation with Ground Source Heat pump system as shown in Fig 11.4, it is observed that the heating and cooling load reduces significantly as compared to the system which did not consider the GSHP. The system is also able to regulate the operative temperature within the set point temperature 18°C for cooling and 24°C for heating.

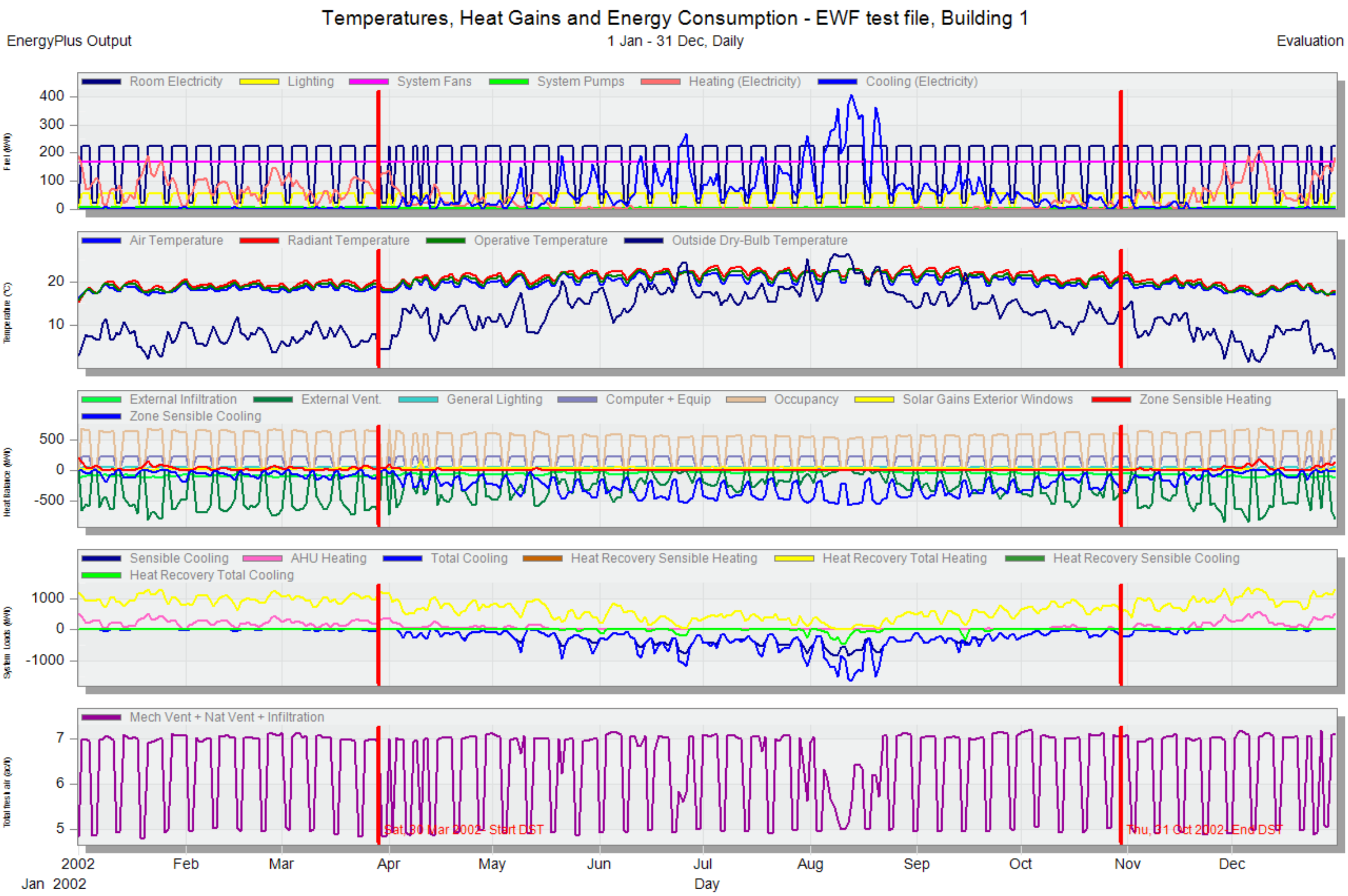


Figure 11.4: Results for the Provinciehuis with EWF and GSHP system.

Since the original situation without the EWF system did not consider ATES system in the simulations, a new simulation was run to check the energy consumption of the original system with ATES system. This was done to compare the EWF + ATES system to the original system with ATES system as it would be a fair comparison due to the high COP values of the ATES system making it more efficient and to evaluate the performance of the EWF system itself and its effect on reducing the energy consumption of the building.

ENERGY COMPARISON: Refurbished Façade option 3 with GSHP							
		Energy Consumption without EWF and with GSHP			Energy consumption with EWF and GSHP		
		Area (m2)	Primary Energy (kWh)	Primary energy (kWh/m2)	Primary Energy (kWh)	Primary energy (kWh/m2)	Reduction %
	Usable Floor area	17,640					
1	Heating		846,000	48	247,644	14.0	70%
2	DHW		35,280	2	35,280	2	-
3	Cooling		403,200	22.8	296,190	16.7	26.5%
4	Ventilation		864,360	49	224,993	12.75	74%
5	Production Equipment		88,200	5	88,200	5	-
6	Lighting		405,720	23	405,720	23	-
	Total		**2,642,760**	**150**	**1,298,027**	**73.6**	**50.8%**

Table 11.1: Total Energy consumed by the Provinciehuis with EWF and GSHP system.

From Table 11.1 it is observed that the EWF system with GSHP reduces the heating energy consumption by 70%, cooling energy by 26.5% and ventilation by 74% as compared to the system without EWF and with GSHP. The overall energy consumption is reduced by 50%. By these results, it can be implied that EWF system is highly efficient in reducing the energy consumption of the building along with the addition of the GSHP system.

11.3. 3D Visualizations

The original façade of the Provinciehuis has been replaced by PV panels and Living Wall System on the South, South West and South East facade along with the Solar Chimney in the South West façade. Figure 11.5 and 11.6 show the impression of the refurbished façade on the South West and South East direction. If Provinciehuis has to be Paris proof, 90% of the façade of the high rise has to be covered with PV panels to generate renewable energy.

Figure 11.5: South West side of the Provinciehuis Utrecht with Solar Chimney and the refurbished facade

Figure 11.6: South East side of the Provinciehuis Utrecht with PV panels and the refurbished facade

The Solar Chimney on the southern façade of the Provinciehuis will be installed floor by floor using the stick system as shown in Fig 11.7 and 11.8. The original façade elements consisting of insulation and granite panel will be removed. The existing concrete slab will support the horizontal structural steel extrusion which will support the curtain wall. The 100mm Rockwool insulation will be added to the existing brick wall followed by 20mm Gypsum light thermal wall. The absorber will be installed after the Gypsum panel and the final layer will be the structural elements of the curtain wall system with glazing.

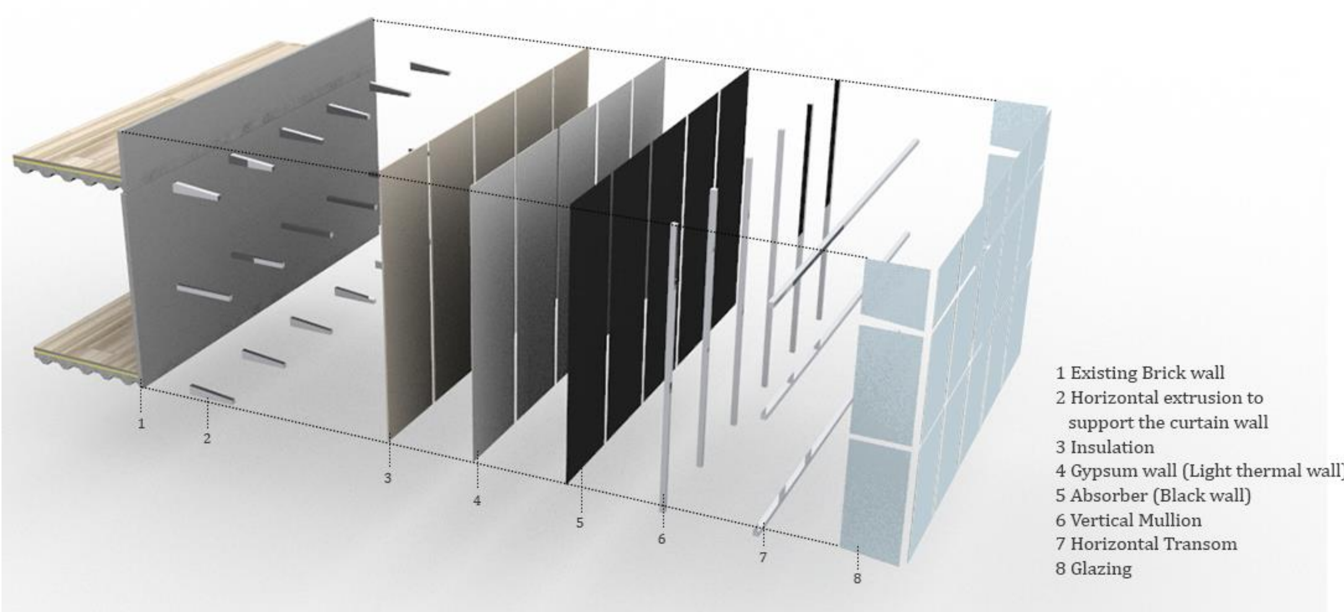


Figure 11.7: Assembly sequence of the Solar Chimney

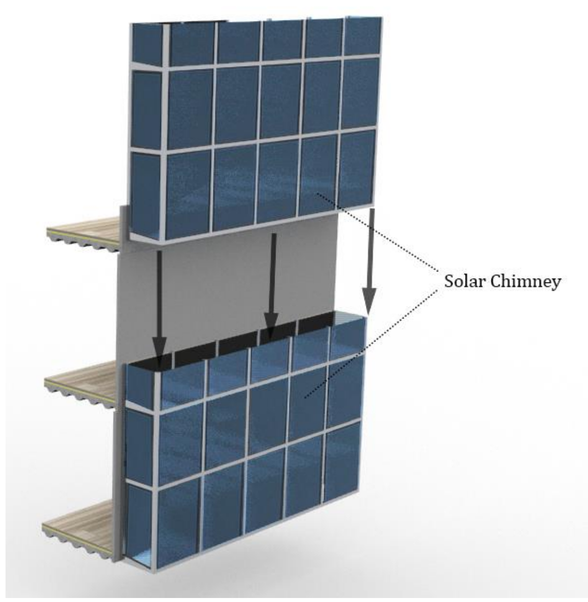


Figure 11.8: Assembly sequence of Solar Chimney

11.4. BENG Calculations

The BENG regulations for office buildings, defined in section 5, were evaluated on the basis of the final energy calculations in Table 11.2. To check if the building satisfies BENG 1, 2 and 3, the annual primary energy consumption of the building was calculated and the energy generated by the building from renewable sources was deducted. Since the ATES system is being used, some parts of the energy consumed will be considered as renewable source of energy along with the energy generated by PV.

From Table 11.2, it is observed that the Provinciehuis Utrecht building with EWF and ATES system satisfies BENG 1, 2 and 3.

Annual amount of energy used for the energy function: Scenario 1						
	COP	Non-Primary energy (kWh)	PEF	Primary Energy (kWh)	Auxiliary energy Non-Primary energy (kWh)	Auxiliary energy Primary energy (kWh)
Heating	5.4	82,284 kWh	1.45	119,311 kWh	36,425	52,816
Cooling	10	0 kWh	1.45	0 kWh	29,619 kWh	42,947 kWh
DHW	3	0 kWh	1.45	0 kWh	11,760 kWh	17,052 kWh
Fans & Pumps	-	28,300 kWh	1.45	41,035 kWh	0 kWh	0 kWh
Lighting	-	405,720 kWh	1.45	588,294	0 kWh	0 kWh
Total				**748,640**		**112,815**

Annual Primary Energy consumption	
Primary energy use including auxiliary energy	861,455
Energy generated by PV	224,076
Annual Primary Energy consumption ($E_{tot\ primary}$)	**637,379**

Annual amount of Renewable Energy	
Heating ($E_{ren.\ heating}$)	362,053
Cooling ($E_{ren\ cooling}$)	266,571
PV ($E_{ren\ pv}$)	224,076
Total amount of Renewable Energy ($E_{tot\ ren}$)	**852,700**

Surface	
Total Useable Floor Area (UFA)	17,640
Surface area of Envelope (SAE)	18445
Ratio	**1.04**

Heating and cooling Energy (Fossil + renewable energy)		
Heating (Pre heating included) ($E_{heating}$)	444,337 kWh	25.2
Cooling (Pre cooling included) (E_{coolng})	492,883 kWh	28

Energy Performance				
BENG 1	**<90 kWh/m2**	($E_{heating}$)+(E_{coolng})	**53.2 kWh/m2**	**Satisfied**
BENG 2	**<40 kWh/m2**	($E_{tot\ primary}$)/ UFA	**36.13 kWh/m2**	**Satisfied**
BENG 3	**>30%**	($E_{tot\ ren}$)/ ($E_{tot\ ren}$ + $E_{tot\ primary}$)	**57.2%**	**Satisfied**

Table 11.2: BENG calculations for High-rise part of Provinciehuis Utrecht

Table 11.2 only considers the high rise part of the Provinciehuis building since the research only focused on the high-rise office part. To check if the entire building satisfies the BENG regulations, the energy consumed per m^2 (kWh/m^2) was calculated for the whole building (including the low-rise and the auditorium), considering the Useable Floor Area (UFA) as 29000 m^2 as shown in Table 11.3.

Annual amount of energy used for the energy function: Scenario 2						
	COP	Non-Primary energy (kWh)	PEF	Primary Energy (kWh)	Auxiliary energy Non-Primary energy (kWh)	Auxiliary energy Primary energy (kWh)
Heating	5.4	135,064 kWh	1.45	195,842 kWh	59,879 kWh	86,824 kWh
Cooling	10	0 kWh	1.45	0 kWh	48,430 kWh	70,223 kWh
DHW	3	0 kWh	1.45	0 kWh	19,333 kWh	28,032 kWh
Fans & Pumps	-	46,524 kWh	1.45	67,459 kWh	0 kWh	0 kWh
Lighting	-	667,000 kWh	1.45	967,150	0 kWh	0 kWh
Total				**1,230,451**		**185,079**

Annual Primary Energy consumption	
Primary energy use including auxiliary energy	1,415,530
Energy generated by PV	224,076
Annual Primary Energy consumption ($E_{tot\ primary}$)	**1,191,454**

Annual amount of Renewable Energy	
Heating ($E_{ren.\ heating}$)	594,186
Cooling ($E_{ren\ cooling}$)	435,870
PV ($E_{ren\ pv}$)	224,076
Total amount of Renewable Energy ($E_{tot\ ren}$)	**1,254,132**

Surface	
Total Useable Floor Area (UFA)	29000
Surface area of Envelope (SAE)	21075
Ratio	**0.72**

Heating and cooling Energy (Fossil + renewable energy)		
Heating (Pre heating included) ($E_{heating}$)	729,350 kWh	25.2
Cooling (Pre cooling included) (E_{coolng})	807,650 kWh	28

Energy Performance				
BENG 1	**<90 kWh/m2**	($E_{heating}$)+(E_{coolng})	**53.2 kWh/m2**	**Satisfied**
BENG 2	**<40 kWh/m2**	($E_{tot\ primary}$)/ UFA	**41.0 kWh/m2**	**Not Satisfied**
Not	**>30%**	($E_{tot\ ren}$)/ ($E_{tot\ ren}$ + $E_{tot\ primary}$)	**51.2%**	**Satisfied**

Table 11.3: BENG calculations for Provinciehuis Utrecht

From the above table it is observed that the Provinciehuis Utrecht building satisfies BENG 1and 3 but does not satisfy BENG 2. To satisfy all the BENG regulations, one solution is to decrease the amount of lighting for the entire building since it contributes to the highest amount of energy consumed by the building. This can be done by introducing motion sensor LED lighting and changing the lighting schedule according to the amount of light required in the space by analyzing the amount of daylight within the space. Another solution is to increase the PV surface which would increase the amount of renewable energy, thereby reducing the total annual primary energy consumption. This solution was opted as it would also help in determining if the building can be Paris proof which will be evaluated in section 11.4.

Annual amount of energy used for the energy function: Scenario :						
	COP	**Non-Primary energy (kWh)**	**PEF**	**Primary Energy (kWh)**	**Auxiliary energy Non-Primary energy (kWh)**	**Auxiliary energy Primary energy (kWh)**
Heating	5.4	135,064 kWh	1.45	195,842 kWh	59,879 kWh	86,824 kWh
Cooling	10	0 kWh	1.45	0 kWh	48,430 kWh	70,223 kWh
DHW	3	0 kWh	1.45	0 kWh	19,333 kWh	28,032 kWh
Fans & Pumps	-	46,524 kWh	1.45	67,459 kWh	0 kWh	0 kWh
Lighting	-	667,000 kWh	1.45	967,150	0 kWh	0 kWh
Total				**1,230,451**		**185,079**
Annual Primary Energy consumption						
Primary energy use including auxiliary energy				1,415,530		
Energy generated by PV				326,097		
Annual Primary Energy consumption ($E_{tot\ primary}$)				**1,089,433**		
Annual amount of Renewable Energy						
Heating ($E_{ren.\ heating}$)				594,186		
Cooling ($E_{ren\ cooling}$)				435,870		
PV ($E_{ren\ pv}$)				326,097		
Total amount of Renewable Energy ($E_{tot\ ren}$)				**1,356,153**		
Surface						
Total Useable Floor Area (UFA)			29000			
Surface area of Envelope (SAE)			21075			
Ratio			**0.72**			
Heating and cooling Energy (Fossil + renewable energy)						
Heating (Pre heating included) ($E_{heating}$)			729,350 kWh			25.2
Cooling (Pre cooling included) (E_{coolng})			807,650 kWh			28
Energy Performance						
BENG 1		**<90 kWh/m2**	($E_{heating}$)+(E_{coolng})	**53.2 kWh/m2**		**Satisfied**
BENG 2		**<40 kWh/m2**	($E_{tot\ primary}$)/ UFA	**37.56 kWh/m2**		**Satisfied**
BENG 3		**>30%**	($E_{tot\ ren}$)/ ($E_{tot\ ren}$ + $E_{tot\ primary}$)	**51.2%**		**Satisfied**

Table 11.4: BENG calculations for Provinciehuis Utrecht

From Table 11.4, it can be concluded that the Provinciehuis Utrecht building satisfies BENG 1, 2 and 3.

