Summer comfort In energy efficient high-rise dwellings

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Summary

Nowadays, the high rate of urban population growth due to immigration and scarcity of land has significantly increased the need for new high-rise dwellings. Meanwhile, the recent building regulations require buildings to be highly energy-efficient to reduce the building's impact on the environment. However, the inherent characteristics of these new energy-efficient high-rise dwellings put them at higher risk of overheating. In addition, with the effect of climate change, the risk becomes even higher in the future. Though this problem could be addressed by the means of active cooling, doing so will increase the energy consumption of the building, confronting the core concept of the energy-efficient dwellings.

Therefore, this thesis investigated passive and energy-efficient solutions for the overheating problem in energy-efficient high-rise dwellings of temperate climate. Design Guidelines helping designers in addressing the overheating problem in tall buildings were introduced. Then, by applying bundles of these solutions through redesigning the façade of a case study building effectivity of the purposed solutions were investigated for the Dutch context.

The simulation results verified that overheating can still be prevented in the future by passive means. A proper combination of the thermal mass, heat dissipation and heat protection techniques with considering adaptivity in thermal comfort displayed that overheating can be prevented even by the end of the century.

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1. Research framework

1.1. Background information

In recent years, there are global concerns toward greenhouse gasses and their environmental impacts. Global warming is a renowned effect caused by these gases. Climate observations already show extreme weather conditions because of global warming (Yao & Hasby, 2013).

It is estimated that housing contributes to almost a fifth of the CO2 emission in the Europe (housingeurope.eu, 2018). To mitigate this problem EU commission issued a directive that expects its members to take measures in order to guarantee that by the end of the 2020 all new buildings are highly energy efficient within which large extent of remaining required energy is covered by renewable energy (EPBD).

To achieve this, European governments have introduced stricter rules to decrease building's energy demand. Since most of these countries are heating dominated, the regulation requires buildings to be highly airtight and insulated to reduce the heating demand (Gupta & Gregg, 2018)

However, studies show that this could cause overheating and inadequate ventilation inside these buildings (Gupta & Gregg, 2018). Many studies over recent years already showed high risk of overheating in energy efficient dwellings (Melcnik et al, 2012; Hamdy & Hensen , 2015; Gupta & Gregg, 2018; Brotas & Nicol, 2017). High temperature, decreases occupants thermal comfort and could cause serious health problems for them (Hamdy & Hensen, 2015; McLoed el al., 2013; Gupta & Gregg, 2018).

Moreover, studies showed, with the current situation of global warming, that average temperature is predicted to increase with more hot periods causing overheating to become more communal in the future. (Hamdy & Hensen, 2015; McLoed el al., 2013; Gupta & Gregg, 2018, ZCH, 2015). Besides that, the predictions show an increase in cooling demand from 25% to 460% by 2080 depending on the location and climate change scenario (Dodoo & Gustavsoon, 2016; Karimpour et al., 2015; Olonscheck et al., 2011).

1.2. Problem statement

High-rise dwellings are at higher risk of overheating compared to different typologies of residences (Hamdy & Hensen, 2015; Lomas & Porritt, 2017; Hamdy et al., 2017)

There are several characteristics in high-rise buildings that make them vulnerable toward overheating (Nebia & Aoul, 2017; Baborska-Narozny & Grudzinsk, 2016; NHBC, 2012; Lomas & Porritt, 2017):

- The market preference which prefers larger glazing without external shading for a better view and daylighting
- Utilization of mostly lightweight material for construction
- Limited ventilation due to apartment typology and high wind speed at the height
- Stack effect caused by community heating pipework in corridors and common spaces.

Addressing this problem with active cooling systems is possible, yet utilizing active cooling methods eventually increases the energy demand, which confronts the energy efficiency policies of the new buildings.

1.3. Objective

The goal of this research is to identify energy efficient and passive measures that could be used to decrease the risk of overheating in energy efficient high-rise dwellings in temperate climate with high window to wall ratio.

As the case study a high-rise dwelling in Netherlands is selected to examine a solution package through facade design. Through this the effectivity of these measures in prevention of overheating in the apartments is examined.

1.4. Research Questions

The main research question is:

How to prevent overheating in energy-efficient high-rise dwellings of temperate climate with high window to wall ratio without using active cooling?

Sub-questions:

What is the definition of an energy-efficient high-rise dwelling?

What are the thermal comfort considerations in energy-efficient dwellings?

What is the definition of overheating?

What are the sources of overheating in buildings?

What are the factors that could increase the risk of overheating in buildings?

What is climate change's impact on the overheating of dwellings?

What are the possible energy-efficient solutions for overheating?

Can these measures help to avoid active cooling in the future as global temperature rises?

1.5. Methodology

In this section the methodology of the research is presented. This thesis consists of four phases which starts with the specification of the topic, then comes the background study. After that methodology of design and analysis will be delivered and last phase is the simulation and evaluation. Later in this chapter each phase will be discussed in detail.

1.5.1. Phase 0: Specifying the topic

At the beginning for specifying and defining the research question, an initial literature study regarding discomfort in energy-efficient buildings was done.

The study showed, that the thermal discomfort -especially overheating- is a major problem in the energy-efficient dwellings (Mlecnik et al., 2011; Rojasa et al., 2015, Figueiredo et al., 2016; Pomfret & Hashemi, 2017).

The subsequent, a discussion was held with the consultancy firm Wolf+Dikken, which is specialized in building physics and services. The main message from this discussion was that the high-rise energy-efficient dwellings are more at the risk of overheating which later further literature review confirmed (Hamdy & Hensen, 2015; Lomas & Porritt, 2017, Hamdy et al., 2017, Nebia & Aoul, 2017; Baborska-Narozny & Grudzinsk, 2016)

1.5.2. Phase 1: Background study

In this phase, a more in-depth literature study was done in order to answer the sub-questions of the research. The sources were collected employing scientific literature search engines and databases such as Google Scholar, Scopus, Taylor & Francis, Researchgate and Science direct. In addition, several PhD theses and national guidelines were studied in order to build background knowledge.

1.5.3. Phase 2: Guidelines & analysis

After completing the literature review, collections of overheating prevention design guidelines were developed.

Next, a case study provided by Wolf+Dickken were analyzed numerically and analytically so that the characteristics increasing the risk of overheating could be found.

1.5.4. Phase 3: Design & evaluation

After the second phase design collections which are suitable for the case dwelling were chosen in order to study the possibility of addressing overheating through facade design. Several design variations were considered and were evaluated through dynamic simulation and design criteria. Then the best characteristics of the design variations were selected for the final proposed design. Lastly, conclusions and suggestion for further development are delivered.

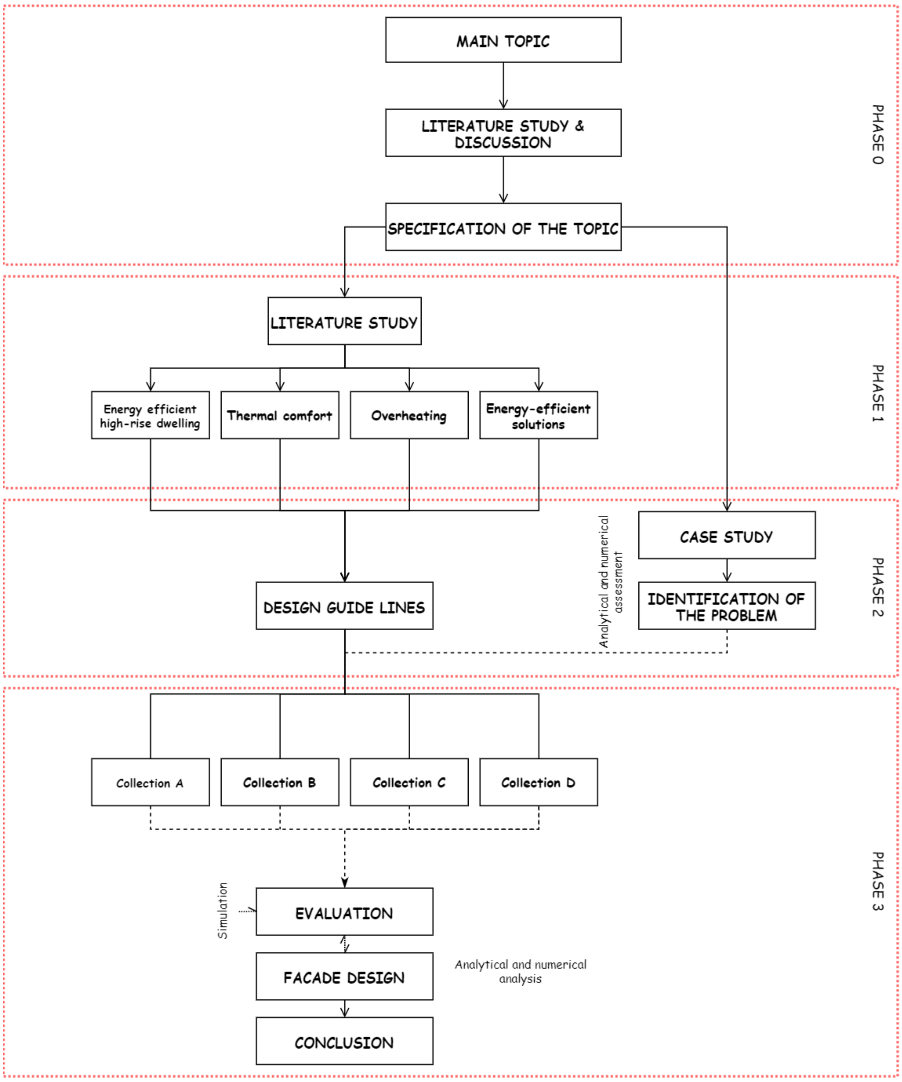


Figure 1.1: Research methodology scheme

2. Energy efficient high-rise dwelling

2.1. Definition of a high-rise dwelling

Looking at the regulations defining high-rise buildings, it can be seen that it is a subjective matter that each country has defined it according to its sociocultural background. For instance, the "National Fire Protection Association (NFPA)" of the US has described high-rise buildings as every building that its occupied levels are higher than 23 m above the lowest level (NFPA, 2013). Or the Dutch government has categorized a high-rise building as buildings with five or more levels. (Rijksoverheid, 2016)

2.2. Energy-efficient buildings definitions

The idea of energy-efficient buildings has been realized by more governments and companies in recent years. There are more than seventy definitions worldwide for the energy-efficient buildings. By realizing the importance of the concept of energy-efficient buildings in recent years, worldwide governments and constitutions have introduced more than seventy different definitions and regulations for these buildings (HU, 2019). In the market of the several European countries, some of these definitions and regulations have been introduced and are in use (Melcnik et al, 2012).

In this section, a brief study on some of the most used definitions and regulations that are introduced and been used in European countries will be shown

2.2.1. Passivhaus

The Passivhaus is a performance-based standard which is considered as a guideline for introducing low energy buildings (iPHA, 2018; McLoed, 2013). This standard is characterized by introducing high levels of insulation, airtight envelope and very efficient mechanical ventilation with a heat recovery system (iPHA, 2018).

2.2.2. Net-Zero Energy Building (NZEB)

An energy-efficient building which produces its entire energy needs by generating renewable energy on its site over a pre-set period is defined as a Net-Zero Energy Building (Hasan et al., 2015; Hu, 2019). NZEBs are classified according to their metric balance (Hasan et al. 2015). As stated by Torecellini et al. (2006) there are four common metric systems used for NZEB:

1. Net-zero site: A "Net-zero site" building generates within its footprint as much energy as it consumes, as evaluated at the site (Torecellini et al., 2006).
2. Net-zero source: This type of energy-efficient buildings generate as much energy as it consumes in a course of time, including the energy loss during the transportation of the energy to the building (Torecellini et al., 2006).
3. Net-zero cost: This type of NZEB balances its costs by selling energy to the grid (Torecellini et al., 2006). The cost depends on the credit factor of the exported energy (Hasan et al. 2015)
4. Net zero-emission: In this type of NZEBs, the CO2 emission of the energy produced by its fossil fuel consumption is compensated by on-site generation of renewable energy (Torecellini et al., 2006).

2.2.3. Nearly-Zero Energy Building (nZEB)

Unlike the quantitative definition of the Net-Zero Energy Buildings, Nearly-Zero energy buildings have a qualitative definition (Hasan et al. 2015). According to the Energy Performance of Buildings Directive (EPBD): "A nearly zero energy building is a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby".

2.2.4. BENG

As it was discussed in the previous section the European Commission has introduced a directive for its members so by 2021 all-new buildings has to be nZEB and members have to introduce new regulation according to their state's requirements (EPBD, 2010). To achieve this, the Dutch government has introduced the "Bijna energieneutrale gebouwen" or in short "BENG". As stated by the Netherlands Enterprise Agency (Rijksdienst Voor Ondernemend Nederland - RVO), from 1st of July 2020, all new residential and non-residential buildings for the construction authorization must sustain the BENG requirements.

BENG has three indicators which were based on the idea of Trias Energetica (Lente Akkoord, 2019). This three-step strategy is looking for to first limit the energy demand and then using renewable energy and finally to use non-renewable energy as efficient as possible (Lente Akkoord, 2019).

The BENG indicators are:

BENG 1:

"BENG 1" is the indicator for heating and cooling energy needs and its unit is kWh per square meter usage area per year (kWh/m^2.y) (Lente Akkoord, 2019).

Heat loss through the thermal shell, heat gain due to the sun shine to inside and the heat and cold loss through air exchange determine the energy balance in the house. Heat losses must be supplemented for a comfortable indoor temperature. In the summer months, the need for cooling plays an important role. BENG 1 concerns the energy required for this.

BENG 1 concerns all the heat gains and heat losses through the building envelope (Lente Akkoord, 2019). Overall, BENG 1 is an indicator for the quality of the envelope and therefore ventilation system is not included in this factor (Lente Akkoord, 2019). However, to determine this factor a natural ventilation system with mechanical exhaust is considered to do the calculations (Lente Akkoord, 2019)

The limit value for BENG 1 is defined by the ratio of loss area (A_{ls}) to the usage area (A_g) (Lente Akkoord, 2019). When this ratio is higher than the limit value for BENG 1 becomes higher (Lente Akkoord, 2019). The relation between the limit value and A_{ls}/A_g can be find in table 2.1.

Ground-level homes		**Residential buildings**	
Geometry	**Limit value**	**Geometry**	**Limit value**
$A_{ls}/A_g \leqslant 1,5$	$\leqslant 55$	$A_{ls}/A_g \leqslant 1,83$	$\leqslant 65$
$1,5 < A_{ls}/A_g \leqslant 3,0$	$\leqslant 55+30*(A_{ls}/_{Ag} -1,5)$	$1,83 < A_{ls}/A_g \leqslant 3,0$	$\leqslant 55+30*(A_{ls}/A_g -1,5)$
$A_{ls}/A_g > 3,0$	$\leqslant 100+50*(A_{ls}/_{Ag} -3,0)$	$A_{ls}/A_g > 3,0$	$\leqslant 100+50*(A_{ls}/A_g -3,0)$
For building constructions lighter than 500 kg / m2, the limit value is 5 kWh / m2.jr higher.			

Table 2.1: BENG 1 limiting value for different building types. Adapted from: Lente Akkoord, 2019

BENG 2:

BENG 2 is the indicator of the primary fossil energy consumption for heating, cooling, hot water and auxiliary energy in the building (Lente Akkoord,2019). In residential buildings, the energy consumption for lighting and appliances are excluded from the BENG calculation (Lente Akkoord, 2019) .The effect of the different types of ventilation system which was excluded in the BENG 1 is of importance in BENG 2 since it has considerable effect on the primary energy consumption (Lente Akkoord, 2019).

Limit values of BENG 2 is shown on table 2.2.

Ground-level homes	Residential buildings
⩽ 30 kWh/m2.jr	⩽ 50 kWh/m2.jr

Table 2.2: Limit values for BENG 2 (in kWh / m^2.jr). Adopted from: Lente Akkoord, 2019

BENG 3:

BENG 3 is the percentage of the renewable energy share in the building (RVO, n.d.). It is calculated by the division of self-generated renewable energy by the total energy consumption (RVO, n.d.). The total energy calculated for BENG 3 is restricted to the energy needed for building-related operations (Lente Akkoord, 2019).

Limit values of BENG 3 could be seen on table 2.3.

Ground-level homes	Residential buildings
⩾ 50%	⩾ 40%

Table 2.3: Limit values for BENG 3. Adopted from: Lente Akkoord, 2019

2.3. Definition of energy efficient high-rise dwelling

As mentioned before, the definition of an energy efficient building and a high-rise building is a subjective matter depending on the regulations of each country.

Since the location of the case building of this report is located in the Netherlands, the definition of an energy efficient high-rise dwelling used in this report is aligned with this country regulations.

According to Dutch government, a nearly- energy neutral high-rise dwelling is a building with more than four floors witch abides BENG regulation. On table 4, please find the limit level of BENG indicators for a normal apartment built with heavy construction material.

BENG indicator	BENG 1	BENG 2	BENG 3
Limit value	⩽ 65 kWh/m2.jr	⩽ 50 kWh/m2.jr	⩾ 40%

Table 2.4: Limit value of three BENG indicators for an apartment.

3. Thermal comfort

As warm-blooded beings, humans need a near steady state temperature in their bodies to live healthy (CIBSE, 2013). The heat released in the body is regulated through heat exchange with environment to keep the internal temperature around 37 C so we could live (CIBSE, 2013). This is a dynamic process since the surrounding environment changes and humans move changing the location. To compensate this, the body has a mechanism that helps to keep the internal temperature almost at a steady state (CIBSE, 2013).

However, for situations where the thermal state of the body is not in a steady state body has a thermal sense to alert us (CIBSE, 2013). So, thermal comfort is a quality of mind in which it is satisfied with our surrounding thermal environment (ANSI/ASHRAE, 2010).

According to Nicol (2012) there are three main reasons that makes studying thermal comfort in the buildings important:

1. By knowing thermal comfort conditions in buildings suitable environments could be designed for the occupants.
2. By knowing thermal comfort condition energy consumption of the building could be controlled efficiency.
3. And it could be used for quality assessment of buildings.

In this chapter, first the steady-state thermal comfort model will be discussed, then comes the adaptive model. Lastly, thermal comfort considerations in energy efficient dwellings will be delivered.

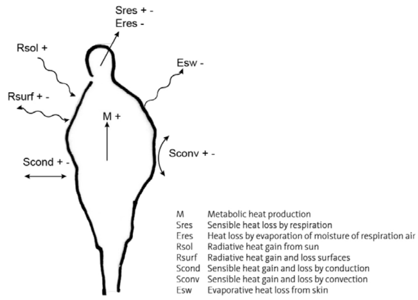


Figure 3.1: Body's heat balance. Source: Alders, 2016

3.1. Steady-state model

This model known as Fanger's model presumes a stationary state energy balance in which energy discharge by metabolism is equal to energy release by body area (Figure 3.1) (Linden et al., 2013).

Using data derived from experiments in a climate chamber, Fanger related the body's heat balance to a expected mean value of votes given by the experiment's participants on a seven point thermal sensation scale (figure 3.2) (Barclay, 2012). From that the value for most favorable thermal comfort could be predicted form environmental conditions, clothing's thermal insulation and body's metabolic rate (Fanger, 1970; ASHREA, 2004).

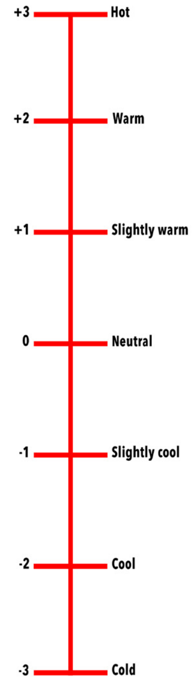


Figure 3.2: This scale was used to assign a numeric value to a given indoor climate. (Adopted from: ASHREA, 2004)

Additionally, Fanger found out that despite the similar thermal conditions, every individuals express their thermal sensation in a different way , because of difference in thermal sensitivity (Porritt, 2012). So he introduced Predicted Percentage of Dissatisfied (PPD) in order to indicate the percentage of occupants how are dissatisfied in a particular thermal situation (Barclay, 2012). As it can be seen in the figure 4 there are still 5% of people dissatisfied even though the Predicted Mean Vote (PMV) is equal to zero.

In the practice, Fanger's model was used in American ASHRAE 55 (2004) and European EN-ISO 7730 (2005) standards determining thermal conditions in buildings. Later it was found out that this model is only actable for buildings with mechanical ventilation systems and it is not predicting thermal comfort in free-running buildings correctly (de Dear et al., 1985; Linden et al., 2002) . Therefore, later Adaptive Comfort model was introduced which comes in next section.

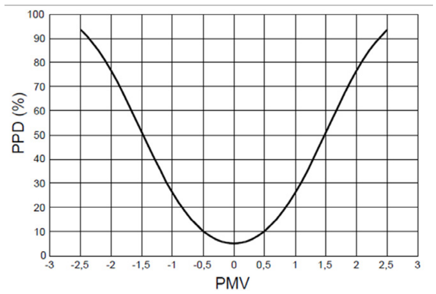


Figure 3.3: Relation between PMV and PPD. Source: ISO 7730

3.2. Adaptive model

This model was first was developed using field study researches (Humphyres, 2016). In this approach, thermal comfort is considered as a dynamic process in which people can get accustomed to the thermal environment and do actions to adopt themselves to it (De Dear et al., 1997). Adaptation could happen based on three classifications (De Dear et al., 1997):

- First is behavioral adjustment in which different modifications such as clothing and posture adjustments could happen in order to get to the thermal balance of the body and environment.
- Second is physiological adjustments in which body response to the environment by physiological actions such as sweating to get to the comfort.
- Third is psychological adaptation in which by being repeatedly exposed to a thermal environment the intensity of the thermal sensitivity will reduce so people get to change their thermal expectation.

This system is only actable for free-running buildings in which occupants have more freedom of act to adapt themselves to the environment (Porritt, 2012). Based on the studies of Nicol and Humphreys (2002) for free-running buildings thermal preference of occupants could be predicted based on the recently outdoor climate experience. This way they were able to find a relation between the mean outdoor temperatures of the past days and indoor comfort temperature.

In practice adaptive comfort model were used in ASHREA 55 (2013) and CEN EN 15251 standard for determining thermal comfort conditions in free-running buildings.

3.3. Thermal comfort in energy efficient dwellings

For the building occupants thermal comfort is a basic factor which if not achieved causes dissatisfaction with the building as a whole. Therefore, some countries and institutes have already developed guidelines for thermal comfort in energy efficient buildings. In this section some of these guide lines will be discussed.

3.3.1. NEN-EN-15251

The European Committee for Standardization has issued EN-15251 guideline for member states in order to support 'Energy Performance of Buildings Directive (EPBD)' in nearly zero energy buildings. In this guideline thermal comfort is of importance. As mentioned before, the adaptive thermal comfort model was used in this standard to determine thermal comfort in naturally ventilated buildings. Yet, EN-15251 suggests comfort temperatures ranges for both naturally and mechanically ventilated systems.

NEN-EN-15251 divides buildings into four groups according to the occupants needs for comfort and space functions. In table 3.1, it can be seen how different groups were divide according the PMV and PPD model.

Category	Thermal state of the body as a whole	
	PPD%	PMV
I	<6	-0.2<PMV< +0.2
II	<10	-0.5<PMV< +0.5
III	<15	-0.7<PMV< +0.7
IV	<15	PMV< -0.7 OR PMV> +0.7

Table 3.1: PMV and PPD limits for different categories of buildings. Source: NEN-EN-15251

NEN-EN-15251 also gives example values for dwellings with mechanical ventilation which is shown in the table 3.2.

Type of building/space	category	Operative temperature	
		Minimum for heating	Maximum for cooling
Residential building: Living spaces (Bedrooms, living room and etc.) Sedentary	I	21.0	25.5
	II	20.0	26
	III	18.0	27
Residential building: Other spaces (Storage, halls and etc.) Standing- Walking	I	18	
	II	16	
	III	14	

Table 3.2: Temperature comfort values for mechanically ventilated buildings. Source: NEN-EN-15251

In free-running buildings thermal comfort is calculated based on the weighted mean outdoor temperature (T_{rm}) according to table 3.3.

Category	
I	Upper limit: T_{max}= 0.33 T_{rm}+18.8+2
	Lower limit: T_{max}= 0.33 T_{rm}+18.8-2
II	Upper limit: T_{max}= 0.33 T_{rm}+18.8+3
	Lower limit: T_{max}= 0.33 T_{rm}+18.8-3
III	Upper limit: T_{max}= 0.33 T_{rm}+18.8+4
	Lower limit: T_{max}= 0.33 T_{rm}+18.8-4

Table 3.3: Allowable indoor temperature limit. Source: NEN-EN-15251

3.3.2. BENG TO_{Juli}

As it was discussed in the previous chapter, buildings which are going to be built after July 1st 2020 must meet the BENG regulation (Lente Akkoord, 2019). Besides the three energy related requirements, the legislator has considered overheating factor (TO_{Juli}) in the summer in BENG. TO_{Juli} limit value has to be meet in order that BENG permit is granted. Although, TO_{Juli} does not guarantee very good thermal comfort condition in the building, it secures acceptable level of thermal comfort during the summer (Lente Akkoord, 2019).

4. Overheating: definitions, sources & factors

Overheating could happen in different types of dwellings, from those which are newly built with good insulation, to the old ones (Sharifi et al., 2019). However, the newly built or refurbished houses which follow the regulations for energy neutral houses seem to be at higher risk of overheating (Sharifi et al., 2019). In this chapter, different definition and assessment methods of overheating, the sources for overheating along with the factors which increases the risk of overheating is presented. Lastly an insight into the overheating conditions of temperate climate dwellings now and in the future is given.

4.1. Assessment and definition of overheating

Overheating in this context, is a word which is used to point out that building occupants are feeling uncomfortably hot. However, this term does not precisely demonstrate when it could be said that a building is over heated. Therefore, there is a need for assessment methods to examine overheating. There are three indicators that overheating can be assessed in respect to them (ZCH, 2015A). These three indicators are: a) thermal comfort, b) health and c) productivity, with a) thermal comfort being the most commonly used indicator in overheating assessment method in building sector (ZCH, 2015A).

Therefore, in this section we are going to look into 6 different out of 130 assessment methods for overheating in buildings which are already in use, were introduced in Europe.

4.1.1. Post occupancy evaluation

The best known way to find out if a dwelling has an overheating problem is by asking its residents. Doing a survey as a post-occupancy evaluation will help to find short comings of a building such as overheating (CIBSE, 2013). According to CIBSE TM52 (2013), if 20% percent of the occupants of a building identify spaces of the building as overheated during a survey then the building is assessed as overheated.

4.1.2. CIBSE static and adaptive overheating guideline

During previous years, the Chartered Institution of Building Services Engineers (CIBSE) has published two guidelines for assessing and predicting overheating in buildings. Having thermal comfort in buildings as their overheating indicator they have published two guides for static and adaptive overheating assessment methods. These methods are:

CIBSE Guide A (2006):

CIBSE Guide A (2006) is a static assessment method for overheating which gives a inclusive instruction to designers to assess the risk of overheating in free-running buildings.

In 2015 this guideline has been mostly replaced by issuing new CIBSE TM52 guideline (ZCH, 2015). This TM52

However, studies by Gupta et al. (2017) suggest that SIBSE A (2006) can still be used for assessing overheating in the bedrooms. Moreover, knowing this 2006 guideline helps designers to have a feeling for overheating risk during there design prior to complex calculations.

According to this guide line a dwelling is overheated if the indoor internal operative temperature surpasses the threshold temperatures more than 1% of the total annual occupied hours (CIBSE, 2006; ZCH, 2015B). The threshold temperatures for living rooms and bedrooms are 28°C and 26°C respectively (CIBSE, 2006).

CIBSE TM52:

TM52 follows the adaptive thermal comfort approach in free-running buildings. This method takes the outdoor temperature changes of the precedent day with a weighting factor into account to calculate a dynamic threshold based on the occupant's sensitivity and thermal expectation (ZCB, 2015B; Gupta & Gregg, 2017).

TM52 introduces three criteria for overheating assessment in free-running buildings which if two of them fails then the space is considered as overheated (CIBSE, 2013).

1. the first criterion specifies, there is a 3% limit for the number of the occupied hours in which temperature in the space could excess the threshold temperature during a year (CIBSE, 2013)
2. the second criterion, the daily weighted exceedance hours should be less than 6 hour in any one day during the year (CIBSE, 2013)
3. the third criterion the absolute maximum daily temperature for space should be less than 4K (CIBSE, 2013)

4.1.3. ATG (Adaptieve Temperatuur Grenswaarde)

This overheating assessment method is based on the adaptive comfort model described in NEN-EN-15251 and ISSO 74 (Witkamp et al., 2019). According to this method, a room is considered 'overheated' if the temperature in it exceeds a given threshold for more than 200 hour a year (Witkamp et al., 2019).

The threshold is calculated based on the comfort classes in NEN-EN-15251 with running mean outdoor temperature (T_{rm}) (Table 4.1).

Category	Limit value
A	T_{max}=0.33 T_{rm}+18.8+2
B	T_{max}=0.33 T_{rm}+18.8+3
C	T_{max}=0.33 T_{rm}+18.8+4

Table 4.1: Limit values based on the running mean outdoor temperature. Source: NEN-EN-15251

4.1.4. Passive House Planning Package (PHPP)

PHPP introduces a static overheating assessment method. In this method, if operative temperature surpasses comfort temperature for more than 10% of the total hours of the year then the dwelling is predicted as being overheated (ZCH, 2015B). In PHPP the limit comfort temperature is set at 26°C, but it can be changed too for assessing different temperatures (ZCH, 2015B).

For assessing overheating in dwellings according to this method, all hours of the year are considered as occupied hours. Overheating is calculated monthly by modeling the space as a dynamic single zone(ZCH, 2015B).

Complying with the limit value assigned at PHPP is mandatory if a building is to secure a Passivhaus certificate (ZCH, 2015B).

4.1.5. TO_{Juli} & GTO

As it was mentioned in the previous chapter, the BENG considers overheating calculation. According to BENG there are two methods to determine overheating in buildings, each of which has to be below a thresholds so the construction permission could be granted.

TO_{Juli}:

TO_{Juli} is an overheating calculation method which indicates the chance of temperature exceedance in a building, in July, the hottest month of the year. The larger the value of TO_{Juli}

is, the greater is the risk of overheating (Lente Akkoord, 2019). However, TO_{Juli} is only a global indicator in which the assessment is based on the averages (Lente Akkoord, 2019). Outdoor temperature peaks, differences among spaces and differences in activity levels are therefore neglected in this method (Lente Akkoord, 2019B).

The calculation of TO_{Juli} is made by averaging living spaces for each orientation (N, NE, SE, S, SW, W, NW). in which the calculated value has to be less than 1.0 for all of them.

GTO:

GTO stands for weighted temperature exceeding hours. This method is based on the Fanger's comfort model (RVO, 2019). In this model exceeding hours are calculated based on the thresholds values which are 25 and 28 based on the function of the space (RVO, 2019).

GTO is a dynamic overheating calculation method in which the temperature exceedance is calculated by a weighting factor (Lente Akkoord, 2019). The weighting factor is based on the degree of temperature exceedance, air and radiation temperature, , relative humidity, air speed, metabolism and clothing resistance (Lente Akkoord, 2019).

Unlike TO_{Juli}, GTO is calculated at zone level which makes it more precise than TO_{Juli} (Lente Akkoord, 2019B). According to BENG, if the temperature exceeding hours do not surpass a treshhold limit of 450 GTO hours then the construction permit may be granted for the building (Lente Akkoord, 2019B). Below, a comparison between TO_{Juli} and GTO method.

TO_{Juli}	GTO
Intended as an indicative calculation	Intended to assess risks of overheating
Calculation at home level	Calculation at room level
Risk mediation	Risks visible per space
Simplified approach	Less simplified approach
Restrictions in measures	Specific measures can be simulated

Table 4.2: Table 9: TOJuli and GTO comparison. (Source: Lente Akkoord, 2019B)

4.1.6. Comparison

Static overheating assessment criteria such as PHPP, TO_{Juli} and CIBSE (2006) provide simple calculation method for assessing overheating compared to the other numerical methods.

Methods such as TM52 and AGT that consider adaptive comfort for assessing overheating provide better understanding of overheating since they consider occupants adaptation to their environmental context.

TM52 is the most complete numerical assessing method since it both considers the degree of temperature exceedance and the hours that a zone is overheated during a day for assessment.

4.1.7. Conclusion

Different overheating assessment methods were discussed and were compared. As the case building of this thesis is located in the Netherlands, two TO_{Juli} and AGT methods associated with Dutch regulation were chosen.

4.2. Overheating sources

In this section the factors that cause overheating in buildings are discussed. Basically, the overheating factors can be divided into three sections: external heat gains, internal heat gains and lack of appropriate ventilation (NHBC,2012).

4.2.1. External heat gains

Sun radiation and high outdoor temperature normally are the two main external factors for overheating a building (NHBC,2012).

Greenhouse effect plays a major rule in the overheating by external factors. Sunlight gets into the building by windows and is absorbed by the surfaces in the building as heat (NHBC, 2012). This heat then is trapped in the building and increases the temperature of the room. This effect plays a favorable rule in the winter. However, it could cause many problems in the summer. One way to solve this problems is by opening the window to ventilate the space. However, by the increase in the outdoor temperature in recent years because of the climate change this may not work in the future (NHBC, 2012).

In recent years, the main focus of the regulations is to introduce better insulation values for envelope components in order to reduce heating demand during winter. However, this is causing a serious problem in the new energy efficient buildings because once such a building is heated, the heat gets trapped within the building (NHBC, 2012).

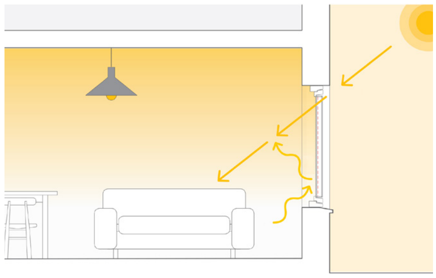


Figure 4.1: The solar gain in energy efficient buildings are trapped in the building. Source: NHBC,2012

4.2.2. Internal heat gains

There are four general sources of heat production in the buildings (NHBC,2012):

1. Lighting
2. Appliances- (like fridges, dishwashers, laptops, televisions and ...)
3. Occupants- (The heat produced by occupants metabolism)
4. Building services- (Boilers, hot water distribution systems and ...)

Like the external heat gains these internal ones have become a problem in energy efficient buildings because of the thermo flask effect of these buildings that trap the heat inside of the building.