11.5. Paris Proof Calculations

When the total annual primary energy consumption of a building is provided entirely from renewable sources, the building is called Paris Proof. In case of Provinciehuis Utrecht building, the annual primary energy consumed by the building is 38 kWh/m^2 (1089 MWh), which considers only the building related energy consumption. The user related energy consumption of the building is estimated to be 5 kWh/m^2, according to the energy calculations provided by DVTadvies (Andrei, 2020). To ensure that the 1089 MWh primary energy is entirely provided by PV panels, the current PV yield of 326,097 kWh is not enough. Therefore, a conceptual exploratory study was carried out by DVTadvies into the possibilities for installing PV panels (Andrei, 2020).

PV on the roof of the Auditorium (Statenzaal)

The total area available on the roof of the auditorium is 1000 m^2. The PV panels can be inclined at 35° angle to the horizontal plane towards the South. From the PV yield calculations of provided by DVTadvies, 185,923 kWh of PV energy can be generated from the Statenzaal's roof considering 188 m^2/WP per PV panel.

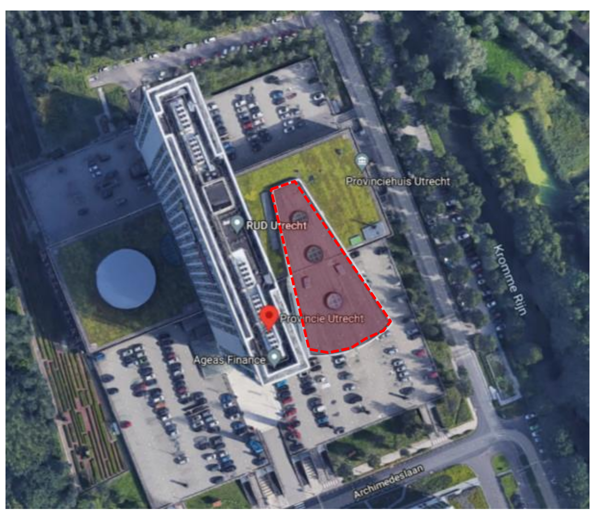


Figure 11.9: Proposal to install PV panels on the Statenzaal roof

PV panels in the garden located in the South West direction.

The total area available in the garden is 1300 m^2. The PV panels can be inclined at 35° angle to the horizontal plane towards the South. From the PV yield calculations of provided by DVTadvies, 228,978 kWh of PV energy can be generated from the garden considering 188 m^2/WP per PV panel.

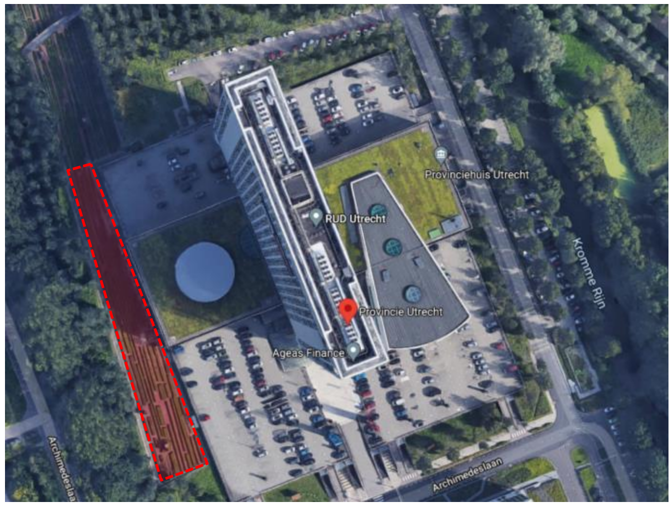


Figure 11.10: Proposal to install PV panels in the Garden on the SW

PV panels on the parking deck

The total area available on the parking deck is 1500 m^2 on the east side and 2500m^2 on the west side. The PV panels will be mostly flat (0° inclination). From the PV yield calculations of provided by DVTadvies, 468,450 kWh of PV energy can be generated from the parking deck considering 125 m^2/WP per PV panel.

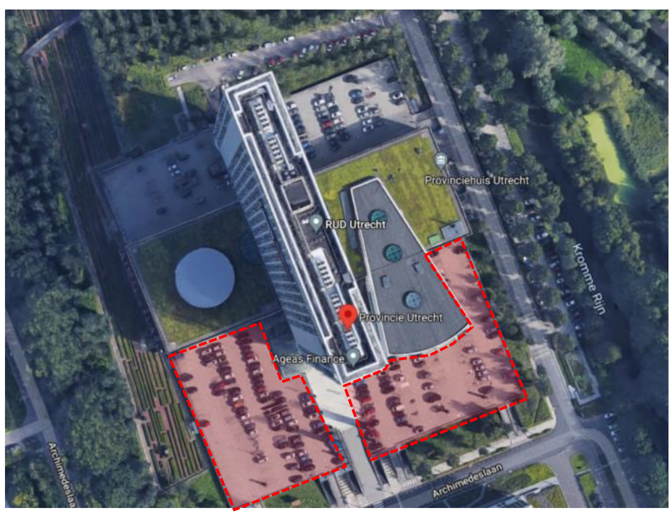


Figure 11.11: Proposal to install PV panels on the parking deck

The total annual primary energy consumed by the building is 1089 MWh and the total renewable energy generated by the building using PV panels is 1209 MWh. Therefore, the primary energy can be completely provided by the PV panels and energy neutrality is achieved on the basis of zero on the meter concept as shown in Table 11.5.

PARIS PROOF	
Annual Primary Energy consumption	
1,089,433 kWh	
Total amount of Renewable Energy	
PV on SW,SE & S facade	326,097 kWh
PV on the roof of the Statenzaal	185,923 kWh
PV panels in the garden (orientation SW)	228,978 kWh
PV on the parking deck	468,450 kWh
	1,209,448 kWh

Table 11.5: Paris Proof calculations for Provinciehuis Utrecht

12. Discussion

12.1. Climate cascade

The design variables defined in section 8.2.4 directly affect the performance of the Climate Cascade in the 4 design options. Since the design options have a combination of single and double Climate Cascades, the values of the variables were different for both the cases. When the same values of the variables for a single Climate Cascade were applied to the calculations of a double Climate Cascade, the fan energy was zero as the pressure at the bottom of the Climate Cascade would be doubled. This excess pressure generated at the bottom of the Climate Cascade is due to the high number of nozzles which increases the pump energy unnecessarily. Moreover, the air temperature achieved at the bottom will not achieve 18°C, thus, increasing the additional heating energy. To avoid excess energy consumption, the values of the variables were changed for double Climate Cascades by increasing the air velocity and decreasing the number of nozzles.

The concept of half Climate Cascade was not explored while developing the design options. The half Climate Cascade concept is when the sprayers are placed at half height of the building instead of the top when the building height exceeds 45m and thus, reduces the pump energy. It was assumed that the decrease in the pump height will decrease the pump energy, but the pressure achieved at the bottom of the Climate Cascade would not reach 150 Pa. To achieve this value, higher number of nozzles would be required, thus increasing the pump energy. Therefore, the effect neutralizes the benefit of the height factor.

As the EWF system is based on the intensity of the external wind, it was assumed that the wind will enter the Climate Cascade and exhaust the air from the Solar Chimney by designing the shafts higher than the terrace floor level and installing a 4 way air flap system which could be controlled via Building Management System (BMS). As the wind factor was not simulated in this research due to limited scope and time, there is a possibility that the EWF system would work better by adding the wind factor in the excel model as the pressure difference at the bottom of the Climate Cascade and the thermal draught of the Solar Chimney could be optimized by controlling the amount of wind entering the Climate Cascade and the velocity of the incoming outdoor air.

12.2. Solar Chimney

The shape and location of the Solar Chimney is an important criterion for improving the efficiency of the chimney. In this research, rectangular shape for the chimney was defined as the excel model was designed to calculate the energy performance of rectangular chimneys. Moreover, the location of the chimney was one-directional, which is less efficient than a multi-directional chimney. According to the design criteria in the literature study, a trapezoidal Solar Chimney with the exterior surfaces facing S, SW and SE direction has high energy yield and higher thermal draught. If a trapezoidal chimney was proposed in one of the design options, the efficiency of the Solar Chimney would have increased, thus, reducing the fan energy and increasing the heat recovered at the top of the chimney.

The proposed design of the Solar Chimney consumes some amount of fan energy during the cooling season as the temperature difference between the outside air and the air inside the Solar Chimney is not enough to increase the thermal draught. One solution to this effect is to naturally exhaust the air from the occupied zones by opening the windows. This solution was not calculated as the calculation methodology was not defined due to the time constraints. If the effect of natural ventilation of exhaust air was considered, the fan energy and the heat recovery would be zero as the chimney will not operate when the thermal draught is low. It is to be noted that opening the windows to exhaust the air will also infiltrate the air inside the occupied zones, thus changing the indoor air temperature leading to thermal discomfort.

12.3. Energy calculations using Design Builder

The design builder software was used to dynamically simulate the building and calculate the energy consumed for space heating and cooling and the effect of the façade on the building energy consumption. Since the EWF system is a fairly new concept, the design builder library does not have an inbuilt EWF system template. Therefore, to simulate the building, the existing HVAC system in the design builder was replicated to function like the EWF system by changing the AHU air supply temperature to constant 18°C and the source of heating and cooling is by the Ground Source Heat pump using boreholes. On the contrary, the EWF system will use ATES system which is not available as a template in the software. The humidity factor, heating and cooling of the air, sprayers, auxiliary fans and heat recovery unit was not considered in the dynamic simulations. Thus, the energy results

considered from the design builder simulation will not have 100% accuracy. The calculated total energy consumption of the building will differ if the EWF system is completely designed on the design builder software.
The results from the design builder for the building with EWF system (see fig 11.4) show heating and cooling at the same time, during the April and October months, as the set point temperatures for heating (18°C) and cooling (24°C) do not have a large temperature difference. Moreover, the heating and cooling energy results in the design builder software does not specify the breakup of the calculation. Therefore, it is possible that the heating and cooling energy consumed by the HVAC system to maintain the 18°C supply air temperature is included in this energy calculation.

12.4. BENG and Paris Proof calculations

The BENG regulations consist of BENG 1, 2 and 3 where BENG 1 is only applicable for newly built structures. This research is a refurbishment project therefore BENG 1 and not completely applicable but it was considered in the calculations in order to validate the reduction in the energy consumption when the façade is refurbished as compared to the original façade configuration. Since the research only focused on the high rise part of the Provinciehuis, 2 scenarios were made: (1) only the high rise part of the Provinciehuis was considered for the BENG calculations (2) all functions of the Provinciehuis was considered for the BENG calculations. This was necessary as the BENG considers the complete building related energy consumption which will be used to compare the energy consumption with other buildings. Moreover, to validate the research with respect to Paris proof agreement, the primary energy consumption of the entire building has to be considered.
According to the BENG regulations, the calculation methodology NTA 8800 should be used for validation. This was not done in this research as the software is not open source. Therefore, excel was used to calculate the primary energy consumption of the building using the PEF factor. These results are not 100% accurate as the objective was to give the first impression of the EWF system and validate the system efficiency and its potential to reduce the energy consumption of the building.

There are some discussions related to the Paris proof calculations with respect to the primary energy consumption. There is no clear conclusion whether the primary energy should be including or excluding the PEF. In the Netherlands, the primary energy of the office buildings should not be more than 50 kWh/m^2, on the other hand, in the European context, the primary energy should be including the PEF which is according to the energy bill. There is no concrete conclusion regarding the same and the DGBC Paris proof committee has also not mentioned any specific requirements. Therefore, the results of the

Paris proof calculations show the first impression of the building and what steps can be taken to make the Provinciehuis Paris proof.

13. Conclusion

This chapter discusses the results and conclusions of the study by answering the following research question: "*How are the **design strategies,** derived from the **Earth, Wind and Fire system**, implemented in the **refurbishment of an office building in the Netherlands** in order **to improve the energy performance**?*"

Within the non-domestic sector in the built environment, the office buildings consume the highest amount of energy in terms of heating, cooling and ventilation. To address this issue, there are regulations or policy implications such as the BENG and Paris Climate Agreement for which office buildings need to adhere to in the near future. In order to achieve energy neutrality, the EWF concept has been researched upon in the past few years. This research contributes to the existing research on the EWF concept by focusing on implementing the EWF system for an office building in the Netherlands by following the recommended EWF design strategies derived by Dr Ben Bronsema and Peter Swier, which could potentially reduce the energy consumption of the building. The selection of the case study was based on a comparative analysis where the chosen case study was Provinciehuis Utrecht building.

The research adopted both basic and dynamic simulation methods to evaluate the energy performance of the Provinciehuis building with EWF system. The basic methodology was conducted using Microsoft Excel and the dynamic methodology was conducted using the Design Builder software.

The findings from the excel calculations show that within the EWF system and its 3 elements, installing 2 Climate Cascades and 2 Solar Chimneys are more efficient than installing single elements. Installing single elements would lead to higher pressure losses in the supply and exhaust ducts, thus increasing the total energy consumption due to the linear shape of the building. Another drawback of using single elements would be the size, which increases with increased ventilation capacities thereby occupying more space within the building and on the façade. This finding also contradicts the design strategy for Solar Chimney which suggests that a single chimney performs better than multiple chimneys (Refer Section 4.8.2). It can also be concluded that the design of the buildings and the amount of pressure required for the system to function influences the number of EWF elements needed to be installed.

The results from the dynamic calculations show that building energy consumption reduces by 50% when the EWF system is implemented as compared to the existing condition. When the operative temperatures from the design builder simulation was applied to the excel simulation, the energy consumption of the building increased marginally. Addressing thermal comfort is also crucial while implementing refurbishment of a building. To evaluate the thermal comfort of the Provinciehuis with and without the EWF system, ATG method was implemented. The ATG graphs of the existing condition showed poor thermal performance while the graphs of the EWF system showed acceptable thermal performance based on the ATG categorization through classes for buildings. To improve the thermal performance further with the EWF system, the ventilation and heating schedule was changed in design builder. Through this step, it can be concluded that the thermal performance of the building was satisfactory with respect to the class B category of the ATG, which signifies minimum requirements. However, this also resulted in the energy consumption of the building increasing by 22%. Therefore, the results for the building with EWF system without any improvements were chosen to meet the main objective of the study.

For further reduction of the building energy consumption, façade refurbishment was essential as it can drastically improve the energy performance. 3 façade options were proposed integrated with PV panels as recommended in the design strategies. The results from the energy calculations of the 3 façade options showed that the third option with Living wall system and BIPV reduce the building's energy consumption. Therefore, it can be concluded that façade option 3 performs the best if major renovation of the building envelope is acceptable. If the building envelope requires minimum alterations with considerable amount of energy reduction, façade option 2 can be chosen. Post refurbishing the façade with Living Wall system and PV, the Ground Source Heat Pump was used through which the energy consumption of the building was reduced by 50% as compared to the original configuration with GSHP. It can be concluded that the high efficiency of the EWF system with GSHP is due to the high COP values for heating and cooling.

From the research conducted and the results obtained, it can be concluded that the EWF system is an efficient way to reduce the energy consumption of the Provinciehuis Utrecht building while also complying with all the BENG regulations along with achieving energy neutrality on the basis of zero on the meter concept. In order to implement the EWF system for other buildings, the most influential design strategies to be considered are:

1. The height of the building should be more than 15.0 m; higher the building, the pressure required to supply and exhaust the air in the Climate Cascade and Solar Chimney will be higher.
2. Refurbishing the façade of the buildings with the integration of the EWF elements would further enhance the energy performance of buildings.
3. Use of heat and cold storage is highly recommended as it can reduce the energy consumption of the building drastically.
4. Use of heat recovery system is highly recommended as it has the potential to reduce the energy consumed by the EWF system by 50%.

13.1. Recommendations for Further Research

As the research only focused on the 2 elements of the EWF system, that is, Solar Chimney and Climate cascade, it would be interesting to study the effect of the ventec roof as it could help in extracting the exhaust air out of the Solar Chimney by creating positive pressure. This would in turn reduce the energy consumed by the fan and the total energy consumption of the building.

Different design options with varying heights of the Climate Cascade can be explored as this will have an effect on the pump energy due to reduction in the height of the climate cascade. This reduction may reduce the pump energy but it may increase the fan energy if the necessary pressure difference is not achieved at the bottom of the climate cascade. Moreover, the number of nozzles can also increase if enough pressure is not achieved thereby increasing the amount of water to be pumped at the top of the climate cascade.

Since the research focused on using the design builder software only to replicate the supply air temperature of the EWF system, the software was not explore further to completely design the EWF and develop it as a template within the design builder library. There is a lack of software applications which could analyze the performance of the EWF system in terms of its energy, comfort and air quality. An innovative solution would be to develop a tool for the same which could give accurate results for the parameters to be analyzed for this system.

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Appendices

Appendix 1: Research Methodology

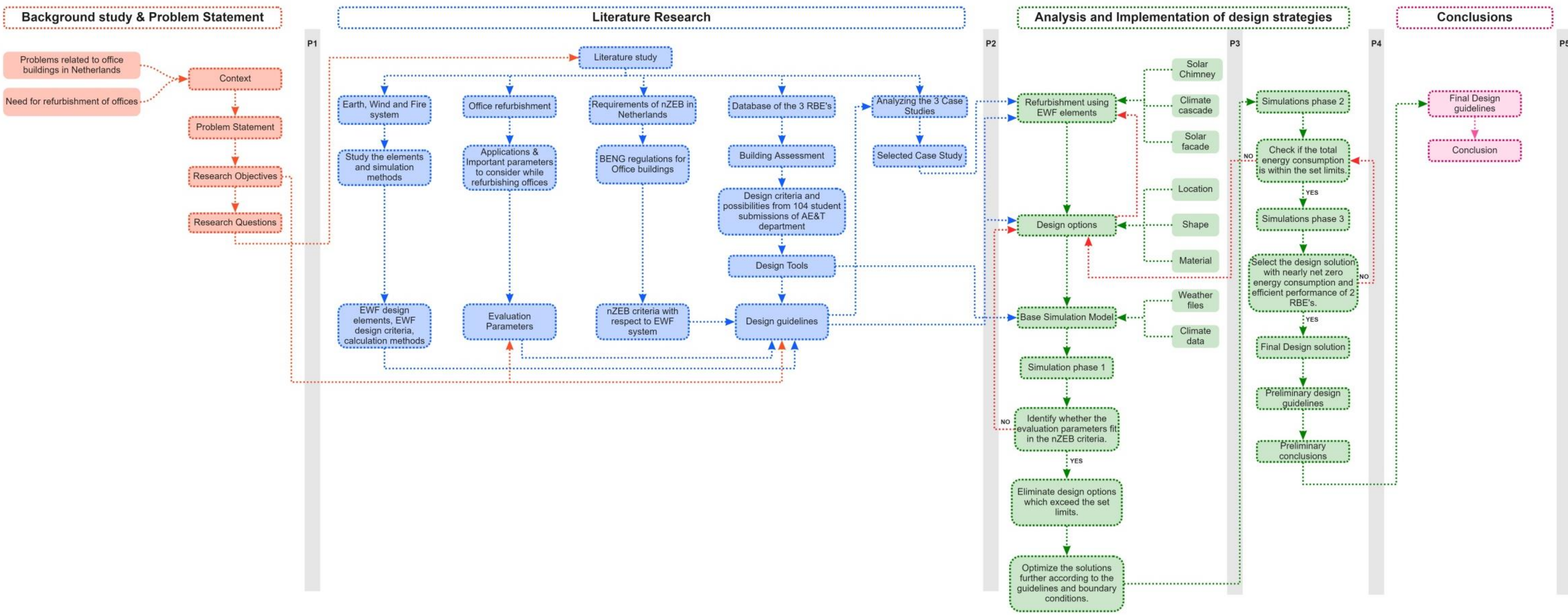


Figure 1: Detailed methodology scheme

Appendix 2: Climate Cascade

Climate cascade as a heat exchanger

The heat transfer is represented by the equation:

$$\Phi = h.A.(\theta_m - \theta_\infty)$$ (Bronsema, 2013)

Where,

Φ = Heat transfer from air to water which is equal to the required enthalpy change of air.