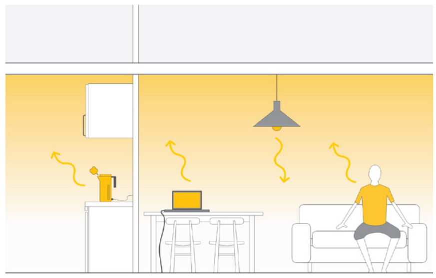


Figure 4.2: Internal heat sources. Source:NHBC,2012

4.2.3. Inadequate Ventilation

The heating effect of the external and internal heat gains can perhaps be limited, but they can never be genuinely removed (NHBC, 2012). One main option to avoid overheating is to transport the accumulated heat outside by ventilation.

Ventilation is important for having good indoor air quality and thermal comfort. To have effective ventilation there have to be enough windows, ventilators, etc. in the building (NHBC,2012). Most of the buildings in Northern European countries benefit only from minimum windows and ventilators for required fresh air. Therefore, the opportunity for purge ventilation is not there, and this results in heat accumulation and overheating.

The risk of this effect is particularly high in new energy efficient buildings, since these are very airtight (Gupta & Gregg, 2018)

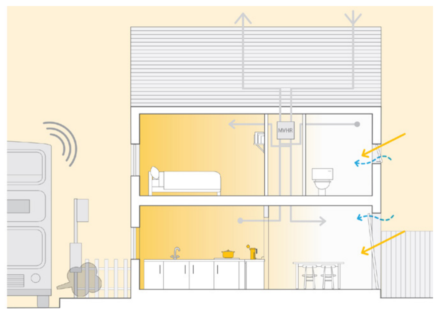


Figure 4.3: Inadequate ventilation because windows are closed. Source: NHBC,2012

4.3. What could increase the risk of overheating?

4.3.1. Site context

The site context could have a major impact on the thermal comfort of the building. Restrictions imposed by the locations of the site, noisy mechanical services near the building, noise from the road and railway could limit the ability of the occupant for using windows for ventilation. (NHBC, 2012). Beside of that, the conditions on lower floors of an apartment could be different from those in upper floors because of the concern for security (NHBC,2012). All of these site factors could cause an increase in the risk of overheating in the building.

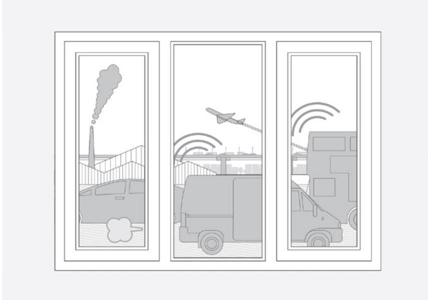


Figure 4.4: Noise pollution nearby the building may discourage the occupants to open the windows for ventilation. Source: NHBC, 2012

4.3.2. Urban heat island effect

The high immigration rate to cities has speeded the urbanization. This has caused scarcity of free space in urban environment and increase in land price which resulted in compactness of urban environment (Brotas & Nicol, 2017). In these dense urban areas the surface materials of the landscaping and surrounding buildings can affect the temperature of this urban environment (NHBC, 2012). Hard surfaces absorb the sun's radiation and later at night they emit the heat which was accumulated during the day (NHBC, 2012). Beside of that, the heat generated by cars, mechanical systems and ... in these urban environments generates heat, too. All these factors add up, and result in the temperature increase of these urban environments (NHBC, 2012). Because of such temperature increase, the ventilation, cooling strategies like nigh-time ventilation could turn to be insufficient (NHBC, 2012).

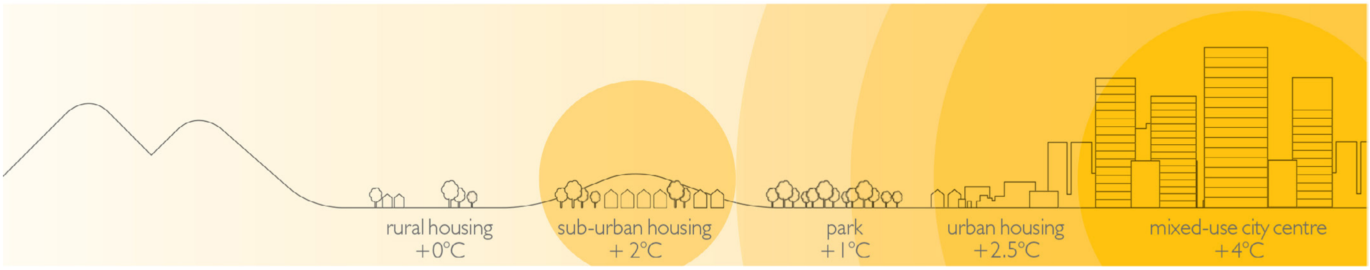


Figure 4.5: This diagram shows the effect of urban heat island effect on the increase of temperature in different scenarios. Source: NHBC, 2012

4.3.3. Orientation

Orientation is one of the key factors affecting the solar gain of the building. A good orientation can provide solar gain in the winter as well as protecting the building against the unwanted gains in the summer. However, most of the times this is not the case because of the limitation of the site or other limitation (NHBC, 2012). For instance, in apartment buildings the flats are repeated in different directions which could cause that similar flats having very different indoor conditions (NHBC, 2012). Homes which have windows facing west has different indoor environment that the same ones facing south since the west facing homes are receiving more sun radiation due to the low-level sun result in temperature increase making this houses susceptible to overheating(NHBC, 2012).

4.3.4. Building design

The building design is the most important factor. If this is spoiled it could cause that all other factors to build up together to cause overheating. In recent years, there has been a tendency of increasing insulation and airtightness in building regulations to reduce the energy consumption in the winter (NHBC, 2012). However, the climate change and neglecting the hot summer days has caused buildings to be designed that are inclined to be overheated (NHBC,2012).

Moreover, the neglections of the potentials of passive ventilation or the local restrictions like noise pollution or security in design phase could increase the risk of the overheating in the building.

In addition to the a.m. problems, in northern Europe there is not a culture to design the building to deal with the summer heat (Lomas & Porritt, 2017). As a result we see many designs with high window to wall ratio or designs without the use of external shading devices, shutters and etc. since buyers are very often more looking for the aesthetic aspects (Lomas & Porritt, 2017).

4.3.5. Thermal mass

The ability of a building material to store and release heat is referred to as thermal mass (NHBC, 2012).

In recent years, the construction industry has increased the usage of the lightweight materials in the construction of walls and etc. to reduce the costs of the construction (Lomas & Porritt, 2017). This resulted high temperature swings during the summer in these compact dwellings with thermally lightweight materials (Lomas & Porritt, 2017). The mentioned reason and the better insulations used in these buildings have increased the risk of overheating in the energy efficient buildings (Lomas & Porritt, 2017; NHBC, 2012)

4.3.6. Service design

Mechanical systems and heating pipe work installed in apartments causes internal heat gains (NHBC, 2012). These could cause overheating, especially if they are not insulated effectively (NHBC, 2012; Lomas & Porritt, 2017). These systems usually run through corridors and common spaces. Even if they are well insulated they still can increase the temperature in these spaces and even cause problems for adjacent units (NHBC, 2012).

Heating systems like radiant floor heating can cause overheating in winter (Kim et al 2019). This could happen because of heat capacity of the floor together with the building's thermal insulation capacity (Kim et al., 2019)

4.3.7. Occupant behaviour

The sensitivity of the occupants to high temperatures and the way they behave to it is an important factor on increasing the risk of overheating (Lomas & Porritt, 2017)

Emery and Kippenhan (2006) in their long time study on influence of occupants behavior on energy use concluded that occupant behavior had a higher impact on energy use than the dwelling construction and insulation.

Studies by Mavrogianni et al. (2017) showed that the summer time residents behavior differs significantly from the assumption made for overheating modeling. In their study they showed that strategies used by occupants for ventilating and shading could put the building in higher risk of overheating.

Morgan et al., (2016) concluded how the occupants behaviour had resulted in overheating in two identical energy efficient houses.

The research of Vellei et al., (2017) on vulnerable occupants like elderlies showed that the residence of these people has higher temperature that of healthy people. They found out that more than 70% of the elderlies household they studied did not turn off the heating system resulting in overheating. They also found out that the heating system was running in dwellings of 30% of the average people.

McGill et al., (2017) discussed that the effect of the residents behaviour in energy efficient dwellings could lead easily to overheating compared to the non-efficient identical ones. They showed that the risk of overheating in these buildings are almost four times of the risk of the non-efficient dwellings.

4.4. Overheating risk in the future

As global warming proceeds, it is expected that overheating risk in buildings to increase (Hamdy et al., 2017). To understand the climate situation in the future, in this section first future climate scenarios in the Netherlands is shown. After that studies reviewing the impact of climate change on overheating risk in the dwellings will be discussed.

4.4.1. Climate change

A climate shift caused by human actions impacting the lower atmosphere is called climate change (Yau & Hasbi, 2012). Knowing the Dutch's future climate scenarios helps to understand the impact of climate change on building behaviour in the future.

The Royal Dutch Meteorological Institute (KNMI) has introduced KNMI'14 report on climate scenarios. In this report KNMI has translated the IPCC 2013 report 'Climate Change 2013 The Physical Science Basis' to the situation in the Netherlands (KNMI, 2014). It has provided four main different future climate scenarios for two time horizons, 2050 & 2085, that is derived from the data available from reference period between 1981 to 2010 (KNMI, 2014). The climate scenarios are from combination of two possible 'Moderate (G)' (+1 °C) and 'Warm (W)' (+2 °C) global temperature increase, and two possible 'Low (L)' and 'High (H)' value changes in circulation pattern (KNMI, 2014). KNMI'14 by its four scenarios provides a guide for decision makers so they could evaluate the climate change consequences when they are making their decisions (KNMI, 2014). Recent findings show a greater possibility toward warm temperature scenarios (W_L & W_H) rather than moderate ones (Alders, 2016). The figure below shows the climate characteristics associated with each of the scenarios:

Season	Indicator	Scenario change values for the climate around 2050				Scenario change values for the climate around 2085			
Climate scenario									
Global temperature rise		+1 °C	+1 °C	+2 °C	+2 °C	+1.5 °C	+1.5 °C	+3.5 °C	+3.5 °C
Air circulation pattern change		Low	Low	High	High	Low	Low	High	High
Winter	Average temperature	+0.9°C	+1.1°C	+1.8°C	+2.3°C	+1.8°C	+2.3°C	+3.6°C	+4.6°C
	Coldest winter day of the year	+1.0°C	+1.5°C	+2.1°C	+2.9°C	+2.1°C	+2.9°C	+4.2°C	+5.8°C
Summer	Average temperature	+0.9°C	+1.4°C	+1.7°C	+2.8°C	+1.7°C	+2.8°C	+3.4°C	+5.6°C
	warmest summer day of the year	+1.0°C	+1.9°C	+2.1°C	+3.8°C	+2.1°C	+3.8°C	+4.2°C	+7.6°C

Table 4.3: Climate data for each of four different climate scenarios. Source: KNMI, 2014

4.4.1. Impact of climate change on building performance

Climate change also affects the building's performance because of lengthy cold seasons, flooding and severe heat waves (UKCIP, 2005). These result in that buildings designed according to the existing regulations to become more and more expensive to operate in the future (Wilby, 2003).

A study on a office building in the Netherlands showed that by 30 year from the study period, 70% higher cooling load is needed in order to achieve thermal comfort (Plokker et al., 2009).

Hamdy et al. (2017) in their study showed that the apartments in middle floor and in middle location of a high-rise dwelling and apartments on the top floor in middle location of the dwelling are the most sensitive dwelling archetypes to global warming.

5. Exploration of energy-efficient solutions to prevent overheating

In the previous chapter it was discussed what causes overheating and which factors contribute to increase the risk of overheating. In this chapter possible energy efficient solutions in different levels of design are explored. First, the measures appropriate on urban level are elaborated. Then, possible actions in spatial design phase to prevent overheating are discussed. After that, possible measures during design of detailing and materialization of the building are discussed. Next the actions that could be taken during simulation and feasibility study phase to reduce the risk of overheating will be presented. Lastly post occupancy solutions for overheating are shown.

5.1. Urban scale measures

District pattern and orientation alters solar gain, wind speed and it's direction (Du, 2019). Besides that, building placement in the site and land use patterns also could significantly affect outdoor temperature and the urban microclimate (Taleghani et al., 2013). In this section we are going to discuss measures that could be taken in urban neighborhood level to reduce the risk of overheating in the dwellings.

5.1.1. Urban wind environment

The characteristics of natural wind near built environment is called wind environment (Du, 2019). This setting can be disturbed by surrounding blocks particularly in the urban area because of the forms and diversity of big adjacent urban elements (Du, 2019). Analyzing wind environment provides useful data for assessing indoor and outdoor comfort (Du, 2019).

Principally, the density of urban settings has a clear correlation with wind environment and hence natural ventilation in the buildings (Santamouris & Asimakopoulos, 1996). The higher the density of the urban setting is the lower the possibility of natural ventilation becomes(Santamouris & Asimakopoulos, 1996).

Studies show that placing the building blocks with a 45 incident degree to the prevailing wind direction in a neighborhood has a significant effect on the wind flow, exposing the building to air currents and thus resulting in better wind-driven ventilation (Zhang et al., 2005; Asfour, 2010).

5.1.2. Urban solar environment

The building blocks arrangement and design has a large impact on the solar gain. An appropriate design can help to reduce urban heat island effect and overheating (Du, 2019). The influencing factors on solar gain and overheating in urban environment are:

- compactness and orientation of the neighborhood,
- building outline,
- block typology,
- paths and surface materials

(Sanaieian et al., 2014; Palme et al., 2019, Taleghani, 2013)

Studies by Taleghani et al. (2013) showed that districts with a courtyard shape could be much more successful in achieving summer thermal comfort in temperate climates.

Studies by Palme et al. 2019 showed that using cool materials for pavement and roofs can reduce the risk of heat island effect and can reduce cooling load by 40%.

5.1.3. Water and vegetation

Water and vegetation both helps in cooling the environment by evaporation (Kleerekoper, 2016). Furthermore, Vegetation can help in cooling by shading the surfaces and water could absorb heat and works as a heat buffer controlling the temperature peaks (Kleerekoper, 2016). Studies shows that using these measure could decrease the urban heat island effect and help to prevent extreme hot summer days in the cities (Kleerekoper, 2016).

5.1.4. Traffic management

Studies show that traffic and car exhaust is one of the key elements causing heat island effect in urban environment (Palme et al., 2019). Making regulations and measures to control traffic during hot summer days can help in mitigating this problematic effect hence reducing the outdoor temperature and overheating risk (Palme et al., 2019).

5.1. Spatial design measures

Proper architectural spatial design has a great impact on solar control and natural ventilation (Du, 2019). This strategy has to be applied from early design stages in building's form, layout and openings (Du, 2019). Later in this section all these measures are going to be reviewed.

5.2.1. Architectural form

The building form has a great influence on the building heat loss and heat gain (Tang, 2002). Designing building shape optimally enables the building to have least heat loss in winter and least heat gain in summer (Du, 2019). The building volume and exposed surface area are two important factor with high impact on thermal capacity and building heat gain/loss respectively (Santamouris & Asimakopoulos, 1996).

5.2.2. Architectural layout

The architectural layout influences the ventilation conditions (Du, 2019). In open plan space, designing the space with appropriate opening distribution can facilitates proper indoor airflow and ventilation (Du, 2019). For space separation, designing the space layout by knowing airflow helps to place partitions in such a way that air channeling happens for proper ventilation (Du, 2019).

5.2.3. Openings

Openings are one of the crucial architectural elements that has a significant effect on the airflow and heat gain/loss of the building. The shape, size and placement of openings are the factors that controls the ventilation conditions and airflow inside the building (Du, 2019).

5.1. Detailing and materialization measures

5.3.1. Ventilation

This section looks at different devices and methods which could help in ventilating spaces of a high-rise building.

Ventilation methods

- **Cross ventilation**

In this ventilation mechanism the pressure difference between openings on different sides of the building causes the air to flow inside the room (Wood & Salib, 2013).

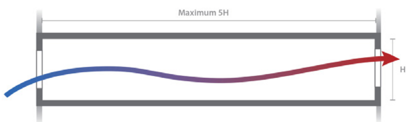


Figure 5.1: Cross ventilation. Source: Wood & Salib, 2013

- **Single-sided ventilation**

In this mechanism air inlet and air exhaust are at the same side of the building (Wood & Salib, 2013).

- **Stack chimney**

This method helps to improve natural ventilation by increasing thermal gains in a chimney in order to utilize stack effect to increase air exhaust (Brittle, 2017). This is achieved by using glass with thermal mass or a highly absorbent material to catch the solar heat in order to increase the temperature of the air inside the chimney to induce buoyancy and thus air exhausts (Brittle, 2017). The suction caused by this helps to ventilate the space.

- **Night-time ventilation**

In this method low-temperature ambient air is circulated in the building and it reduces the temperatures of indoor air and thermal mass causing building have a better thermal condition in the following day (INIVE, 2006)

Devices

- **Wing wall**

This strategy helps to increase ventilation on windward side of the building (Khan et al., 2008). The wings causes induced pressure difference on each of its sides, enhancing the air flow rate (Mak et al., 2006). Studies by Mak et al. (2006) shows that using wing walls can twofold the ventilation rate of a room with single-sided ventilation. They also showed that best wind incident angle to have the highest performance is at 45 degree.

- **Turbine ventilators**

This system consists of vertical vanes mounted on a frame in a spherical or cylindrical array which works as a wind-driven air extractor (Khan et al., 2008). It is connected to a shaft and when wind blows to the vanes causes the turbine to rotate (Khan et al., 2008). This rotation causes a vacuum inside the shaft which leads to air extraction (Khan et al., 2008). In the situation of no wind, the shaft works as a chimney and air extraction happen by stack effect (Khan et al., 2008). This eventually leads to effective natural ventilation in the building.

- **Pressure-controlled air inlets**

These types of inlets secure a persistent natural airflow independent from the pressure difference caused by stack effect or wind flow (Santamouris & Wouters, 2006). Their main task is to prevent over-ventilation (Santamouris & Wouters, 2006). There are three types of pressure-controlled inlets, namely, low-pressure inlets, high-pressure inlets and active inlets, each suitable for different situations (Santamouris & Wouters, 2006)

- **Natural supply & mechanical discharge**

In this method the air is extracted using mechanical means, causing an under pressure in indoor environment which forces to air enter from the outdoor environment (ter Haar, 2015).

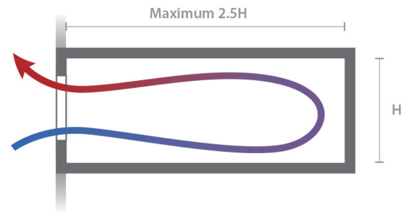


Figure 5.2: Single-sided ventilation. Source: Wood & Salib, 2013

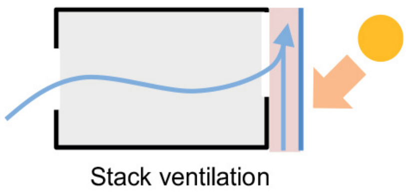


Figure 5.3: Using stack effect to induce natural ventilation. Source: (Konstantinou & Prieto Hoces, 2018)

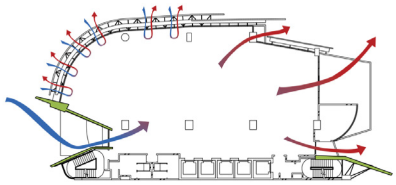


Figure 5.4: Wing walls highlighted in green, capture wind and allow for ventilation. Source: Wood & Salib, 2013

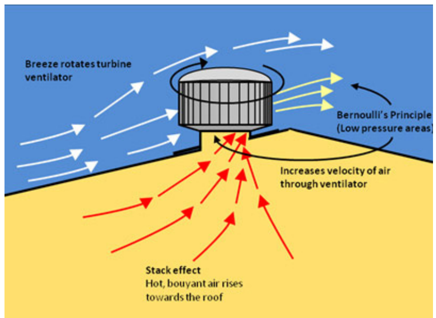


Figure 5.5: Working principle of turbine ventilation. Source: roofwhirlys4africa.co.za

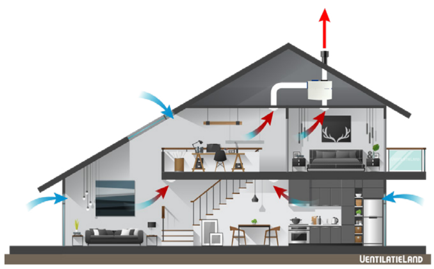


Figure 5.6: Air extraction via mechanical means and supplying through windows and vents. Source: ventilatieland.nl

- **Mechanical supply with natural discharge**

In this ventilation method air is forced out by inducing indoor air pressure (ter Haar, 2015). In this system air is supplied by mechanical means. Generally, the cooled outdoor air is supplied inside cooling the indoor rooms and then it is exhausted from window and vents.

- **Ventilated Double-skin façade**

Adding an additional layer of glazing outside the building façade a double-skin façade is made (Knaack et al., 2007). This system helps building with ventilation and extra sound insulation (Knaack et al., 2007). Later different types of double skin facades are shown.

1. Second-skin Façade

Double façade provides a height internal buffer zone in which solar gains can be captured in (Brittle, 2017). The heat gain increases the air temperature and stack effect causes air to rise and just like the solar chimney the stack induced ventilation happens (Brittle, 2017). Solar shades also could be incorporated in this system to reduce solar gain in the rooms (Brittle, 2017).

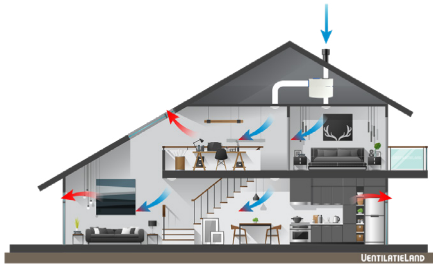
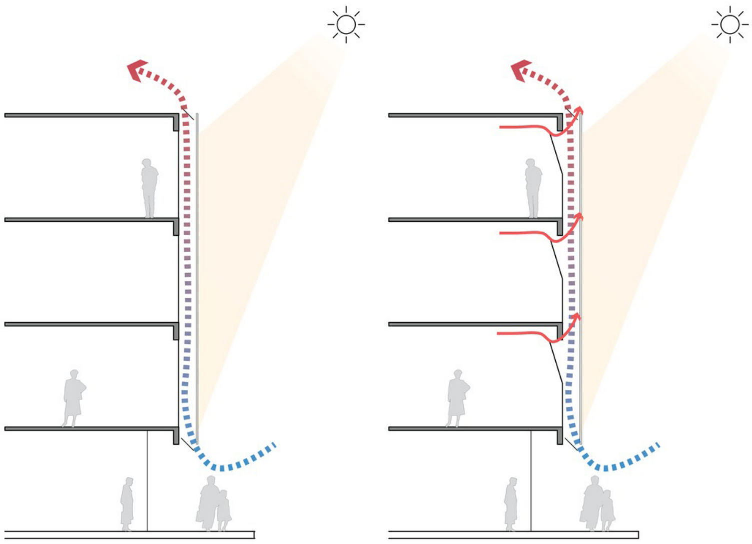


Figure 5.7: Supplying air using mechanical means. Source: ventilatieland.nl



—>Figure 5.8: Working principle of double-skin façade. Source: Souza, 2019

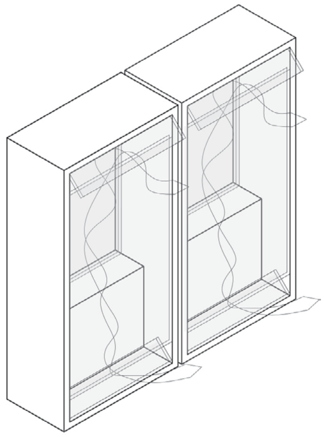


Figure 5.9: Supplying air using mechanical means. Source: ventilatieland.nl

2. Box-window façade

In this type of double skin façade, the second layer is added to storey-high box window (Knaack et al., 2007). There are openings at top and bottom of the box in order to offer individual control over ventilation (Knaack et al., 2007).

3. Shaft-box façade

The most effective type of double skin façade is shaft-box façade (Knaack et al., 2007).

Individual box windows release their discharged air into a vertical shaft which is attached to the façade and is extended over several floors (Knaack et al., 2007). This causes stack effect in the shaft increasing the efficiency and ventilation (Knaack et al., 2007).

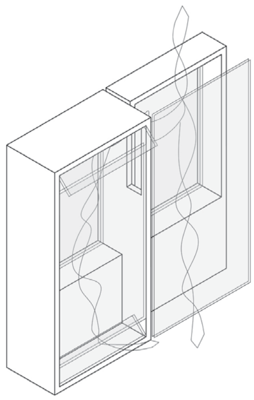


Figure 5.10: Supplying air using mechanical means. Source: ventilatieland.nl

4. Alternating façade

By offering different ventilation possibilities, alternating façade answers most of ventilation requirements (Knaack et al., 2007). Alternating façades are basically single-skin facades that second skin layer is added locally where needed, therefore having the advantages of both (Knaack et al., 2007).

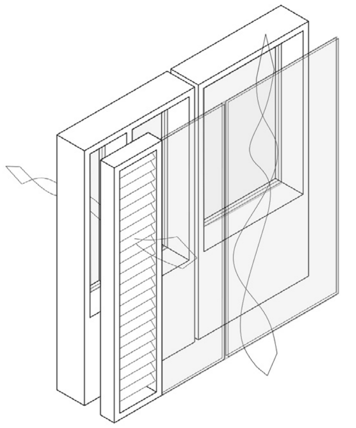


Figure 5.11: Alternating façade. Source: Knaack et al., 2007

5. Corridor facade

These types of double-skin facades are second skin facades segmented at floor level to minimize the stack effect. The benefit of this façade is it enables natural ventilation effectively from all directions since it distributes positive air pressure in all directions (Wood & Salib, 2013)

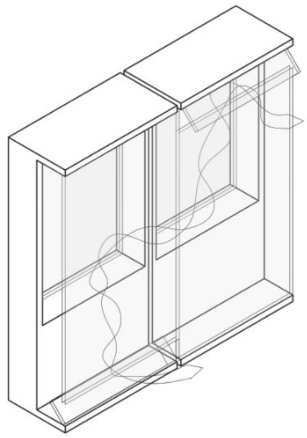


Figure 5.12: Corridor facade. Source: Knaack et al., 2007

6. Integrated façade

These types of facades use both ventilation opportunities of conventional facades and also incorporate active environmental and lighting control systems in the façade (Knaack et al., 2007).

The study by Ibraheem et al. (2017) on a high-rise building in hot-arid climate showed that using integrated façade with internal shading could reduce the cooling load by more than a half.

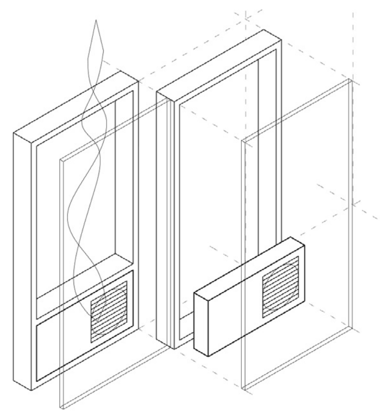
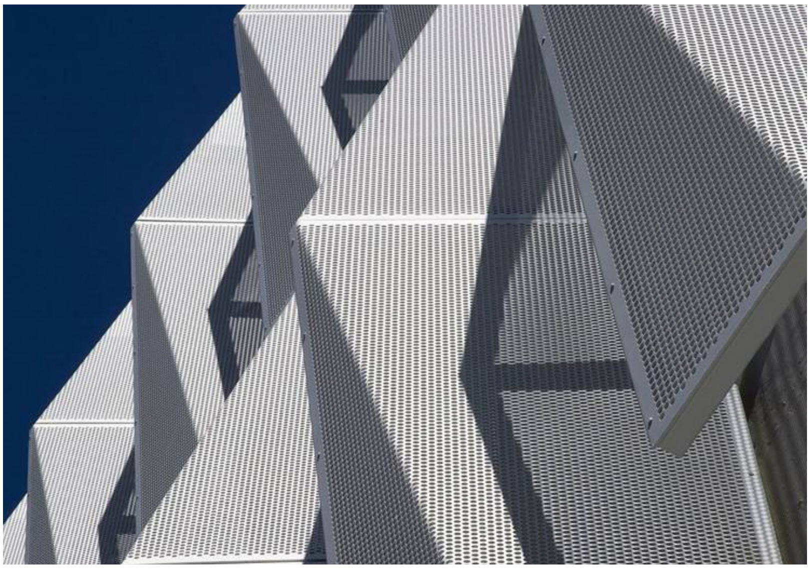


Figure 5.13: Integrated façade. Source: Knaack et al., 2007

- **Windscreens**

One of the problems associated with high-rise buildings is the high wind speed at height. High wind speed limits the ability of natural ventilation since it causes unpleasant draught inside the building. One way to make natural ventilation possible even at high wind speeds is using windscreens (Mărginean,2019). Windscreen usually are made of perforated metal sheets and they are placed in front of the operable windows (Mărginean,2019). Providing both shade and possibility of natural ventilation at high wind speed. Vegetation too could work as a windscreen by reducing high wind speeds (Mărginean,2019).



—>Figure 5.14: Perforated metal mesh beside shading could decrease the wind pressure by 35%. Source: www.archro.com

- **Internal vents**

Utilizing internal vents helps to have effective natural ventilation. Alders (2016) in her study showed that placing vents above the internal partitions such as internal doors reduces the risk of overheating remarkably.

5.3.2. Thermal storage and insulation

Insulation

Although insulation is one of the components that increases the risk of overheating by minimizing the heat loss, it also could help to reduce the external heat gain. Placing the insulation in the right position could help to provide comfort both in summer and winter. Studies by Gupta & Gregg (2012) showed that external insulation has a notable effect on reducing overheating both now and in the future. Studies by Porritt et al. (2012) shows that insulating internal walls could have a limited effect on reducing the risk of overheating. Lomas & Kane (2013) showed that insulating the loft has a significant effect on reducing the risk of overheating and increasing the comfort in the summer.

In addition, insulating the building services helps to reduce internal heat gain therefore the overheating risk (NHBC, 2012).

Adaptive insulation

These types of insulations are capable to change their insulation state from insulated to conductive in order to adapt the building skin to the varying outdoor environment (Cui & Overend, 2019). Currently there are five mechanism that through which adaptive insulation could be achieved. These fives are (Cui & Overend, 2019):

- Active vacuum
- Mechanical contact
- Suspended particles
- Pipe-embedded insulation
- Phase change

Between these five, adaptive insulations working with mechanical contact mechanism are most feasible ones that already been used in aerospace industry (Cui & Overend, 2019).

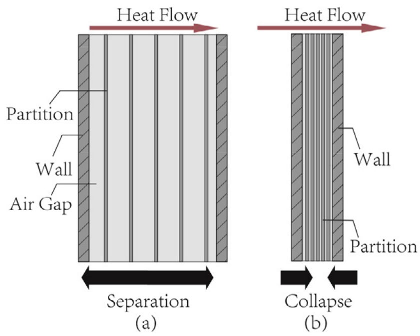


Figure 5.15: Adaptive insulation with mechanical contact mechanism in two insulated and conductive state. Source: Cui & Overend, 2019

Thermal Storage

In this method heat is stored in a storage medium in order to utilize this heat in another time (NHBC, 2012). The time period for energy storage could be a day, a week or even a year (Roaf et al., 2003) This method could be used for summer cooling and prevention of overheating.

- **Thermal mass**

As previously mentioned heavy construction materials such as concrete has the ability to store heat (NHBC, 2012). During the day materials with high thermal mass absorbs the sun radiation preventing sharp temperature peaks in the indoor environment (NHBC, 2012). This heat then is released during the night allowing the mass to cool down. The thermal mass need to be appropriately cooled so it could be effective during the long periods of hot weather (NHBC, 2012). It is best to use this method in combination with night-time ventilation.

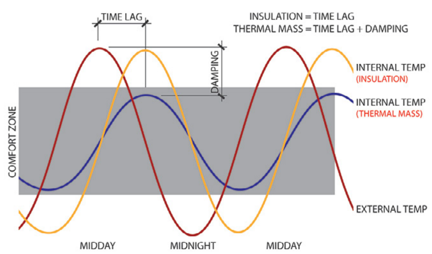


Figure 5.16: The efftect of thermal mass in indoor temperature. Source: Habian, 2015

- **Phase-changing materials**

These are materials with the ability to store heat as latent heat and release it during the phase changing (Khalifa, 2013). Used as thermal energy storage, PCMs can regulate temperature over a 24 hour cycle to store and release the heat (Khalifa, 2013). By using PCM lack of thermal capacity could be compensated without radical structural changes in the building (Diaconu, 2011).

At day time PCM can decrease risk of overheating in the building by changing phase (Khalifa, 2013). Yet, there are two aspects associated with PCM that needs to consider. Firstly, high summer night temperature causes PCM not changing phase and not working for overheating in the next day (Khalifa, 2013). Secondly, If building is not well designed with regard to ventilation and air moisture, condensation could happen on the PCM containers (Khalifa, 2013).

There are different approaches to use PCM in buildings. PCM could be integrated in walls, floors and windows so it could be used as passive thermal storage (Hu, 2019). It also could be used integrated with a ventilation system working as a active heat dissipator (Hu, 2019).

5.3.3. Glazing and shading

The total solar radiation passed through the façade is determined by the shading and the total solar energy transmittance of the glazing (Hausladen, 2005). In this section different shadings and glazing effective for reducing solar gains will be reviewed.

Shading

These elements help in protecting the internal spaces from unwanted solar radiation, therefore reducing external gains and risk of overheating. The ideal shading systems are the ones that admit enough solar light into the building while protecting the room from the excessive heat gain.

Shadings can be divided into two parts, External and Internal shading.

- **Internal shading**

These components are generally used to prevent glare caused by direct sunlight (NHBC, 2012). Yet, they prevent solar radiation from reaching deep in the space heating the room (NHBC, 2012).

Prriot et al., studied the effect of using internal window blinds and curtains and showed although limited they can reduce overheating since heat gain is trapped between the glazing and the shading.

- **External shading**

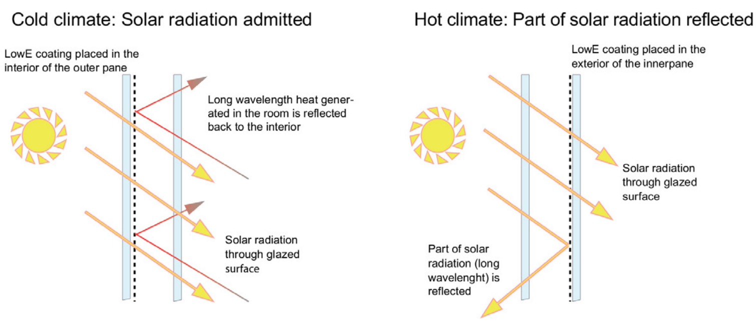
External shadings are the most effective shading systems since the solar radiation is blocked before it reaches the window (Hausladen, 2005). Generally external shading systems could be divided into two main categories of fixed shading systems and movable shading systems.