A= Active surface of the Climate Cascade determined by the cumulative area of the water droplets, product of the number of droplets formed per unit of time and its duration of stay.

h = Heat transfer coefficient

$\theta_m - \theta_\infty$= Temperature difference between water (θ_m)and air (θ_∞)

The heat flow between air and water in a Climate Cascade is determined by the required thermal power, expressed in the formula:

$$\Phi = q_{v.l}.\rho_l.(h_{l.in} - h_{l.out})$$ (Bronsema, 2013)

Where,

Φ = Heat flow [W]

$q_{v.l}$ = volume flow air [$dm^3 .s^{-1}$]

ρ_l = density of air [g. dm^3]

$h_{l.in}$ = enthalpy of the air at entry [Jg^{-1}]

$h_{l.out}$ = enthalpy of the air at exit [Jg^{-1}]

The heat flow consists of a sensible component Φ_v and a latent component Φ_l, at which:

$$\Phi = \Phi_v + \Phi_l$$ (Bronsema, 2013)

The sensible heat transfer in a Climate Cascade can be described with the general formula:

$$\Phi_v = A_{dr}.h_{c.dr}(\theta_{dr} - \theta_\infty) + A_{wnd}.h_{c.wnd}(\theta_{wnd} - \theta_\infty)$$ (Bronsema, 2013)

Where,

Φ_v = sensible component heat flow [W]

A_{dr} = cumulative surface water droplets in the spraying zone [m^2]

$h_{c.dr}$ = convective heat transfer coefficient of air on droplets [$Wm^{-2} K^{-1}$]

θ_{dr} = temperature of water droplets [°C]

θ_∞ = temperature of air flow [°C]

A_{wnd} = total wall surface [m^2]

$h_{c.wnd}$ = convective heat transfer coefficient air and walls [$Wm^{-2} K^{-1}$]
θ_{wnd} = temperature of the wall [°C]

The latent heat transfer in a Climate Cascade can be described in an analogous way with the general formula:

$$\Phi_v = A_{dr}.K_{dr}.r(c_{d.opp} - c_{d.\infty}) + A_{wnd}.K_w.r\ (c_{d.wnd} - c_{d.\infty})$$ (Bronsema, 2013)

Where,
Φ_v = sensible component heat flow [W]
A_{dr} = cumulative surface water droplets in the spraying zone [m^2]
K_{dr} = mass transfer coefficient humidity on droplets [ms^{-1}]
r = evaporation heat of water at the condensing temperature [$J.g^{-1}$]
$c_{d.surface}$ = water vapour concentration at the surface of the droplets [gm^{-3}]
$c_{d.\infty}$ = water vapour concentration in the air [gm^{-3}]
A_{wnd} = total wall surface [m^2]
K_w = mass transfer coefficient air humidity on wall [ms^{-1}]
$c_{d.wnd}$ = water vapour concentration at the surface of the wall [gm^{-3}]

The spray spectrum

For designing the spray spectrum, it is essential to determine the properties of the drop, diameter, area and volume.
The average droplet diameter is expressed mathematically in the formula:

$$D[1,0] = \frac{\sum n.d}{n}$$ (Bronsema, 2013)

Where,
$D[1,0]$= average drop diameter. Often written as d_{10} [mm]
d = diameter of individual drops [mm]
n = number of drops
The relationship between the average drop diameter and its average volume is written as:

$$D[3,0] = \sqrt[3]{\frac{\sum n.d^3}{n}}$$ (Bronsema, 2013)

Where,
$D[1,0]$= average droplet diameter by volume or VMD, Volume Mean Diameter, often written as d_{30} [mm]

Similarly, the relationship between the mean droplet diameter and their mean area is written as:

$$D[2,0] = \sqrt[3]{\frac{\sum n.d^2}{n}}$$ (Bronsema, 2013)

Where,
$D[2,0]$= average droplet diameter on surface or SMD, Surface Mean Diameter, often written as d_{20} [mm]
The relationship between the mean droplet diameter and the mean surface area is usually expressed in the Sauter Mean Diameter SMD that is written as:

$$D[3,2] = \frac{\sum n.d^3}{\sum n.d^2}$$ (Bronsema, 2013)

Where,
$D[3,2]$= Sauter Mean Diameter, often written as d_{32} [mm]

The active surface of a Climate Cascade is determined by the cumulative surface area of the water droplets that are simultaneously in the cascade. This cumulative area is a function of the number of drops and the SMD d_{32}. The number of drops depends on the water flow and the VMD d_{30}. The residence time of a drop in the Climate Cascade is a function of the height and of the fall speed, which in turn is directly related to the weight and thus to the VMD d_{30}. The falling velocity of a drop or a drop collection is determined by the initial speed, gravity and air resistance. During the fall, the speed increases with the gravitational acceleration g but due to the increasing speed also increases the air resistance. The air resistance is determined by the drag coefficient C_w, which depends on the nature of the flow, laminar, turbulent or intermediate, expressed in Reynolds' number Re according to the formula:

$$Re = \frac{d_{dr} \cdot \rho_l \, (w_{dr} - w_l)}{\mu_l}$$ (Bronsema, 2013)

Where,
Re = Reynolds number
d_{dr} = drop diameter [m]
ρ_l = density of the air [$kg.m^{-3}$]
w_{dr} = speed of the drop [ms^{-1}]
w_l = air speed [ms^{-1}]
μ_l = dynamic velocity air [Pa.s]

Laminar flow occurs at Re ≤ 1 and turbulent flow at Re ≥ 300
The drag coefficient C_w can be calculated by the formula of Wallis:

$$C_w = \left(\frac{24}{Re}\right).(1 + 0.1\ R_e^{0.687})$$ (Bronsema, 2013)

The minimum inlet pressure for most sprinklers is 0.5 bar with an initial speed in the spray spectrum is realized from ≈ 10 ms^{-1}. The final velocity is independent of the initial velocity. For the sprinkler system, this means that the initial speed can become low; gravity then does its job to reach the final velocity. The pressure at the nozzles can therefore be low, so that the pump energy can be limited. The final velocity w v, t of a water droplet, where the gravity mg is in equilibrium with the drag force F_w is given by the formula:

$$w_{dr.t} = w_l + \sqrt{\frac{2.m.g}{\rho.A_{dr}.C_w}}$$ (Bronsema, 2013)

Where,
$w_{dr.t}$ = final velocity of a drop [ms^{-1}]
w_l = air speed [ms^{-1}]
m = mass of drop [kg]
g = gravitational acceleration
A = projected area of drop [m^2]
C_w = drag coefficient

The heat transfer coefficient by convection $h_{c.dr}$ in the spray zone from air to water drops is a function of several variables such as temperature, speed of the media, viscosity, thermal conductivity, turbulent or laminar flow and geometry of the drops. The following relationship can be used for $h_{c.dr}$:

$$Nu = \frac{h_{c.dr}.d_{10}}{\lambda} = 2 + 0.6\ Pr^{\frac{2}{3}}.Re^{\frac{1}{2}}$$ (Bronsema, 2013)

Where,
Nu = Nusselt's number
$h_{c.dr}$ = convective heat transfer coefficient [$Wm^{-2}\ K^{-1}$]
λ = thermal conductivity coefficient [$Wm^{-1}\ K^{-1}$]
Pr = Prandl's number
Re = Reynolds number

For air in the temperature range of 20 ˚C - 40 ˚C, Pr ≈ 0.71 (Recknagel, 2010) applies.

$$Re = \frac{d_{10\,.}\,(w_{dr} - w_{\infty})}{v}$$

Where,
w_{dr} = speed of the drop [ms^{-1}]
w_{∞} = speed of air [ms^{-1}]
v = kinematic viscosity [$m^2.s^{-1}$]

The relative air velocity $(w_{dr} - w_{\infty})$ of a water droplet with respect to the air is in high degree depending on the droplet diameter d.

Appendix 3: Solar Chimney

Convective heat transfer coefficient

Free convection

$$h_{c.v} = 1.51\,(\theta_w - \theta_\infty)^{0.33}$$

Where,

$h_{c.v}$ = heat transfer coefficient (free convection) [$Wm^{-2}K^{-1}$]

θ_w = wall surface temperature [°C]

θ_∞ = air temperature in the main stream [°C]

Forced convection

$$h_{c.g} = 4\,w^{0.8}$$

Where,

$h_{c.g}$ = heat transfer coefficient (forced convection) [$Wm^{-2}K^{-1}$]

w = air speed [ms^{-1}]

Mixed convection

Re << $\sqrt{Gr}$ Free convection predominates

Re > $\sqrt{Gr}$ Forced convection predominates

Mixed convection formula according to Molina & Maestre:

$$h_c = 3\left(\theta_{gl.w} - \theta_{\infty.in}\right)^{1/3}$$

Where,

$\theta_{\infty.in}$ = air temperature at the entrance of the Solar Chimney [°C]

Convective heat transfer and energy performance

Thermal efficiency

$$\Phi_c = n_{z.ref}.\Phi_{zon} = g.\Phi_{zon} - U^*_{gl}\left(\theta_{gl} - \theta_e\right) - U^*_w.p.(\theta_w - \theta_a)$$

Radiation model

The radiation emission from one surface to another can be expressed as:

$$\Phi_s = A.\varphi.\varepsilon.\sigma.T^4$$

Where,

Φ_s = radiation emission [W]

A = surface area [m^2]

φ = visibility factor

ε = emission coefficient

σ = radiation constant 56.7 x 10^{-9} [$Wm^{-2}K^{-4}$]

T = Temperature [K]

Net radiation exchange between black wall and parallel glass wall with visual factor φ is expressed as:

$$\Phi_{s.w} - \Phi_{s.gl} = h_{str}.A.(\theta_w - \theta_{gl})$$

Or

$$\Phi_{s.w} - \Phi_{s.gl} = h_{str}.A.(T_w - T_{gl})$$

Where,

$\Phi_{s.w}$ = wall heat output by radiation [W]

$\Phi_{s.gl}$ = glass heat emission by radiation [W]

T_w = wall temperature [K]

T_{gl} = glass temperature [K]

Thermal draft

Law of Gay-lussac expresses the formula for thermal draft:

$$\Delta p = \rho_0 \left[\frac{T_o}{T_1} - \frac{T_o}{T_2}\right].g.h$$

Where,

Δp = thermal draft [Pa]

ρ_0 = density of air at 0°C [$kg.m^{-3}$]

g = gravitational constant [ms^{-2}]

T_o = air temperature at 0°C [K]

T_1 = air temperature outside [K]

T_2 = air temperature in chimney [K]

H = height of the column [m]

Flow model

Dynamic pressure is expressed in the formula:

$$P_d = 0.5.\rho.w^2$$

Where,

P_d = dynamic pressure [Pa]

ρ = density of air [$kg.m^{-3}$]

w = air speed [ms^{-1}]

Pressure loss due to friction is expressed in the formula:

$$\Delta p = \lambda \frac{1}{D_h}. 0.5. \rho. w^2$$

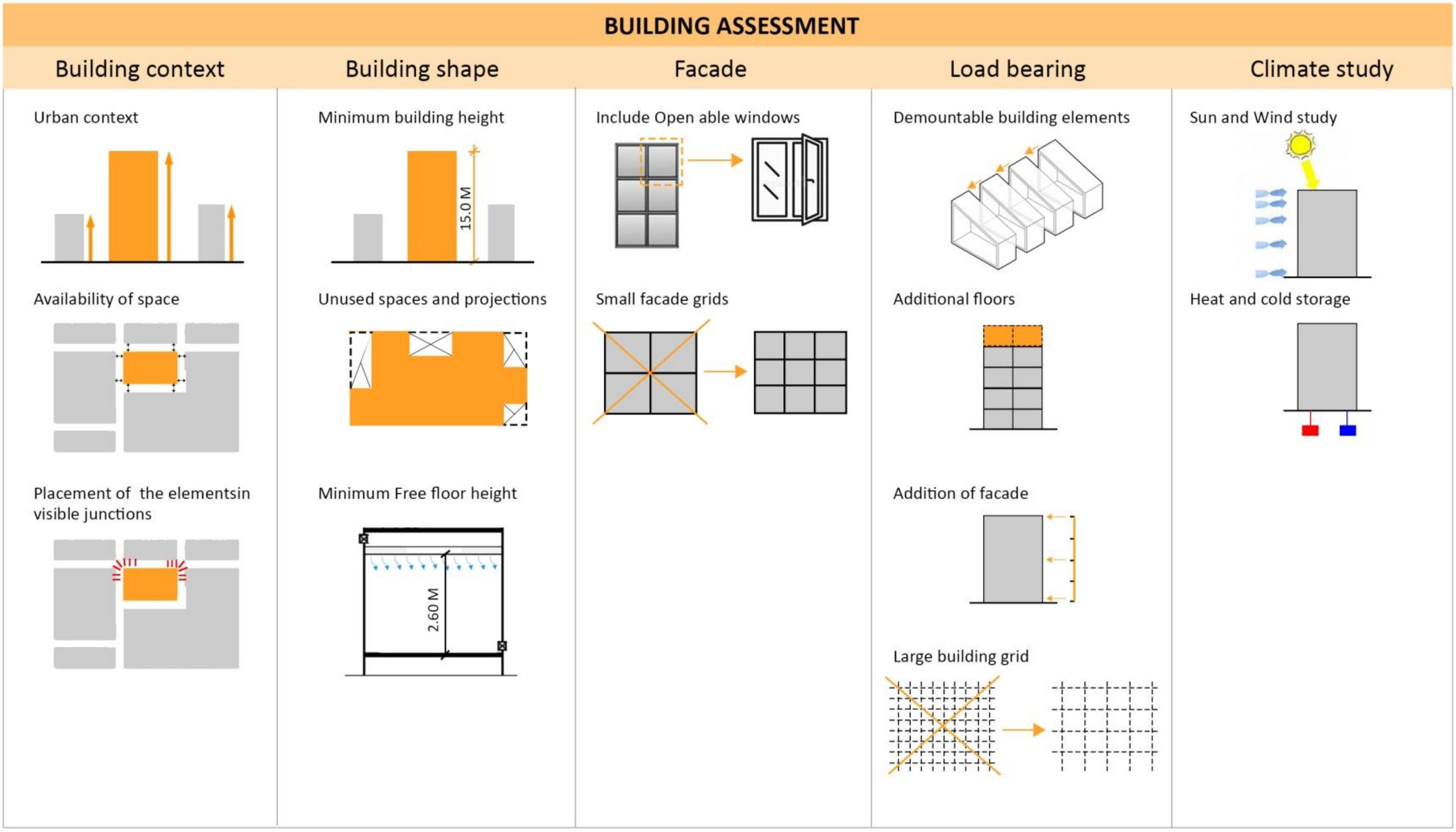
Where,
λ = friction factor
L = length of the channel [m]
D_h = hydraulic duct diameter [m]
ρ = specific mass of air [kg.m^{-3}]
w = average air speed [ms^{-1}]

Thermal capacity of Solar Chimney is expressed in the formula:

$$P_{th} = n. H_{verd}. B. R. \Phi_{zon}. n_z$$

Where,
P_{th} = thermal power [W]
n = amount of floors
H_{verd} = floor height [m]
B = width of Solar Chimney [m]
Φ_{zon} = radiation flux [Wm^{-2}]
R = reduction factor net/gross area
n_z = efficiency

Appendix 4: Building Assessment Criteria



Appendix 5

CLIMATE CASCADE

In the building

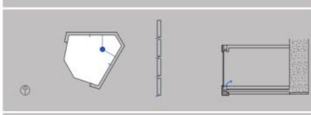
By making a cut out in the core of the building a space is created for the climate cascade. The inner ring is for the cascade, the outer ring for the supply of the air.

Also a cut out design but the supply air is distributed through the space via a raised floor. By making the cascade transparant a climatic architectural element is created.

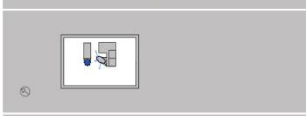
By surrounding the cascade with staircases the interaction of the cascade with building occupants is increased.

A round cut out might be more efficient for the load bearing structure. The supply shunt are accomodated in existing vertical shafts.

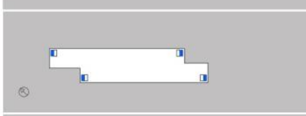
The cut out could create space for both the climate cascade as well as the vertical distribution shafts for supply air.



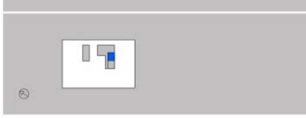
By creating more climate cascade ... ADD TEXT ...



The climate cascade could be emphasized by making it more expressive inside the building.

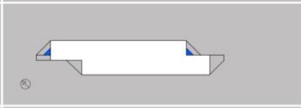


The vertical installation shafts in the existing building could be used for the climate cascade and supply shunts.

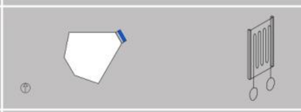


In the facade

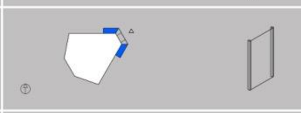
A cascade could be added built up from elements. The droplets inside the cascade could be visualised in the facade to emphasize its working principle.



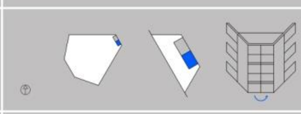
Niches in the building could be filled up with climate cascade(s). In this way the amount of facade area is reduced which enhances the energy performance of a building.



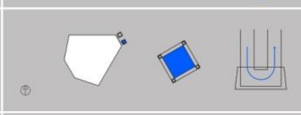
A smart skin could be used. In this way transparancy is achieved without influencing the performance of the cascade.



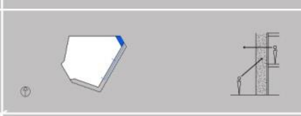
An entrance can be enhanced by placing the cascades around it. The addition of a print on a glass panel could work as sun shading and function as a communication tool.



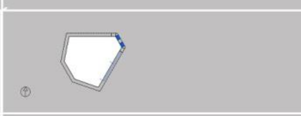
Space could be created by making a cut out in the facade. By using transparent surfaces in the facade the cascade is made explicit, but this design is subtle.



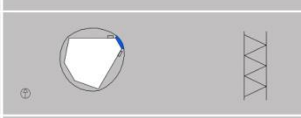
The cascade and the supply shaft could be visualised together by adding to 'towers' the the building that are connected at the bottom.



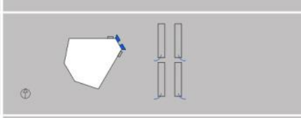
The cascade could be made visible from both the inside and outside. Louvers could be used to reduce the heat load on the transparent surfaces.



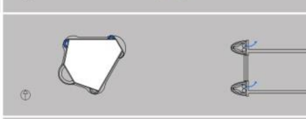
ETFE panels with a sunshading layer. In this way transparancy is achieved without influencing the performance of the cascade.



Automatically controlable horizontal sunblinds could be used to reduce the heat load on the cascade. By using LED lights the working principle of the cascade could be emphasized.

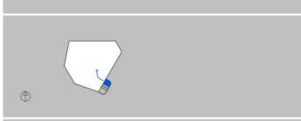


By keeping cascades as small as possible, the needed pump capacity to pump up the water is reduced together with the duct sizes.

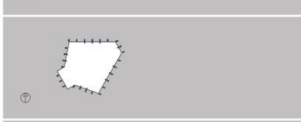


The cascades and ducts could be smoothly visualised by adding a layer around the ducts and EWF elements that changes the shape of a building.

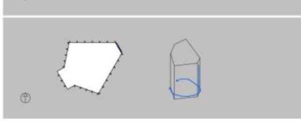
The supply and exhaust ducts could be placed on the facade. This could be useful when the free floor height is limited.



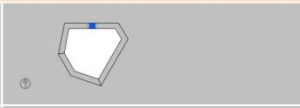
A whole EWF unit could be connected to the building to control the natural airconditioning in the building.



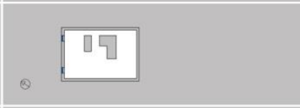
Small cascades seprate from the building with vertical supply shunts could be created. By the reducing the size of the cascade the performance is improved.



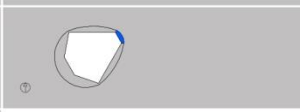
In this design a lot of small cascades and supply shunts are placed on the facade. In this way a verticality in the architectural design is achieved.



The cascade and supply shunts could be placed next to each other in a double facade. In this design integrated LED PV glass is used at the outer layer of the facade.



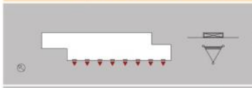
Cascade and supply shunts could be placed in front of each other in a double facade.



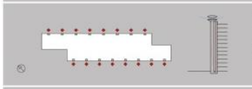
The cascade could be placed behind an extra facade layer.

SOLAR CHIMNEY

Separate from the building

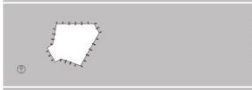


Seperate chimney's could function as sun shading device and to get more daylight into the building.

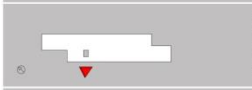


Reuse old material to construct the chimney.

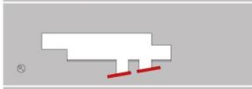
Put a small ventec roof on top of the chimney to improve its performance.

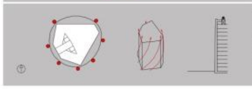


A lot of small chimney's around the building would add character but compromise on its performance.



One large seperate chimney would have a better performance than a lot of small chimney's. Seperation of the building would allow more daylight in the building.





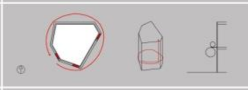
Swaying chimney's around the building wouldn't compromise its performance but add more architectural identity. Add heat recovery on top incl. turbine to produce energy.

Connected to the building

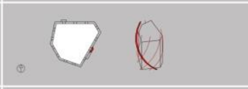
A chimney could be designed like it bumped into the existing building. By combining it with an atrium the distribution of exhaust air could also be arranged.

An expressive 'proboscis'-like chimney could be added to the building.

The chimney's and supply/exhaust shunts could be made expressive/explicit in the shape of an extra facade layer that is wrapped around the building.



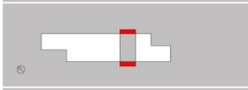
The collection of the exhaust air at the bottom of the building could be made expressive with big shunt channels that circle around the building.



The diagrid structure could be emphasized with a swaying chimney and exhaust shunts in different directions around it.

Seperate facade elements with difference characteristics (depths, material) could be designed for the different EWF elements.

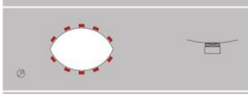
A trapezium shaped chimney with integrated exhaust shunt could be should. The shape doesn't necessarily improve it's performance.



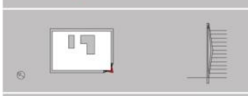
Whole floor elements could be removed to create an atrium with chimney's that stick out of the building.

Chromatic painting that fades due to temperature differences could be used to emphasize the working principle of the solar chimney.

A whole EWF unit could be connected to the building to control the natural airconditioning in the building.

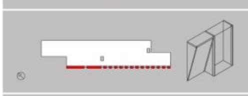


Repetative positioning of the chimney's could be used to give the building shape more character.

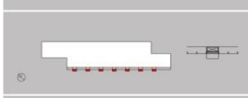


When the chimney is positioned in the corner of a building with a double facade de chimney could be emphazised by it's shape.

The level off expression in the facade could depend on the orientation of the facade. By doing so the building could get more connected with its surroudings.



The facade elements could be placed at an angle and so the chimney's with their straight vertical appearance are emphazised.



The chimney's could be 'pressed' outside to increase solar gains and to create space for exhaust shunts.

In a diagrid structure the diagonal space between the load bearing structure could be filled up with chimney's.

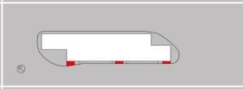
The temperature rise of the air could emphazised with LED lights that are intergrated in the chimney.

Information about the performance of the chimney could be displayed on the glass of the chimney's.

In the facade

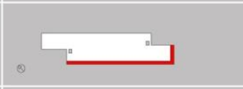
The niches in the building shape could be filled up with chimney. This doesn't make them very expressive but is effective from a climatic point of view by reducing the facade area.

The chimney could be expressed a bit in the facade by delecate changes in the shape of an extra facade layer.



The chimney('s) could be hided behind an extra facade layer that is wrapped around the building.

The chimney('s) could be hided behind an extra facade layer that is wrapped around the building.



By creating a solar facade the building shape is kept the same but the building performance is improved.

The chimney could be hided in an extra facade layer but delicately emphasized by an orientation of glass facade sheets.

Space for the chimney's could be created by making cut outs in the structure if the structure allows this.

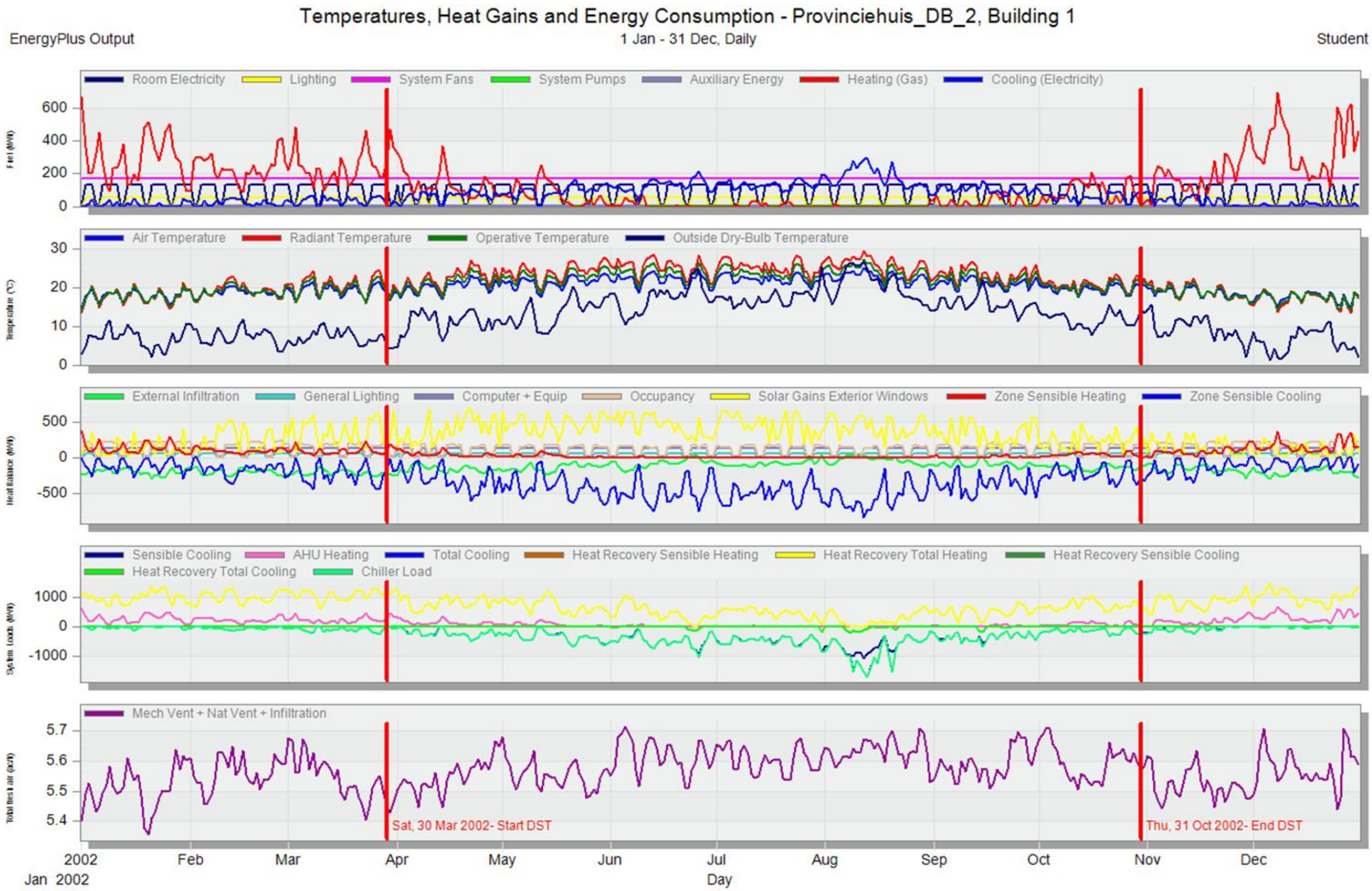
Space for the chimney could be created by cutting off a part of a corner of the structure if the structure allows this.

On the roof

By adding a greenhouse on the roof of a building, air could be sucked out of the building due to the overpressure in the greenhouse.

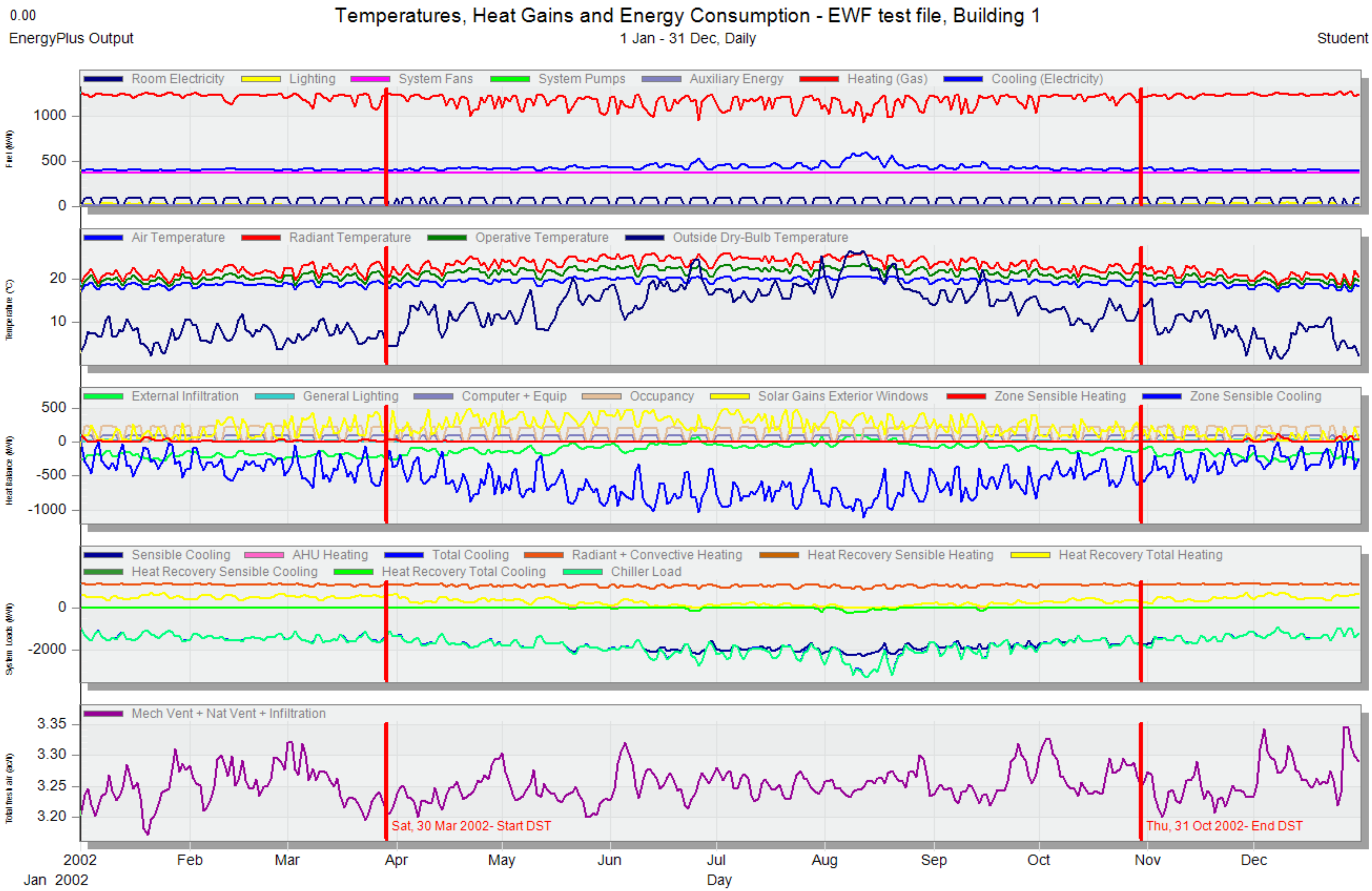
Appendix 6

Simulation setting: Mechanical ventilation, heating, cooling Lighting, computer, other equipment are on according to the default office schedule in Design Builder library.



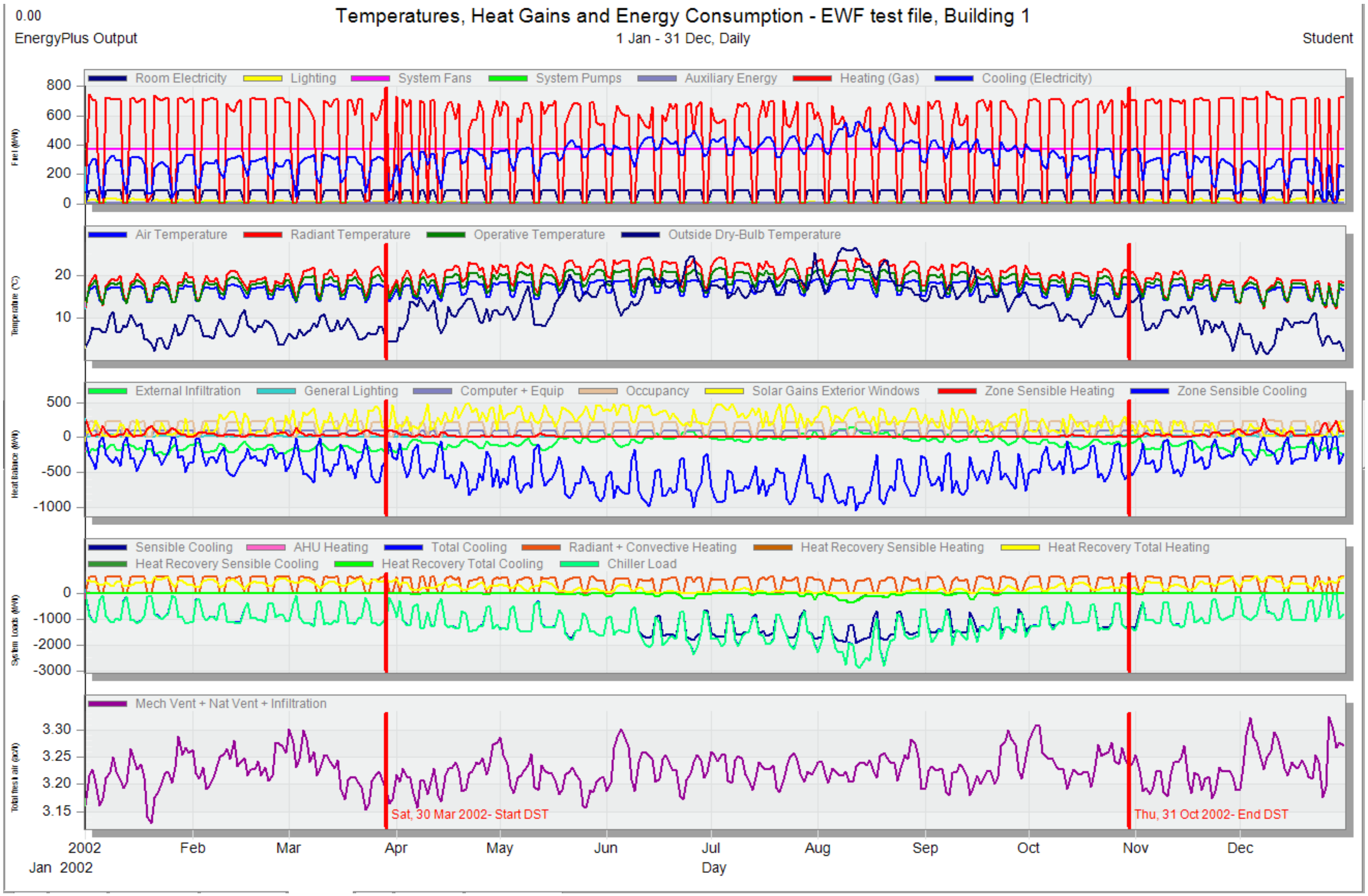
Appendix 7

Simulation setting: Mechanical ventilation, Lighting, computer, other equipment are on during weekdays and off during weekends and holidays. Heating by Radiator and Chilled ceiling for cooling is on 24/7.