For fixed shading systems, overhangs, fixed louvers, fritted glass, fixed meshes and green façade could be named. The advantage of fixed external shading is that it needs little to no maintenance.

For movable shading devices, moveable louvers, blinds and sliding shading could be named. These devices are very effective in reducing the external gains in the summer. However, the disadvantage is high capital and maintenance cost due to the exposure to the weather and high wind speed (Hausladen, 2005).

Double and triple glazing with low-E coating

Double and triple glazing with low e coating make the windows more insulated reducing the heat loss. This reduces the heat exchange with outdoor environment which depending on the weather condition could be beneficial or problematic. Glazing allows sun radiation to enters causing heat gain in the room. This is problematic in the summer. Depending on the position of the coating the solar heat gain coefficient (SHGC) of the glazing changes. Using glazing with Low SHGC helps to reduce the risk of overheating (Prriot, 2012).



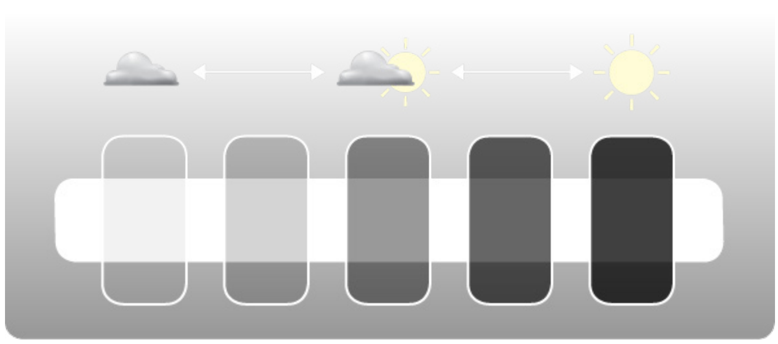
—>Figure 5.17: The influence of coating position on solar admittance. Source: Konstantinou & Prieto Hoces, 2018

Responsive glazing

There are different types of responsive glazing each working in different categories of responsiveness (Hu, 2019). There are three different categories of responsive glazing.

- **Photochromic glazing**

Colour changing or photochromatic glazing that change colour when exposed to light (Hu, 2019). These type glazing absorbs the incoming light and causes a property change which in known as colour changing (Hu, 2019). The glazing changes between absorptive and reflective depending on the solar incident (Hu, 2019). These types of glazing could be used to reduce the solar heat gain in summer.



—>Figure 5.18: Photochromic glazing. Source: https://responsiveskinprototype.wordpress.com/materials/

- **Thermochromic glazing**

In this type of responsive glazing, the thermochromic coating absorbs heat, which leads to a chemical reaction and phase transformation (Hu, 2019). VO2 is a well-known thermochromic material. When VO2 is exposed to infrared waves, it changes it's atomic structure to a crystalline metallic structure, which helps in blocking infrared radiation, thus reducing heat gain (Hu, 2019).

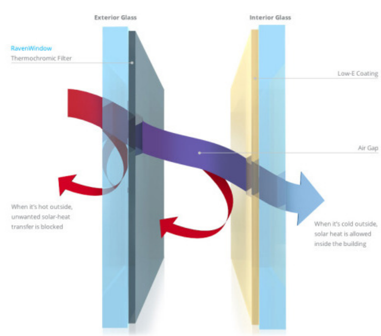


Figure 5.19: The diagram shows how thermochromic filter works. Source: www.ravenwindow.com

- **Electrochromic glazing**

Second type is electrochromic glazing which can change solar transmittance value in response to a low voltage (Hu, 2019). When the voltage is removed the glazing goes back to its original condition (HU, 2019).

However, The biggest disadvantage of responsive glazing is their high cost.

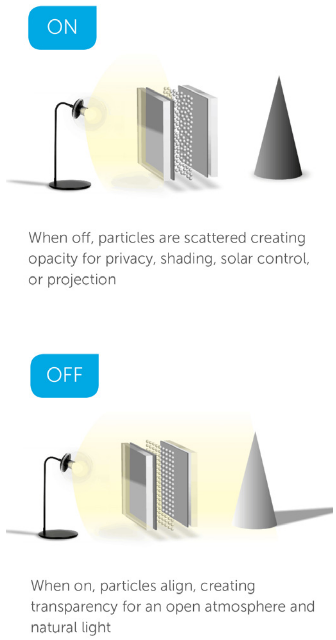


Figure 5.20: Photochromic glazing. Source: https://responsiveskinprototype.wordpress.com/materials/

5.3.4. Evaporative cooling

In this method similar to phase change materials the latent heat is used in order to reduce the air temperature. The water absorbs the heat gains and changes its phase from water to vapor in the humidity content of indoor environment (Konstantinou & Prieto Hoces, 2018). In order to work, this method needs effective air circulation so the saturated air could be replaced with unsaturated one (Konstantinou & Prieto Hoces, 2018).

There are two direct and indirect methods to implement evaporative cooling in the building.

5.3.5. Cool coatings

Walls with light colour are a known traditional method for solar heat gain reduction in southern Europe (Porritt, 2012). Light coloured bricks has much lower absorptivity value compared to dark ones reducing the external heat gain therefore reducing overheating risk in the summer (Porritt, 2012). Moreover, solar reflectance coatings on materials also helps in reducing the solar absorptivity (Porritt, 2012)

Synnefa et al. (2007) in their studies showed that light colour material on the roof surface with low thermal resistant could reduce the cooling load by almost a half.

Kolokotroni et al. (2011) in their study decreased the indoor air temperature by 2.5 C by reducing the roofs absorptivity from 0.9 to 0.4 by using the cool coating.

5.3.6. Comparison

In this section, devices and methods helping in reducing overheating risk in energy-efficient high-rise dwellings were reviewed. To summaries the reviewed methods and strategies, in this part, these methods are qualitatively compared in a table in seven areas which are described later.

The comparison happens in seven areas of:

- Architectural impact: The effect on the layout of the building and its appearance.
- Maintenance: How easily the maintenance could be done.
- Cost: How expensive the solution is compared to the normal construction costs of a building.
- Structural impact: The impact of the solution on the structure. How much load it forces on the building structure.
- Acoustics: How good the solution is in protecting the indoor space from outdoor and neighbouring apartments noise.
- Construction Impact: How bulky and space consuming the solution is.
- Effectivity: How effective the solution is in reducing the risk of overheating.

<table>
<tr><th rowspan="2">Solution</th><th colspan="4">Architectural Impact</th><th colspan="4">Maintenance</th><th colspan="4">Cost</th><th colspan="4">Structural Impact</th><th colspan="4">Acoustics</th><th colspan="4">Construction Impact</th><th colspan="4">Effectivity</th></tr>
<tr><th>None</th><th>Limited</th><th>High</th><th>Very high</th><th>None</th><th>Basic</th><th>Normal</th><th>Hard</th><th>Normal</th><th>Acceptable</th><th>High</th><th>Very high</th><th>None</th><th>Low</th><th>Acceptable</th><th>High</th><th>No effect</th><th>Normal</th><th>Good</th><th>Excelent</th><th>None</th><th>Limited</th><th>Bulky</th><th>Very bulky</th><th>Basic</th><th>Positive</th><th>Good</th><th>Very good</th></tr>
<tr><td>Wing wall</td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td></td></tr>
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<tr><td>Pressure-controlled air inlets</td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td></td><td></td><td>×</td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td></tr>
<tr><td>Natural supply & mechanical discharge</td><td></td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td></tr>
<tr><td>Mechanical supply with natural discharge</td><td></td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td></tr>
<tr><td>Baffle system</td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td></tr>
<tr><td>Second-skin Façade</td><td></td><td></td><td></td><td>×</td><td></td><td>×</td><td></td><td></td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td></tr>
<tr><td>Window-box facade</td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td><td></td><td></td><td colspan="2">×</td><td></td><td></td><td colspan="2">×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td></tr>
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<tr><td>Corridor façade</td><td></td><td></td><td></td><td>×</td><td></td><td>×</td><td></td><td></td><td></td><td></td><td colspan="2">×</td><td></td><td></td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td></tr>
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<tr><td>Low SHGC Glass</td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td></tr>
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<tr><td>Indirect Evaporative cooling</td><td></td><td colspan="2">×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td colspan="2">×</td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td colspan="2">×</td><td></td><td></td><td></td><td>×</td><td></td><td></td></tr>
<tr><td>Cool coating</td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td></tr>
<tr><td>Solar chimney</td><td></td><td></td><td></td><td>×</td><td></td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td>×</td><td></td><td></td><td></td><td></td><td></td><td>×</td><td></td><td>×</td><td></td><td></td></tr>
<tr><td>Static external shading</td><td></td><td></td><td>×</td><td></td><td colspan="2">×</td><td></td><td></td><td colspan="2">×</td><td></td><td></td><td></td><td colspan="2">×</td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td></td></tr>
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<tr><td>Internal vents</td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td><td></td><td>×</td><td></td><td></td><td>×</td><td></td><td></td><td></td><td>×</td><td></td><td></td><td></td></tr>
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5.4. Feasibility and simulation measures

Although feasibility and simulations studies do not impact the risk of overheating directly, inaccurate simulation could cause wrong perception that leads to implementing wrong design in the building, which later could affect people's health. Climate file and occupation schedules are the most important factors affecting the simulation. Later in this section, these two are discussed.

5.4.1. Weather file

Climate files are the most influential parameters affecting the simulation (KOTIREDDY et al., 2017). Choosing the right weather file with right climate scenario could lead to better decision and design (KOTIREDDY et al., 2017). After choosing the right climate file it has to be aligned to the building urban context to include the effect of heat urban island effect in the simulation.

5.4.2. Occupation schedule

Wrong implication of occupation schedule could cause serious misinterpretations resulting bad design with high risk of overheating. Many studies shows since the bedrooms are only studied for schedule occupation between 10pm to 8pm have serious overheating problems (). Today it might not be the case anymore since many use their bedrooms as study rooms (RVO, 2019). Moreover, with increasing number of elderly people who spend most of their times in their homes the risk of mis schedule resulting in overheating is much higher (RVO, 2019). Finding the right schedule during the overheating studies is of importance lack of it could lead to serious health problems.

5.5. Post occupancy solutions

As it was discussed in chapter 4, the sensitivity of occupants to temperature and their behaviour is an essential factor that can increase the risk of overheating. Besides that, the different situation in real conditions and the differences caused during the design could change the building behaviour and cause overheating. Following measures relating to occupant behaviour and building management are discussed.

5.5.1. Occupant behavior

Residents generally do not know how to behave if their building is overheated. The complexity of energy-efficient buildings makes it even harder for them, especially the elderly, to operate the building correctly in the case of temperature exceedance. Therefore, explicit instruction is needed to be given to the occupants so they could operate the building correctly to reduce the risk of overheating.

5.5.2. Weather file

Building management systems with sensors and actuators could significantly help in monitoring and operating the building. Using these systems, building managers could detect overheating at early stages. By providing action protocols for occupants and building manager, they would know how to behave during heatwaves, helping them to take actions to mitigate the problems associated with overheating (Gupta et al., 2017).

5.6. Conclusion

In this chapter, passive and energy-efficient solutions which help in the prevention of overheating were presented. Within the first three sections, the main design strategies which can be taken to prevent and minimize overheating were discussed. The discussed design strategies do not challenge each other, but instead, they complete each other for making a better thermal environment in the building. The proposed strategies could be divided into three categories on how they treat heat.

Table 5.2: Design solutions categories

	Reducing heat gains	Heat dissipation	Thermal storage
Urban level	**1. Urban solar environment:** • compactness and orientation of the neighborhood • building outline • block typology **2. Traffic management**	**1. Urban wind environment** **2. Water and vegetation**	**1. Urban solar environment:** paths and surface materials
Architectural level	**1. Architectural form** • Heat gain area **3. Openings** • Solar heat gain	**1. Architectural form** Heat loss area **2. Architectural layout** Ventilation and airflow **3. Openings** Heat loss area and ventilation	
Detailing and Materialization	**1. Insulation** • Building services insulation • Internal/External insulation • Adaptive insulation **2. Shading** • Internal shading • External shading • In-between shading **3. Glazing** • Double and triple glazing with low-E coating • Responsive glazing	**1. Ventilation devices** • Wing wall • Windows • Turbine ventilators • Natural supply & mechanical discharge • Mechanical supply with natural discharge • Ventilated Double-skin façade **2. Evaporative cooling** **3. Cool coating**	**1. Thermal mass** **2. Phase-change materials**

6. Design Guidelines

In this phase, design guidelines and strategies based upon the research done in the previous chapter will be delivered. These guidelines are categorized into four stages, according to the design level and utilization stages. The guidelines were deduced from literature and case studies of the overheating solutions explored in the previous chapter. The guidelines are categorized according to the effect they are having on the thermal environment into six classes based on the heat treatment categorization introduced in the previous chapter.

In this chapter, First, guidelines on the urban level scale will be introduced. Then, guidelines for architectural layout design are reviewed. After that, guiding principles for materialization and detailing are given. Finally, rules and strategies for overheating prevention during the occupancy time will be discussed.

6.1. Urban level scale

The urban environment has a significant effect on the building's indoor conditions. Poor urban microclimate conditions could make the indoor environment unpleasant and make the operation of the buildings expensive due to the lack of passive design resources. In this section, some guidelines in the urban level will be introduced to help designers to design for prevention of overheating in the buildings.

Heat dissipation:

1. Orienting the buildings and the streets with a 20-30 degree rotation from the prevailing wind helps for having effective ventilation (DeKay & Brown, 2014)
2. The streets facing the prevailing wind should be wide enough for effective wind flow through the neighbourhood
3. Introducing parks, lakes and greenery in streets with higher altitude will help to cool the neighbourhood since the air becomes denser and breezes through the lower streets (DeKay & Brown, 2014)
4. Introducing green edges on the streets facing the prevailing wind helps in reducing the temperature of the incoming air.
5. Introducing green parks and water ponds on the junction of the streets could reduce the risk of urban heat island in the adjacent area since the cooler air from these spaces is distributed to the adjacent streets by the wind (Kleerekoper, 2016)
6. Locating the high-rise buildings in the downwind area from lower height districts benefits the neighbourhood wind environment.
7. Introducing laws and regulation for obligatory green roofs in dense urban environments could reduce the risk of urban heat island effect.

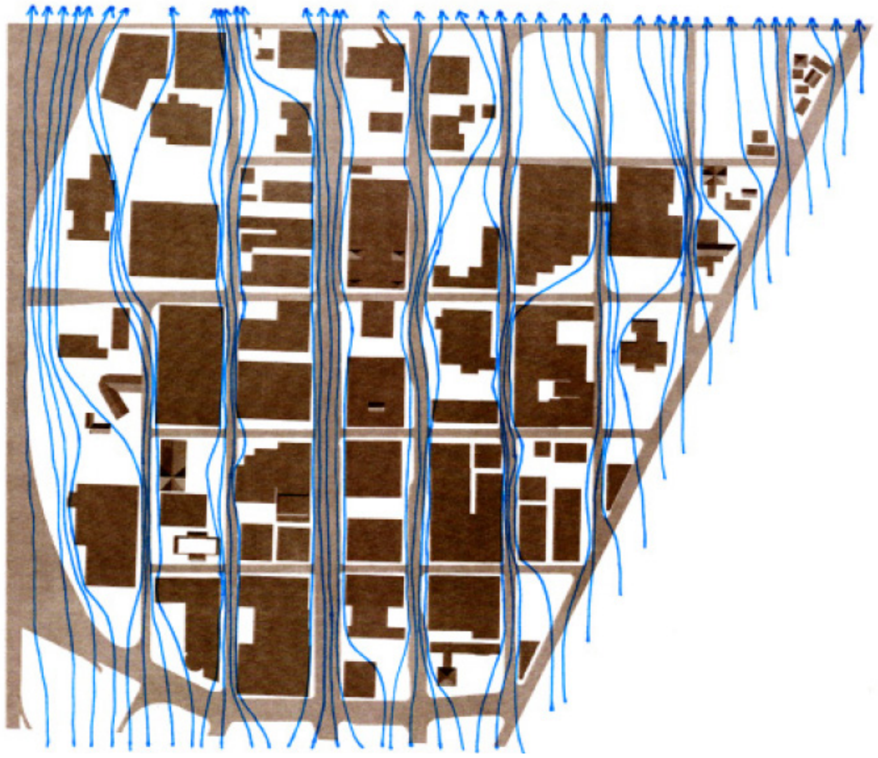
Thermal storage:

8. Using cool pavements for urban flooring could reduce heat accumulation; therefore, the risk of heat island effect (Kleerekoper, 2016)

- ***Example: "City of Chattanooga downtown", Tennessee, USA***

Designed by Green vision studio, Chattanooga downtown integrates several urban cooling strategies. The above-mentioned design guidelines were used in the planning of Chattanooga downtown.

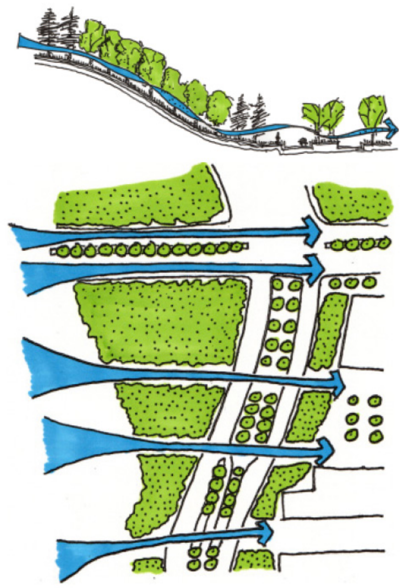
The wide streets facing the prevailing wind increases the natural ventilation potential of downtown (DeKay,2012)(Figure 6.1).



—> Figure 6.1: The wind goes through the wide main streets. Source: DeKay,2012

The greenery introduced at the street crosses and between the buildings with the green edges helps in reducing the incoming wind and guiding the wind flow through the passages in between buildings (DeKay,2012) (Figure 6.2). Besides that they shade the ground and with the light colour cool pavement reduce the risk of urban heat island (DeKay,2012).

—> Figure 6.2: The open green spaces help in reducing the incoming air temperature and redirecting it through in between paths. Source: DeKay,2012



The undeveloped city altitudes were heavily planted with trees and vegetation so that at night, cooled air could flow to the city from these green city districts (DeKay,2012) (Figure 6.3).

Figure 6.3: At night, cooled air of the planted hills belows to the city. Source: DeKay,2012

Reducing heat gains:

9. Arranging buildings with east-west elongation help in reducing the heating-cooling demand by increasing winter gains while reducing the summer gains (Kleerekoper, 2016)
10. Configure building blocks to shade each other in summer.
11. Grouping buildings in a courtyard shape could reduce the risk of overheating in summer (Kleerekoper, 2016)
12. Spreading urban attraction functions in the city to decentralize urban density in order to reduce the urban heat island effect.
13. Introducing trafficking measures and regulation in summer helps in reducing car traffic, hence reduces the risk of heat island effect (Kleerekoper, 2016)

Reducing heat gains + Heat dissipation:

14. During the planning, special attention should be given to the street's orientation, its layout, and the spacing between buildings so that each building could have enough access to the natural resource for passive cooling, heating and ventilation.
15. Minimizing the solar gains on urban fabrics while maximizing night sky exposure on them helps in reducing the urban heat island effect (DeKay & Brown, 2014)

- *Example: "Hashtgerd New Town", Iran*

Hashtgerd New town is a 35 ha sustainable city development project done by German and Iranian researchers. This project looked into urban strategies for reducing the cooling-heating load of the buildings.

The buildings were arranged in a courtyard shape with east-west elongation for the reduction of the cooling & heating load (Seelig,2011) (Figure 6.4).

The arrangement of the blocks are in a way that blocks the dusty-hot wind and admits the cool mountains wind breezes into wide northern streets (Seelig,2011) (Figure 6.5). The green edges too, help in reducing the incoming wind.

Figure 6.4: Arrangement of buildings in a courtyard shape. (Seelig,2011)

Figure 6.5: The trees and vegetation reduce the risk of urban heat island effect.. (Seelig,2011)

—> Figure 6.6: Cool air from the mountains enters from the North. (Seelig,2011)

6.2. Architectural design level

Building's architectural layout and form have a significant effect on overheating. In this section, overheating prevention design guidelines during architectural configuration, layout and shape design stage are given.

Heat dissipation:

1. The plan should be not too deep so that cross-ventilation could be used. A rule of thumb is that the depth of the building should not be more than five times the height for sufficient cross ventilation (Smith, 2008)
2. Utilization of both wind-driven and buoyancy-driven ventilation strategies improves the ventilation driving forces and the effectivity of natural ventilation.
3. For effective ventilation, the opening area should not be less than five per cent of the floor area (Smith, 2008)
4. The rooms and spaces that allow a wide range of temperature swings could be placed in between of the zones with stricter comfort criteria and heat sources as thermal buffer zones. This way, the temperature of the protected rooms could be controlled easier (DeKay & Brown, 2014)
5. The vertical and horizontal access facilities should be arranged in a way that they do not hinder the airflow across the zones (DeKay & Brown, 2014).
6. Designing of the plan and section should be as open as possible so that wind-driven airflow, buoyancy-driven airflow or both could be utilized for ventilation.
7. For effective single-sided ventilation, the depth of the room should not be more than 2.5 times the height (Smith, 2008)
8. The effect of interior layout and furniture placement on natural airflow should be considered during the architectural layout design, since they have a direct impact on natural ventilation performance.

- *Example: "Kanchunjunga Apartments", Mumbai, India*

Designed by Charles Correa, the Kanchunjunga building is a high-rise dwelling that uses both wind-driven airflow and buoyancy-driven airflow for natural ventilation. This is achieved by the open section-plan design. For open design, the vertical access was arranged in every two floors, and internal corridors were avoided to make an obstacle-free air corridor between the zones (DeKay & Brown, 2014). By defining zones with a difference in height, buoyancy-driven ventilation was utilized to induce the wind-driven ventilation and also to minimize the use of internal partitions which hinders the air movement (DeKay & Brown, 2014). Buffer zones were made by using shaded green terraces facing the prevailing wind which both blocks the solar radiation and wind storm, allowing pleasant cool air to flow to the apartment (DeKay & Brown, 2014).

Figure 6.7: Big environment protected opening helps in having effective wind-driven ventilation. Source: http://dome.mit.edu/handle/1721.3/58062

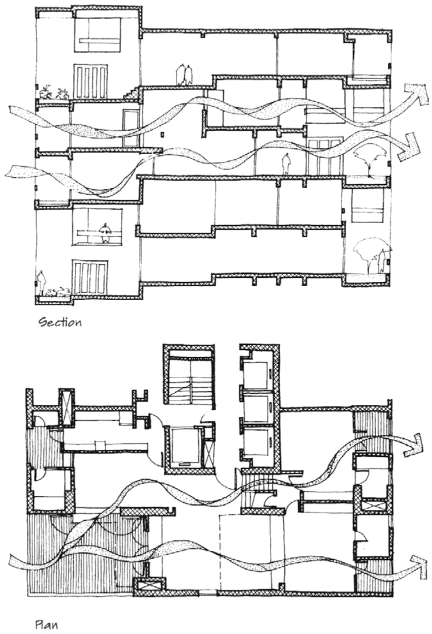


Figure 6.8: Open plan/section design with appropriate depth helps in having effective natural ventilation. Source: DeKay & Brown, 2014

Heat dissipation, ctd:

9. Locate the zones with high internal heat generation near the envelope for effective natural cooling.
10. Orient the openings and vents from the direction of the prevailing wind with a 45-degree orientation to have effective ventilation.
11. Configure the rooms with similar cooling needs and occupant

schedule together in a zone, in order to make the utilization of the cooling strategies easier and energy-efficient.

- ***Example: "Another Sky", India***

—> Figure 6.10: Balconies and shading elements in the form protects the building from excessive solar gain. Source: archdaily.com

Designed by Designhaus Solutions architects, Another Sky utilizes several heat gain control and ventilation.

strategies to provide good thermal conditions for the occupants. The openings on four directions and the oriented balconies provide effective cross ventilation for the apartments. The balconies provide shading for the big openings of the apartments, which could become fully open to cool the kitchen and the internal spaces.

Heat dissipation, ctd:

12. Horizontal access elements could effectively be used for enhancing airflow.
13. For effective cooling control, it is better to place the rooms that benefit from the cold, such as kitchen and bedrooms, on the North.
14. Stack effect could be used as an effective ventilation strategy in high-rise buildings since it is an intrinsic characteristic of these buildings.
15. The bulky ventilation strategies such as solar chimneys, atria, wind tower and exhaust shafts should be thought of in the plan configuration so they could be integrated into the building's layout.

Thermal storage:

16. High ceilings manage the heat swings and reduce the chances of radical temperature swings (DeKay & Brown, 2014).
17. Bulky thermal storage solutions, such as thermal mass, should be integrated into the architectural design.

- ***Example: "EMV Social Housing"***

Figure 6.11: The placement of the kitchen near the openings provide effective cooling in the kitchen. Source: archdaily.com

Designed by feilden Clegg Bradley studio, several heat dissipation techniques and heat protection techniques were integrated in the EMV Social housing architectural design in order to prevent overheating. The court yard arrangement of the buildings help them to shade each other and prevent excessive solar gains. Also, movable sliding shutters were used in the design to further reduce external heat gains.

Cross ventilation and buoyancy driven ventilation are key strategies in the used in architectural design. Each apartment has two aspects looking at the street and the court yard allowing cross ventilation (Bizley, 2010). For night time cooling, big stack effect shafts with solar exhaust chimneys at top were integrated into the design in order to use this effect for effective comfort ventilation.

—> Figure 6.12: In this picture, big extruded stack ventilation chimneys from the roof can be seen. Source: feilden Clegg Bradley studio, n.d.

Each apartment has its stack exhaust duct. This way, the acoustic and odour problem associated with shared chimney ducts were solved (Bizley, 2010). The chimney ducts were designed and sized according to the volume of the apartments and the shaft height (Bizley, 2010). At night, the interior vents connecting to the shaft will open automatically, allowing night-time flush cooling (Bizley, 2010). The exhaust vents at the top of the chimney, too, could be controlled to control the exhaust rate (Bizley, 2010). Also, the wind billowing across the chimney generates negative pressure helping the stack exhaust (Bizley, 2010).

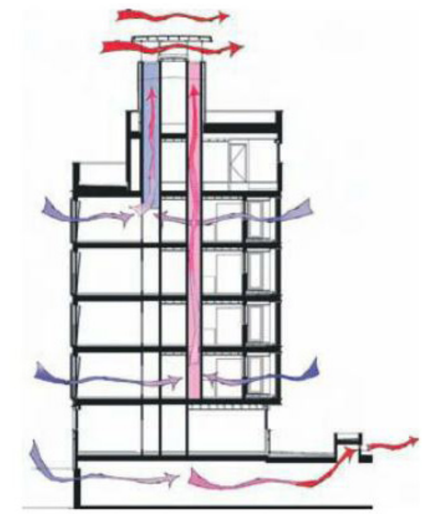


Figure 6.13: Nighttime ventilation strategy. Source: Bizley, 2010

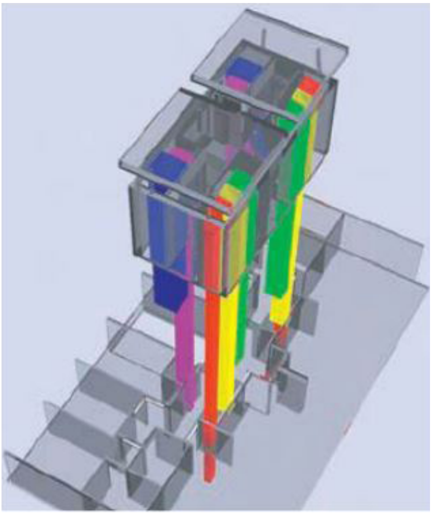


Figure 6.14: Diagram shows ventilation exhausts of each apartment. Source: Bizley, 2010

Reducing heat gains:

18. Using self-shading forms and elements such as overhangs in buildings helps in reducing the solar heat gains.
19. Designing the form of the building in an elliptic shape increases the compactness of the building, which decreases the cooling-heating needs. In addition, this form improves the aerodynamics of the high-rise building (Raji, 2018).

- ***Example: "ARTE S", Malaysia"***

Designed by Spark architects, the ARTE S high-rise dwelling has an elliptical shape that both improves the aerodynamics of the building and decreases the cooling need of the building. The balconies designed for each floor protects the apartments from sun radiation while it allows floor height openings to fully open up for effective ventilation.

Figure 6.15: Elliptical shape of the building helps in reducing the cooling needs. Source: Archdaily.com

—> Figure 6.16: The openings could fully open up for effective single-sided ventilation. Source: Archdaily.com

6.3. Detailing and systems design guidelines

Reducing Heat gains:

1. Insulating building services such as hot water pipe works limits heat transmission to the adjacent zone. (EST, 2005)
2. Using energy-efficient electrical devices and lighting besides reducing energy consumption reduces the internal heat production diminishing overheating risk (EST, 2005).
3. Make use of external shading since they are very effective in reducing overheating. Fixed horizontal shadings are beneficial in protection from the high sun. Fixed vertical external shadings are useful on the west and east-facing windows. The best type of external shading devices are moveable devices such as shutters that protect the whole window from solar gains.

- ***Example: "Hotel Amstelkwartier"***

The façade of hotel Amstelkwartier in Amsterdam is made of a single skin façade with adaptable, moveable shading panels. The panels are controlled with a BMS system which adapts the panels according to the occupancy and outdoor climate conditions. When the room is unoccupied, the panels are closed. The panels block the solar radiation in summer, preventing external heat gains. While in winter it limits the heat loss through the façade.

Additional data and examples on the usage of external shading devices can be found in Appendix A.

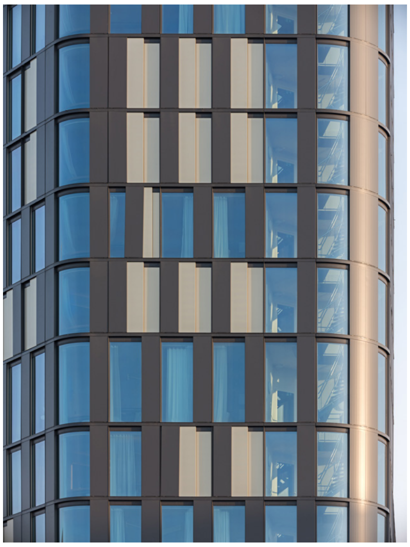


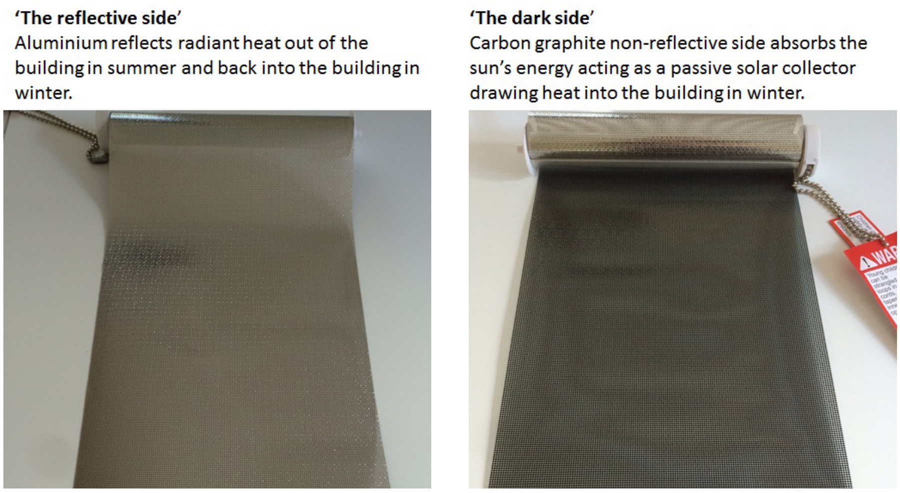
Figure 6.17: Moving panels of hotel Amstelkwartier. Source: www.qo-amsterdam.com

4. Make use of internal shading. Reflective internal solar shadings are most beneficial internal shading devices in overheating reduction.

- ***Example: "iSolar Blinds"***

First developed by NASA, iSolar blinds are made of perforated aluminium coated polyethylene laminated to carbon graphite. The screens are transparent, allowing for visual access to the outside view when in use. The aluminium coated side works as a solar reflector in summer, reflecting over 80 percent of incoming sun rays. In contrast, the graphite laminated side works as a solar absorber in winter.

Additional data and examples on the usage of Internal shading devices can be found in Appendix A.



—> Figure 6.17: The Isolar blinds are transparent on inside, allowing for visual access to outdoor view. Source: www.arcthermalproducts.co.uk

5. Use low solar energy transmittance glazing to reduce solar heat gains.

6. Make use of responsive glass on South, West and East façade.

- ***Example: "ECONTROL"***

The Econtrol glass developed by EControl-Glas GmbH uses an electrochromic coating to change the solar transmittance. The solar transmittance could be altered from almost 60% to 10% by applying an electrical voltage to the glass. This change in glazing's g-value helps in reducing the solar heat gain and therefore, reducing the overheating risk. The benefit of this system is that it gives excellent architectural freedom since there is no need for the use of mechanical indoor-outdoor shading devices using this system. The significant advantage of the Econtrol systems is that it only uses electricity when it is changing the dimming level of the glass.

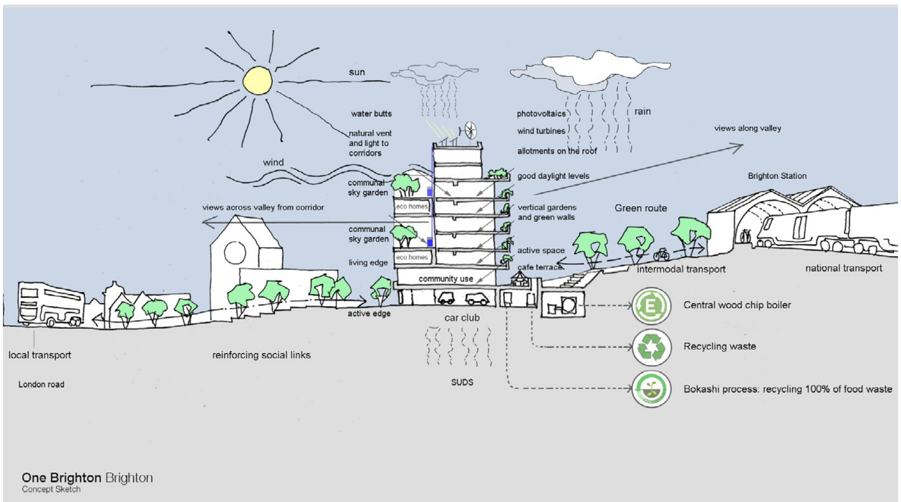
—> Figure 6.18: Each pane could be controlled to have a specific dimming level. Source: www.econtrol-glas.de

7. Use light colour finishing on the horizontal surfaces, green roofs or shading the roof by PV panels to reduce the solar gains of horizontal surfaces.
8. Make use of external insulations since positioning the insulation on the outer layer helps in protecting the inner layers from solar gains.
9. Insulate the unoccupied zone with a high internal load to prevent heat transfer to adjacent occupied zones.

- ***Example: "ONE BRIGHTON"***

Designed by Feilden Clegg Bradley studio, several sustainable design principles were used by architects that besides energy efficiency and sustainability helped in making a thermally comfortable environment, especially in summer. Introducing mini rooftop gardens and terraces and using PV panels on the roof, beside they are enabling residents to have their food farm and energy plant, and it protects the rooftop and balcony's walls from excessive solar gains. Furthermore, the use of low energy, high-efficiency lightings and appliances, thermal mass and effective natural ventilation helps in preventing heat accumulation and overheating in the building.

—> Figure 6.19: Rooftop of One Brighton dwelling. Source: Feilden Clegg Bradley studio



—> Figure 6.20: Concept sketch of energy-efficient strategies used in One Brighton building. Source: Feilden Clegg Bradley studio

Heat dissipation:

10. Provide air inlets with an effective area of at least 5% of the floor area for natural ventilation. (W. Brenner et al., 1985)
11. Locate away or protect air inlets from noise sources.

12. Use pressure-controlled air inlets or windscreens to provide natural ventilation, in areas where high wind speed restricts natural ventilation.

- *Example: "Highlight Towers"*

The façade of the Highlight towers in Germany are made of single skin façade. The buildings are ventilated through openable windows, protected by perforated steel panels which protect the air inlet from high wind speed and rain (Wood & Salib, 2013). The perforated panel is also integrated with a sound-absorbing material protecting the indoor environment from outside noise. The windows are operated through electrical means allowing both the building management system and the user to control the ventilation (Wood & Salib, 2013).

13. Ventilate service voids to reduce internal heat loads (Dengel et al., 2016 [BRE]).
14. Using ventilation systems with natural supply and mechanical discharge or mechanical discharge and natural supply helps in ventilating single-sided apartments to ensure a minimum amount of fresh air and air circulation in the apartment.
15. Make use of mechanical ventilation with summer by-pass when MVHR system must be used.
16. Using indoor vents induces the indoor airflow. This solution could be especially beneficial in double and multi-sided apartments connecting zones with different orientations together for effective ventilation.
17. If the plan is not too deep, sound insulated vents and ducts could be used on the ceiling and ground to connect the air path of the adjacent apartments for more effective cross ventilation.
18. Placing wet ceramics or spraying water on the path of air inlet helps in reducing the incoming air temperature by evaporative cooling. This could happen in a closed cycle in order to use the cooled surface as a radiative cooler or in an open cycle to use the cooled air for ventilation and cooling.

Figure 6.21: The hinged windows and the perforated steel windscreen. Source: (Wood & Salib, 2013).

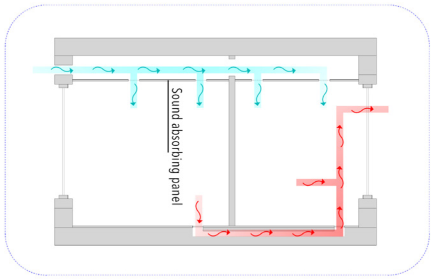
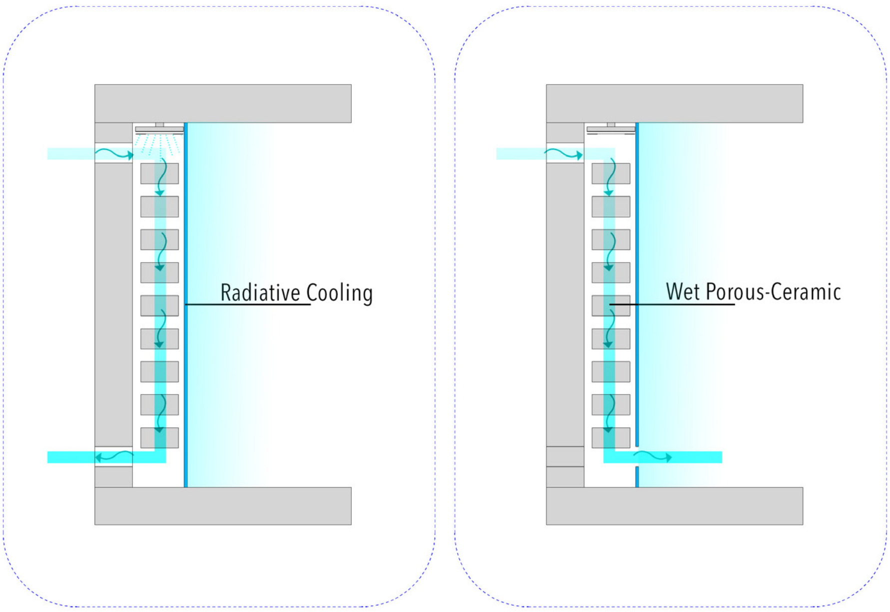


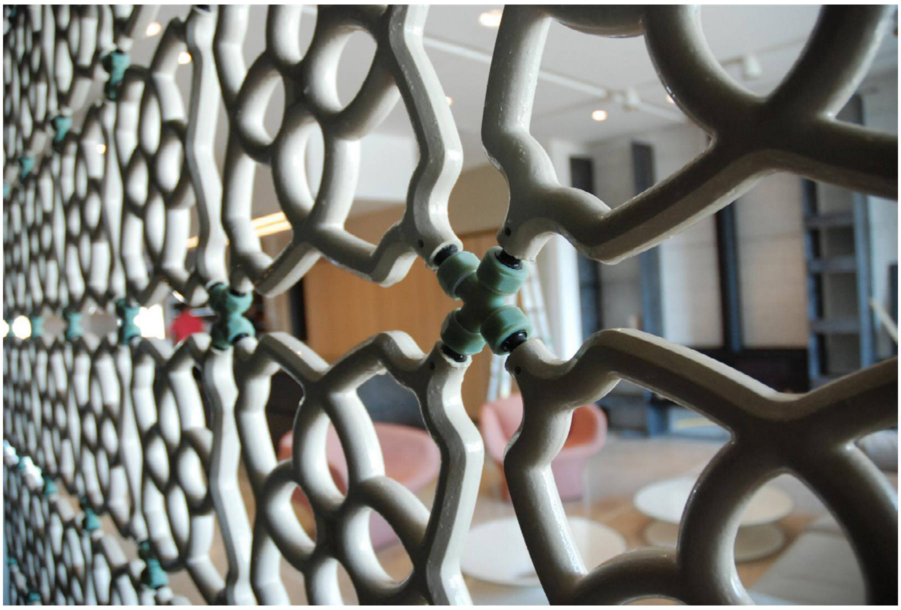
Figure 6.22: Air paths could be made between adjacent apartments to enable cross ventilation.



—> Figure 6.23: Using prous ceramics both direct and indirect evaporative cooling systems could be utilized in the building.

- *Example: "Ecooler ceramics"*

Designed by Kahn studio, Ecooler uses the principle of clay pots for evaporative cooling. The water runs through the shaped ceramics making it to be trapped in the microstructures of the ceramic. Then, water trapped on the surface evaporates cooling the surrounding air. This system could be used inside or outside. Using the Ecooler on outside in addition to cooling could help to providing shading for the windows.



—> Figure 6.24: Ecooler system used as an interior partition. Source: www.studiokahn.com

Thermal storage + Heat dissipation:

19. Make use of large areas of exposed thermal mass.
20. Place the thermal mass near the windows and air inlets. This way, the thermal mass could benefit more from night-time ventilation.
21. Integrate PCM into the construction materials such as gypsum boards or concrete blocks to increase the thermal
22. Make use of PCM by exposing it to natural supplied air to reduce the inlet air temperature.
23. Reschedule mechanical ventilation for night cooling in order to recharge the thermal storage for the following day

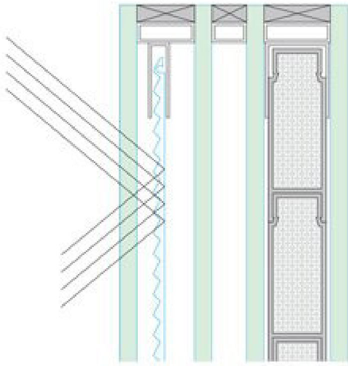


Figure 6.25: The prismatic in the outer cavity reflects high solar rays reducing heat gain. Source: www.glassxpcm.com

Heat protection + Thermal storage:

24. PCM could be used in the cavity of multi glazing windows, both increasing thermal capacity of the window and working as a heat protection device.

- *Example: "Glass X"*

Founded by Dietrich Schwarz, Glass x develops and produces glazing units with an integrated PCM layer. The units are made of 4 glass layers making three cavities. The inner cavity is filled with PCM, and other cavities are filled with noble gasses to reduce thermal conductivity. The translucent PCM protects the indoor environment from the sun gain during the day. Each square meter of the glazing unit provides 1185 Wh of heat capacity protecting the indoor environment from the overheating. Some products developed by Glass x such as GlassX crystal use a prismatic layer in the outer cavity to further protect the indoor environment from sun rays.

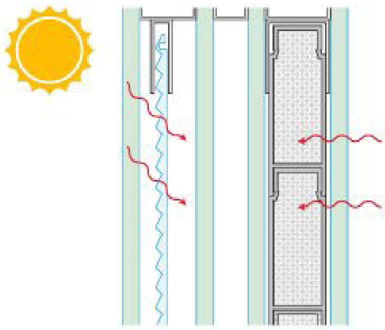


Figure 6.26: The PCM prevents heat accumulation in the room during hot summer days. Source: www.glassxpcm.com

Heat protection + Heat dissipation:

25. Wing walls can be used as vertical shading and also for improving natural ventilation where wind-induced ventilation is not sufficient to ventilate single-sided zones

- ***Example: "Bloomberg's European headquarters"***

Designed by Foster + Partners, Bloomberg's European headquarters building benefits from the aerodynamic fins placed on the façade. The fins both work as a shading device protecting the interior space from the sun and as an aerodynamic wing wall helping the natural ventilation.

26. Make use of climate facades with shading when the building envelope needs to be protected from extreme environmental influences. Influences such as, high wind speed, moisture, high surrounding noise which all reduce the possibility of natural ventilation.

- ***Example: "Riverhouse – One River Terrace"***

The façade of the Riverhouse residential high-rise in New York is made of window-box double-skin façade with a cavity of 11.5 cm. The vents and passive dampers on the skin regulate the ventilation in the cavity depending on the season. The inner skin windows are fully openable and are used for ventilation. For sun protection solar blinds are used in the cavity to prevent excessive heat getting inside the building.

Additional data and examples of climate facades can be found in Appendix A.

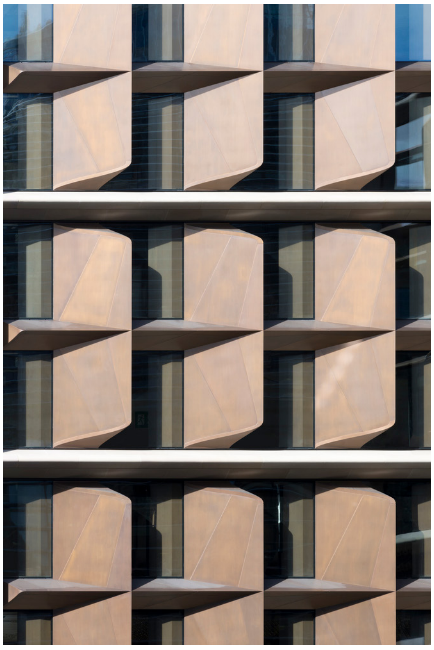
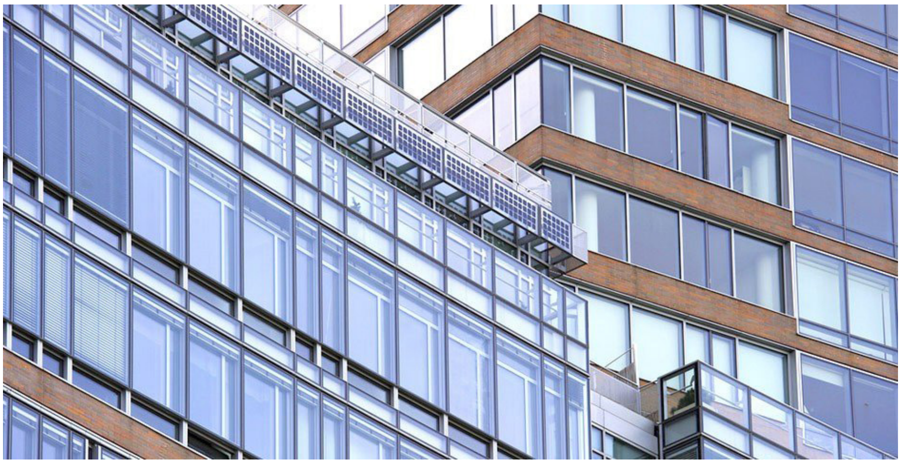


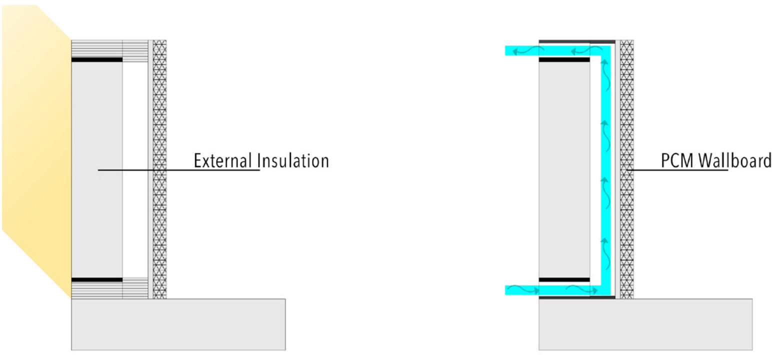
Figure 6.26: Aerodynamic wings on the Bloomberg's headquarters façade. Source: Archdaily.com



—> Figure 6.27: Unitized window-box facade of Riverhouse. Source: www.nynesting.com

Heat protection + Heat dissipation+ Thermal storage:

27. External and adaptive insulations could be used with PCM integrated wallboards to keep a room cool. The external insulation protects the building from the sun radiation during the day, and PCM wallboard could regulate the indoor temperature by preventing high-temperature swings. At night the adaptive insulation could be closed to allow fresh air movement in the cavity between the insulation and the wallboard. This way, the trapped heat will get out, and the PCM could be regenerated again to its solid-state (Figure 6.28).



—> Figure 6.28: Right: External insulation protecting the inner layer from solar gain at day. Left: ventilating the cavity to regenerate thermal storage.

28. Make use of PCM integrated internal shadings. The PCM used in the shading will delay the heat accumulation in the cavity between the shading and the window making time for heat dissipation

6.4. During occupancy guidelines

As mentioned in the previous chapter, the occupant behaviour, and how the building is managed has the most significant effect on overheating risk. In this section, some guiding strategies for overheating prevention during the occupancy of the building is given.

Building management guiding strategies:

1. The building manager should observe the buildings thermal behaviour using BMS or In-situ periodic measurements in order to take measures and to provide guidance for users for overheating prevention.
2. Building managers should develop heatwave plans and guidance to minimize the risk in the heatwave period.
3. Building managers should develop and use a sensor's fault detection tool to prevent wrong detections and faulty actions by the automated system (Kolokosta et al., 2011)
4. The dwelling occupancy can be sorted in three general categories according to the user occupancy schedule: low, medium and high occupancy.
   a. The low occupancy residents are those that during the working days are not at home.
   b. The medium occupancy residents are those during the working day some occupants are out, and some are at home.
   c. The high occupancy residents are occupants that all days are present in the home, such as the elderly or people who work from home. The designer should sort buildings according to these schedules to suggest giving homes with a higher risk of overheating to occupants with low occupancy schedule to reduce the risk of overheating.

Automated building management:

5. Smart thermostats or BMS systems should be used to prevent excessive heating in the winter.
6. Install building management system in apartments:
   a. A combination of smart plugs, sensors, actuators and building management system could substantially help in controlling the occupant's behaviour to prevent overheating. By using data from sensors or manual inputs, an intelligent system could find the user's presence schedule and their thermal preferences. Then BMS systems could operate the building using actuators and smart plugs to control ventilation, lighting, appliances and shadings in the absence of the occupant to reduce heat accumulation. The BMS system should provide a dynamic guide for the user using sensors, so whenever a user takes action, it could show the user how much time it takes so the user could feel the change and also warn the occupant in case of an action that would increase the overheating risk.
   b. Make use of wireless sensors and actuator since they are easier to maintain and to operate.
   c. Make use of machine learning algorithms in BMS to record the occupants' responses and preferences regarding the thermal

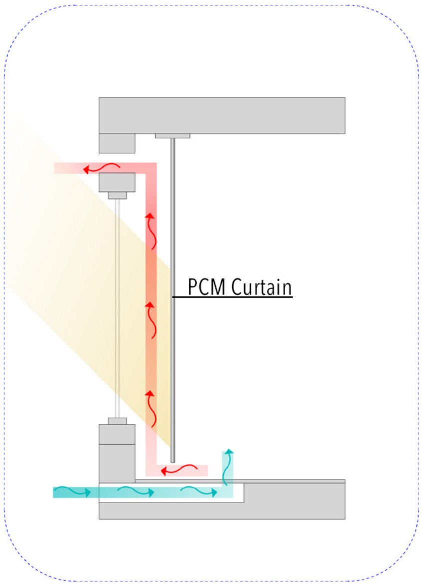


Figure 6.29: PCM integrated curtains.

environment to manage the building according to the user's preference.

d. For thermal environment control, make use of algorithms based on adaptive thermal comfort.

Occupant behavioural guidelines:

7. Using energy-efficient appliances and lighting beside saving energy, reduces the internal gains by reducing the chance of heat accumulation.
8. Through taking energy-reducing actions such as skipping dishwashers and washing machines "dry" cycle and letting the warm summer weather do the drying, the occupant could reduce overheating risk by diminishing plenty of internal loads.
9. Do the cloth washing and dishwashing at night.
10. Close the sun shading when the room is not occupied to prevent heat accumulation when the room is vacant.
11. Taking cold showers and drinking cold water increases the user's resilient to high temperature.
12. Make use of smart electrical plugs. These devices provide a smart electrical outlet that can be used to supply power for appliances. The user could provide a schedule or remotely control the appliances to monitor and operate them. Also, since appliances still consume energy and produce heat when they are in hibernate mode, these devices could completely prevent energy consumption when the device is not in use.

7. Case study

Designed by V8 architects, Cooltoren is a 150 m tall energy-efficient high-rise dwelling located in Baankwartier of Rotterdam. The building has 50 floors and is expected to be ready by the end of 2020. In total, the building accommodates 284 apartments with different typologies and sizes ranging from 50 m2 to 421 m2. The first two floors house commercial and storage spaces and there is a three-floor construction adjacent to the tower housing occupants' cars and bikes.

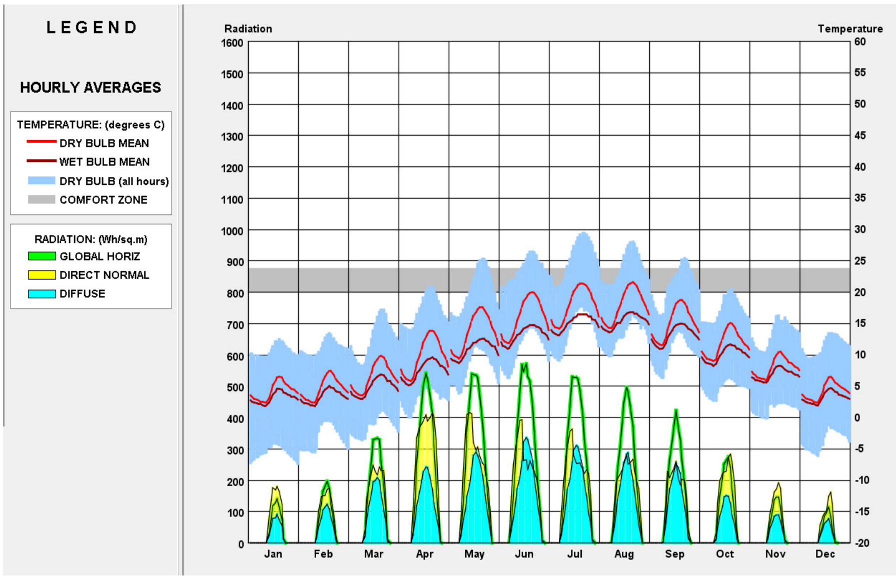
—> Figure 7.1:Cooltoren designed by v8 architects. Source: V8 architects

In the previous chapter, various design guidelines and strategies useful in reducing overheating risk in energy-efficient high-rise dwellings were given. Therefore, to do further studies on the effectivity of the design guidelines in addressing the overheating problem both now and in the future, Cooltoren building was chosen as a case study.

In this chapter first, the building's urban context and its architectural layout will be analyzed and studied. Then an analytical analysis will be conducted in order to find the most problematic archetype in the building. Lastly, a numerical study on the selected floor will be held.

7.1. Urban Context analysis

Located in Baankwartier Cooltoren is located in the Cool neighbourhood in the centre of Rotterdam. Looking at the weather conditions of the site, Rotterdam has a temperate oceanic climate (Cfb) according to the Köppen climate classification system. Figure xx demonstrates the climate conditions of the Rotterdam region. Being a heating-dominated climate, still, it can be seen that there is a good chance of temperature exceedance during the summer. With the rare occurrence of the extreme weather days, winters and summers are considered mild in this climate. Therefore, this climate allows for natural cooling during the summer.



—> Figure 7.2: Rotterdam's monthly durinal averages. Exported from climate consultant 6

Located in the proximity to the lake and parks, suggest a stable thermal environment in the Cooltoren's neighbourhood with low risk of heat island effect. The green edges and the 1500m2 green roof on the Cooltoren's parking reduce the risk further (Figure 7.3).

—> Figure 7.3: The proximity to the water and green area reduces the risk of the urban heat island. Source: V8 architects

Being the tallest building in a neighbourhood with low-rise buildings, no construction shades the tower and obstructs the path of prevailing south-west wind. This provides a rich environment with abundant natural energy resources for Cooltoren to use.

7.2. Architectural Design analysis

Located in a post-war made district with many low rise buildings, in order to connect the tower to the urban context the building is divided into two shapes. The first six levels of the Cooltoren is elongated on north-south direction, connecting the tower to the surrounding urban context. From the seventh floor, the square shaped tower starts up to the top. Having a square plan helps in reducing the heating and cooling needs of the buildings because of the plan compactness.

—> Figure 7.4: Rectangular base and square tower. Source: V8 architects

The tower has a self-shading form because of the balconies. Every apartment has access to at least one shaded balcony. The placement of the shaded balconies in front of the bedrooms protect the bedrooms, which are known as the most vulnerable spaces to temperature exceedance, from overheating.

—> Figure 7.4: Continuous ribbon balconies shade mid-crown apartments. Source: V8 architects

Looking at the architectural layout, the floors of Cooltoren has ten different plan layouts, 4 of which are for the base, and 6 of them make the square tower's floors. The only difference between each similar architectural layout is in the dimension of the balconies and the window wall ratio.

The window wall ratio is not consistent. The walls accessing to the balconies have a window-wall ratio of 65 to 75 per cent both in the tower and the base, while the window-wall ratio of the other walls ranges from 50 to 65 per cent in tower and 25 to 65 per cent in the base.

Considering architectural layout, the first six floors make a rectangular base of the building as mentioned before. Each of these floors has at least five to six single-sided apartments facing west. Apartments at these levels are well shaded by the surrounding trees and buildings. Having access to balconies with fully openable doors makes the natural ventilation effective in the apartments. However, the great depth of the plan and fixed unopenable windows limits the effectivity of the ventilation in some of the apartments. Moreover, the lack of openable windows on all sides of double-sided apartments reduces the effectivity of natural ventilation by eliminating the opportunity of cross ventilation.

As can be seen in figure 7.6 the tower is divided into four parts.

The tower accommodates six types of plan layouts as it can be seen in figure 7.7. Layout A, B, C & D are used for City-Chic apartments, Layout D is used for Mid-crown apartments, and Layout E & F are used in the Penthouses.

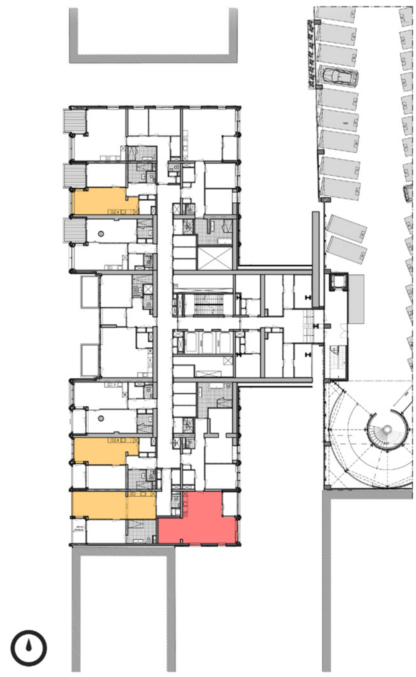


Figure 7.5: Third level floor plan. The zone coloured in yellow shows the rooms with high depth to height ratio, limiting the effectivity of natural ventilation. The zone highlighted in red shows a double-sided apartment with great depth and operable windows only on one side. Source: V8 architects.

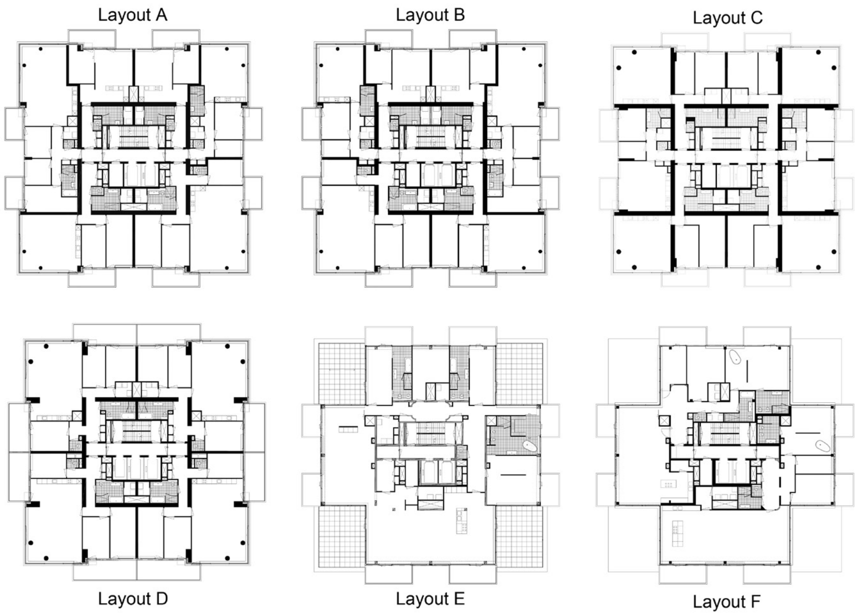


Figure 7.6: Tower's floor plan layouts. Source: V8 Architects

Generally, looking at the tower's floor plans, it can be seen that thick structural concrete walls were integrated into the architectural layout providing thermal mass for the apartments. In order to do further analysis on the effect of plan layouts on the overheating risk, table 7.1 was made to assess the layout and their potential impact on overheating risk.

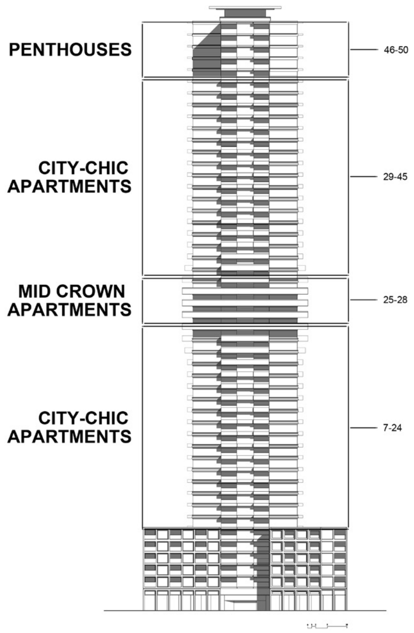


Figure 7.5: Apartments are divide into four groups. Source: V8 architects

Table 7.1: Assessment of the layouts and their possitive/negative effect on overheating

	Architectural aspects that could help to reduce the overheating risk	Architectural aspects that could exacerbate the overheating risk
Layout A	+ Openable windows and doors on the double-sided apartments facing south make cross-ventilation possible.	– Tiny single aspect unshaded bedroom facing east and west – Openable windows only on one side in the apartments facing North – Internal partitions hinder airflow
Layout B	+ Openable windows and doors on the double-sided apartments facing south make cross-ventilation possible.	– Tiny single aspect unshaded bedroom facing east and west – Openable windows only on one side in the apartments facing North – Internal partitions hinder airflow
Layout C	+ Openable windows and doors on all double-sided apartments make cross-ventilation possible. + Placement of kitchen near the envelope enables effective heat dissipation.	– Single-sided apartments facing west and East – Tiny single aspect bedrooms – Internal partitions hinder airflow
Layout D	+ Openable windows and doors on all double-sided apartments. Makes cross-ventilation possible. + Fully shaded bedrooms. + Continuous balconies shade the apartments on Mid-Crown. + Placement of kitchen near the envelope enables effective heat dissipation.	– Internal partitions hinder airflow
Layout E	+ Proper airflow through the apartment. + Operable windows and sliding doors on all sides. + Placement of kitchen near the envelope enables effective heat dissipation. + Main zones and spaces benefit from cross ventilation.	– High surface to volume ratio
Layout F	+ Placement of kitchen near the envelope enables effective heat dissipation.	– High surface to volume ratio – Zones only benefit from single-sided ventilation. – Internal partitions hinder airflow

7.3. Analytical overheating analysis

In order to identify the most problematic floor layout with zones with a higher risk of overheating, an analytical calculation was conducted. For calculations TO_{juli} overheating assessment method was used. In this section, first, the apartment selection workflow is described, then the calculation method is described, and at the end, the results are concluded.

7.3.1. Workflow

In order to narrow down the number of selected floors for calculations, extreme representatives of each floor layout were chosen to study (Figure 7.7).

In every selected apartment, one zone with a higher chance of overheating was selected to study. For instance, the highlighted zones in figure 7.8 have properties such as heat gain from two sides or single-sided ventilation that makes them susceptible to overheating. Therefore highlighted zones were selected for analytical calculation.

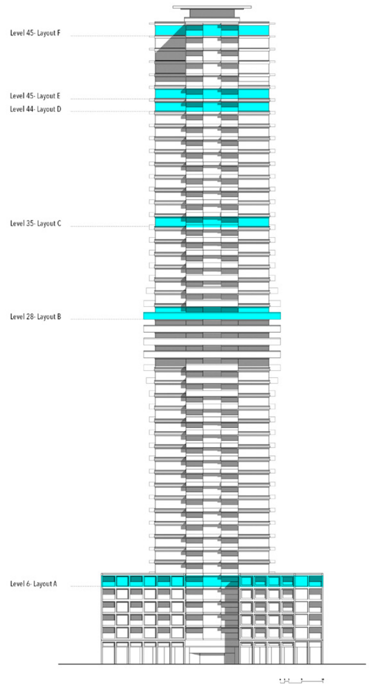


Figure 7.7: Selected floors for overheating calculation. Redrawn from Source: V8 architects

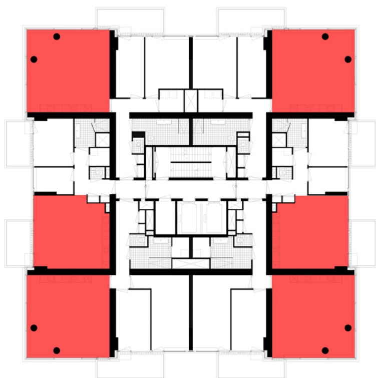


Figure 7.8: Selected rooms for overheating study from level 35-type "C" layout.

7.3.2. TO_{juli} calculation

As described in chapter 4, TO_{juli} is an analytical indicator that predicts the risk of temperature exceedance in a zone. TO_{juli} can be calculated according to NEN 7120 using UNIEC2 software. However, in order to be able to do simple hand calculations using spreadsheets, the TO_{juli} indicator was simplified in collaboration with a fellow student, Prateek Wahi.

TO_{juli} is calculated using this formula:

$$TO_{juli;i} = \frac{Q_{beh;koud;juli;i}}{(H_{T;koud;i} + H_{V;koud;i}).t} \quad (1)$$

In which:

$TO_{juli;i}$	Numerical value for the risk of overheating in the month of July calculated for zone i	K
$Q_{beh;koud;juli;i}$	Cooling Requirement for Zone I for the month of July	MJ
$H_{T;koud;i}$	Heat Loss coefficient due to transmission of zone i	W/K
$H_{V;koud;i}$	Heat Loss coefficient due to the ventilation of zone i.	W/K
t	Length of the month of July	Ms

The complete method and the detailed calculation method of the mentioned variables are described in appendix B.