Appendix 8

Simulation setting: Mechanical ventilation, Lighting, computer, other equipment are on during weekdays and off during weekends and holidays. Heating by Radiator and Chilled ceiling for cooling is on only in weekdays during cooling and heating season.

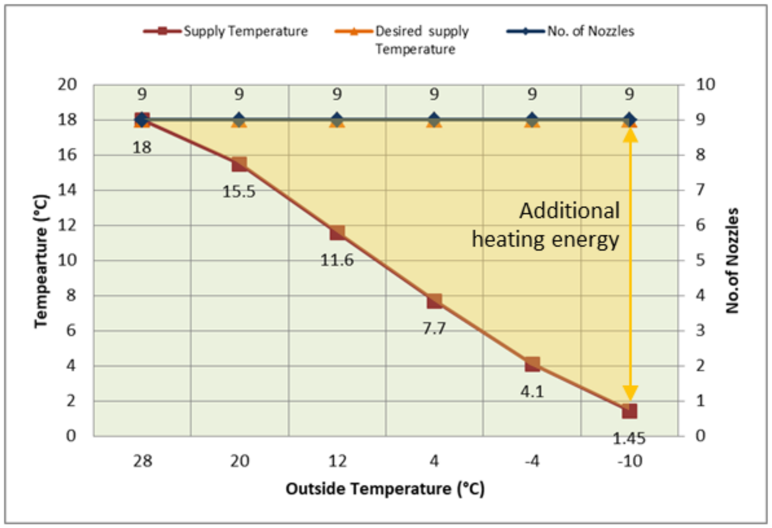


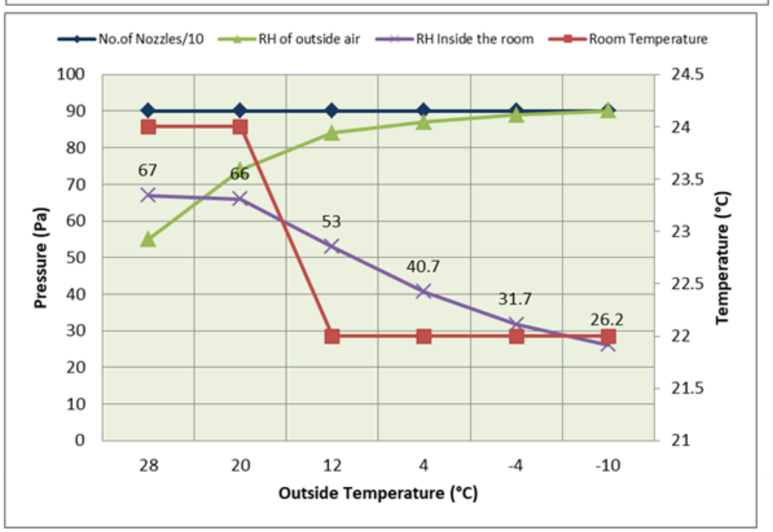
Appendix 9

Comparing the design variables of Climate Cascade for design case 1 & 3.

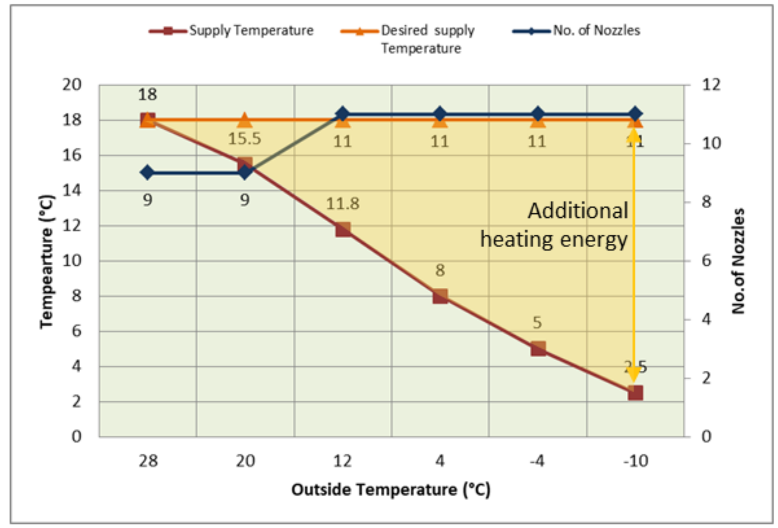
CLIMATE CASCADE: Single Cascade

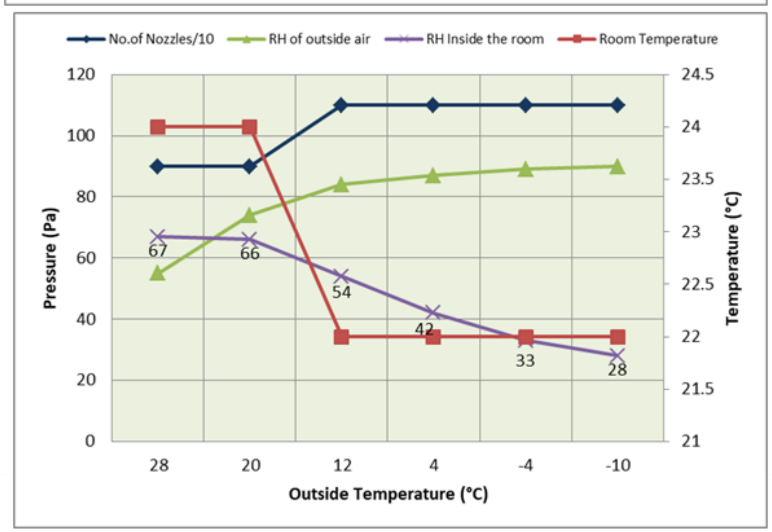
CASE 1= 1 Climate Cascade & 1 Solar Chimney





CASE 3= 1 Climate Cascade & 2 Solar Chimneys



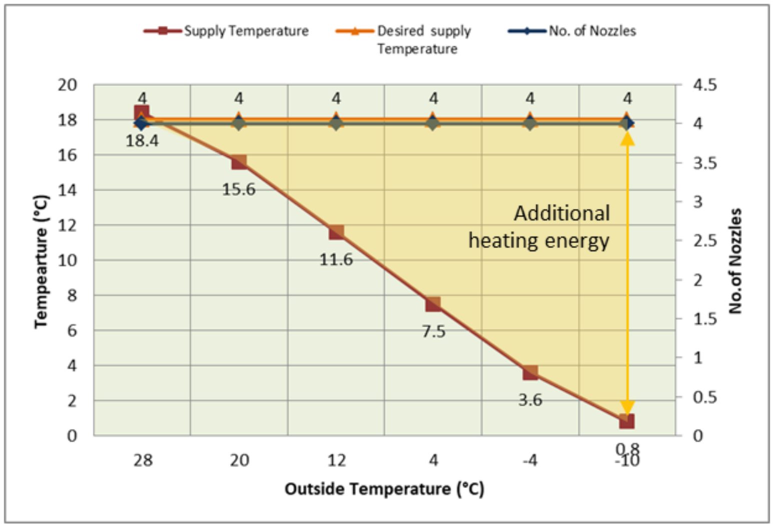


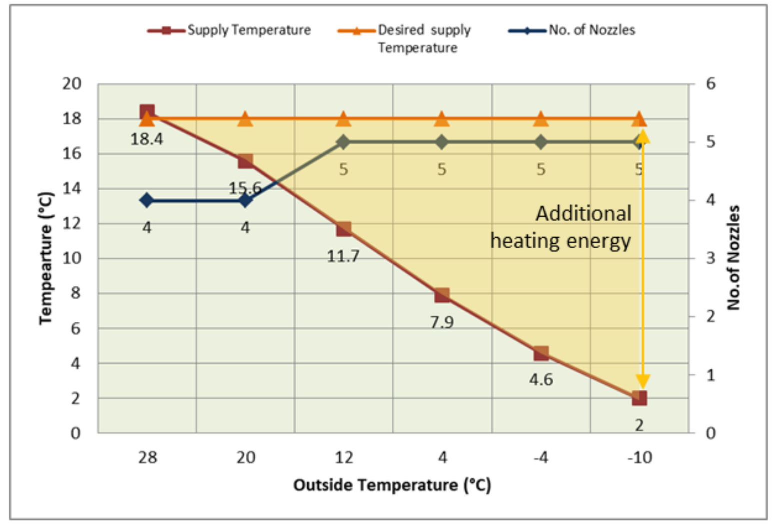
Appendix 10

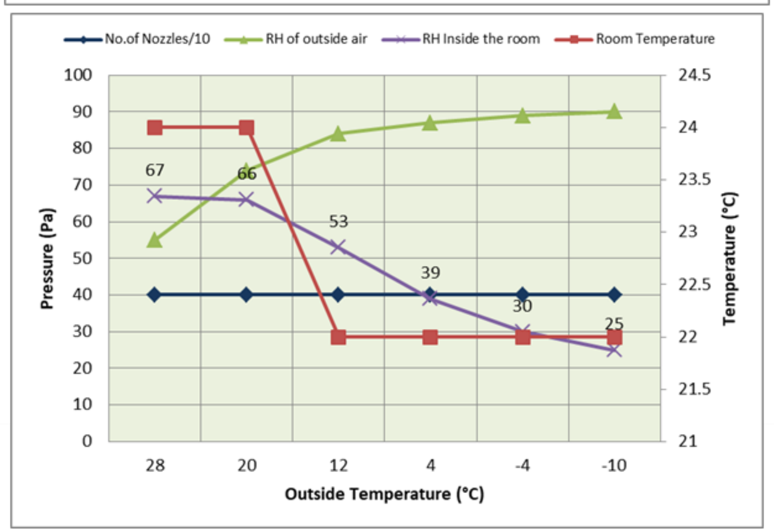
Comparing the design variables of Climate Cascade for design case 2 & 4.

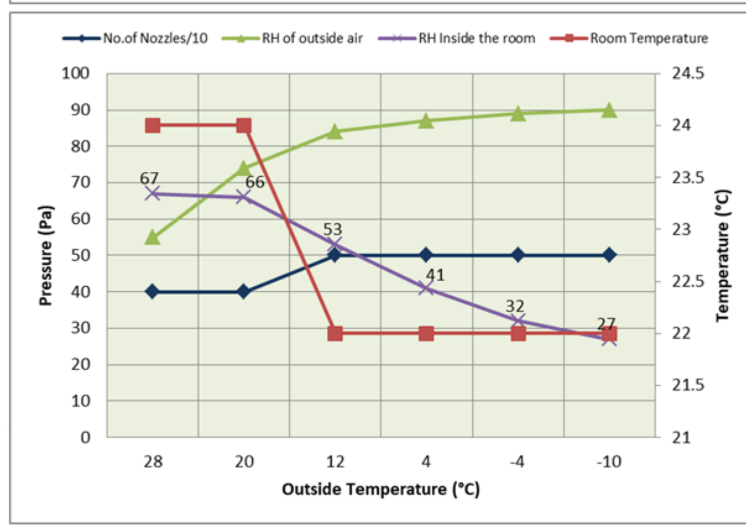
CLIMATE CASCADE: Double Cascade

CASE 2= 2 Climate Cascades & 2 Solar Chimneys	CASE 4= 2 Climate Cascades & 1 Solar Chimney





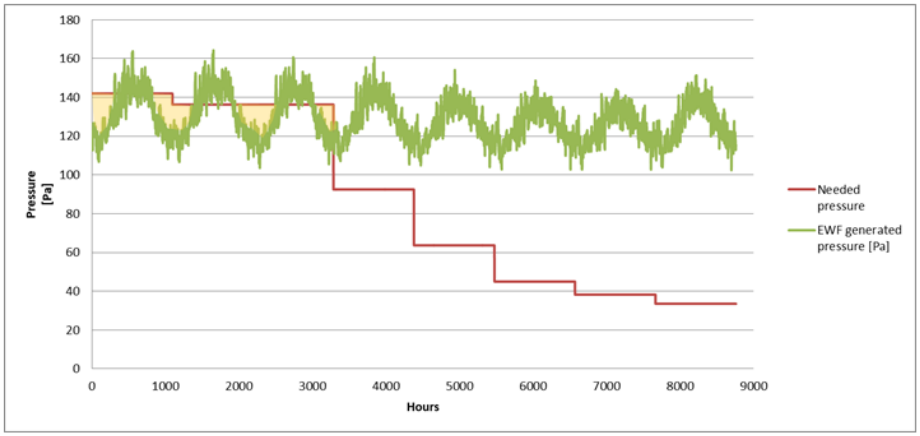


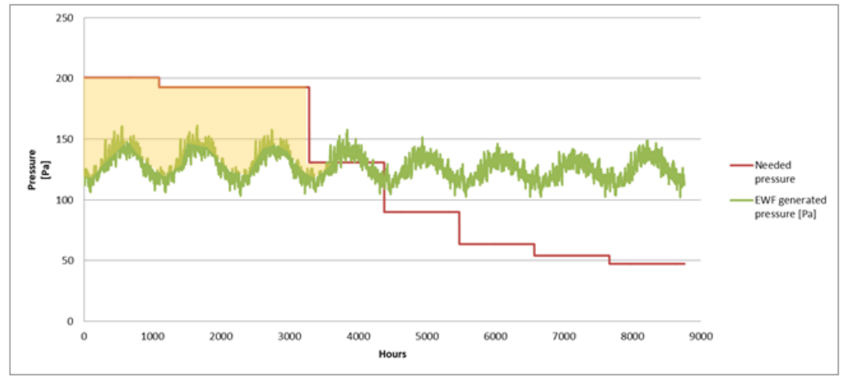


Appendix 11

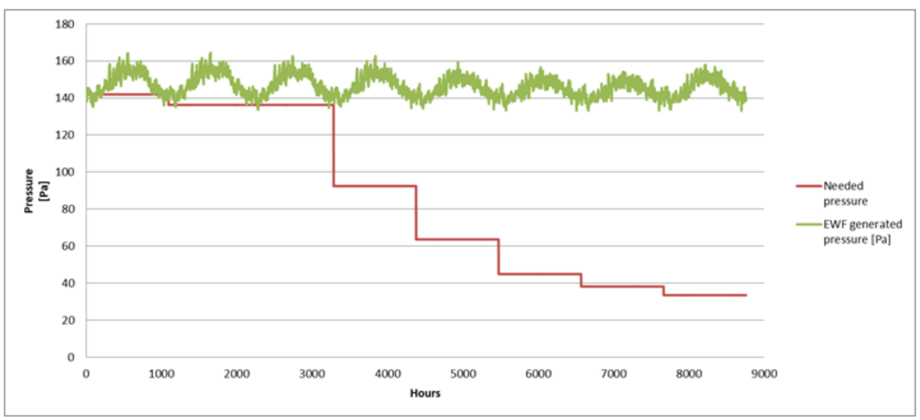
Comparison of fan energy of Climate Cascade for all design cases

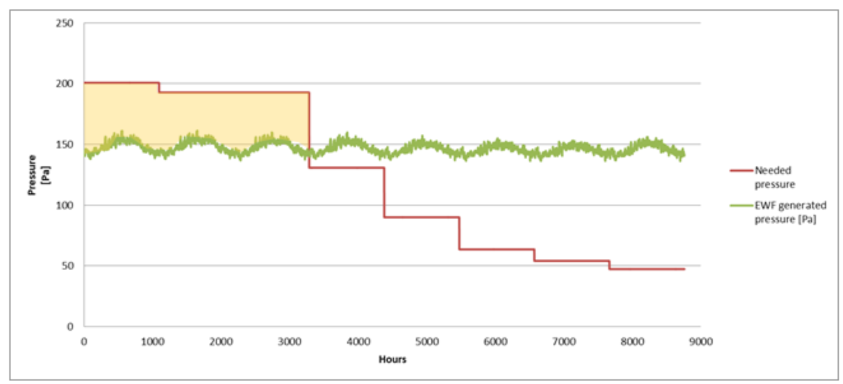
CLIMATE CASCADE: GENERATED PRESSURE	
CASE 1= 1 Climate Cascade & 1 Solar Chimney	CASE 2= 2 Climate Cascades & 2 Solar Chimneys





CASE 3= 1 Climate Cascade & 2 Solar Chimneys	CASE 4= 2 Climate Cascades & 1 Solar Chimney



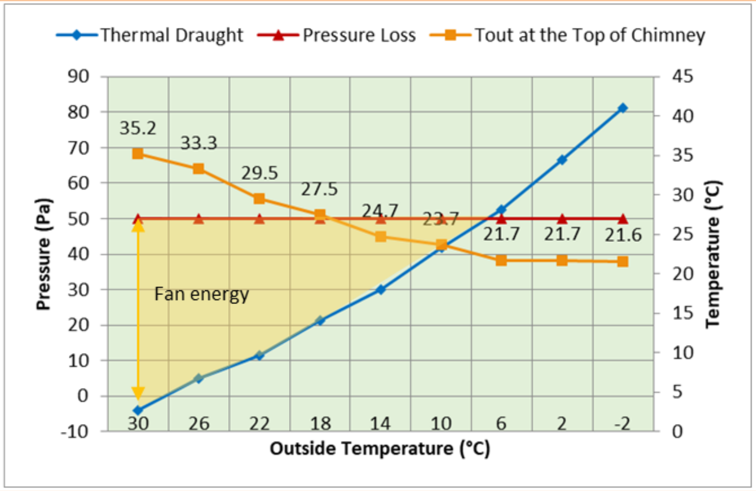


Appendix 12

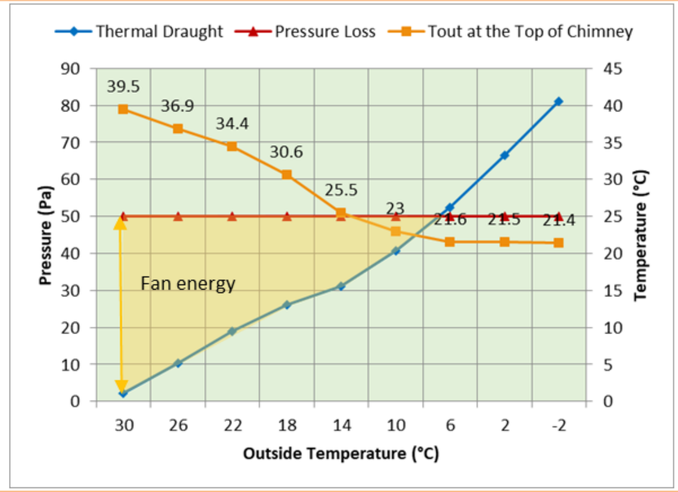
Comparing the design variables of Solar Chimney for all 4 design cases.

SOLAR CHIMNEY: Thermal draught, Pressure loss and Tout

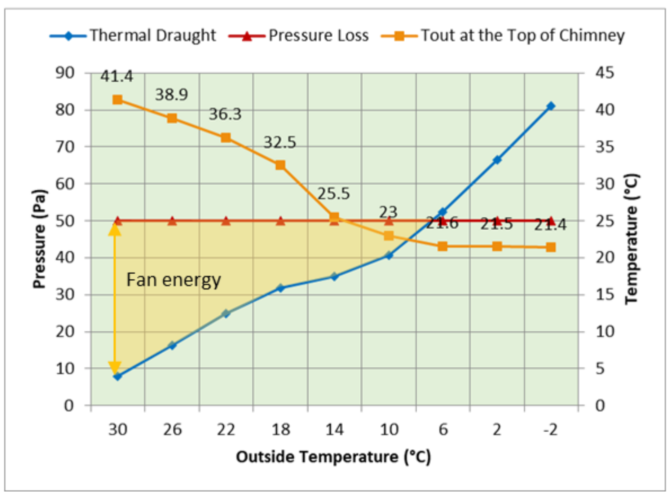
CASE 1= Single Chimney



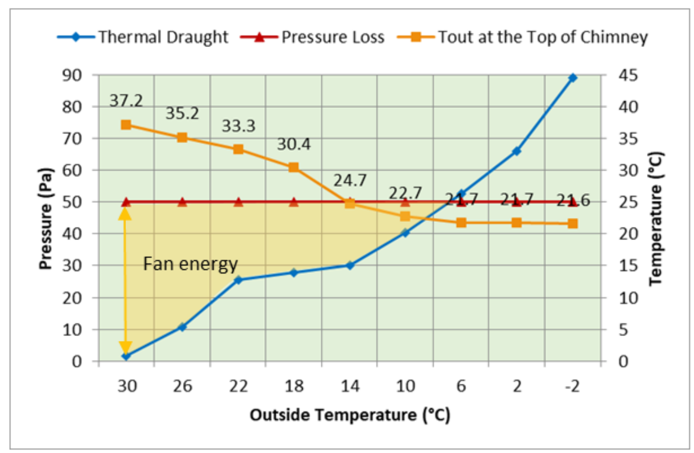
CASE 2= Double Chimney



CASE 3 = Double Chimney



CASE 4= Single Chimney

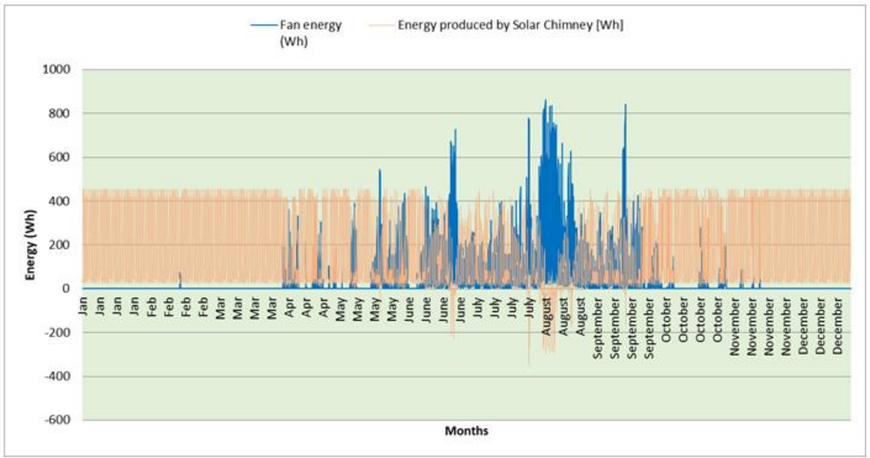


Appendix 13

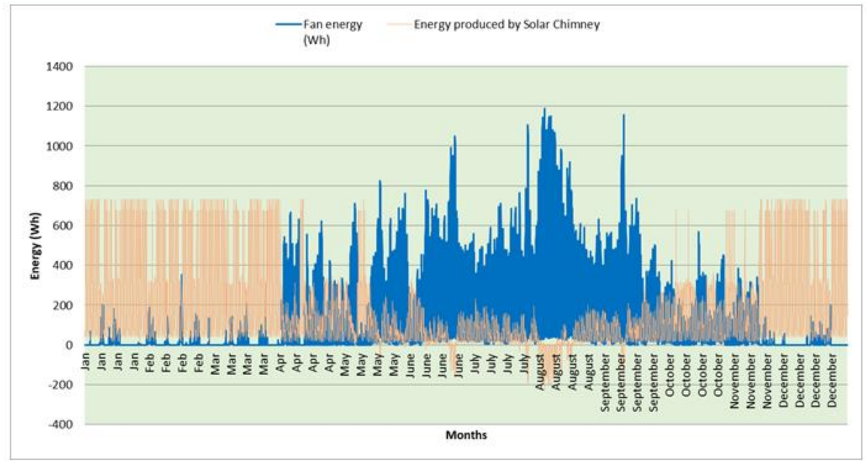
Comparison of fan energy of Solar Chimney for all design cases.

SOLAR CHIMNEY: Fan energy

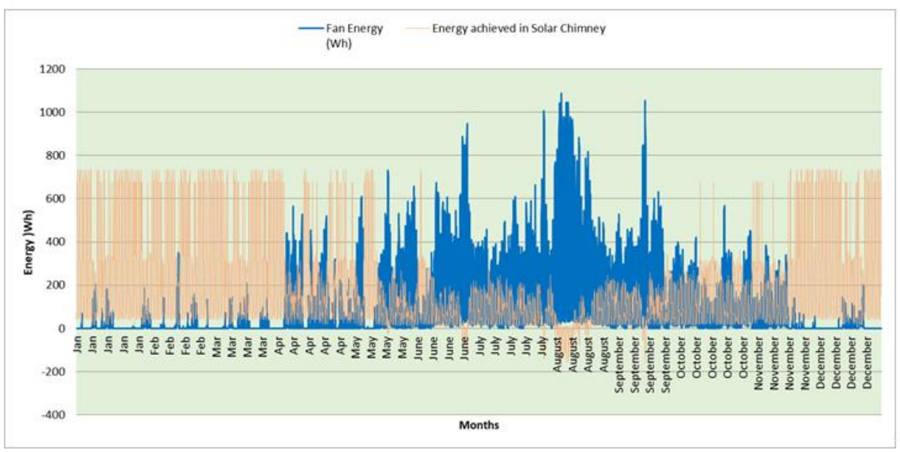
CASE 1= Single Chimney



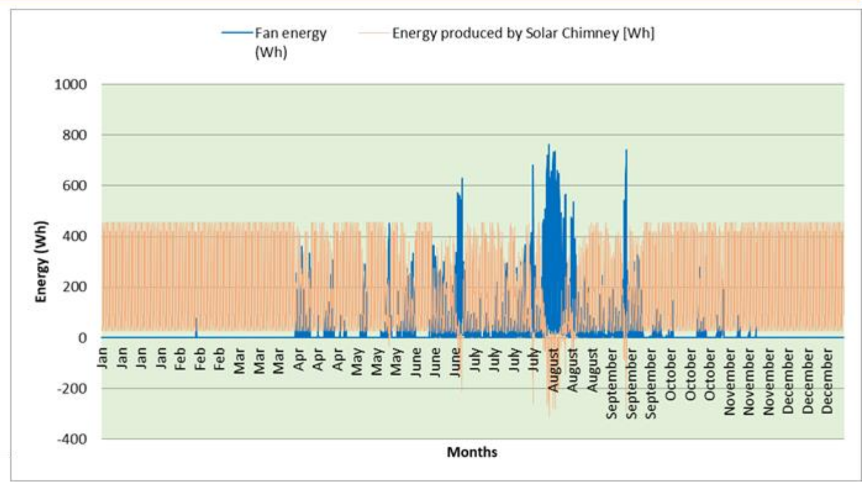
CASE 2= Double Chimney



CASE 3 = Double Chimney

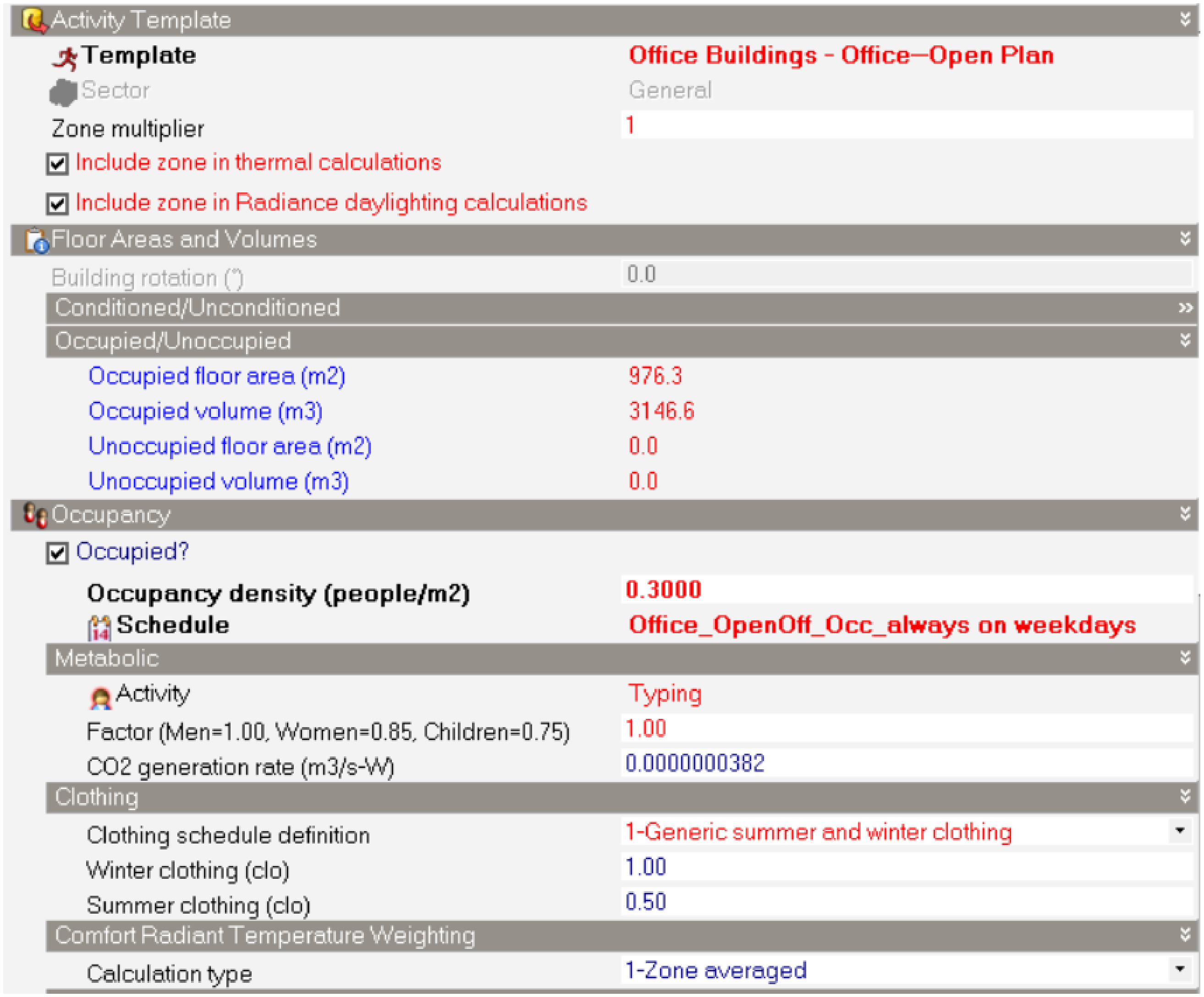


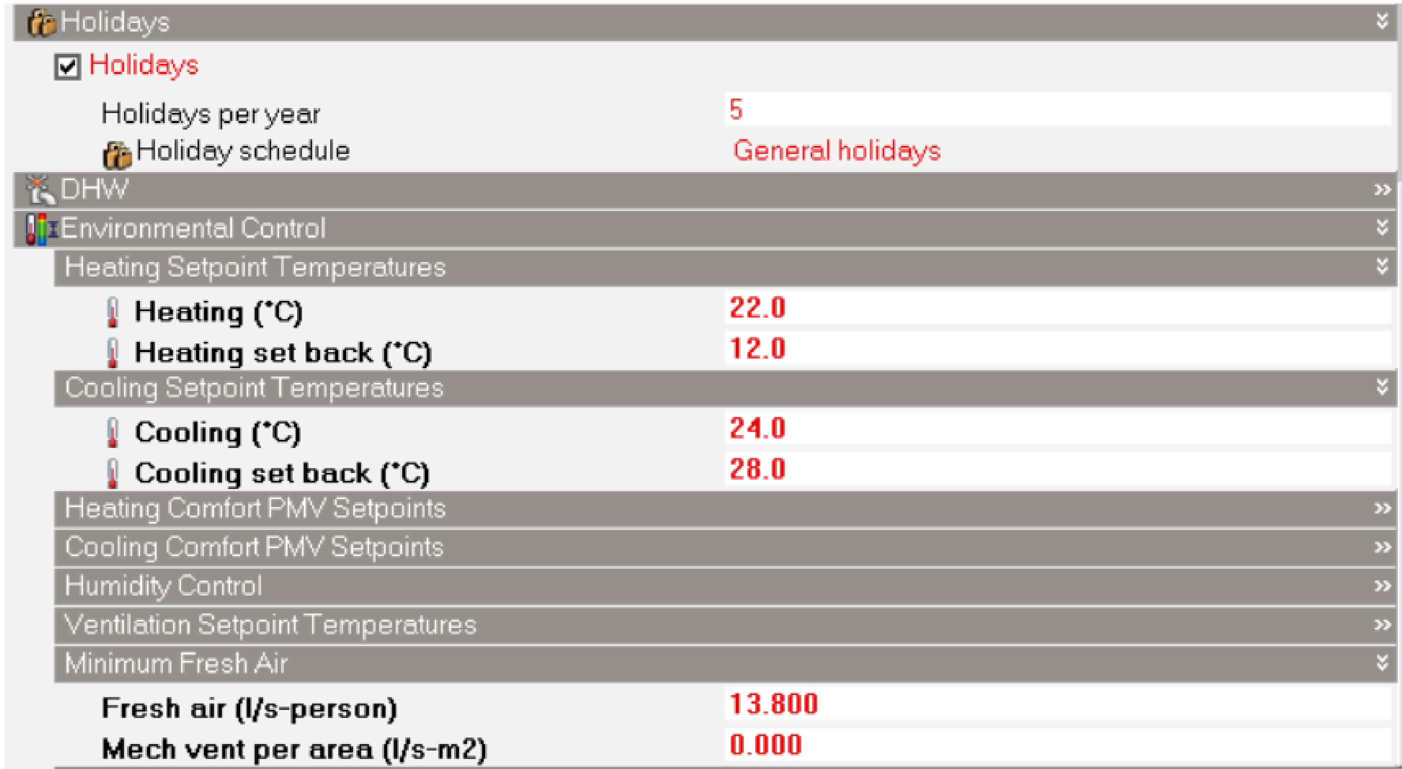
CASE 4= Single Chimney



Appendix 14

The activity data, construction, heating/cooling data used in the Design Builder for the design option with Refurbished façade and EWF system.