Selected zone's dimensional & construction parameters that were used in the calculations are as below:

—> Table 7.2: Selected zone's dimensional parameters

Parameter	Description
Zone Area	Area of the space excluding walls [m^2]
Zone Perimeter	Perimeter of the analyzed zone [m^2]
Wall Area	Total area of the zone's exterior walls including the opaque and transparent part [m^2]
Roof Area	Area of the zone's roof [m^2]
WWR	For exterior walls accessing balconies: 75% For all other walls: 65%

—> Table 7.3: Selected zone's construction properties

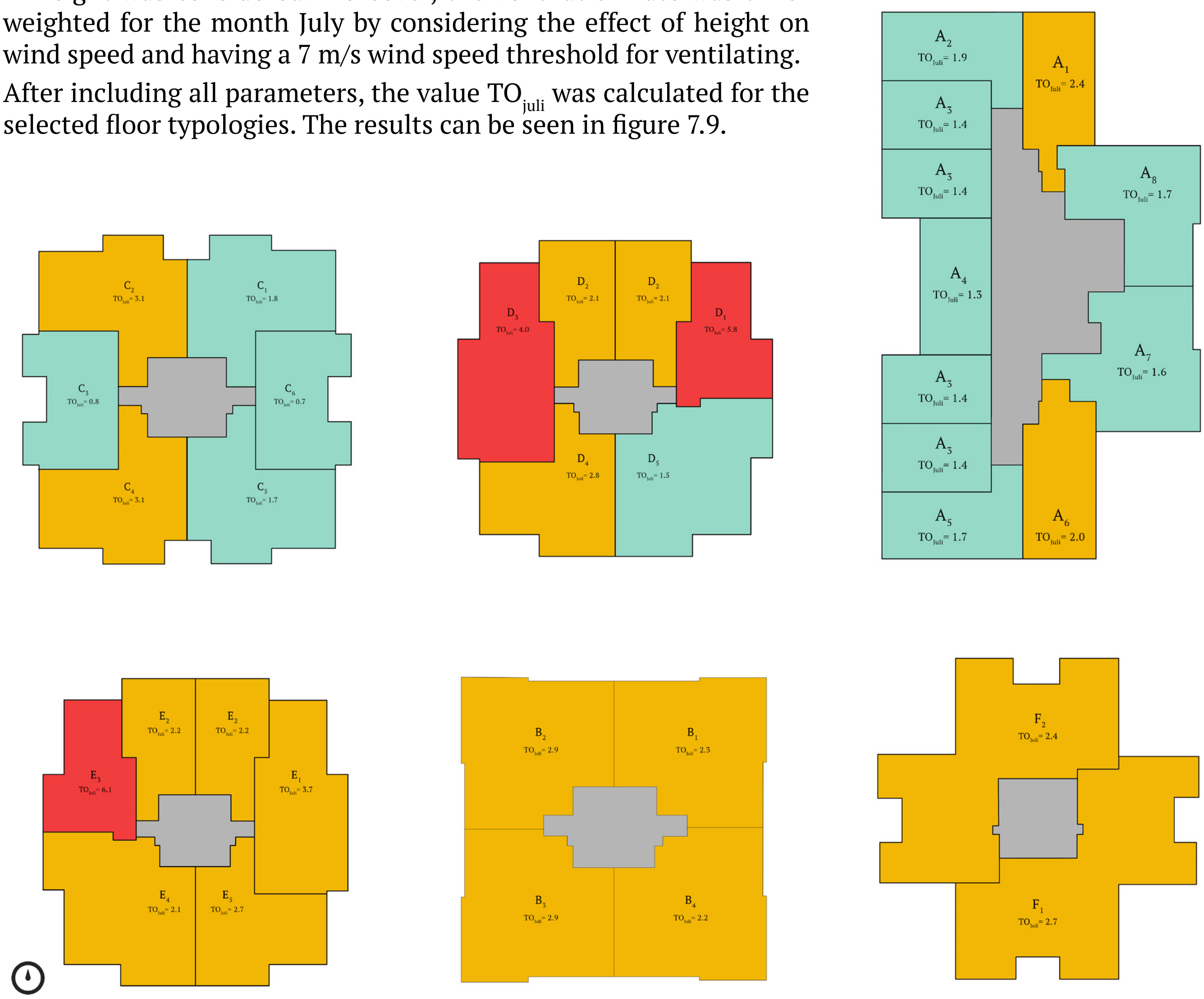
Parameter	Description
Specific Effective Thermal Capacity	Thermal capacity of heavy construction: 450 KJ/m2K were used
U-value of window openings	For openings accessing the balconies: 1.58 W/m2K For all other openings: 1.21 W/m2K
g-Value of glass	For windows facing the North: 0.6 [-] For windows facing South, West & East: 0.35 [-]
U-Value of Opaque Part	0.22 W/m2K
U-Value of Roof	0.17 W/m2K

The apartments are ventilated through mechanical and natural ventilation. The highly efficient mechanical ventilation with heat recovery and summer bypass provide minimum fresh air for occupants. Natural ventilation in this building is used in order to provide additional cooling and fresh air. Therefore, in the calculations, both natural ventilation and mechanical ventilation were considered.

In order to consider the effect of height on the overheating risk, the average temperature decrease of 1 centigrade degree for every 100 m height was considered. Moreover, the ventilation rate was time-weighted for the month July by considering the effect of height on wind speed and having a 7 m/s wind speed threshold for ventilating.

After including all parameters, the value TO_{juli} was calculated for the selected floor typologies. The results can be seen in figure 7.9.

Figure 7.8: TO_{juli} results of Cooltoren's different typologies.



0⩽ TO_{jul}<2 Little to no risk of overheating

2⩽ TO_{jul}<4 oderate risk of overheating

4⩽ TO_{jul} very high risk of overheating

7.3.3. Discussion of the analytical results

According to NEN-7120, zones with TO_{juli} values higher than 2 and lower than 4 show a moderate to high risk of overheating and values greater than 4 show a high risk of overheating. The results show that the representative zones in "Layout D "and "Layout E" show a higher risk of overheating. Comparing the two layouts, it can be seen that these two layouts are the mirrors of each other on the North-South axis. Between these two, the TO_{juli} indicator reveals that zones in "floor 45-layout E" show a higher tendency toward overheating.

Looking at the "floor 45-layout E", it can be seen that zones in apartments facing North show a higher tendency toward overheating. At first look, this is unexpected, as the North facing apartments rarely see the direct sun radiation. Explanation of this effect is that these Northern zones have several characteristics that made them more susceptible to overheating:

- Although "E1" & "E3" zones are double-sided, they have operable windows only on one side. Making all North facing zones benefiting only from single-sided ventilation
- The low altitude East and West sun penetrates deep into these double-sided rooms making the temperature to rise
- The higher solar transmittance value of the North facing windows compared to the other faces causes that Northern windows are admitting more solar energy into the rooms

The mentioned reasons in addition to the small size of the zone "E3" makes it more prone to overheating.

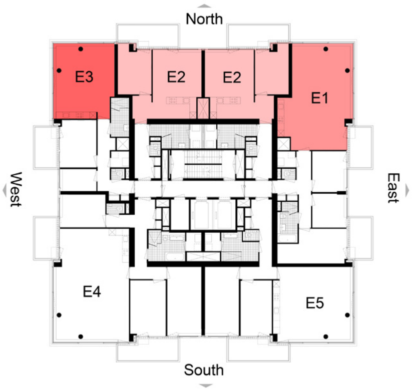


Figure 7.9: Double-sided zones facing North in "layout E" does not have operable windows on the north side, making them more prone to overheating.

7.4. Numerical Overheating analysis

After finding the most problematic plan layout in the previous section, a numerical overheating analysis was done using Design Builder software for the selected level. Then in order to investigate the effect of the level's height on overheating, the selected layout was also modelled for level 9 (28 m), in order to investigate the effect of the floor height on the risk of overheating. These two floors also will be analyzed during the future weather conditions in order to investigate the behaviour of the building by the year 2100. The detailed building performance modelling workflow can be found in Appendix C.

7.4.1. Results and discussion

The results of the building performance simulation for the 45th floor (132 m) is presented in this section. The overheating hours were calculated for occupied living zones. The unoccupied zones, such as storage and bath, were only included to study their effect on the living zones. However, they were excluded from the calculation of temperature exceedance hours.

In order to get a better understanding of the results and to make comparisons between different overheating assessment methods, the results were interpreted according to two, ATG and CIBSE (2006) overheating assessment methods.

For ATG assessment method, the Exceedance hours were calculated using adaptive thermal comfort thresholds defined in ISSO's "Thermisch Comfort" guide. The guide categorizes residential zones in three comfort classes (Table 7.4).

	Per zone
Very good	⩽10 Exceedance hours of ATG
Good	⩽70 Exceedance hours of ATG
Acceptable	⩽200 Exceedance hours of ATG
Overheated	>200 Exceedance hours of ATG

Table 7.4: AGT limit values according to comfort classes. Source: ISSO, 2019

In which:

According to the guide, designers should always aim to achieve at least "Good" level, meaning temperature could only exceed adaptive

Very good	Never or almost never uncomfortable high temperatures
Good	Limited uncomfortable warm indoor temperature during the hot summer period
Acceptable	In the warm summer period, the house will regularly be uncomfortable and warm

thermal comfort temperature less than 70 occupied hours. The “Acceptable” class is only for cases with a very unpleasant orientation that hardly could achieve a “Good” class only by passive means.

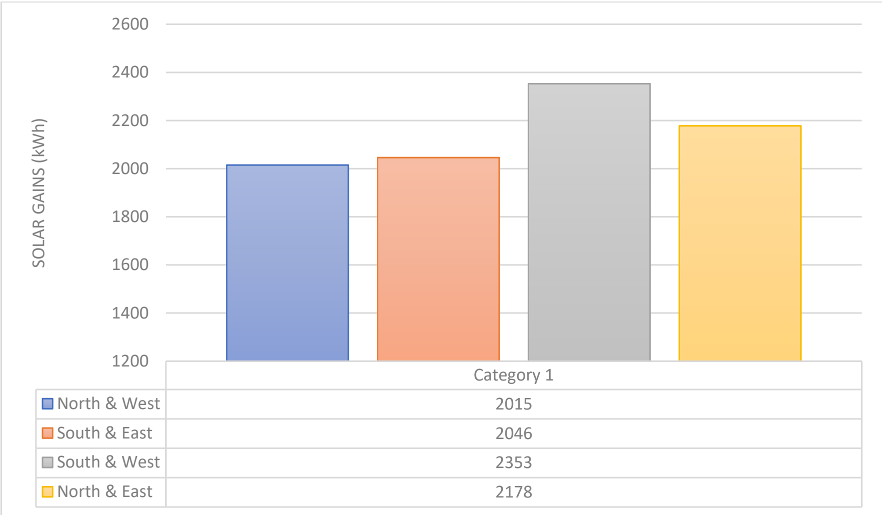
As mentioned in chapter 4, the temperature thresholds of CIBSE (2006) static overheating method for bedrooms is 26 °C and for living rooms is 28 °C. According to this method, a living zone is overheated if the temperature exceeded the threshold for more than 1% of annual occupied hours.

Figure7.10: Simulation results of level 45

Figure 7.10 shows the simulation results according to two mentioned overheating assessment methods. The difference between these two methods is noticeable. The static method considers all of the zones as overheated, while the ATG method considers several of the bedrooms as comfortable. Both methods indicate that large rooms on the south side have better thermal conditions. The North facing bedrooms, have a higher average temperature, making them not comfortable according to the static method. However, the adaptive method shows that the temperature swings on these rooms are well inside the occupant’s comfort zone that these rooms can be considered to have excellent thermal conditions.

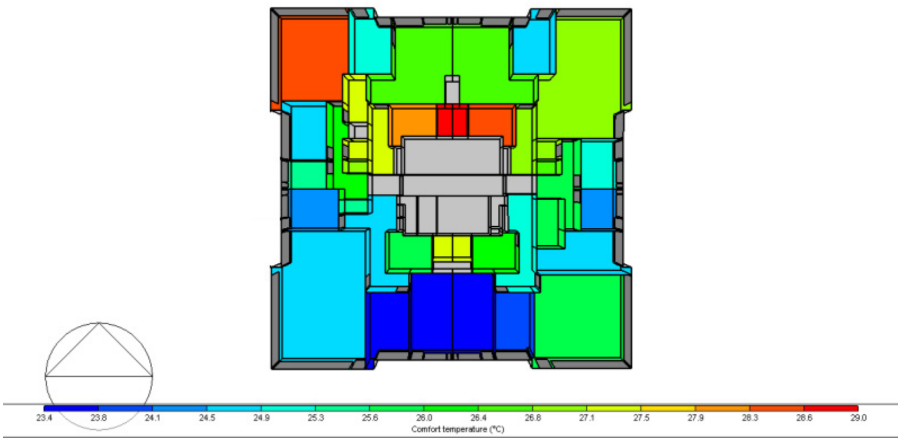
Looking at the results, identical to the TOjuli assessment, all the double-sided zones and living rooms are overheating at level 45. As TOjuli predicted, the double-sided livingrooms at North (“E3” & “E6”) are at higher risk of the overheating compared to other rooms. Two reasons of high external gains and single-sided ventilation make these spaces more susceptible towards extreme temperature exceedance.

Figure 7.11 compares the solar gains of the double sided living room "E5" to the zone "E3". As can be seen, despite facing North, the Livingroom "E3" has as much solar gain as "E5". The reason for that is the higher solar transmittance value of the "North" facing glasses which allow more solar energy to enter the room.



—> Figure 7.11: Double-sided zones solar gains

The only disparity between the analytical calculation and the numerical calculation is the livingroom "E4". The analytical calculation predicted that "E4" zone is at lower risk of overheating compared to the other zones. Even though "E4" zone is overheating less than the other double-sided zones, the overheating problem in this zones is still much higher than that of the "E1" and "E2" zone. This difference happens because TOjuli is using the average temperature of the zone during the month of July to predict the overheating risk. Therefore the extreme temperature swings are not considered in this method. As evident in the figure 7.12, the single-sided zones facing North (E1 & E2) have higher average temperature than the zone "E4", making them be at higher risk of overheating according to TOjuli.

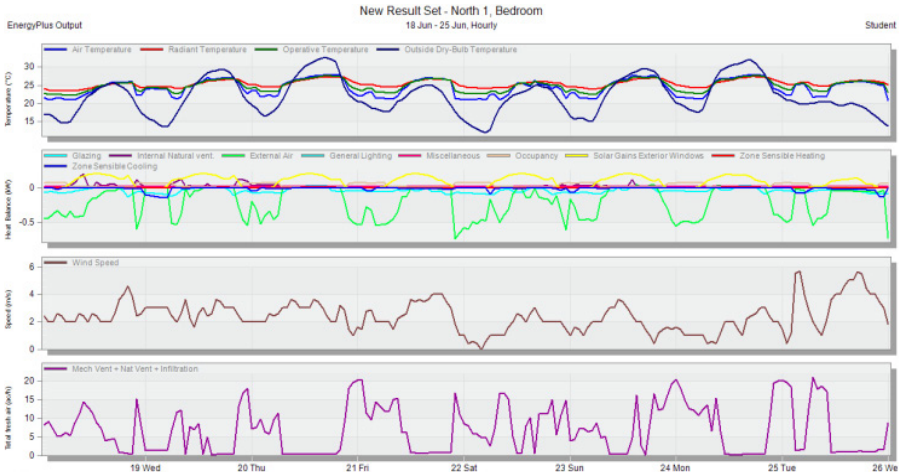


—> Figure 7.12: Average comfort temperature during the month of July.

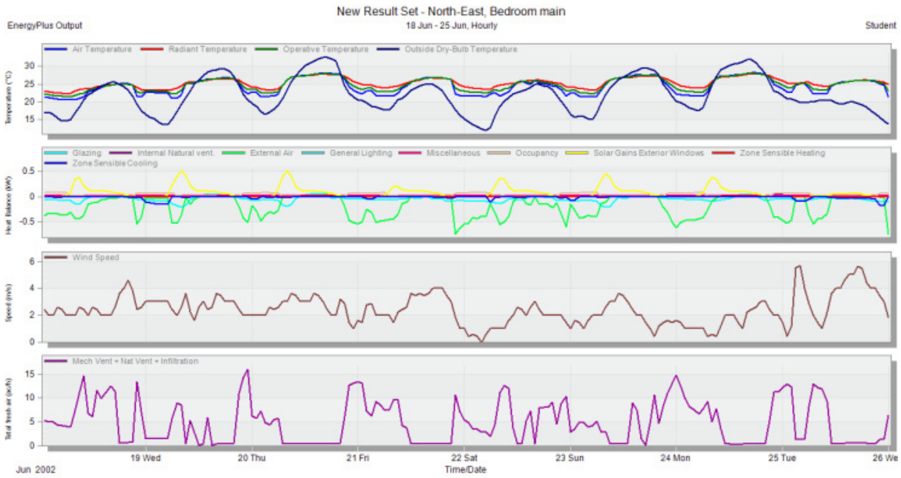
Heatwave behaviour

In order to get an understanding on the behaviour of the occupied zones during a heatwave period, these zones were studied in detail.

The results show that, generally, North facing and East facing zones have a more stable indoor environment with lower temperature swings (Figure 7.13 and 7.14).

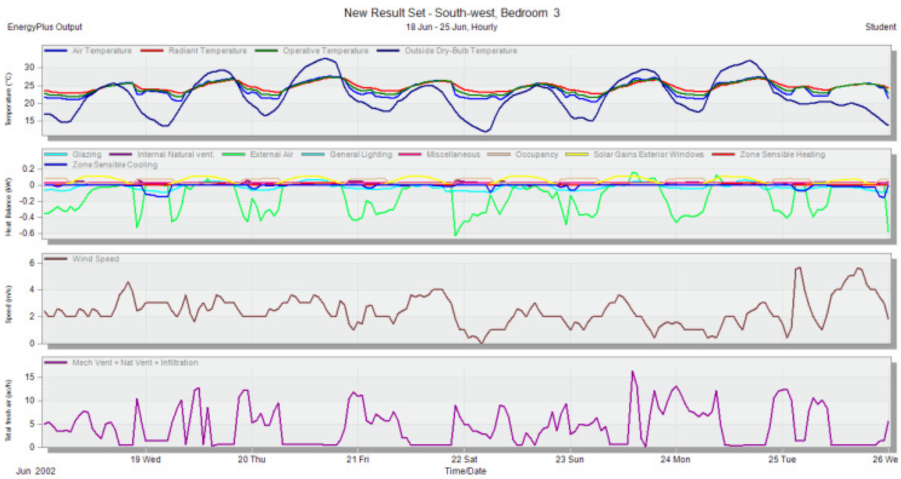


—> Figure 7.13: Bedroom “E1-1”



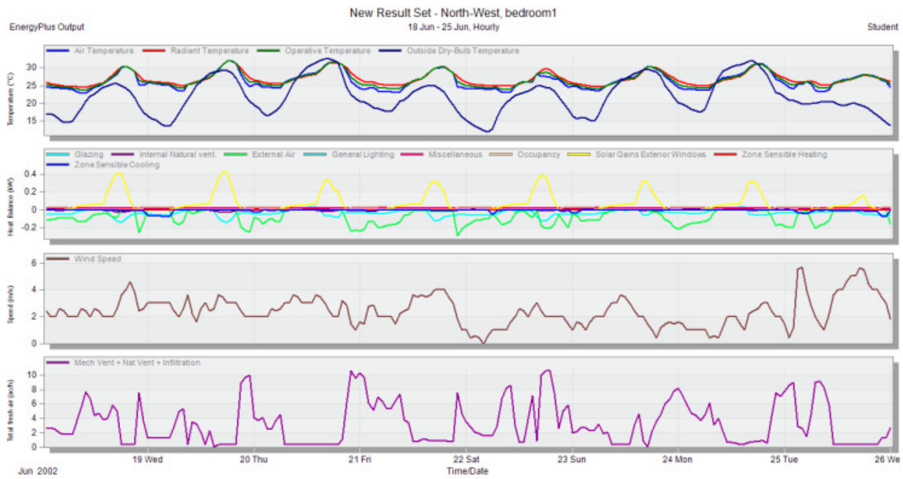
—> Figure 7.14: Bedroom “E6-3”

The south-facing bedrooms show similar behaviour, as can be seen in figure 7.15. Throughout the day, these zones show a very low, temperature fluctuations. The balconies always shade these bedrooms from high altitude south solar radiation protecting them from high external gains. Besides, the larger size of these bedrooms and their high thermal mass ensures a stable indoor environment throughout the day.



—> Figure 7.15: Bedroom “E4-2”

Figure 7.16 shows the example behaviour of a west-facing zone. As can be seen, these zones have a severe overheating problem with high temperature swings during the heatwave period. The reason for that is when the solar radiation peaks at afternoon the heat already have accumulated in the thermal mass, allowing solar radiation to overheat the space.



—> Figure 7.16: Bedroom “E3-1”

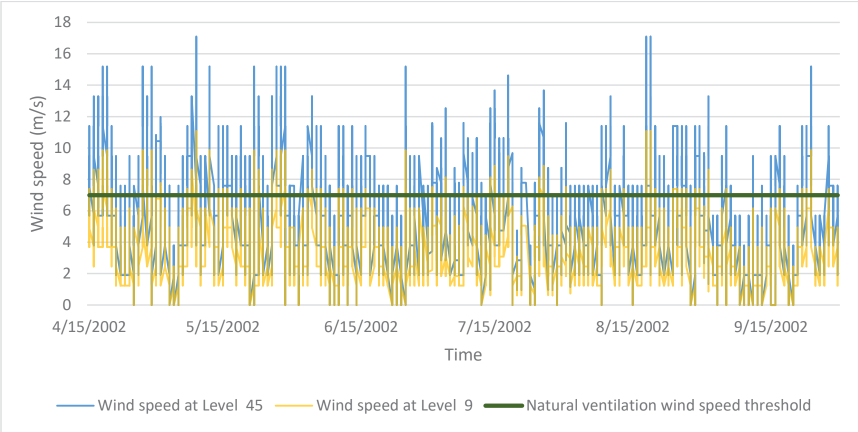
For a more detailed overview of the behaviour of the zone during the heatwave period, please read appendix D.

7.4.2. Comparison between different levels

As mentioned before the selected layout were modelled in two representative levels in the tower with almost the same plan layout in order to study the effect of height on overheating. The results can be seen in figure 7.17.

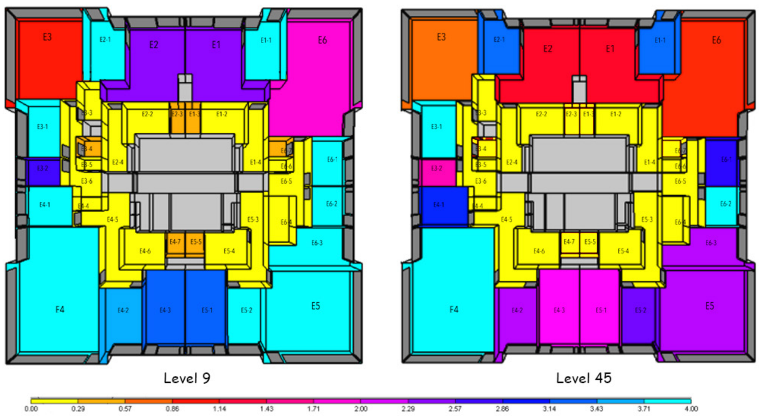
Figure7.17: Overheating results at two levels

As can be seen in the results, the North and West facing “E3” zone is the most problematic zone in both levels. Comparing two levels, it is evident that all living rooms, which are the zones with high internal gains, are overheating on upper levels. The reason for that is the high wind speed at elevation. At higher altitudes, the wind speed increases significantly. Since there is no wind protection on the air inlets, the windows are closed at wind speeds higher than 7 m/s, reducing the ventilation rate and therefore heat dissipation. As can be seen in figure 7.18, for two-third of the time the wind speed at level 45 is higher than the threshold wind speed for natural ventilation, meaning that zones can only benefit from natural ventilation for only one-third of the summertime.



—> Figure 7.18: Wind speed at 28m and 132 m.

Figure xx. shows the average air change rate of the zones during the running period. As evident, most of the zones on level 9 have air change rate higher than 4 ac/h compared to only three zones on level 45. In addition, this graph shows that North facing living rooms have low ability for natural ventilation because of the lack of openings for ventilation. As evident, the 'E3' zone has the least amount of air change rate, meaning it has the least ability for heat dissipation and therefore, higher risk of overheating.



—> Figure 7.19: Average air change rate (ac/h) of the simulated zones.

7.4.3. Future thermal conditions

In order to understand the behaviour of the building in future weather conditions, a study was done using future weather projections. To enable assessment of overheating in projected future weather conditions, these weather projections were included in weather data files. The author, in collaboration with Prateek Wahi utilized KNMI Klimaatscenario transformation program and design-builder in order to make future climate weather data files for building performance simulation. KNMI Klimaatscenario transformation program uses past recorded weather data time series and translates them to selected future weather scenarios. After obtaining future temperature data for worst predicted scenarios, then Design Builder software was used in order to produce weather data files used in the building performance simulator software.

The detailed weather data file transformation method can be found in appendix E.

Looking at level 9 (28 m), it can be seen that by 2050, most of the zones still have comfortable thermal conditions. However, by this time, all double-sided zones will start to overheat or to get regularly warm during the summer period. In addition, the west-facing bedrooms will start to get frequently uncomfortable, but they still will remain in the ATG's threshold. By 2085, all the double-sided zones will overheat. Likewise, west-facing bedrooms will start to overheat and get uncomfortably warm.

Looking at level 45 (132 m), it can be seen that by 2050, all west-facing zones will overheat. By 2085, all North facing zones and East facing zones will overheat or get regularly warm.

Figure7.20: Level 9 apartments behaviour during the future weather projections.

Figure7.21: Level 45 apartments behaviour during the future weather projections.

Comparing the results of both levels, it can be seen that the bedrooms on the North and South will not overheat by 2085. These bedrooms are well oriented and shaded, protecting them from solar radiation. Also, it is noticeable that bigger bedrooms with a higher thermal mass show a lower tendency towards overheating in the future.

Detailed results can be found in Appendix D.

7.5. Conclusion

Analyzing the overheating problem in the case study by both analytical and numerical overheating assessments methods and comparing them together showed the ability of TOjuli overheating assessment method in accurately predicting the overheating problem in the apartments. This shows that despite being a simple analytical overheating calculation method, TOjuli can be very useful in predicting overheating in the dwellings. Though, it should be interpreted cautiously by having the temperature averaging effect and the characteristics of different orientations into the mind.

Overall, from the analytical and numerical overheating assessments on the case study building, Positive and Negative characteristics of Cooltoren concerning their impact on overheating were concluded in table 7.5.

<table>
<tr><th></th><th>Positive characteristics</th><th>Negative characteristics</th></tr>
<tr><td>Heat gains</td><td>+ Balconies shade main bedrooms
+ Low solar transmittance value of the South, East and West facing glazing reduces solar gains</td><td>– Tiny single aspect unshaded bedroom facing east and west
– High solar gains from Northern windows because of the high solar transmittance value of the North facing glazing
– Overheated zones or zones with high internal load causes adjacent zones to get overheated or get uncomfortable</td></tr>
<tr><td>Heat dissipation</td><td>+ Openable windows and doors on the double-sided apartments facing south make cross-ventilation possible
+ Mechanical ventilation with summer bypass makes free cooling possible</td><td rowspan="2">– Inadequate ventilation in apartments facing North because of single-sided ventilation and small openings
– Due to the inadequate ventilation thermal mass cannot be recharged during the night
– Openings are not protected from rain and high wind speed making natural ventilation impossible for a great amount of time on upper floors
– Internal partitions hinder airflow
– Zones with lower thermal mass are at greater risk of overheating in the future</td></tr>
<tr><td>Thermal storage</td><td>+ High thermal mass provides a stable indoor environment with small temperature swings
+ Big bedrooms with structural walls have additional thermal mass which makes them quite stable toward diurnal temperature swings</td></tr>
</table>

8. Preliminary design

In the previous chapter, the beneficial and problematic architectural aspects of the selected case study towards overheating were investigated.

In this chapter, case study's preliminary solution design procedure, exploring conventional design methods, is discussed. First, the design requirements set by Wolf+Dikkens are listed. After that, solution packages are introduced and are pre-assessed by hand calculations in order to achieve a shortlist of the most promising concepts. Finally, the shortlisted design concepts are analysed numerically.

8.1. Design requirements

The design requirement set by Wolf+Dikkens for the facade solution is as follow:

- Visual Field: The solution should not restrict the visual field of the occupants.
- Acoustic comfort: The solution should not harm the indoor acoustical quality
- Construction impact: The solution should not be bulky, taking valuable indoor space
- Cost: The overall cost of the solution should be less than 45000 Euro for each floor

8.2. Developing solution concepts

Considering the Cooltoren's architectural characteristics and design requirements set by Wolf+Dikkens selected guideline solutions are investigated in this section to develop design concepts. A preselection study was done in which the guidelines and solutions were assessed by their impact on the cost, indoor space, acoustic, visual field, performance and residents privacy. The guidelines then were shortlisted for further studies.

8.2.1. Reducing external heat gains

In order to study the effect of different heat reduction solutions, simple calculations were done for assessment and comparison.

Reducing the solar transmittance value of the Northern windows

Analysing the Cooltoren showed that high solar transmittance value of the Northern window causes additional solar gains and thus overheating. A simple calculation was done to investigate the effect of reducing the SGHC value of Northern windows on winter and summer solar gains.

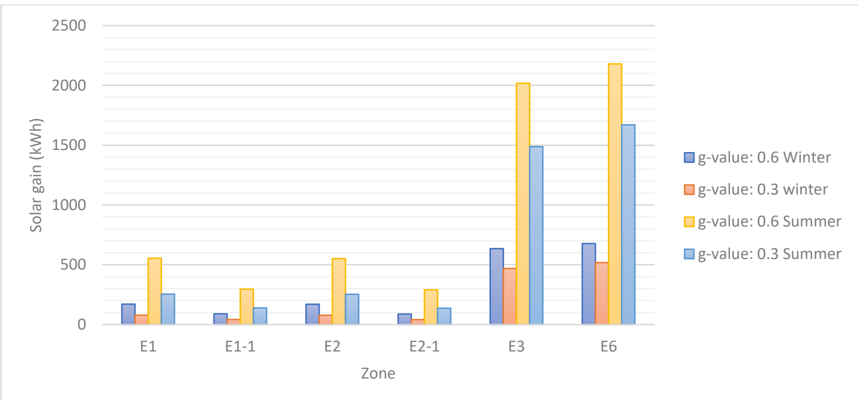


Figure 8.1: Effect of solar transmitance value of the North facing windows on solar gains

Figure 8.1 shows the solar gains of the North facing zones with different g-values during different seasons. It is evident that although reducing the g-value of the North facing windows will reduce the beneficial solar gains in the winter, but the benefit of heat gains reductions during the summer outweigh its drawback.

Being a preliminary design option, for all of the following design variables, reduction of the Northern windows SGHC value is considered.

External shading

Different shading strategies were simulated in order to study their heat reduction potential.

Static shading strategies such as overhangs and vertical shading elements were studied to investigate their impact on the reduction of solar gains.

Table 8.1 presents overhang's shading solar reduction factors for Cooltoren's windows on different orientations. As can be seen for overhangs with depths higher than 1.2, greater depths does not help that much on solar reduction. Therefore the 1.2 m overhang depth is chosen as the optimum length considering the shading effect and size.

Depth of the overhang (m)	N (-)	E/W (-)	S (-)
0.0	1.00	1.00	1.00
0.4	0.94	0.89	0.79
0.8	0.9	0.79	0.64
1.2	0.88	0.72	0.53
1.6	0.86	0.66	0.5
2	0.85	0.61	0.49
2.4 or more	0.84	0.57	0.48

—>Table 8.1: Solar reduction factor of overhangs. Derived from: SAP, 2012

Table 8.2 show the solar reduction factor of vertical shading elements for different orientations. As evident for vertical elements with a length of more than 1 meter the solar reduction factor doesn't change much. Hence, the 1 m vertical shading length was chosen.

Length of the Vertical element (m)	N (-)	E/W (-)	S (-)
0.0	1.00	1.00	1.00
0.5	0.83	0.88	0.83
0.75	0.77	0.83	0.78
1.0	0.73	0.80	0.74
1.25	0.71	0.77	0.72
1.5	0.69	0.75	0.71
1.75	0.67	0.73	0.70
2.0 or more	0.66	0.72	0.7

—>Table 8.2: Solar reduction factor of vertical shading. Exported from Design Builder

For the calculations the vertical elements were considered to be made of metal mesh with a g-value of 0.15 in order to not limit the view.

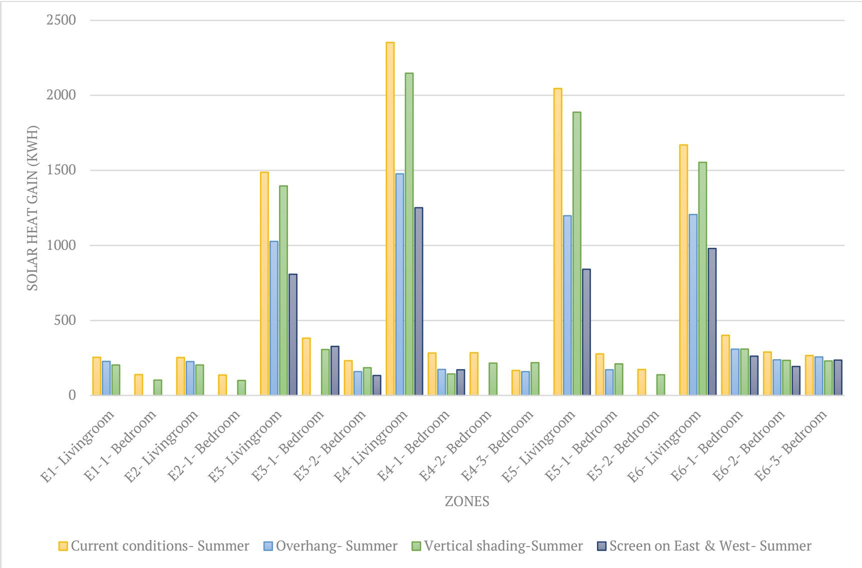
Considering the screens and vertical awnings, they are the most beneficial shading elements reducing solar gains. However, the high cost of these products makes them costly to use. On the other hand, these elements are most effective on East and West facing window protecting the rooms behind from horizontal solar radiations. Therefore, to reduce the shading surfaces in analytical studies, the screens were only applied to the East and West facing windows. The studies were done considering automatic screen with a g-value of 0.1(-) with a solar control sensor set to 100 w/m2.

Figure 8.2 & 8.3 shows the total solar heat gains of different shading strategies on the Cooltoren's rooms during the running period.

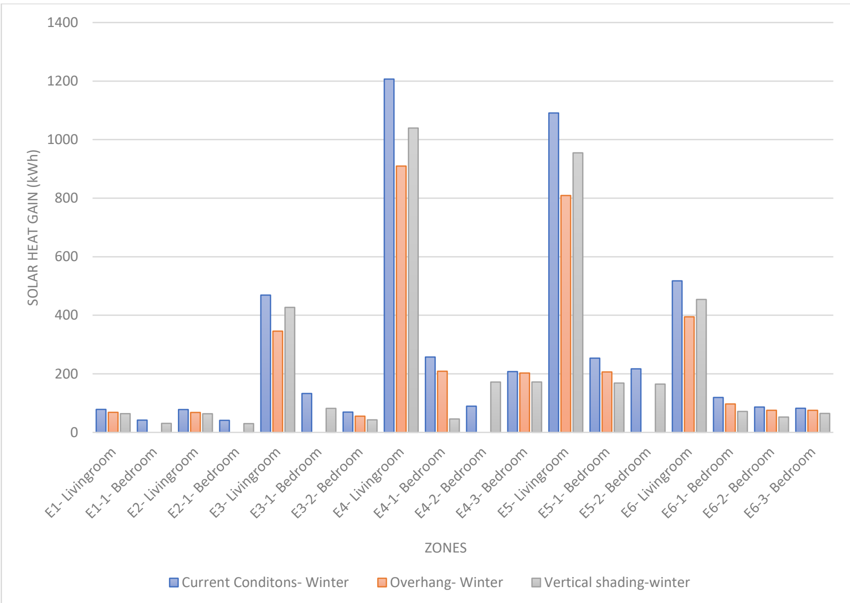
As is illustrated, screens on the East and West windows have the most solar reduction effect on the double-sided zones. After that overhangs are the most effective strategies on double-sided zones and South facing bedrooms.

According to the graph, the vertical shadings are the most effective shading strategy on North facing single-sided zones and bedrooms with balconies.

Analysing the effect of static shading elements on the beneficial winter gains, it can be seen that the effect is negligible. Suggesting that static shading elements could be implemented on the buildings without drastic effects on the winter solar gains.



—>Figure 8.2: Effect of shading solutions on solar reduction during the summer



—>Figure 8.3: Effect of static shading solutions on solar reduction during the winter

Solar reduction design concepts

After considering the effect of different shading solutions on the Cooltoren's zones, three shading concepts for the tower were developed. These concepts are:

1. Minimising solar radiation

In this concept, all three shading strategies in their best performance orientations are combined together. As shown in the illustration, Sunscreens are placed on the West and East facing windows of the double-sided zones to minimise the horizontal sun's solar gains. Overhangs were considered on the Northern and Southern zones and on the bedrooms without balconies for solar reduction. Lastly, vertical shading elements are placed on the shorter sides of the bedrooms with balconies to provide shading.

2. Minimising architectural impact

In this design concept, the shading configuration with the least architectural effect on the original appearance and design of the building is chosen. In this design variation, sunscreens are purposed for Eastern and Western façade and vertical shading for the sides of the balconies.

3. Minimising maintenance

In this shading design concept, only static shading elements are used because of their fixed nature and little to no need for maintenance. Overhang shading elements are applied in all directions, and vertical shading elements are used on the sides of bedrooms balconies.

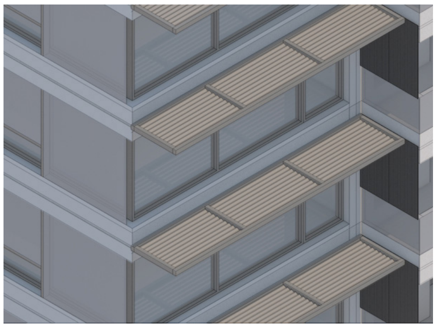


Figure 8.4: Minimising solar gains

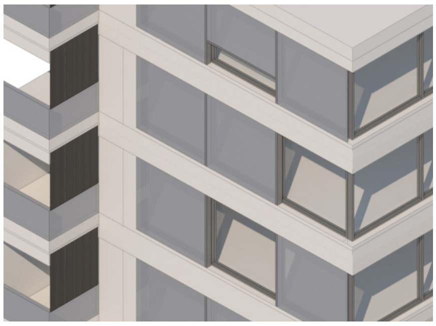


Figure 8.5: Minimising architectural impact

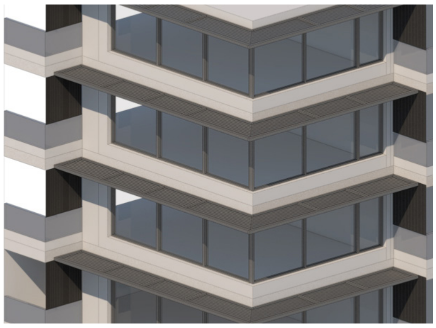


Figure 8.6: Minimising maintenance

8.2.2. Increasing heat dissipation

From the case study analysis, it was concluded that the three major problems of:

1. single sided ventilation,
2. wind speed at height and
3. insufficient openings

limits the heat dissipation. This causes heat accumulation in the zone. Moreover, lack of heat dissipation hinders recharge of thermal storage, reducing the positive effect of thermal mass. For solving the heat dissipation problem, two concepts were developed using design guidelines.

1. Rescheduling mechanical ventilation

Cooltoren's apartments benefit from type D ventilation systems. Each apartment uses a Brink Renovent Excellent 300 ventilation unit for providing fresh air. This energy-efficient ventilation unit has summer bypass allowing free cooling by bringing outside air to the rooms. This system is utilised with CO2 sensor on Cooltoren apartments to control the indoor air quality by providing minimum fresh air.

Looking at the specification of the ventilation system on table xx it can be seen that it has a maximum ventilation capacity of 225 m3/h. The ventilation unit can be rescheduled in order to work in full capacity during the night and when the outside air temperature is lower, in order to cool the indoor space and recharge the thermal mass for the following day. The benefit of this strategy is that no changes on the facades openings is needed to be done. Operable windows in current design just can be used as additional natural ventilation sources for providing purge ventilation when the outdoor conditions allow for it.

Fan setting (Factory setting)	0	1	2	3
Ventilation capacity (m^3/h)	50	100	150	225
Related Power (W)	9.0-9.2	13.7-15.2	22.0-29.2	46.8-66.2

—>Table 8.3: Brink Renovent Excellent 300 ventilation unit specifications. Source: Brink, n.d.

2. *Increasing natural ventilation*

Cooltoren's openings are not sheltered from the high wind speed at height, making it unfeasible to ventilate the rooms for a great amount of time during the summer period. In addition, some of the apartments do not have sufficient openings making them overheat even at lower levels which wind speed do not hinder natural ventilation.

To solve this, additional openings with wind shelters could be provided in order to make purge ventilation for natural cooling possible. Windscreens could provide effective wind shelters by softening the wind speed. Combining ventilation grills with acoustic insulation protects the indoor environment form the outside noise. Adding a layer of open weave textile provides a functional rain/windscreen that makes natural ventilation possible by decreasing the incoming air pressure (Figure 8.7.)

The study by Hendriks (2010) shows that the principle of using fabric screens for providing natural ventilation at height by reducing wind pressure is feasible. In addition, studies on wind sheltering by Hagen & Skidmore (1971) showed that porous windbreaks could reduce the wind speed of the leeward side of the windbreak by up to 50%. Considering the same reduction effect for the purposed windscreen will make natural ventilation possible for 92% of the summer period for apartments at level 45 and 100% of the summertime for apartments at level 9 (Figure 8.8).

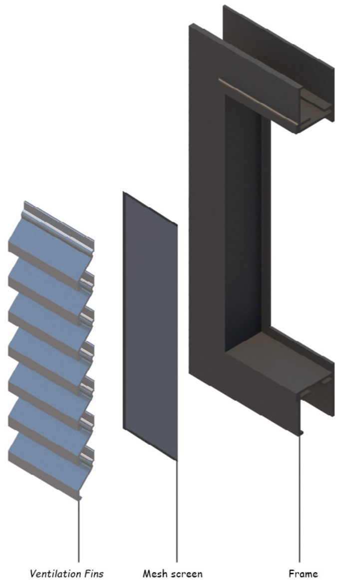
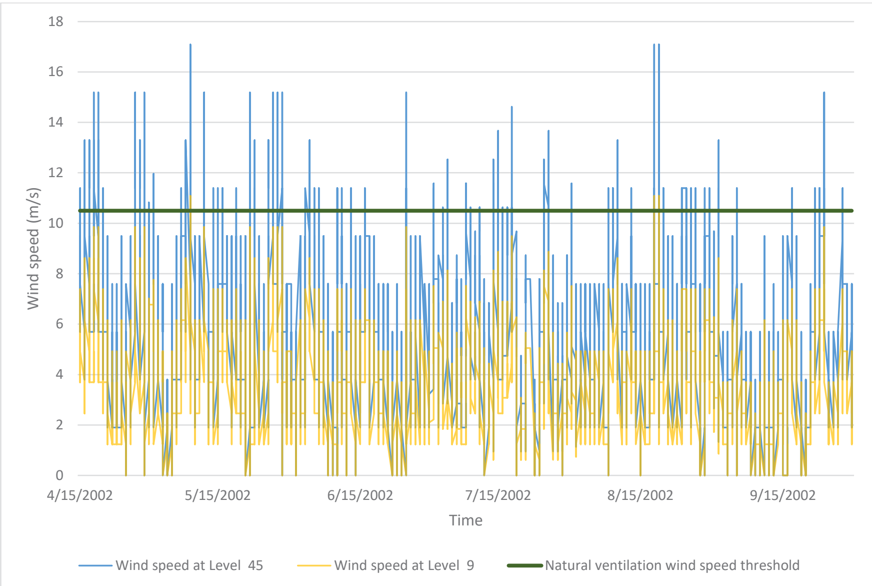


Figure 8.7: Combing mesh screens with ventilation grills for sheltering the indoor environment from high wind speed.



—>Figure 8.8: The new ventilation threshold by the ventilation solution.

Integrating this system with sliding window systems could provide an adaptive burglar-proof ventilation system (Figure). In addition to this system, regular bottom hinged windows should be installed on South and North windows to make both, purge ventilation during the calm days, and cross ventilation possible.

This concept tries to increase natural ventilation while reducing mechanical ventilation. However, because of the energy-efficient benefits of the mechanical system, especially in winter, it will not be removed from the design. Also, mechanical ventilation can be used during storms and very high wind speeds, when natural ventilation is not possible, in order to provide minimum fresh air for the occupants.

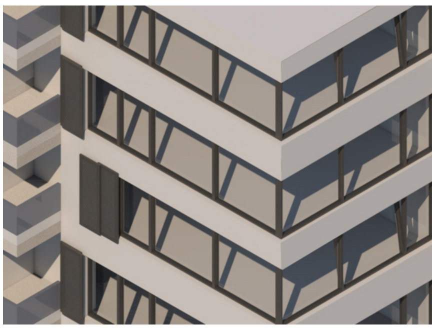


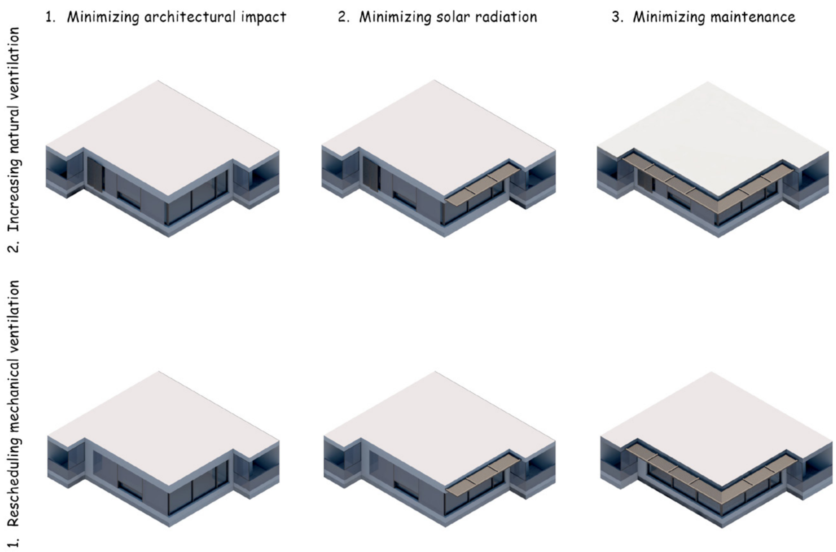
Figure 8.9: The sliding windscreen can be installed on unglazed corners.

8.2.3. During occupancy considerations

As mentioned in chapter 6, utilisation of energy-efficient appliances and lighting reduces internal gains and therefore, the overheating risk. In addition, using smart homes systems with sensors and actuators will help to prevent overheating since it regulates the building when the user is not present. Smart systems could reduce the risk of overheating by helping the user to take right control actions.
Therefore, for further studies, the lighting load of the apartments was reduced to 3 w/m2 by considering energy-efficient lighting. Smart home systems with actuators and sensors were considered for automatic operation of the windows, sunscreens and appliances.

8.3. Developing decision-making matrix

In the previous section, three solar shading concepts and two heat dissipation concepts were developed. Combination of these design concepts makes six design variations to study (figure 8.10).



—>*Figure 8.10: Design variations*

In this section, first, the analysing workflow is given. After that, the results are presented and discussed. Finally, a decision-making matrix is developed to compare the characteristics of the design variables.

8.3.1. Analysing workflow

1. Overheating

Each design variation was simulated in the Design-Builder software and was investigated with present and future condition weather files. Detailed simulation workflow can be found in Appendix F.

2. Visual Field

In order to study the effect of the design variations on the visual field, a grasshopper script was developed. The script compared the current design visual filed with the shading solutions in order to find how much they obstruct the view. During the comparison, moveable solutions such as the sliding ventilation grill and moveable sunscreens were not considered as an obstruction since they can change position. Detailed workflow can be found in Appendix G.

3. Cost

The estimated cost of each design variation was calculated from the price range that was gathered from the internet and companies and was compared with the current design. Also, estimated differences between the energy consumption of each design variation with the current model were calculated, and the estimated energy prices per summer period were included.

8.3.2. Results and discussion

1. Overheating assessment results

The results of the overheating assessment according to ATG method, can be seen in table 8.4.

Reviewing the results, it can be noted that the design variations with increasing natural ventilation concept had overall better thermal conditions.

—>Table 8.4: Design variation's overheating assessment

	Overheating					
	Present		2050		2085	
	Acceptable	Overheated	Acceptable	Overheated	Acceptable	Overheated
1: M.M & R.M.V	E3-Livingroom (T.E.H: 110)	None	E5-Livingroom (T.E.H: 77)	E3-Livingroom (T.E.H: 259)	E5-Livingroom (T.E.H: 189) E6-Livingroom (T.E.H: 140) E4-Livingroom (T.E.H: 137) E3-2-Bedroom (T.E.H: 82)	E3-Livingroom (T.E.H: 422)
2: M.M & I.N.V	E3-Livingroom (T.E.H: 72)	None	E3-Livingroom (T.H.E: 146)	None	E5-Livingroom (T.E.H: 146) E4-Livingroom (T.E.H: 110)	E3-Livingroom (T.E.H: 207)
3: M.A.I & R.M.V	None	None	E5-Livingroom (T.H.E: 163) E3-Livingroom (T.H.E: 100)	None	E3-Livingroom (T.H.E: 199) E4-Livingroom (T.H.E: 155)	E5-Livingroom (T.H.E: 290)
4: M.A.I & I.N.V	None	None	E5-Livingroom (T.H.E: 152)	None	E4-Livingroom (T.H.E: 124) E3-Livingroom (T.H.E: 105)	E5-Livingroom (T.H.E: 255)
5: M.S.G & R.M.V	None	None	E3-Livingroom (T.H.E: 81)	None	E3-Livingroom (T.H.E: 171)	None
6: M.S.G & I.N.V	None	None	None	None	E3-Livingroom (T.H.E: 101)	None

T.H.E: Temperature exceedance hours of ATG
M.M: Minimising maintenace
M.A.I: Minimising architectural impact
M.S.G: Minimising solar gains
R.M.V: Rescheduling mechanical ventilation
I.N.V: Increasing natural ventilation

Taking a close look at the results of the first and second design variation, the "E3-Livingroom" zone is getting uncomfortably warm during the simulation period, but it still remains in the acceptable range.

By 2050, the variation with the rescheduling of the mechanical ventilation will have the "E3-Livingroom" overheated and the "E5-livingroom" starting to get uncomfortable. Looking at the overheating trend of the first design variation, the smaller double-sided zones and bedroom will get overheated and uncomfortably warm by 2085. This trend is different from the second design variation, although having the same solar shading concept with the first one. In the second variation, the South facing double-sided zones are at higher risk of overheating except the small "E3-Livingroom". All bedrooms have "very good" & "good" thermal conditions in this variation.

Analysing the third and fourth variation, it appears that minimising the West and East solar radiation with screens, will reduce the overheating problem of the double-sided zones facing North significantly. It can be seen that double-sided zones facing South are at higher risk of overheating in these design variation. The reason for this is the solar gains at noon since these zones are not sheltered from the Southern sun rays. Considering the single-sided zones facing North and South, it is evident that only vertical shading on the shorter edges of balconies and increasing ventilation were sufficient to keep these rooms from getting overheated.

Considering the design variations with the "Minimising solar gains" shading concept, no zone will get overheat by 2085. The results suggest, being small double-sided zones with high internal gains, the "E3-livingroom" will still get uncomfortably warm by 2085, though in an acceptable range of ATG. Suggesting that small double-sided zones with high internal load, even with minimising solar radiation, are not resilient toward climate change.

2. Visual field assessment results

The result of the visual filed assessment in different design variations is presented in figure 8.11.

Overall, it can be seen that the design variations with minimising architectural impact concept have the best visual access between the three.

Going to the details, the design variations with overhangs (M.M & M.S.G), have a good unobstructed view in bigger double-sided zones. The graph suggests that the overhangs are only visible in the immediate adjacency of the glazing. This obstruction is almost has been addressed in the design variations with canopies only on one side (M.S.G). Overhangs may not cause much of problem for bigger living rooms; however, the visual obstruction caused by them is problematic for smaller rooms since the main circulation area is near the window. Besides, these bedrooms already are encapsulated between the rooms with balconies which reduce the visual access further.

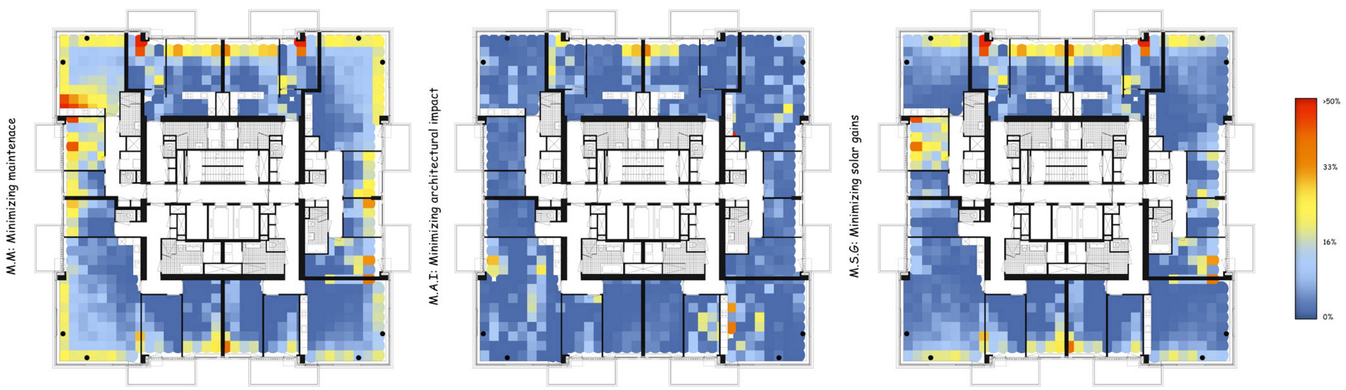


Figure 8.11: The visual filed blocked compared to the current situation. The colours indicated how much of the visual field is blocked in that point compared to the original design.

3. *Cost assessment result*

M.A.I & R.M.V

Item	quantity (m2)	Price per unit (Euro)	Overall cost (Euro)
Zip Screen	70	200-300	~14000-21000
Metal mesh	43	70-150	~3000-6500
Total Cost (Euro)	~17000-28000		
Electricity Usage	296 Kwh additional energy usage per year		
	296 kwh * 23 cents: 68.1 Euro		

M.A.I & I.N.V

Item	quantity (m2)	Price per unit (Euro)	Overall cost (Euro)
Zip Screen	70	200-300	~14000-21000
Metal mesh	43	70-150	~3000-6500
Ventilation Flaps	4	300-500	~1200-2000
Sliding Shutters	10	600-900	~6000-9000
Total Cost (Euro)	~24000-39000		
Energy saving	238 Kwh energy saving per year		
	238 kwh * 23 cents: 54.7 Euro		

M.M & R.M.V

Item	quantity (m2)	Price per unit (Euro)	Overall cost (Euro)
Overhang	72	70-150	~5000-11000
Metal mesh	43	70-150	~3000-6500
Total Cost (Euro)	~8000-17000		
Electricity Usage	296 Kwh additional energy usage per year		
	296 kwh * 23 cents: 68.1 Euro		

M.M & I.N.V

Item	quantity (m2)	Price per unit (Euro)	Overall cost (Euro)
Overhang	72	70-150	~5000-11000
Metal mesh	43	70-150	~3000-6500
Ventilation Flaps	4	300-500	~1200-2000
Sliding Shutters	10	600-900	~6000-9000
Total Cost (Euro)	~15000-28000		
Energy saving	238 Kwh energy saving per year		
	238 kwh * 23 cents: 54.7 Euro		

M.S.G & R.M.V

Item	quantity (m2)	Price per unit (Euro)	Overall cost (Euro)
Overhang	48	70-150	~3000-7000
Zip Screen	44	200-300	~9000-13000
Metal mesh	43	70-150	~3000-6500
Total Cost (Euro)	~15000-27000		
Electricity Usage	296 Kwh additional energy usage per year per floor		
	296 kwh * 23 cents: 68.1 Euro		

M.S.G & I.N.V

Item	quantity (m2)	Price per unit (Euro)	Overall cost (Euro)
Overhang	48	70-150	~3000-7000
Zip Screen	44	200-300	~9000-13000
Metal mesh	43	70-150	~3000-6500
Ventilation Flaps	4	300-500	~1200-2000
Sliding Shutter	10	600-900	~6000-9000
Total Cost (Euro)	~22000-37000		
Energy saving	238 Kwh energy saving per year		
	238 kwh * 23 cents: 54.7 Euro		

Overall, as can be seen, fixed shading solutions with rescheduled mechanical ventilation are the cheapest variation. However, they require additional energy use each year. Solutions with increasing natural ventilation concept are expensive solutions, but they save a little bit by reducing electricity consumption each year.

8.3.3. Developing decision-making matrix

<table>
<tr><th rowspan="2"></th><th colspan="2">Thermal comfort</th><th colspan="2">Visualfield</th><th colspan="2">Cost</th></tr>
<tr><th>Advantage</th><th>Disadvantage</th><th>Advantage</th><th>Disadvantage</th><th>Advantage</th><th>Disadvantage</th></tr>
<tr><td>M.M & R.M.V</td><td>+ All bedrooms in the comfort range by 2085
+ No overheated zone in the present condition simulation</td><td>- Small double sided Livingroom start to overheat by 2050.
- All double sided zones become regularly warm by 2085. By this time the small overheated zone will overheat severally</td><td rowspan="2">+ Good visual filed on the larger double sided zones.
+ Unobstructed view with a 2m distance from the window in the larger rooms</td><td rowspan="2">- Obstructed view in the bedrooms in between balconies
- obstructed view on the corners of the smaller living rooms</td><td>+ Most economical solution.</td><td>- Additional energy bills</td></tr>
<tr><td>M.M & I.N.V</td><td>+ All bedrooms in the good comfort range by 2085
+ No overheated zone by 2050</td><td>- Small double sided Livingroom start to overheat marginally by 2085</td><td colspan="2">+ Economical shading solution
+ Savings in energy bills by reducing the mechanical ventilation energy consumption</td></tr>
<tr><td>M.A.I & R.M.V</td><td rowspan="2">+ All bedrooms in the good comfort range by 2085
+ Vertical shadings are very effective in providing good thermal condition for North and South single sided rooms</td><td rowspan="2">- Smaller double sided zones facing south will overheat by 2085</td><td colspan="2" rowspan="2">+ Very good visual field in all zones despite marginal obstruction on the corners.</td><td colspan="2">- Additional energy bills</td></tr>
<tr><td>M.A.I & I.N.V</td><td>+ Savings in energy bills by reducing the mechanical ventilation energy consumption</td><td>- Most expensive combination</td></tr>
<tr><td>M.S.G & R.M.V</td><td colspan="2">+ No Overheating problem
+ All bedrooms in the good comfort range by 2085</td><td rowspan="2">+ Good visual field on the larger double sided zones, having overhang only on one side the visual field is less obstructed near the immediate adjacency.</td><td rowspan="2">- Obstructed view in the bedrooms in between balconies</td><td>+ Economical variation</td><td>- Additional energy bills</td></tr>
<tr><td>M.S.G & I.N.V</td><td colspan="2">+ No Overheating problem
+ All zone in good comfort range by 2050</td><td>+ Savings in energy bills by reducing the mechanical ventilation energy consumption</td><td>- Costly</td></tr>
</table>

9. Proposed design using conventional solutions

In chapter 7, thermal characteristics of Cooltoren's floor layouts considering overheating were examined. It was shown that different layouts show diverse behaviours towards overheating. In addition, numerical calculations indicated that even the same floor layout shows different behaviours at different heights. In chapter 8, overheating prevention solutions for a selected floor with the highest risk of temperature exceedance was investigated. Six different design variations were simulated, and the ability of them in overheating prevention were investigated. Then the pros and cons of each design variation were concluded in a matrix.

In this chapter, the information gained in the previous chapters are used to propose the most beneficial façade combination.

9.1. Redesign procedure

9.1.1. Heat dissipation

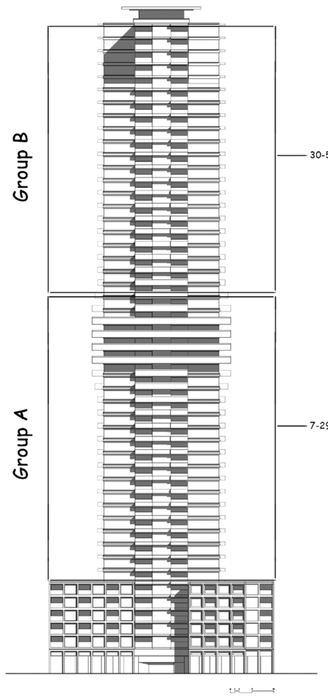
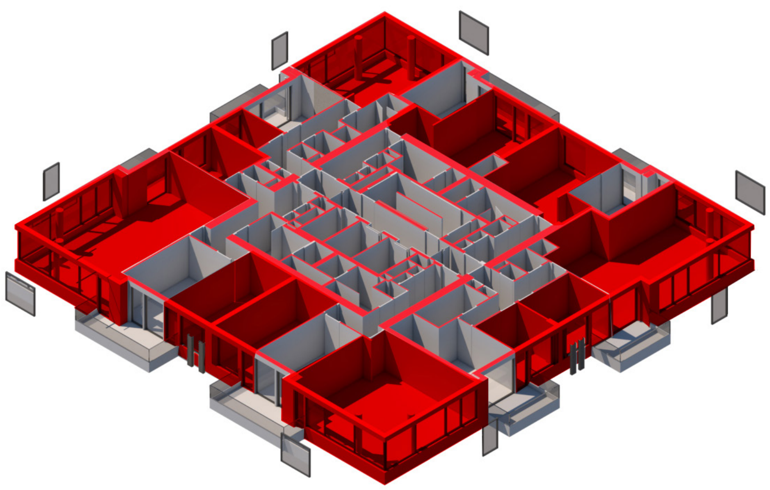


Figure 9.1: Ventilation groups. Redrawn from source: V8 architects

Because of the different wind speeds at different heights, diverse ventilation strategies can be applied to the high-rise building. Therefore, the building was divided into two ventilation groups according to the allowable ventilation time at height (Figure 9.1).

Group A:

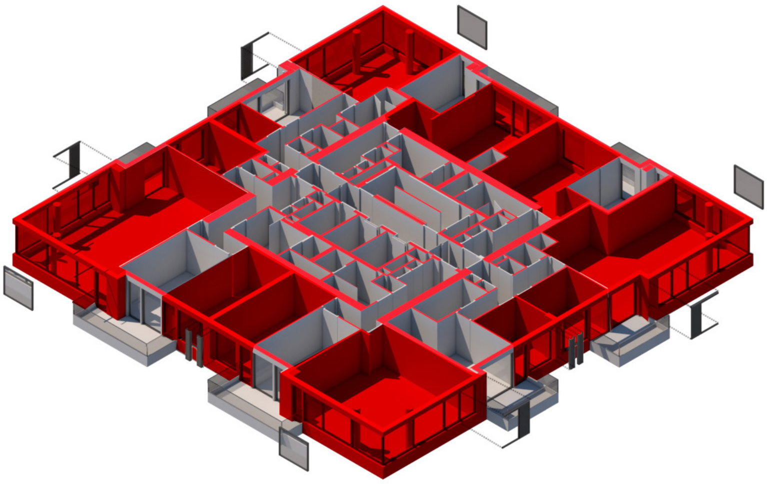
In this group, natural ventilation can happen for more than 60 % of the summertime without any windscreens. The primary heat dissipation happens with natural ventilation. During the night and in times in which windspeed does not allow natural ventilation, the mechanical ventilation unit is rescheduled to work in full capacity for ventilative cooling. For natural ventilation of the double-sided zones, bottom hinged windows are considered on all sides. For ventilation of bedrooms that are place in between balconies ventilation flaps with rain screen were considered (Figure 9.2).



—> Figure 9.2: Adding additional bottom hung windows and ventilation flaps to the rooms.

Group A:

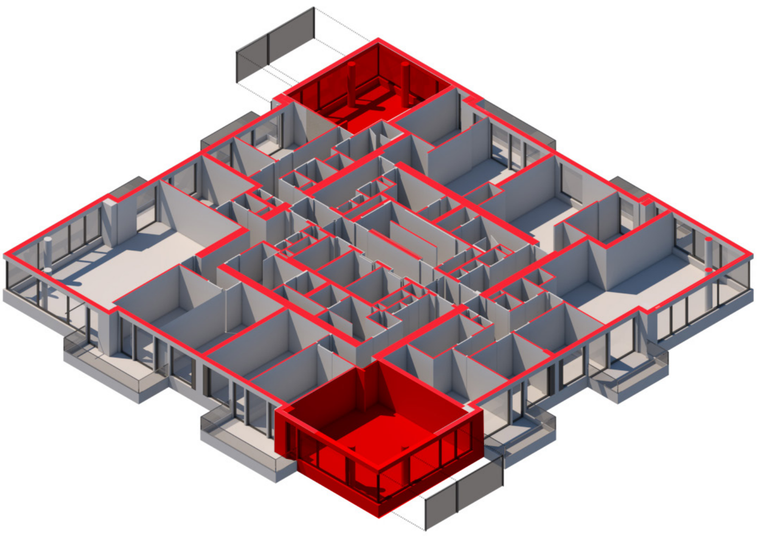
In this group "increasing natural ventilation" concept as in chapter 8 were applied on the apartments. Sliding windows were connected to the sliding shutter, in which windbreaker fabric and acoustic material were integrated. Additional operable windows were applied on the second side of the double-sided zones to provide cross ventilation for calm days.



—> Figure 9.3: Sliding windows and shutter were integrated together and were applied on the double-sided zones. Ventilation flaps were applied on the rooms between balconies.

9.1.2. Heat protection

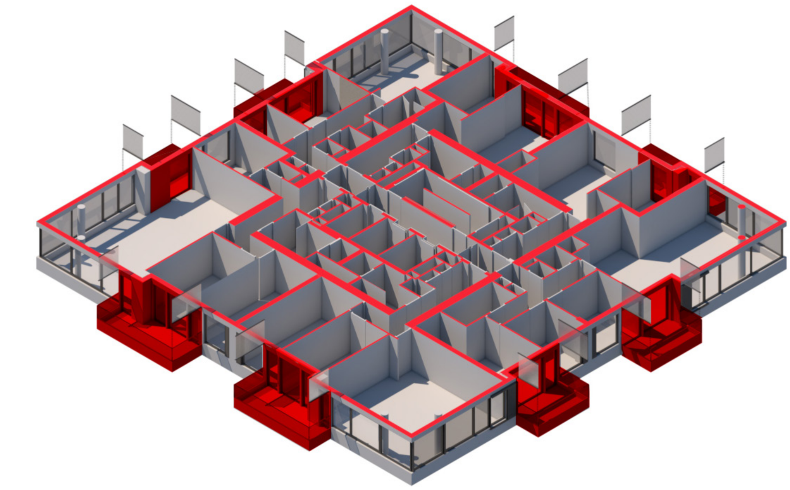
As seen in the previous chapters, small double-sided zones are at high risk of overheating. Therefore, screens should be applied to the East & West facing windows of the smaller double-sided zones (Figure 9.4). Two families of screen shading systems were considered for apartments in “Group A” and “Group B”. Apartments at first ventilation group are exposed to high-speed winds for shorter period of the time making it possible to utilize conventional cable screens for shading. However, apartments at the second group are under higher wind pressure, for which screens with the zipping system should be utilized.



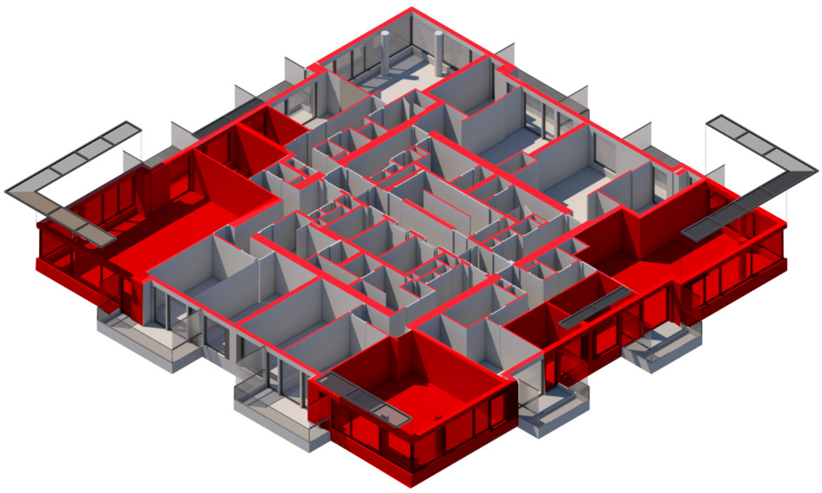
—> Figure 9.4: Applying screens on the small double-sided zones

As shown in chapter 8, the most efficient way to prevent overheating in the rooms with balconies and bedrooms in between them, is to apply vertical shadings with metal mesh on the shorter sides of the balconies (Figure 9.5). The metal mesh will provide shading while not blocking the view permanently.