Holidays
Holidays
Holidays per year
5
Holiday schedule
General holidays
DHW
Environmental Control
Heating Setpoint Temperatures
Heating (°C)
22.0
Heating set back (°C)
12.0
Cooling Setpoint Temperatures
Cooling (°C)
24.0
Cooling set back (°C)
28.0
Heating Comfort PMV Setpoints
Cooling Comfort PMV Setpoints
Humidity Control
Ventilation Setpoint Temperatures
Minimum Fresh Air
Fresh air (l/s-person)
13.800
Mech vent per area (l/s-m2)
0.000


Computers
On
Power density (W/m2)
5.00
Schedule
Office_OpenOff_Equip
Radiant fraction
0.200
Office Equipment
On
Power density (W/m2)
12.00
Schedule
Office_OpenOff_Equip
Radiant fraction
0.200

Construction and Openings data

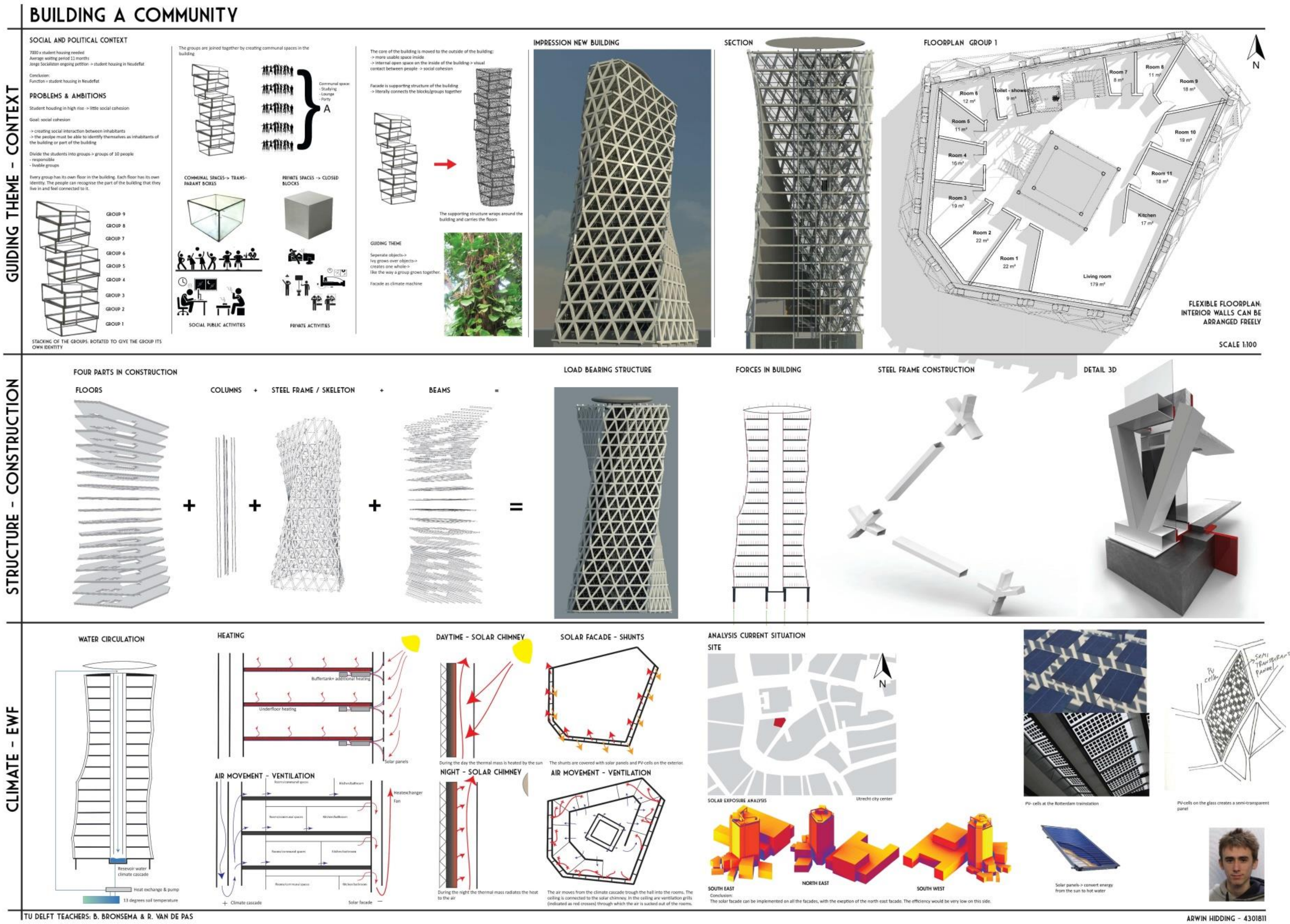
External Wall		
1	Material	Granite façade panels
	Thickness (m)	0.020
2	Material	Brickwork
	Thickness (m)	0.15
3	Material	XPS Extruded Polystyrene
	Thickness (m)	0.020
4	Material	Gypsum Plasterboard
	Thickness (m)	0.025
R-Value		3.5 m^2K/W

External Glazing	
Type of Glazing	Double Glazing with ventilated cavity
U-Value	1.2 W/ m^2K
Light transmission	80%
Solar Shading	
Internal Blinds	Blinds with high reflectivity slats
Position	Mid-pane
Control	Solar
Operation	According to Occupancy Schedule

Roof		
1	Material	Cast Concrete(Dense)
	Thickness (m)	0.050
2	Material	Aerated Concrete Slab
	Thickness (m)	0.26
3	Material	Gypsum Plaster
	Thickness (m)	0.007
R-Value		2.0 m^2K/W

Appendix 15

Some Examples of the 104 Posters submitted by students from the AE&T department for the master's course Delft Seminars on Building Technology 2013-2015 Q1 & Q3.



Delft Seminars in Building Technology

AR1A075 2014/15 - Q1 Tutors - Mauro Parravicini & Ben Bronsema

Natalia A.Valdes Cano / 4417933

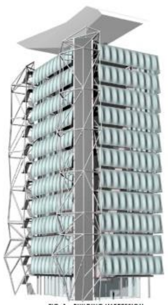


FIG. 1 - BUILDING IMPRESSION

Design Strategies

EWF Climate System / New Structure / Layer Up the Building

EWF / Stack Ventilation: One of the strategies, within a comprehensive approach, is the implementation of the EWF principles -designed by Ben Bronsema. By applying the EWF principles added internal & external shafts -drive the cool and hot air in the building. Second, integrate the EWF components as architectural features. Third, low temperature heating and high temperature cooling system with seasonal aquifer thermal storage coupled with heat pumps and solar collectors, distributeed via climate ceiling system. Fourth, Harvest Sunlight. Add rooftop PV system in the Town hall bldg. Fifth, LED lighting with occupancy and day lighting sensors, integrated via a Building energy management system (BEMS).

Layered Facade. Modulated Box Window double facade with variable ETFE cushions supported on a lightweight tubular structure, with operable panels and shading capacity. Ventilated glazing and vertical sun tracking shading. Layered Up facade. Increase building insulation by providing a double skin with operable components for IN/OUT hot-cold air circulation.

Urban Revitalization / Buildings Synergy / Coupled Solutions

Building energy use reciprocity: Maximize energy generation by integrating building features. Roof mounted PV and building integrated PV I.E. Utilize the town hall roof for PV collectors. Connect the Tower and the Town Hall Buildings via a Super Atria to support Urban revitalization of both buildings.

Maximize use of the plaza: Convert the plaza into a Green Park, reducing storm water runoff and encouraging activities in the plaza. Open the buildings ground floor to the plaza -new park. Link the Plaza park and the River park. Standalone PV based outdoor lighting elements. Storm water management system

Comfort / Flexible Open Floor Plan / Operable Facade / User Controllability

Open Floor Plan. Remove all interior partitions by increasing building floor plan flexibility, consequently flexibility use of the space. Maximize building facade openness: Maximize transparency -increase relationship with outdoors. Operable facade. User controllability of the building interior micro-climate. Natural ventilation supplemented with mechanical ventilation with heat recovery.

Acoustics. Add sound absorbers and acoustic carpets for interior acoustic comfort. Zoning of the buildings according to activities

FIG. 5 CONCEPT IDEA

FIG. 6 ETFE EXAMPLE

Site / Building Data

General Data

Building Type	Office
Location	Stadhuisplein 2 te Eindhoven
Coordinates	+51° 26' 6.0786",+5° 28' 50.9082"
Year Built	1969
Tower Typical Fl Area	543.2 M2
Floor Count Basement +	BG + 12 Office Floors + Machine
Total Tower Area	7560 M2

Heating:
Heat system : LBK and convectors
Gas consumption : 113 430 m³ per year (Gas-fired boilers)
Heating power: 534 kWt
Heat : 848 MWht

Cooling:
Current cold generation : electric chillers
Cold- release system : LBK and coolers
Electricity consumption cooling: 72 MWhe
Cooling capacity : 340 kWt
Cooling demand : 252 MWht
Degree of Insulation: Very poor

Site Design Strategies

1. Tower South West / South East Orientation allows for maximum sunlight harvesting: Solar facade, Solar Chimney.
2. Maximize building facade openness: Maximize transparency, under controlled environment (sun shades / mesh facades) and increase comfort of building users towards a supportive flexible opens-pace workplace.
3. Synergy of buildings: Utilize the town hall roof for PV collectors.
4. Connect the Tower and the Town Hall Buildings to support Urban revitalization.
5. Maximize use of the plaza: I.e Green Park and reduce storm water runoff.

FIG. 7 SITE PLAN DIAGRAM

2030 Challenge

As we approach the year 2030, the challenge to build net zero energy buildings becomes more technically challenging and complex, as well as more achievable. The amount of available wind and solar energy has always been abundant; the technology to harness renewable energy systems advances daily.

The 2030 Challenge proposes targets for the energy consumption of not only new buildings, but also the existing already built environment, reducing fossil fuel consumption. By 2030 the goal is that new and renovated buildings will be net zero energy, or require no fossil fuels, and emit no greenhouse gases.

Objectives

Energy efficiency
By reducing building energy use throughout the combination and integration of multiple energy saving measures.

Urban Revitalization
By integrating the Stadhuisplein Complex (Tower, Town-Hall & Plaza with the Site) by maximizing connectivity and use of energy synergistically.

User Comfort
By providing direct/indirect contact with the environment. By increasing building floor plan flexibility in a flexible work environment And, by increasing user controllability of Building interior micro-climate.

FIG. 7 - LOCATIONAL PLAN / SATELLITE IMAGE

FIG.8 - EXISTING BUILDING PHOTO

Design Theme

Layer Up / Reduce Mass / Increase Air / Composite Material / Filtering Facade / Modulated System

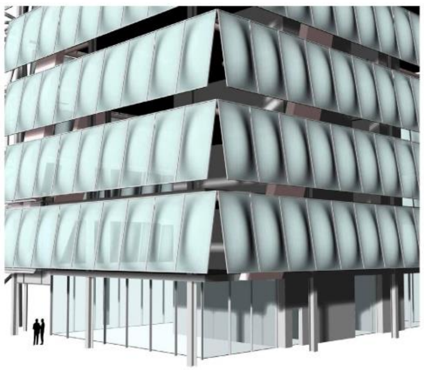


FIG. 2 - BUILDING IMPRESSION / ETFE CUSHIONS FACADE

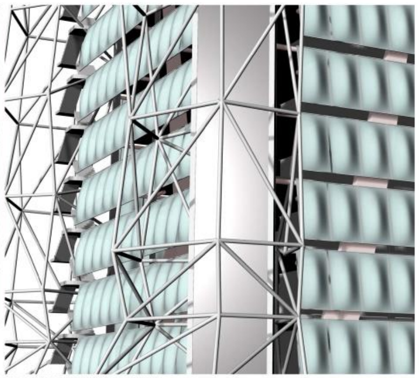


FIG. 3 - BUILDING IMPRESSION / SOLAR CHIMNEY

Earth - Wind - Fire Concept

Natural Ventilation / Climate Cascade / Solar Chimney / Ventec Roof

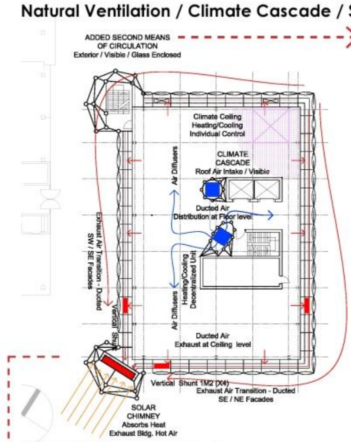


FIG. 4 - FLOOR PLAN DIAGRAM / EWF APPLIED CONCEPT - N.T.S.

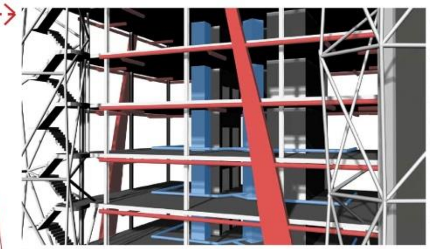


FIG.9 - BUILDING FRESH AIR SUPPLY & HOT AIR EXHAUST SYSTEMS / MODEL PARTIAL VIEW

Designed by **Ben Bronsema**. EWF Concept drives the proposal of the climate system. The fundamental principle is to supply natural ventilation by the movement of air due to the gain and lose of pressure and temperature between water and air.

The main components of the system are **the solar chimney, the ventec roof and the climate cascade.** Year round operation, the design proposes **integrating** these components into the existing structure. It locates the climate cascade (4M2) in the core of the building -visible to the users, not exposed to sunlight and enclosed by insulating glass panes. The solar chimney faces the south corner of the building, exterior and highly visible. In addition, the natural ventilated double layer facade acts as the thermal and waterproofing barrier.

The air from the climate cascade is ducted and from the ground floor up, it supplies air thought-out the building at floor level via the elevated floating deck. The exhaust air is ducted and discharged through the ceiling out to the facade sandwich, in vertical shunts, it is carried over to the solar chimney's bottom level and exhausted over the roof. At the penthouse mechanical floor, a heat recovery unit harvest heat generated by the chimney and re-circulates it back to the **building machine.**

Additional component:
Shunt Ducts. Vertical ducts move air up/down and horizontally through the floors and ceilings to the offices.
Solar chimney: consists of a translucent layer on the outside and an insulated layer on the inside covered with black foil to enhance the heat gain.
Double Facade: Provides **layered thermal barrier** while also providing ventilation **control** to the users. In summer, it allows hot air to escape. In winter, air is trapped inside to heat up and act as insulation. Cooling and Heating integrated in the ceiling fed by reversible ground heat pumps.

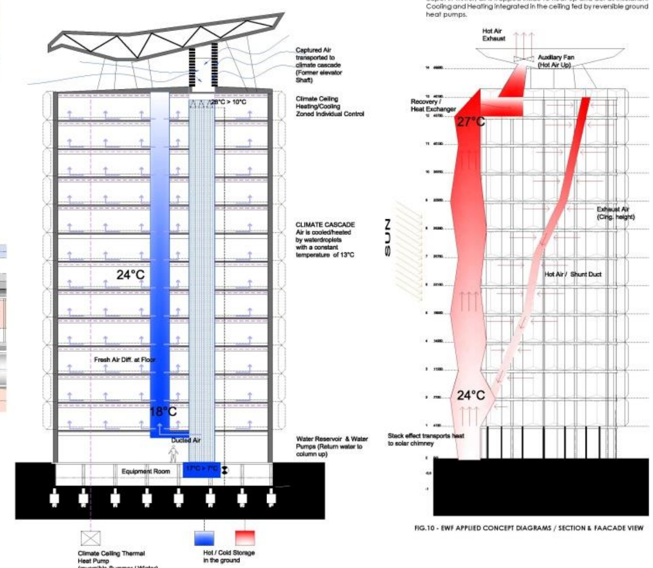


FIG.10 - EWF APPLIED CONCEPT DIAGRAMS / SECTION & FAACADE VIEW

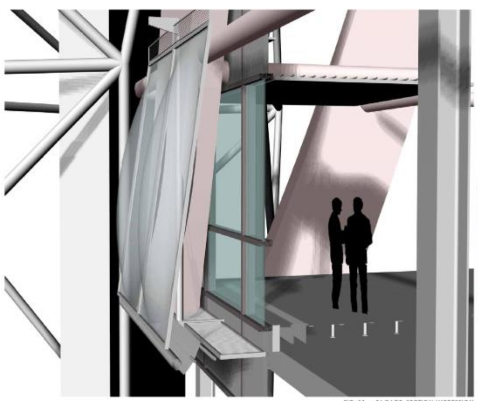
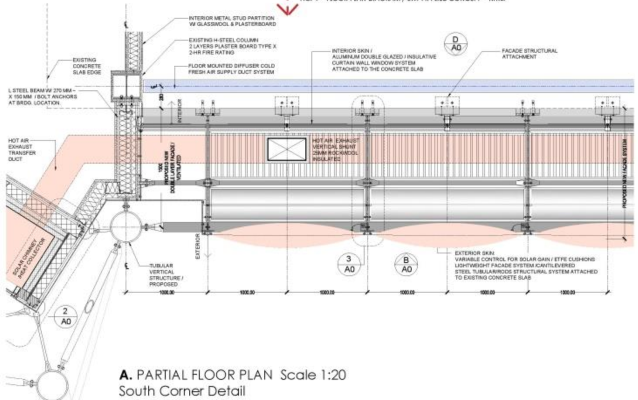
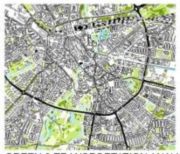


FIG. 11 - FACADE SECTION IMPRESSION

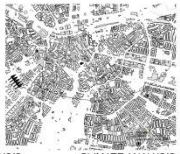


A. PARTIAL FLOOR PLAN Scale 1:20
South Corner Detail

ON-SITE BUILDING PICTURE



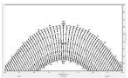
GREEN & TRANSPORTATION ANALYSIS



CLIMATE ANALYSIS

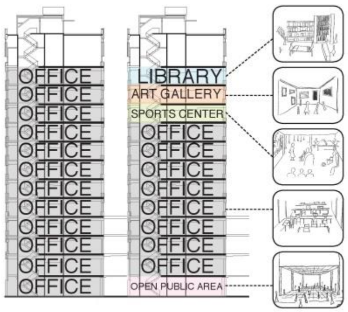
HEIGHT ANALYSIS

SITE PLAN DIAGRAM



SUN DATA DIAGRAM

CONCEPT DIAGRAM



FUNCTION DIAGRAM

Building Data:

1.General Data:

Building Type: Office
Location: Stadhuisplein 2 te Eindhoven
Coordinates: +51 26' 6.0786", +5 28' 50.9028"
Year Built: 1969
Tower Typical Floor Area: 543.2 M2
Floor Count Basement + BG + 12 Office Floors + Machine Total
Tower Area: 7560 M2

Heating:

Heating System: LBK and convectors
Gas consumption: 113 430 m3 per year (Gas-fired boilers)
Heating Power: 534 KWt
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Current cold generation: electric chillers
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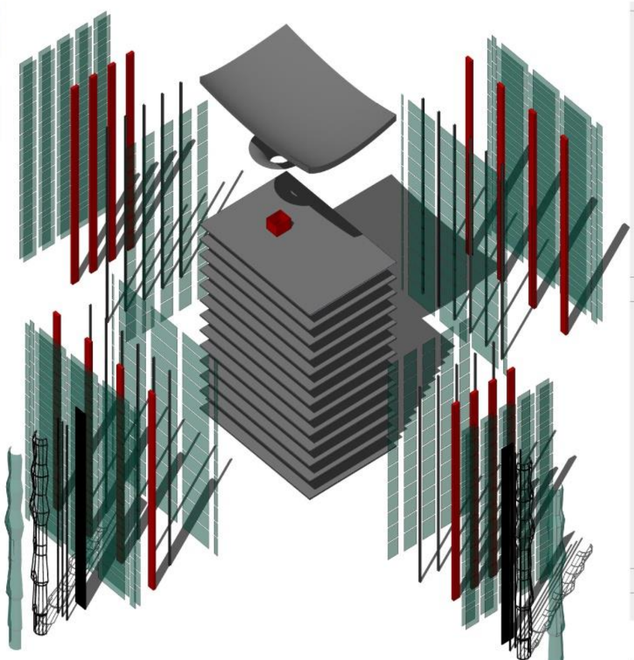
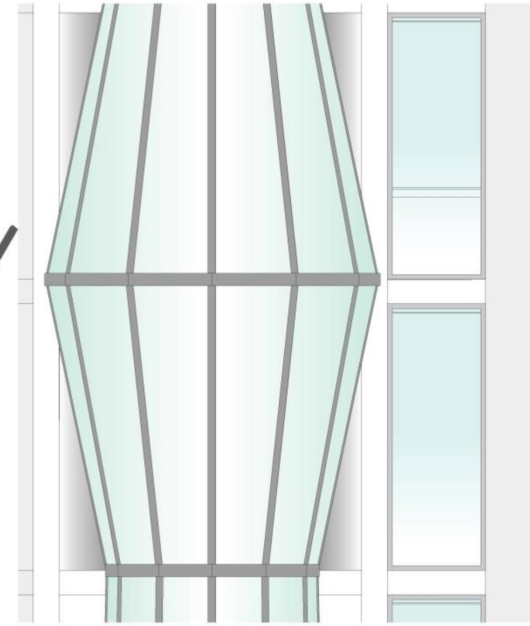
Electricity consumption: 340 KWt
Cooling Capacity: 340 KWt
Cooling Demand: 252 MWht
Degree of Insulation: very poor