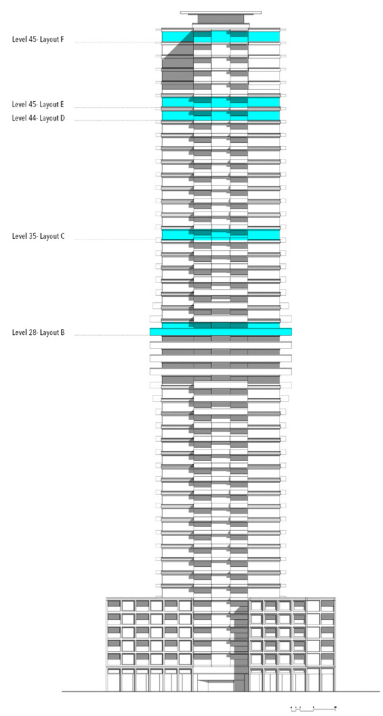
As shown in the previous chapter, the larger double-sided zones can be effectively shaded with 1.2 m long overhangs without the risk of getting overheated in the future. Likewise, in order to eliminate overheating risk for the smaller South facing double-sided zones, a 1.2 m long overhang was considered for the South orientated openings of these zones too. Smaller 60 cm long overhangs were selected for the bedrooms that are placed in-between balconies of the East and West, in order to maintain the view while limiting the incoming solar gains.



—> Figure 9.5: Mesh screens on balconies. They both provide shading and allow for view.



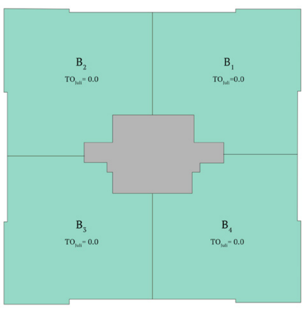
—> Figure 9.6: Overhangs were applied to bigger double-sided zones and zones with south-facing windows. Smaller overhangs were applied on the East and West facing bedrooms.

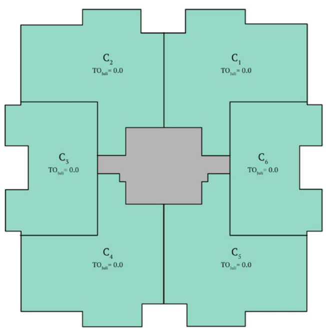


9.2. Overheating assessment results

In this section first, the representative level of each floor layout was assessed by TOjuli to investigate the effect of the new design on the overheating risk. Then the results of numerical simulations on Level 9 (26 m) and Level 45 (132 m) using future weather projections is presented. Detailed simulation workflow can be found in Appendix E.

9.2.1. TO_{juli} assessment

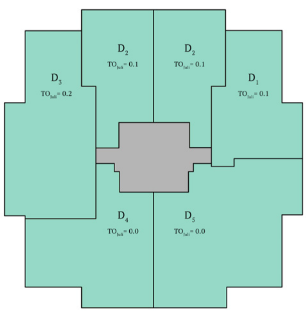


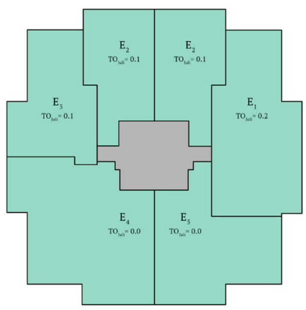


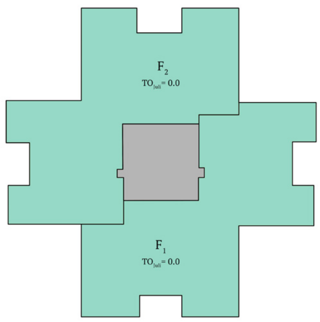
0≤ TO_{jul}<2 Little to no risk of overheating

2≤ TO_{jul}<4 oderate risk of overheating

4≤ TO_{jul} very high risk of overheating







As TOjuli results indicate, none of the tower's layouts will have an overheating problem with the new façade design in the present conditions.

9.2.2. Future weather assessment

Figure 9.7: Level 45's (132m) Temperature Exceedance hours of ATG during future weather projections

Figure 9.8: Level 9's (28m) Temperature Exceedance hours of ATG during future weather projections

As is evident, even with the worst-case scenario of climate change, none of the zones will overheat by the end of the century. Although a number of the West-facing zone's and smaller rooms will get regularly warm. Also, single-sided zones on lower levels are at higher risk of temprature exceedance in lower levels because the effectivity of ventilation is lower in these levels.

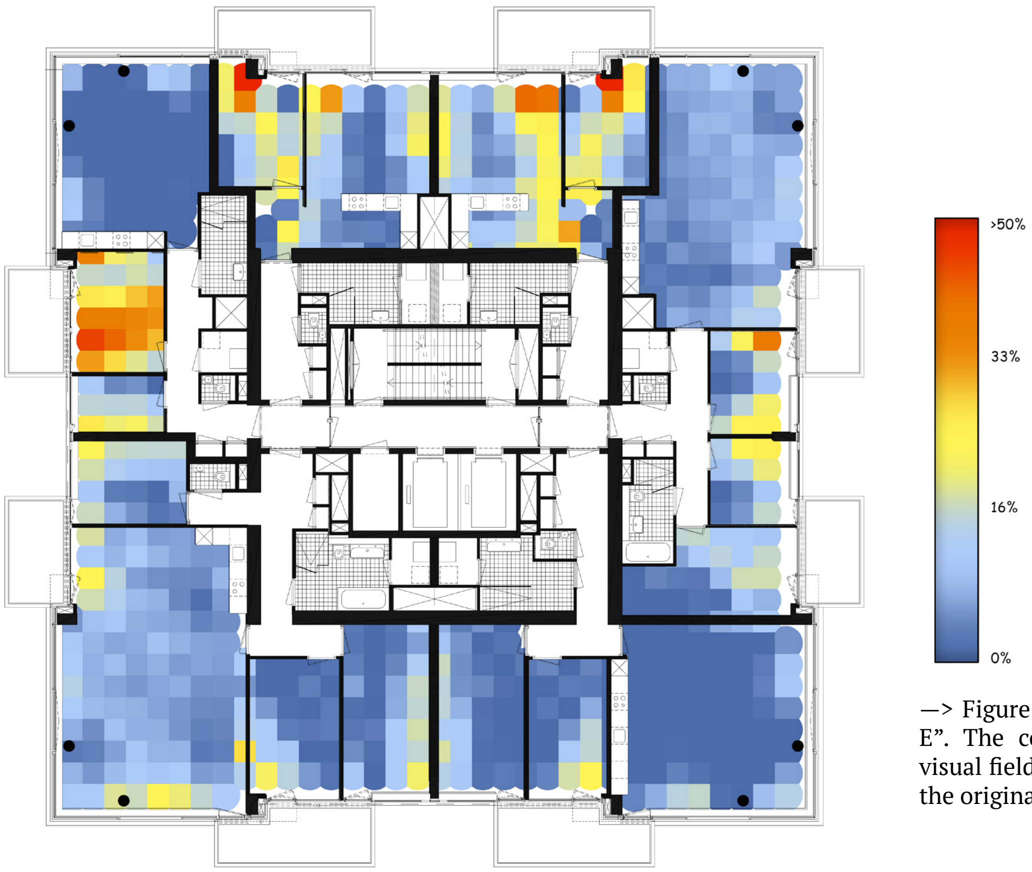
9.3. Visual field overview

“Layout D” and “Layout E” are the dominant architectural layout’s in the Cooltoren. These two layouts are the mirror of each other in South-North direction. The smaller size of living zones in these floor plans makes the effect of the obstruction in the visual field to be more unfavourable. The new façade design tried to limit the effect of static shading elements on the visual field. The tower’s floors are positioned in such a way that two continuous floors have different plan layouts. This results in a two-floor gap between the overhangs in double-sided zones limiting the disruptive effect of the shading element on the visual field (Figure 9.9 & 9.10).

Figure 9.9: Different plan layouts in different level result in the rotation of the overhangs limiting its effect on the visual field.

—> Figure 9.10: Overhangs were applied to bigger double-sided zones and zones with south-facing windows.

Figure 9.11 shows the result of the visual field simulation. As can be seen overall, the bigger bedrooms and double-sided zones have a good visual field in all directions. However, the smaller bedrooms and those bedrooms which are blocked at its sides by balconies have visual field obstruction issues adjacent to the walls.



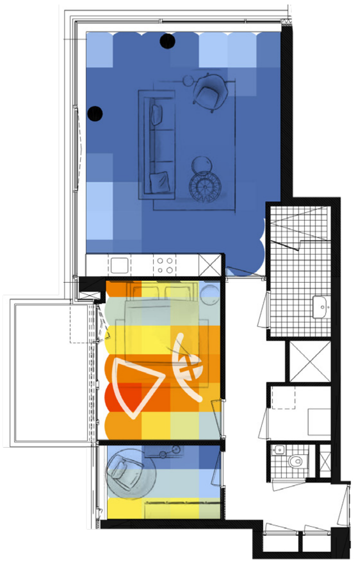
—> Figure 9.10: Visual field in “Layout E”. The colours show how much the visual field is obstructed compared with the original design

—> Figure 9.11: Standing person field of view from the position indicated in the plan.

—> Figure 9.12: Sitting person field of view from the position indicated in the plan.

—> Figure 9.13: Standing near the window occupant could find the sky marginally obstructed by the overhang.

—> Figure 9.14: Standing near the window the overhang of the apartment is visible.



|_> Figure 9.15: Occupant field of view from the position indicated in the plan.

9.4. Cost overview

In order to have a better understanding of the investment cost of the proposed facade, a detailed price list was made from the inquires from the companies whose products were considered in the design. The price lists were made for level 9 and level 45 as representatives of Group A and Group B ventilation groups. The price list only includes the additional costs of the added elements compared to the original design. Costumer prices for the façade items of level 45 and level 9 can be seen in Table 9.1 and table 9.2, respectively.

Item	quantity	Unit	Price per unit (Euro)	Overall cost (Euro)
Dexone horizontal sun louvre	47.2	m^2	70	3234
Solozip Screen (220*200)	2	-	984	1968
Solozip Screen (330*200)	2	-	1437	2874
HAVER Architectural Mesh	42.6	m^2	150	6390
Wicona ventilation Flaps	3.6	m^2	500	1800
Additonal cost for sliding window	9.6	m2	150	1440
Baier sliding shutter	10.6	m^2	800	8480
Open woven vinyl mesh	10.6	m2	50	530
Motorizing windows -Soonkst actuator	44.7	m^2	80	3476
SELVE Home Server	6	-	350	2100
Total Cost (Euro)			**32292 €**	

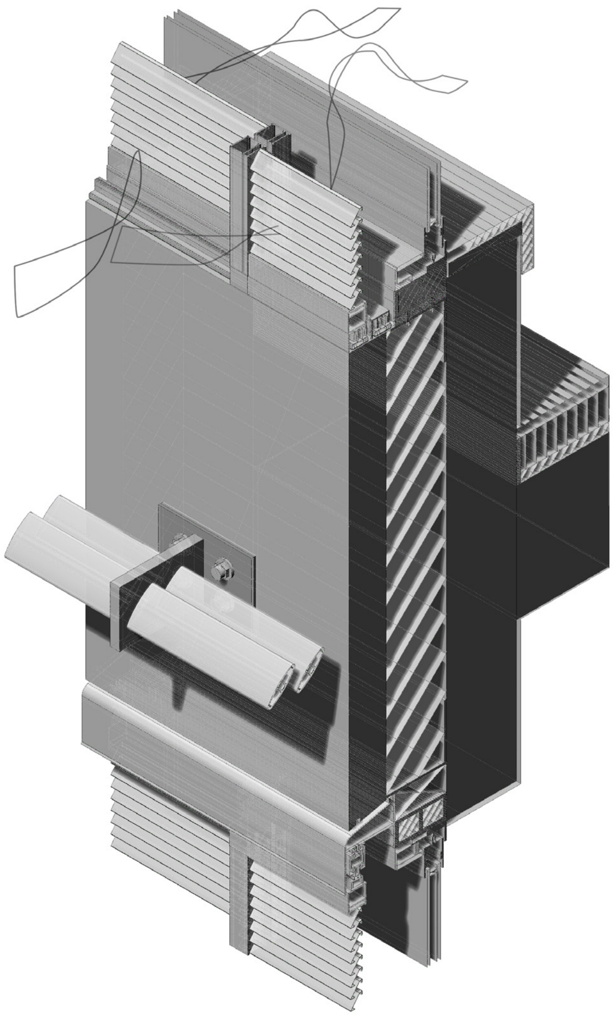
—> Table 9.1: Standing near the window the overhang of the apartment is visible.

Item	quantity	Unit	Price per unit (Euro)	Overall cost (Euro)
Dexone horizontal sun louvre	47.2	M^2	70	3234
Sigara Screen (220*200)	6	-	689	4134
HAVER Architectural Mesh	42.6	M^2	150	6390
Wicona ventilation Flaps	3.6	M^2	500	1800
Additional cost for hinged window	27.2	M^2	60	1632
Motorizing windows -Soonkst actuator	44.7	M^2	80	3476
SELVE Home Server	6	-	350	2100
Total Cost (Euro)			**22766 €**	

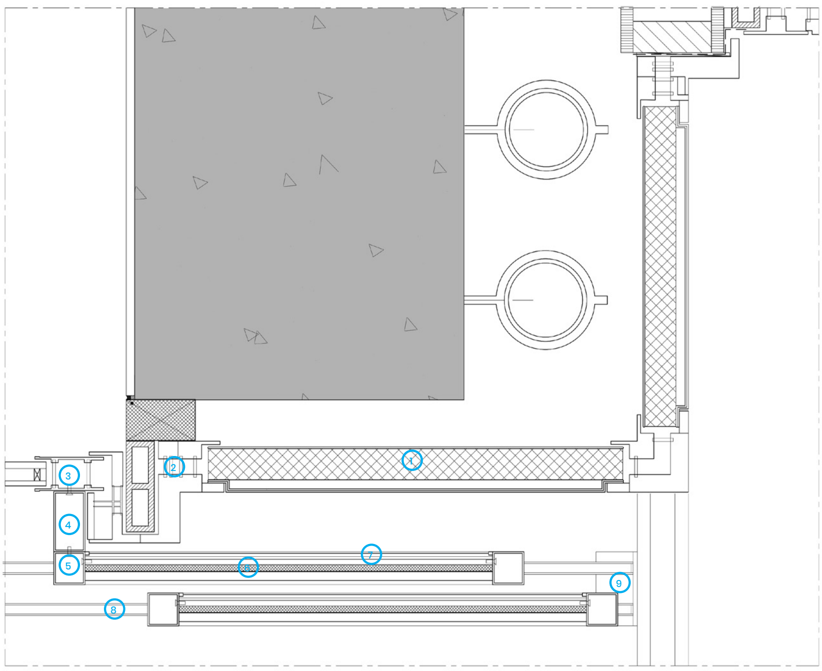
—> Table 9.2: Standing near the window the overhang of the apartment is visible.

9.5. Technical drawings

In this section architectural schematic drawings and details are delivered.



—> Figure 9.17: Isometric section of the window shutter connection and the horizontal shading elements.



—> Figure 9.17: Horizontal section from the connection of the sliding shutter to the window.

1. Insulated aluminum panel
2. Side hinged opening aluminum frame
3. Aluminum sliding window:

g_{total}-value= 0.35 (-)

u_{total}-value= 1.21 (W/m^{2}K)

4. Aluminum profile to conect the window to the sliding shutter.
5. Sliding shutter frame
6. Ventilation slats with acoustic indulation
7. Wind breaker fabric
8. Guide rail
9. Steel support bracket

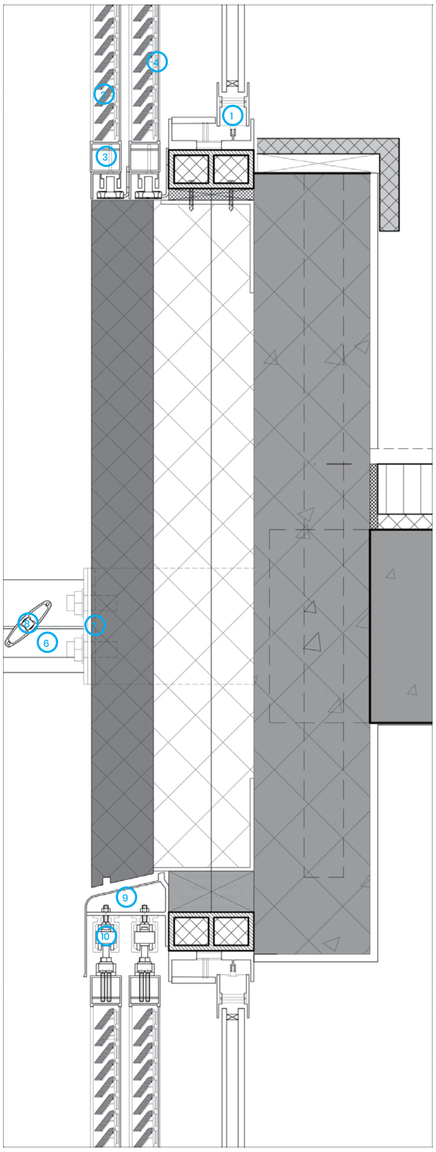


Figure 9.18: Vertical wall section from the connection of the sliding shutter to the window

1. Aluminum sliding window:

   g_{total}-value= 0.35 (-)

   u_{total}-value= 1.21 (W/m^{2}K)

2. Ventilation slats with acoustic indulation
3. Sliding shutter frame
4. Wind breaker fabric
5. Guide rail & slider
6. Horizontal shading mounting frame
7. Steel plate
8. Aluminum slats
9. Aluminum cover and carrier profile
10. Carriage

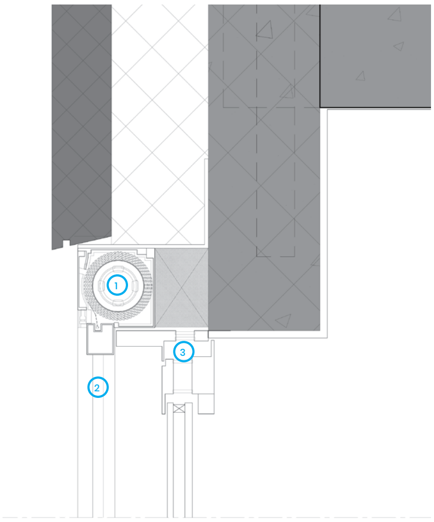


Figure 9.19: vertical section from the vertical screens

1. Vertical awning with zipping system
2. Guide rail
3. Bottom hunged window with aluminum frame:

   g_{total}-value= 0.35 (-)

   u_{total}-value= 1.21 (W/m^{2}K)

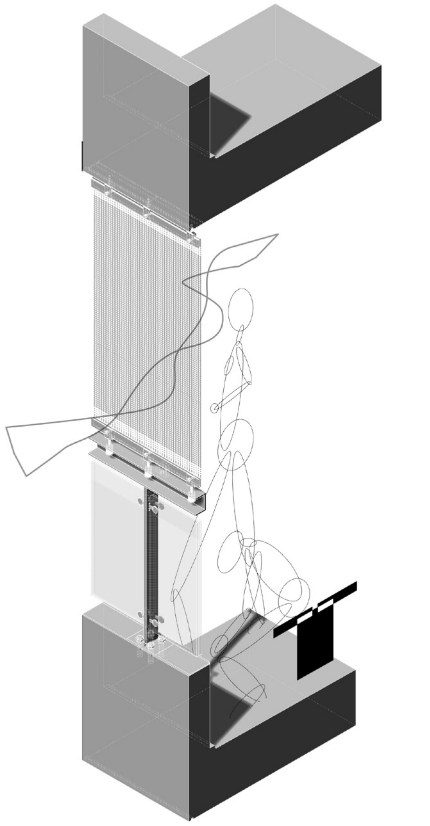
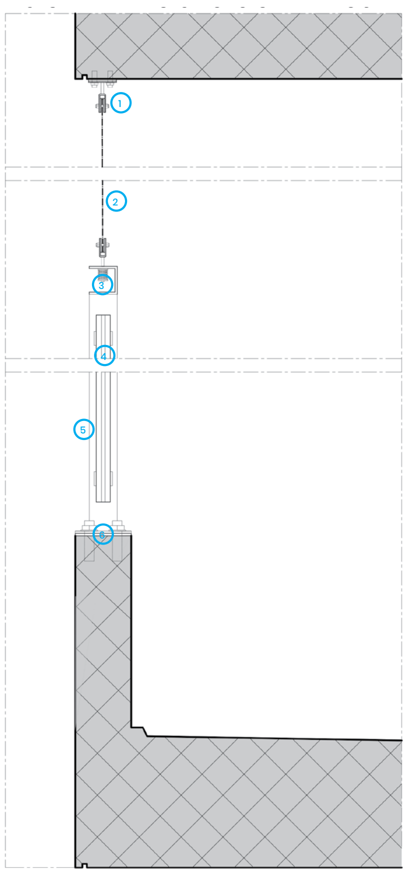


Figure 9.20: Isometric section of the balcony.



—> Figure 9.21: Vertical section from balcony's mesh screen

1. Anchor
2. Steel mesh screen

   g-value= 0.2 (-)

3. Pressure control spring
4. Laminated glass
5. Steel support for railing
6. steel plate

9.6. Final visualization

Figure 9.22: Final appearance of the building. Redesigned source: V8 architects

10. Exploring innovative solution concepts

In the previous chapters conventional redesign options for the Cooltoren building were proposed and it was proven that it is robust enough to prevent overheating in the future. Next, in order to explore more of unconventional and innovative solutions for overheating several innovative design concepts were explored which can be reviewed in the Appendix H. Then strong points of these concepts were taken to develop an innovative design solution for the Cooltoren building.

In this chapter, first, this innovative design and the logic behind it is reviewed. Then the overheating results and design remarks are given. After that, visual access of the proposed design is reviewed and finally technical drawings are delivered.

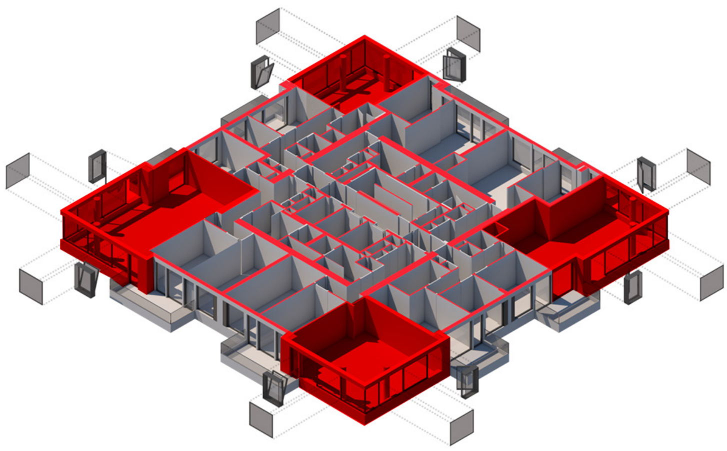
10.1. Design configuration

10.1.1. Ventilation & heat dissipation

Three ventilation methods for the living zones of Cooltoren helping in overheating prevention were developed. In this section each of these concepts with the logic behind them is explained.

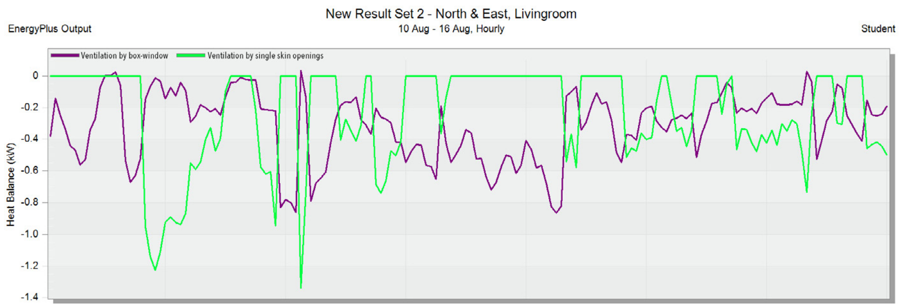
- ***Ventilation on double sided zones***

Based on the alternating façade principles, double skin box-window modules were considered for the double sided zones. The combination of double skin box-windows with tilting windows on the single skin part make ventilation possible in all weather conditions.



—> Figure 10.1: Benefiting from the alternating façade principle by adding box-windows and bottom hung windows to the façade

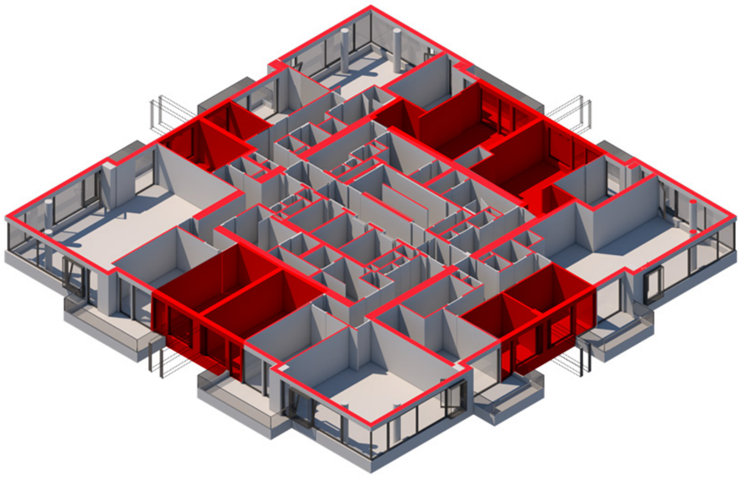
Figure 10.2 shows the heat loss due to ventilation by single skin and double skin ventilation components used in this concept. As clear, during the times when the outside weather does not allow for ventilation by tilting windows the box window can provide ventilation. Also, in times when the weather is calm and wind speed allows for direct ventilation tilting windows could provide ventilation for heat dissipation.



—> Figure 10.2: Contribution of ventilation components in the façade on heat loss by ventilation.

- ***Pressure controlled ventilation flap***

For rooms positioned in between balconies ventilation flap systems were considered (Figure 10.3).



—> Figure 10.3: Adding ventilation modules to the rooms in between balconies

Each ventilation device consists of two modules (Figure 10.4). The first module is made of conventional ventilation flaps to provide purge ventilation especially in calm days. The second module consists of pressure control ventilation slats connected to an air tunnel and is used to provide comfortable flush ventilation in windy and stormy days. The ventilation principle is that the device opens into a tunnel that directs the air to the ceiling (Figure 10.5). The proximity of the high speed air to the ceiling causes the air to be attached to the ceiling's surface due to the Coandă effect. In this way, the incoming wind draught would not make comfort problems for the user. Also, in stormy days and days with high wind speed the ventilation slats with a self-regulating system will modulate the opening to further decrease the risk of unpleasant draughts.

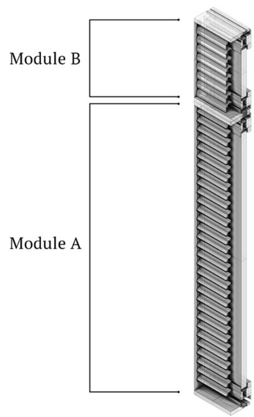


Figure 10.4: Configuration of the ventilation module

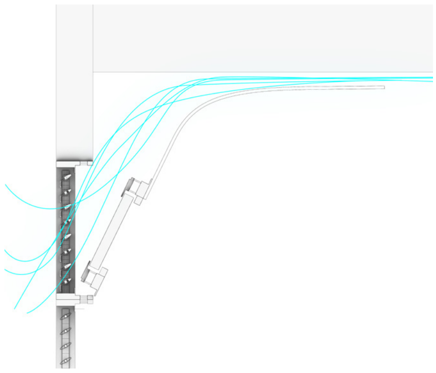


Figure 10.5: The tunnel jets the air in parallel to the ceiling and the air sticks to the ceiling's surface due to the Coandă effect reducing the chance of unwanted draught.

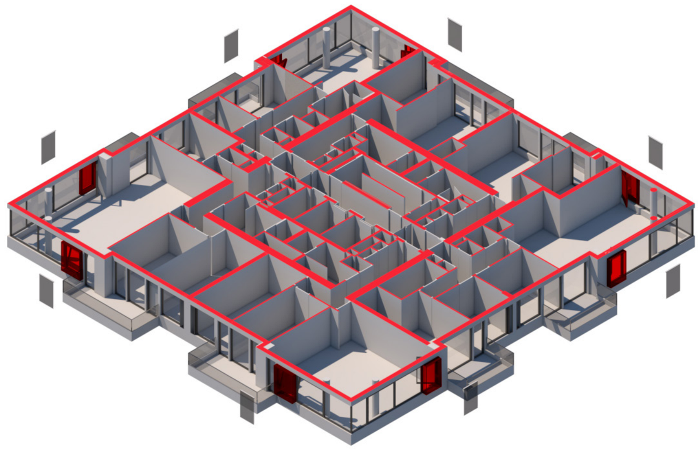
- ***Decentralized ventilation***

The introduced ventilation modules makes purge ventilation possible on all occasions when the outdoor temperature is lower than the indoor temperature. For energy-efficient ventilation during winter and occasions when outdoor temperature is higher than indoor temperature decentralized ventilation units with a heat recovery system were considered. In figure 10.6 the considered decentralized ventilation unit with a ceramic heat recovery system can be seen. Having a heat recovery efficiency of 90.6 % the ventilation unit could provide required fresh air when the outdoor temperature does not allow for ventilative cooling. Also, since these small units eliminate the need for duct works less material is used, therefore reducing the embodied energy of the building.

—> Figure 10.6: LUNOS e² 60 decentralized ventilation unit with ceramic heat recovery system. Source: www.lunos.de

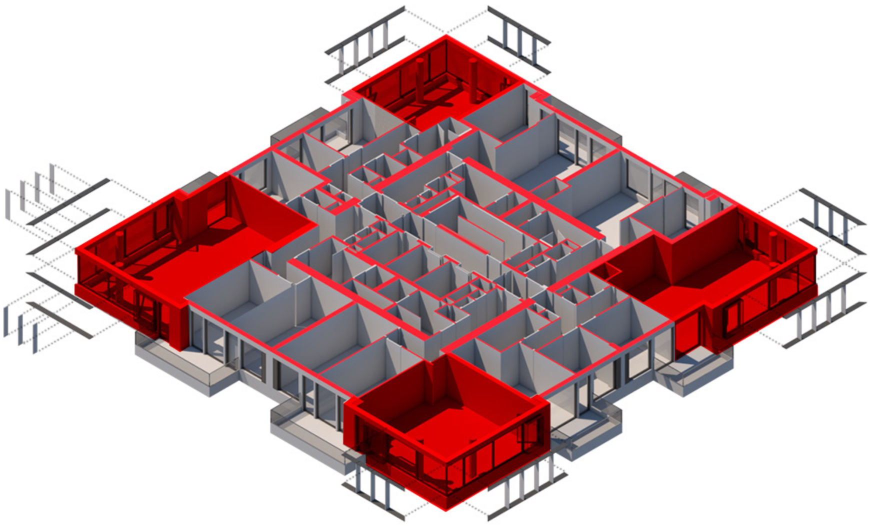
10.1.2. Heat prevention

Reflective screens were considered for the cavity of the box-window modules. Positioned in between glass elements the shading element is protected from high windspeed.



—> Figure 10.7: Window screens used in the box-window elements.

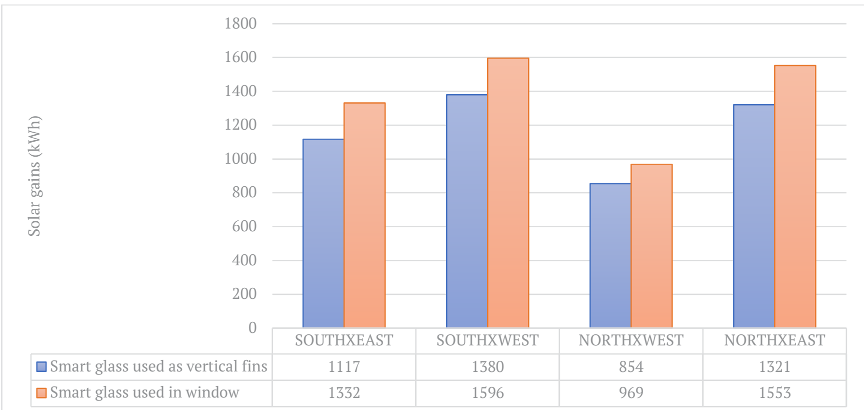
To shade the single skin part of the living rooms liquid crystal smart glass was applied as vertical fins to provide shading.



—> Figure 10.8: Static shading elements using smart glass on double sided zones.

The 30 cm deep smart fins are anchored to the extruded sill and frame. This configuration was chosen to optimize the effective reduction of solar gain with minimal usage of the liquid crystal glass.

Figure 10.9 shows a comparison of two usage scenarios with equal area of liquid crystal glass.



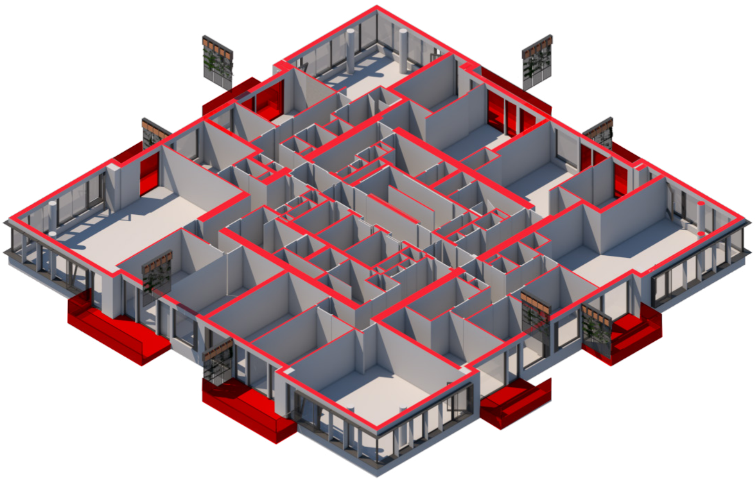
	SOUTHXEAST	SOUTHXWEST	NORTHXWEST	NORTHXEAST
Smart glass used as vertical fins	1117	1380	854	1321
Smart glass used in window	1332	1596	969	1553

—> Figure 10.9: Results of solar gains of double sided zones with two smart glass usage strategies.