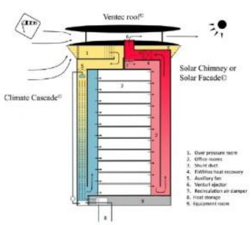


PARTIAL EXTERIOR FACADE
Scale 1:20

BETTER WORKING QUALITY
"CATALYST" TO ACTIVATE CITY /

EARTH WIND FIRE CONCEPT: SOLAR CHIMNEY / CLIMATE CASCADE / VENTEC ROOF

Delft Seminars on Building Technology (Q3 2014-2015) AR1A075 Tutors: Mauro Parravicini, Ben Bronsema Student: Yang Zhang (4432665)



EARTH WIND FIRE CONCEPT DIAGRAM

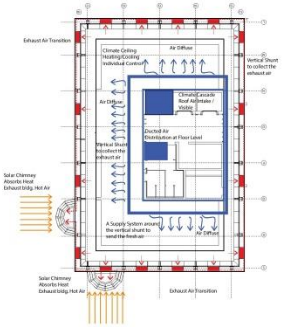
Design strategies:

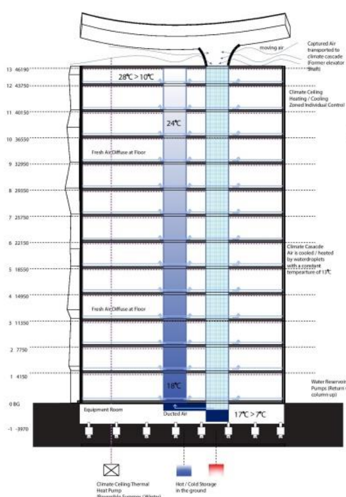
1. Integrate the EWF Principles.
Designed by Ben Bronsema, the EWF Climate System includes solar chimney, climate cascade and vented roof. In order to integrate the EWF components as architecture features to the original building, internal and external shafts and collectors are added to drive the cool and hot air in this building. By the analysis of the local climate, the solar chimneys are added to the SW and SE facade to take advantage of the maximum solar energy. The function of the solar chimney is twofold: exhaust of ventilation air and harvesting the solar energy. One of the original elevator shaft is used as the climate cascade to drive the fresh cool air into the interior. And the new air supply shuts are added under the raised floor around the supply core. The exhaust air is collected at the new added shunts around the facade with PV panels. And then they are sent to the solar chimney to move out of the building from the Ventec Roof.

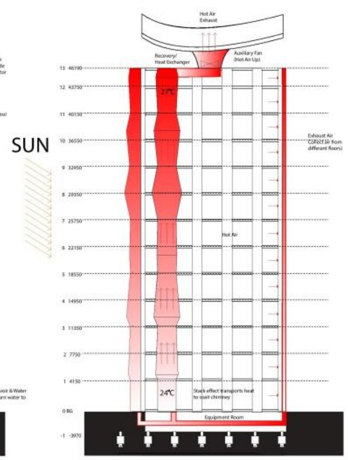
2. Structural Design.
The existing tower has a steel frame of HEA columns at a uniform structure grid, with poured in place concrete flat slabs over underground structure of piles foundation. 1M horizontal windows span along the perimeter, 4MM natural limestone cover the panel demarcating the floors. The building materials are basically natural stone, glass, concrete, steel and aluminium. The core appears to be of reinforced concrete servicing as the shaft for services, lifts and stairs.

The original steel columns are kept as the main structure working together with the service core. The secondary steel structure are added to the original one on the SW and NE facade to support the solar chimneys.

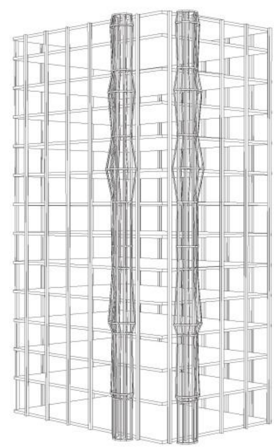
3. Urban Revitalisation.
Because of the height among the surrounding buildings, it is easily to become a landmark. More public functions are added to this building to invite the local inhabitants to activate this old constructions. And at the same time, without the interior partitions, the open flexible space is useful for circulation of the air.



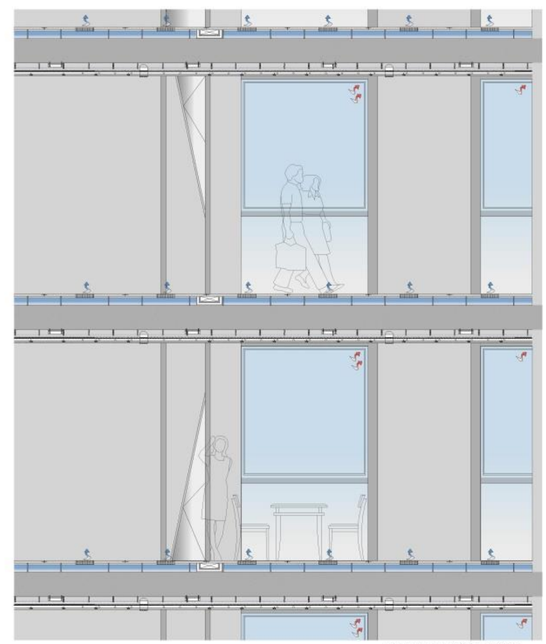




EWF APPLIED CONCEPT DIAGRAMS /
FLOOR PLAN & SECTION & FACADE VIEW

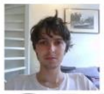


STRUCTURE DIAGRAM



PARTIAL INTERIOR FACADE
Scale 1:20

Delft Seminars on Building Technology



Jasper Vos 1533649 (AR1A075) 2014/2015 Q1

Tutors: Mauro Parravicini , Ben Bronsema

OPENING UP THE OFFICE

Fig. 1a

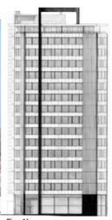


Fig. 1b

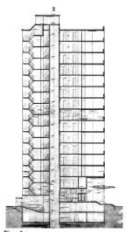


Fig. 1c

Fig. 2a

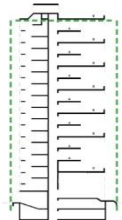


Fig. 2b

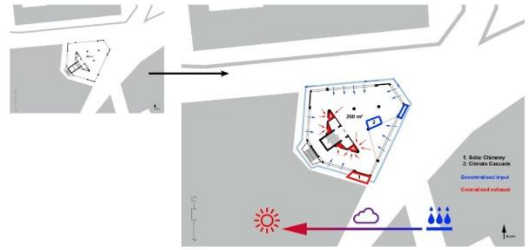


Fig. 4a

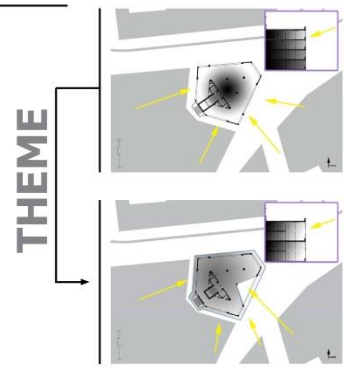


Fig. 3

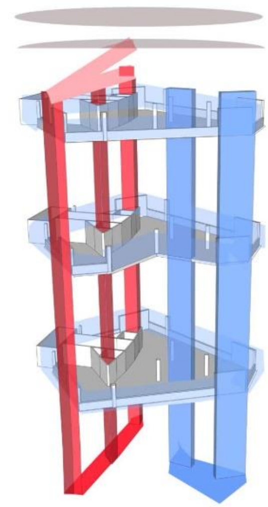


Fig. 4b

Fig. 8a

Fig. 8b

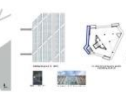


Fig. 8c

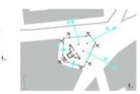


Fig. 8d

Fig. 1
Old situation
1a. The Neudeflat today
1b. Elevation of south/east facade
1c. Section on long side of the building

Fig. 2
New situation
2a. Schematic design of S/E facade
2b. Schematic section introducing a new building envelope and opening cuts in floors

Fig. 3
Theme

Opening up the building by taking out cuts of the floors. creating double high indoor 'sky gardens' and letting in more light into the center of the building

Fig. 4
Climate Concept
4a. Schematic floorplan introducing Earth, Wind and Fire concept. locations of vertical shafts can be seen.
1. Solar chimney
2. Climate cascade
building uses decentralised in put of fresh air and centralised exhaust via existing shafts in the building core.
4b. 3d schematic view of EWF concept airflow applied to Neude flat.

Fig. 5
Building fragment

3d section of chosen building fragment Horizontal airsupply ducts follow the facade. Ducts follow the cut out shape so that double high facade is kept clear and fresh air is supplied towards the center of the building. alsо the functioning of the climate cascade can be seen as the walls of it are translucent (dark blue on the left)

Building analysis:

After visiting the Neudeflat in Utrecht a lot of things can be said about the building. First of all the 1960's building stands in the hart of the city next to the neudeplein. The building (59m) really stands out because the surrounding buildings are much lower (+/- 20m). Except from direct streetview because of surrounding trees. The building has a triangular floorplan. The building is really energy inefficient and has thermal bridges all over the facade. There is no mechanical ventilation. the building overheats in summer and is cold in winter. The floorhight is limited (3meters). The Building has a concrete construction with a core and loadbearing parts in the facade. In the center of the building it's dark because daylight can not penetrate far into the building. The building is not in use at the moment since the last users are moving out. positve things about the building is the nice view and the central location.

Making changes:

First of all the building needs to be properly insulated. Herefor is chosen to create a new building envelope. which has it's own construction. It is wrapped around the building as a seperate layer. The design is based on two Guiding themes: 1) Earth, Wind an Fire; a natural ventilation concept based on the difference in airpressure and 2) Opening up the building.

Guiding theme:

The guiding theme for this project is opening up the building. By that it means that in the future one can work inside this building and doesn't feel locked up inside. The limited floor hight and little light inside the center of the building cause these locked up feelings and therefor need to be changed. On every second floor an opening towards the south is made to let more daylight into the building. These openings create a double high atrium which is used as an indoor 'sky garden' . Due to the cut outs the users may lose some floorspace but gain much more valuable things: the feeling of freedom, openess and a healthy work-environment.

Climate Concept: Earth, Wind and Fire

This ventilation concept is based on the difference in airpressure. Three main elements are influential and work together to create an optimal airflow through the building. These elements are called: the Ventec roof, the Solar chimney and the Climate cascade. This presentation about a fragment of the building focuses more on the Climate cascade and the airsupply into the building. The climate cascade is a vertical shaft in wich water drops like rain. In this project the climate cascade is put in a central location and made translucent to show the functioning. So people can see the actual rain inside the shaft. Due to the limited floorhight the horizontal airsupplyducts can not be put in a lowered ceiling. This conclusion in combination with the needed new building envelope has led to the idea of letting the horizontal ducts follow the facade. Cold air is best supplied in near the floor so the ducts can be used as integration of the parapet. Hot air is exhausted via the existing core of the building and flows via the solar chimney and ventec roof out of the building. The excesive heat can be regained in the top of the solar chimney and be stored in the ground for when it's needed.

2030 proof:

To make the building still functioning well in 2030 it needs to be more sustainable.
First of all the Earth, Wind and Fire (EWF) concept is applied. Second, creating a healthyworking environment with flexoffices in the middle of the city is a strategie that could really work for a city as Utrecht. And third argument is of estetic nature, The facade is kept simple and clear to let the building blend in with the surroundings and not stand out in the middle of lowrise resedential buildings.

Fig. 6
Exploded view

From left to right:
1 Existing structure with double high room
2 prefab steel plant containers
3 new envelope structure
4 aluminium curtain wall (inside)
5 double glazing low-e coated
6 insulation
7 sandwichpanel insulated aluminium with building integrated pv-cell
8 aluminium curtain wall (outside)

Fig. 7
Schematic section

1 decentralised cold air outlet to centralised hot air exhaust.

2 No direct sunlight into offices in summer due to angle and in winter due to plantshading.

3 visual experience of green while working due to openable windows in second skin

Fig. 8
analysis drawings

8a. bad routing becaus of dead ends.
8b. create open floorplan and improof circulation
8c. proposed use of building integrated pv cells in west facade
8d. analysis of view in al facades

Fig. 5

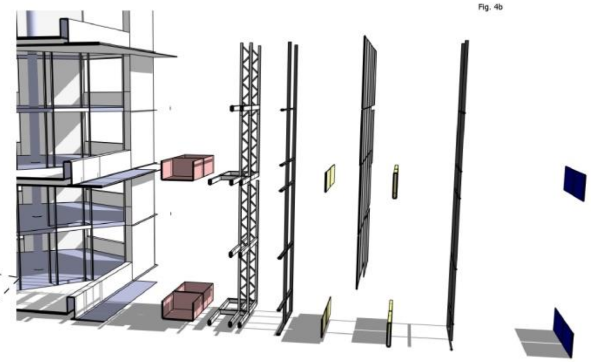
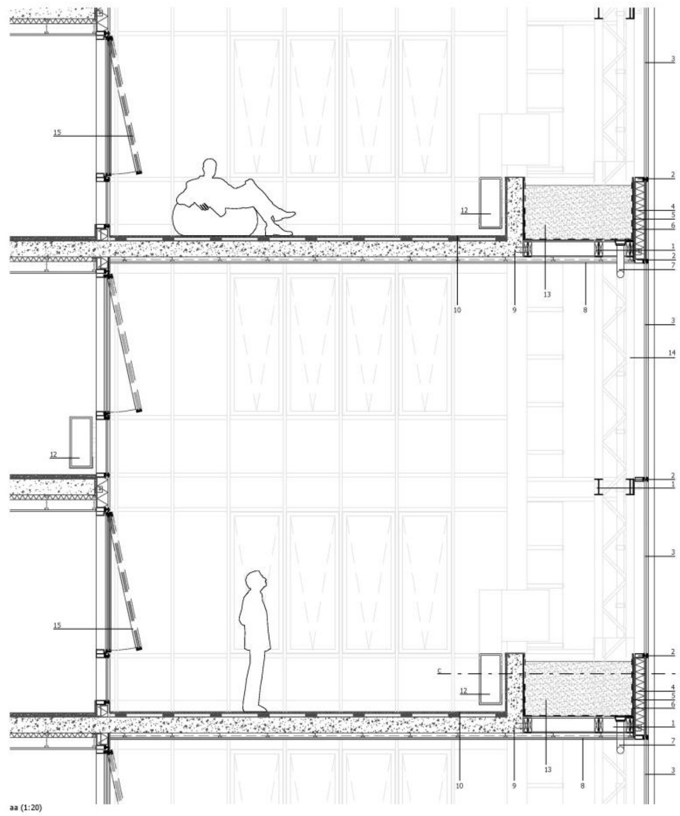


Fig. 6

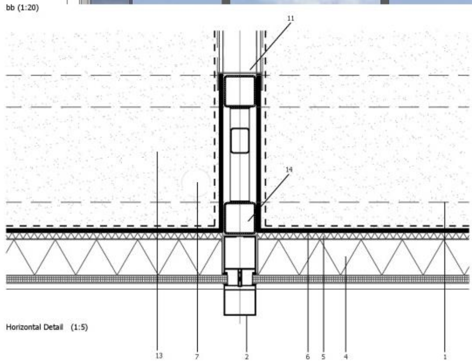
Fig. 7

bb (1:20)

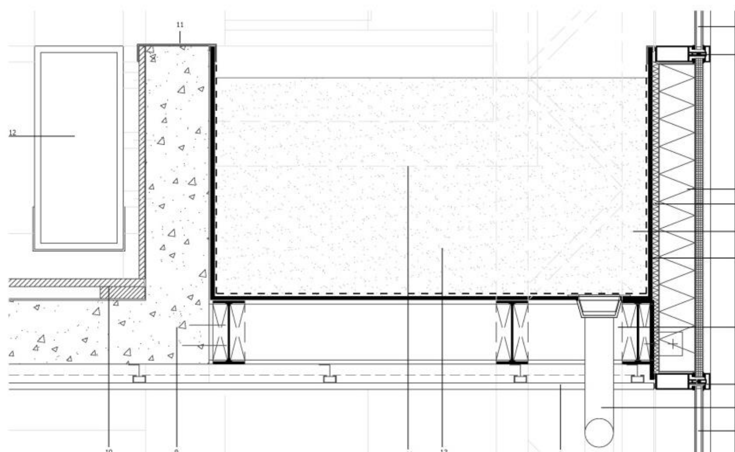


aa (1:20)

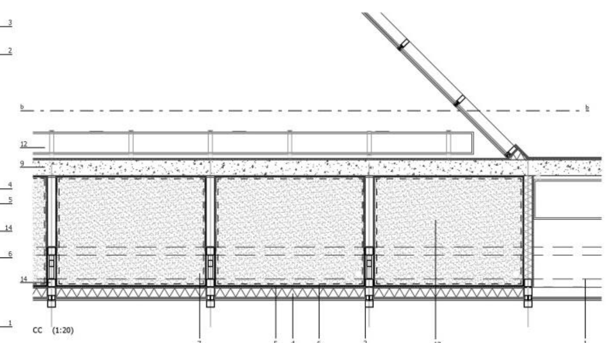
Elevation (1:20)



Horizontal Detail (1:5)



Vertical Detail (1:5)



CC (1:20)

1	steal construction profile IPE 200	8	lowered ceiling , perforated steel sheet with acoustic mat
2	aluminium curtainwall system 125mm mullion	9	200 mm concrete (existing), 17 mm multiplex sheet
3	double glazing low-e coating	10	floor: 3mm foil, 30mm sleepers, 30 mm wooden flooring
4	prefab sandwich panel insulated aluminium with building integrated PV-cell	11	aluminium covering sheet 3mm
5	insulation 20mm	12	horizontal airsupply duct with air outlet every 1800mm
6	prefab plantcontainer 12 mm steel with waterprofing	13	soil
7	gutter pipe	14	construction steel 2x 100 mm box beam with truss
		15	openable window