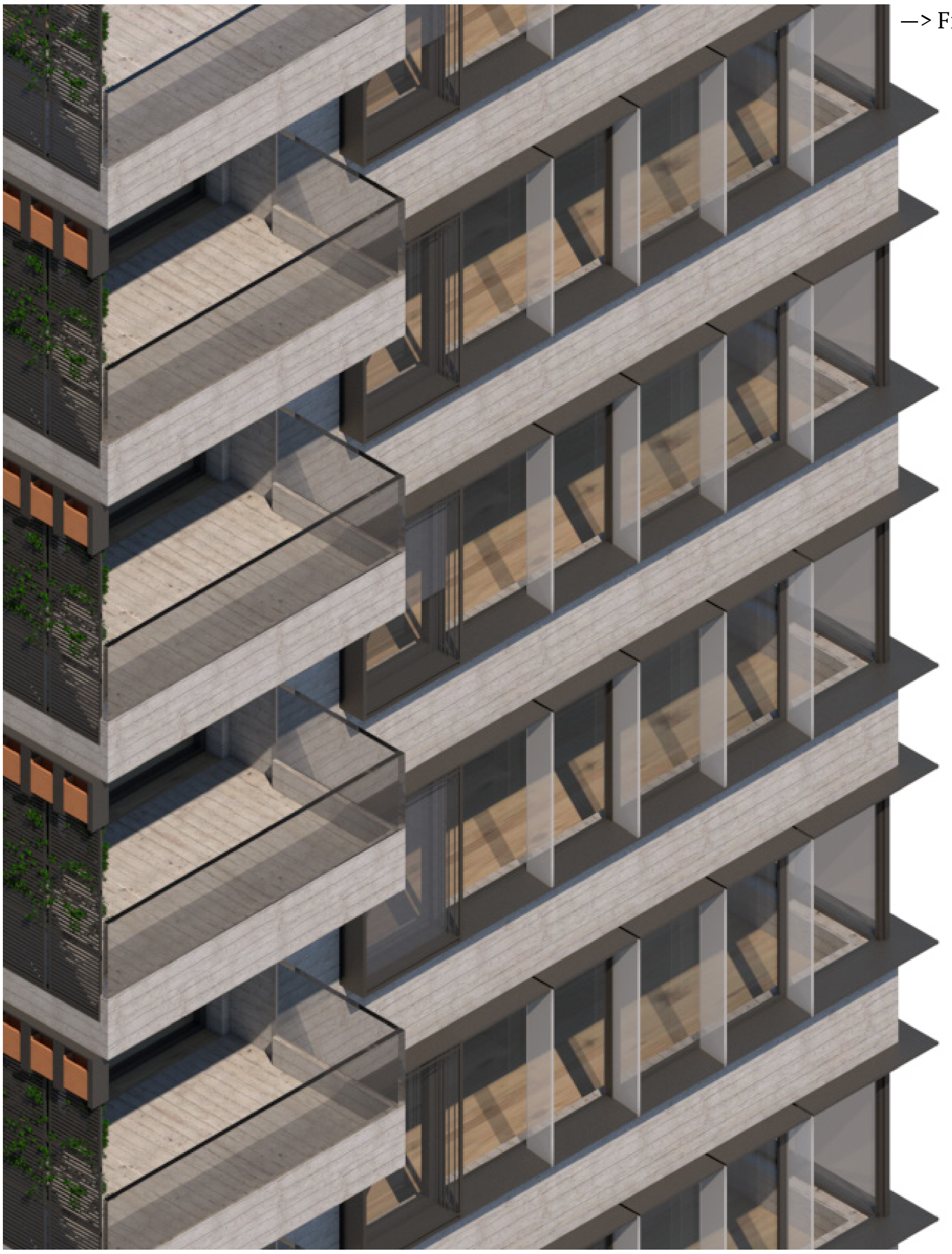
Smart glass used in window: In this strategy one of the glass panes of the double sided zones which is oriented to east or west was covered with smart glass. The pane covered a 4.2 m2 area.

S***mart glass as vertical fins***: In this strategy the same area of smart glass as in the previous strategy was divided into smaller parts which were installed as vertical shading fins.

To provide shading for bedrooms and privacy for the balconies green walls were considered on the inner edge of the balconies (Figure 10.10).



—> Figure 10.10: Green walls on the inner side of the balconies



—> Figure 10.11: Design visulization

10.2. Design configuration

Once the strategies were defined, their performance were examined using numerical calculations. The detailed workflow of the building performance analysis for the purposed strategies can be found in Appendix L.

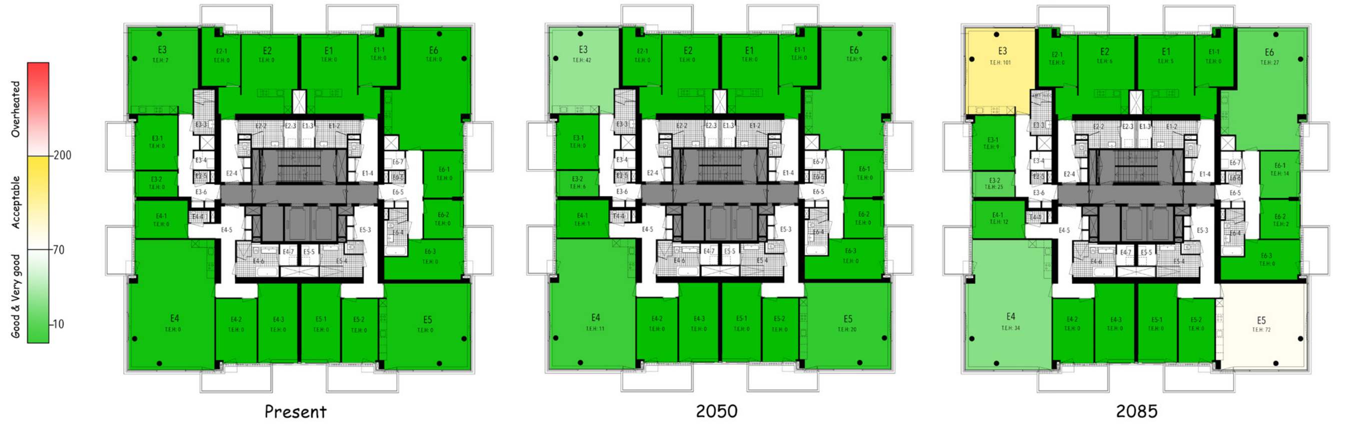


Figure 10.12: Overheating results of the 45th level (132m).

As the results show, with these strategies none of the living zones will overheat in the future.

Nevertheless, it can be seen that by 2085 smaller double sided zones "E3" & "E5" will get uncomfortably warm.

- ***Overheating considerations:***

During the simulation several important issues were detected that should be noted regarding design and occupants influence on indoor conditions.

Figure 10.13 presents the thermal conditions of the cavity of the box-window module. As can be seen, though the screen will reduce the solar radiation on the inner pane, however, since the depth of the cavity is very narrow the temperature of the surface in contact to the cavity will increase and thus the radiative temperature increases drastically. To reduce this problematic effect the depth of the cavity could be increased to more than 70 cm. This might not be a good solution for the residential buildings since big cavities could occupy valuable apartment's space.

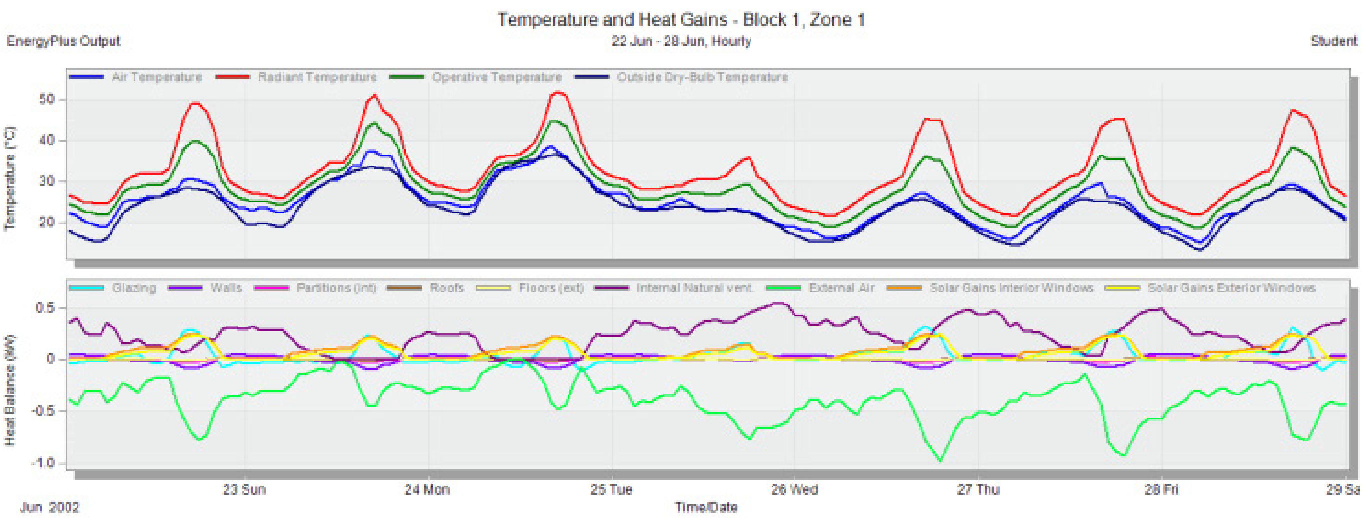


Figure 10.13: Temprature swings in the cavity during typical summer week

Another problem associated the box-window system can be seen in figure 10.14. As evident, if the user opens the system when the cavity temperature is higher than the indoor temperature it will cause high heat gains that could reduce the comfort or even result in overheating. Using additional temperature sensors in the cavity and smart systems and actuators could help to prevent this problem, however using these systems will increase the cost of the modules.

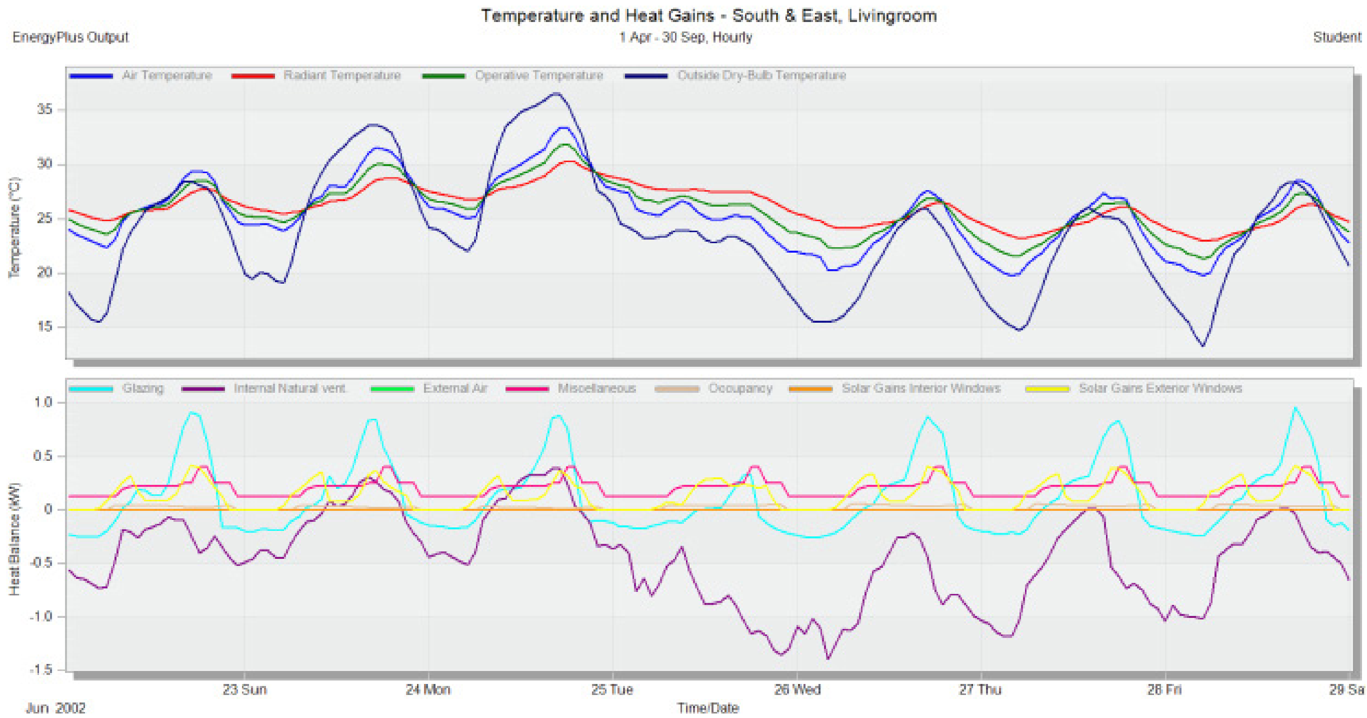
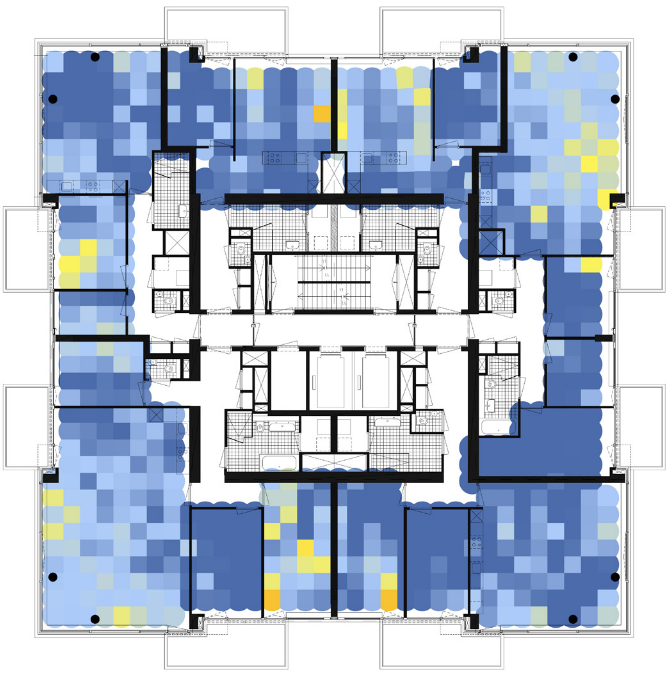
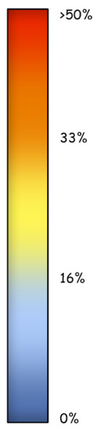


Figure 10.14: Heat balance of the “E5” livingroom

10.3. Visual field overview

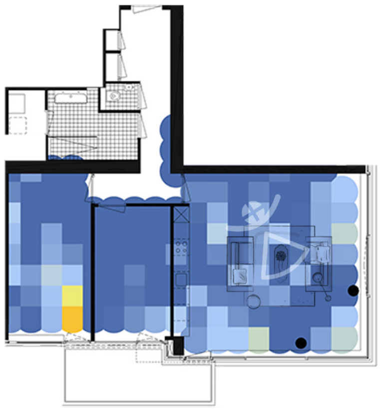
Figure 10.15 shows the result of the visual field study. Overall, all living zones have very good visual access. As can be seen, the visual field of the rooms that are in direct contact with the inner edge of the balconies has been reduced compared to the original design because of the green wall. Also, the extruded frames and window boxes have reduced the visual access in the living rooms.





—> Figure 10.15: Visual field in “Layout E”. The colours show how much the visual field is obstructed compared with the original design

—> Figure 10.16: The smart glass in transparent mode does not restrict the visual access to the outside



—> Figure 10.17: The smart glass in opaque state

—> Figure 10.18: Low impact of the vertical shading elements on visual access

—> Figure 10.18: Bedroom view

10.4. Technical drawings

In this section architectural schematic drawings and details are reviewed.

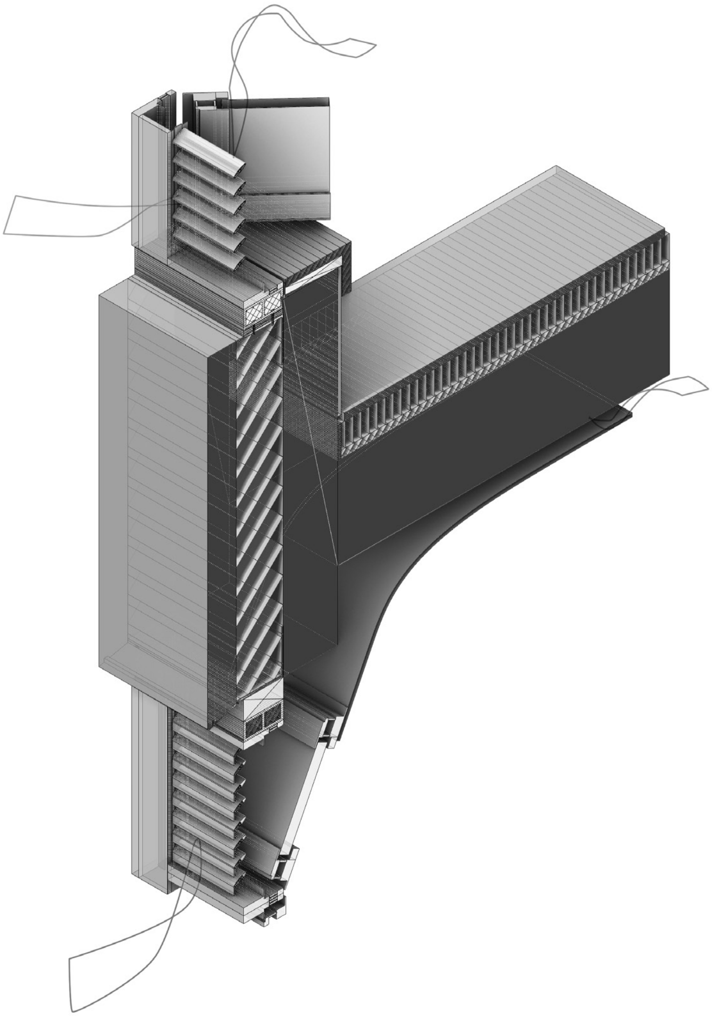


Figure 10.19: Isometric section of the ventilation flaps

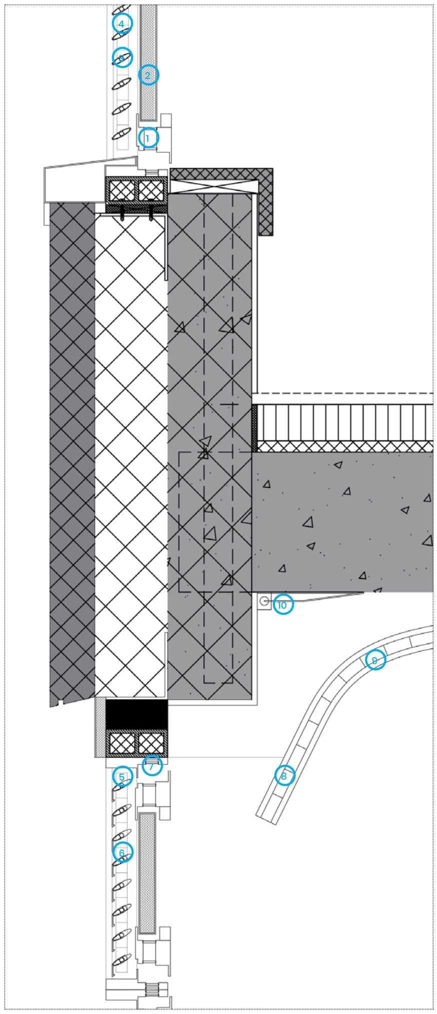


Figure 10.20: vertical section from the ventilation flap

1. Tilt & turn aluminum frame
2. Insulated aluminum panel

   u_{total}-value= 1.21 (W/m²K)
3. Ventilation slats with acoustic material
4. Mounting frame
5. Type 1 pressure control slats
6. Type 2 pressure control slats
7. Aluminum tilting frame

   u_{total}-value= 1.21 (W/m²K)
8. Curving Stud
9. Plasterboard
10. Negative pressure control

Figure 10.21: Exploded isometric of the self-regulating slat
Two types of ventilation slats were considered in order to make automatic modulation during windy and stormy days possible.

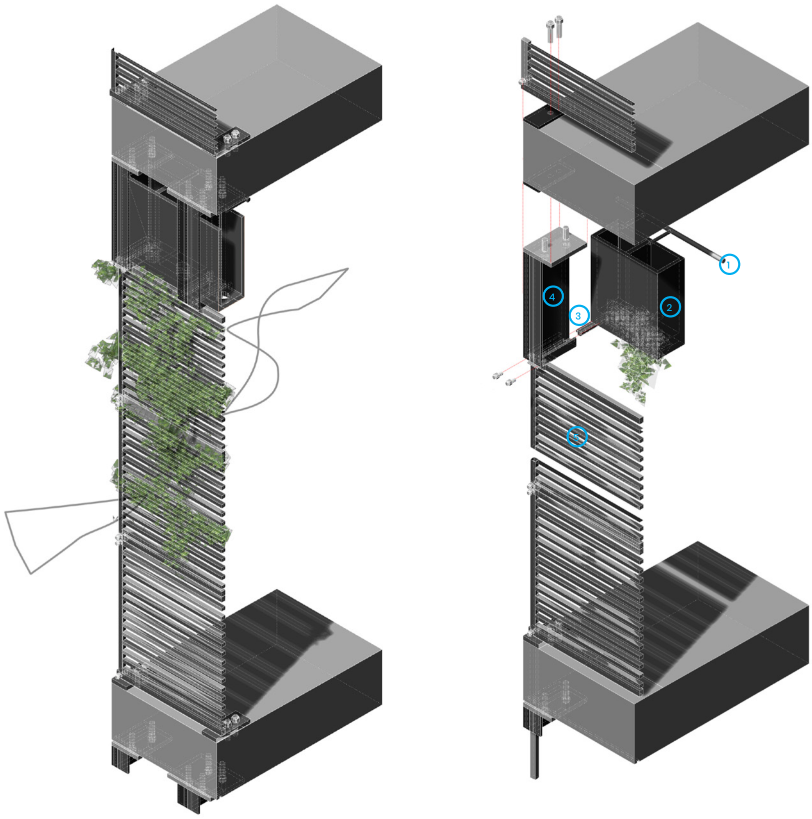


Figure 10.21: Isometric section and exploded isometric of the green wall. Bulky planter box where moved up to increase the operable area of the balcony.

1. Irrigation pipes
2. Upside planter box
3. Guide rail & slider
4. Steel support
5. Wooden fence

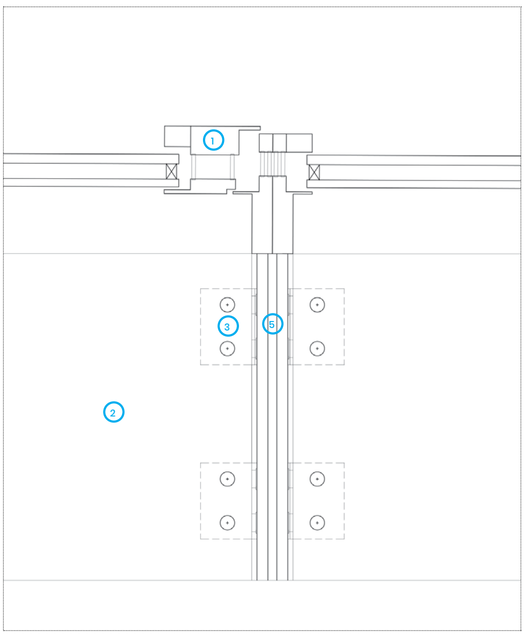
Figure 10.22: Vertical and horizontal section from the vertical fins

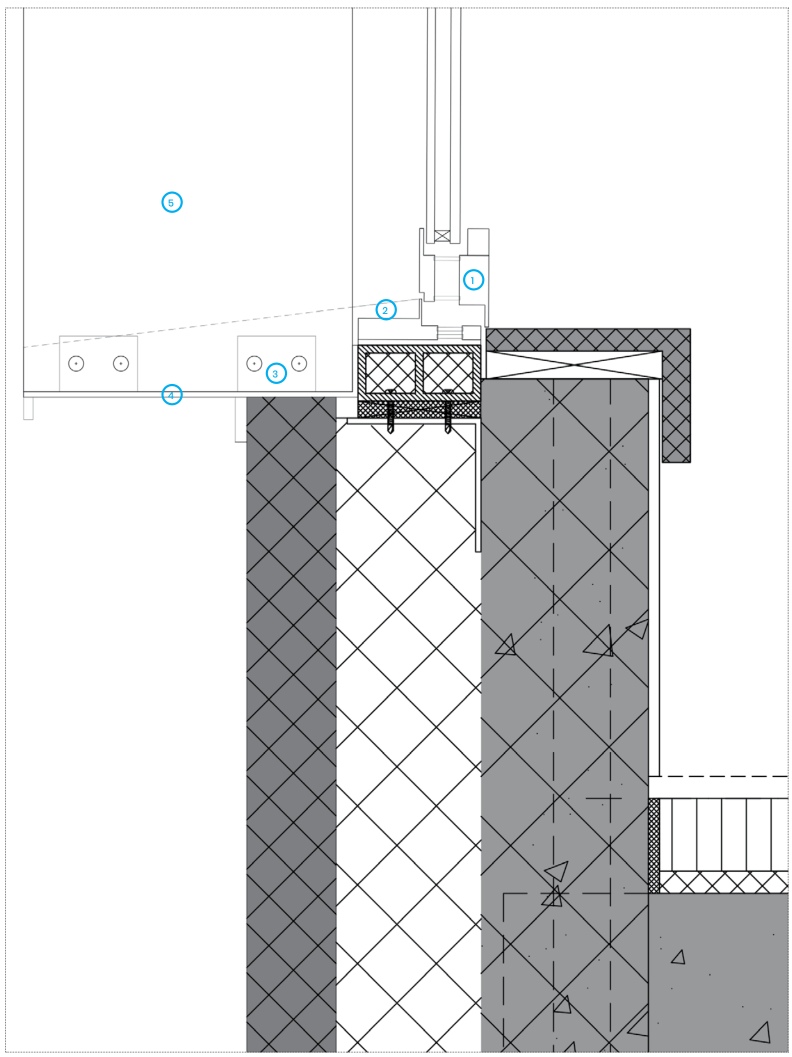
1. Bottom hunged window with aluminum frame:

   g_{total}-value= 0.35 (-)

   u_{total}-value= 1.21 (W/m^2K)

2. Window Sill
3. Steel connector
4. Steel plate
5. Liquid crystal laminated glass





11. Conclusions

The aim of this study was to find resolutions for overheating problem in energy-efficient high-rise dwellings without using active cooling and reducing its glazing area. Design guidelines that could help designers and users in mitigating overheating were introduced. A case study in the Netherlands was investigated in order to examine the effectivity of the proposed guidelines in preventing overheating both now and in the future, with a worst case climate change scenario. The simulation results obtained by redesigning the case study verifies that overheating can still be prevented in the future by passive means. A proper combination of thermal mass of the building, heat dissipation and heat protection techniques with considering adaptivity in thermal comfort displayed that overheating can be prevented. The results suggest that these measures can be effective even with the worst case climate change scenario for 2085 time period. In spite of this, the building performance simulation indicated that smaller rooms and rooms with lower thermal mass will get problematic in the future. Although, the beneficial effect of thermal mass will decrease in the future, because of the higher average temperature at night, it still regulates the living zones from severe daily temperature swings that could cause overheating in a room.

Analyzing the overheating risk in the case study building using numerical and analytical calculation methods showed the potential of the analytical assessment methods in reliably predicting the overheating risk in the dwellings. This indicates, despite being a simple overheating calculation method, that analytical methods such as TOjuli can still be very useful in predicting overheating in the apartments. However, the results of TOjuli should be interpreted cautiously by considering the different characteristics of orientations into account.

The overheating evaluation of the case study's simulation using different assessment methods, displayed a significant difference between two adaptive and static overheating assessment criteria. While the ATG method which is based on the adaptive thermal comfort shows a lot of flexibility in achieving thermal comfort by taking the user adaptivity into account, the CIBSE (2006) method which is based on a static temperature threshold shows little to no resilience. Complying with overheating methods with static threshold cannot be achieved in the future since the average outdoor temperature will increase significantly. It showed that using overheating assessment methods which are based on the adaptive thermal comfort model are more flexible in design and the requirements can be easier achieved. This is in line with the EPBD suggestions in NEN-EN-15251 which prefers adaptive thermal comfort for assessing thermal comfort in free-running buildings.

11.1. sustainability review

As results shown a proper combination of thermal storage, passive heat dissipation and heat protection techniques can prevent overheating in energy-efficient high-rise dwellings. In spite of this, improved thermal comfort and energy-efficiency does not necessarily mean that these measures could make a building sustainable. Several other factors such as building's life cycle, the effect on building placement and wider urban and social context too should be considered.

According to Ramesh et al. (2010) Operational energy accounts for the 80 to 90 % of total building's life cycle energy while embodied energy accounts for 10 to 20 %. Utilizing proposed passive measures while increasing the embodied energy could still contribute to total lifecycle energy reduction by decreasing operational energy. In addition, a building that benefits from future proved passive overheating prevention methods protects its occupants from harmful, severe thermal discomforts due to the energy shortages and blackouts.

As shown thermal mass and storage is a big contributor to overheating prevention especially in the future with the effect of global warming. The results proposed that small rooms and rooms without enough thermal mass are at higher risk of overheating and will overheat. However, with the recent population growth in the cities and increasing need for apartments for accommodating these new residents, using bulky thermal storage solutions or making spaces bigger could reduce the availability of accommodations for these growing population resulting in unfavorable urban sprawl and hence higher overall energy consumption in the urban context. Therefore, integrated research in all architectural and urban levels is needed so the results of this research could be used for sustainable development.

11.2. Limitations

There were some limitations during the study which need to be taken into account when the results of the research is going to be interpreted. There are several uncertainties tied with building performance simulations of high-rise dwellings. First of all, the temperature and wind speed changes at different heights of a high-rise building. Although the Design Builder software takes the varying wind speeds at different heights into account, it does not take the temperature variations into consideration. Considering that there is a 150 m difference between the top and the bottom of the case study building, this could result in a 1.5°C temperature difference between the two extremes which could affect the results.

In addition, the wind pressure coefficients of high-rise buildings are varying with height and shape on different sections of the buildings. However, in order to consider this effect wind tunnel tests or detailed CFD simulations would need to be done on the building which were out of the scope for this research. Therefore, default wind pressure coefficients in the Design Builder were used for this study.

Another limitation was the validation of the building performance simulation. Since the case study building was not completed by the time of this study and because there were no temperature data available for the building. Although the building performance simulations were done using national energy performance simulation guidelines such as ISSO 32, ISSO Kennispaper: Thermisch Comfort (2019), the simulation results could vary with the in real situation results.

The ATG method which was used in this study for assessing overheating in the living zones was originally created for office buildings. Although it is indicated in NEN-EN 15251 that it can be applied for "residential use", there has been no research carried out in residential buildings to study its effect on thermal comfort (ISSO, 2019). However, ISSO Kennispaper: Thermisch Comfort (2019) writers suggest that the ATG method is currently the most realistic method for predicting overheating in residential buildings.

11.3. Further research

This research provides a first direction for designers which could help them in preventing overheating in their designs by taking climate change into account. Further research is needed to support this approach.

- This study focused primarily on the effect of temperature exceedance on thermal comfort for overheating assessment in dwellings. Further research should be done to include the effect of temperature exceedance on the health during the overheating assessment.
- Further researches and simulation should be done in order to investigate the combined effect of each of the purposed design solutions on energy efficiency and other comfort criteria's such as daylighting.
- This research only considered the effectivity of the measures in providing energy-efficient overheating preventive solutions during the summer. Further research should done on energy and comfort effect of the purposed measures during the winter.
- Further research should be done on the energy saving protentional of the purposed measures.
- Detailed CFD simulation could be done in order to explore the scope of effectivity of the purposed measures in a high-rise dwelling.
- This research only focused on a specific location with specific climate for overheating studies. Implement these solutions on various climatic conditions and locations and comparing them together could help to build up better understanding of this phenomena.
- In this thesis only solutions on the building component level were investigated, further overheating studies and simulation on different urban and architectural design scales should be done to find how designer should adopt themselves to the climate change in these design contexts.
- Further research is needed to study the effect of the purposed solutions on bigger sustainable overview.
- Field surveys and measurements should be done to explore the occupants response to overheating and to specify adaptive thermal comfort model for residential buildings.

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https://thecooltower.nl/

Appendix A. Case studies

This appendix presents case studies that benefit from different overheating prevention methods at detailing and materialization design level.

The reviewed case studies are studied and qualified in different aspects which later are defined.

The comparison happens in eight areas of:

1. Architectural impact: The effect on the layout of the building and its appearance.
2. Maintenance: How easily the maintenance could be done.
3. Cost: How expensive the solution is compared to typical construction costs of a building.
4. Structural impact: The impact of the solution on the structure - How much load it forces on the building structure.
5. Acoustics: How good the solution is in protecting the indoor space from outdoor and neighbouring apartments noise.
6. Construction Impact: How bulky and space consuming is the solution.
7. Effectivity: How effective the solution is in reducing the risk of overheating
8. Technology readiness level: The European commission report of "HORIZON 2020 – WORK PROGRAMME 2014-2015" divides techonologies according to their development phase into 9 categories. These categorise are:

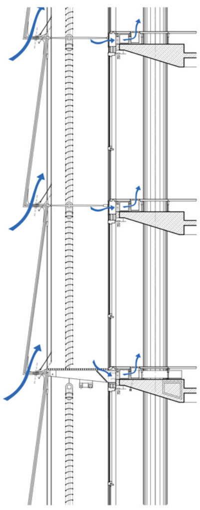
- o TRL 1: Observation of basic principles
- o TRL 2: Formulating the concept of the technology
- o TRL 3: Proofing the concept by experiments
- o TRL 4: Validating the technology by laboratory experiments
- o TRL 5: Validating the technology by in-situ experiment
- o TRL 6: Demonstrating the technology in the related environment
- o TRL 7: Validating the system prototype in an operational environment
- o TRL 8: Completed and qualified system
- o TRL 9: The final system has been proven to work in an operational environment

Post tower Bonn

The façade of the post tower in Bonn, Germany is made of the Double-skin corridor façade. The depth of the façade in two North and South orientations are different because of the different conditions. The depth of the cavity in south façade is 1.7m and the depth in north is 1.2m (Wood & Salib,2013).. The second skin facilitates natural ventilation at height and shades are integrated in the cavity for solar control. The idea behind this building is to give individual direct access to the outside air to the users. To do so every user has access to operable windows and fresh outside air is delivered through pivoting horizontal flaps of the second skin (Wood & Salib,2013). The corridor façade transmits the noise made in neighbouring rooms, to solve this translucent acoustic insulation is used to limit the noise transmission of the adjacent rooms (Wood & Salib,2013).

Disadvantage:

The considerable depth of the second-skin façade makes this strategy very expensive because of the significant loss of useable area.



Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
			×

Construction Impact			
None	Limited	Bulky	Very bulky
			×

Effectivity			
Basic	Positive	Good	Very good
			×

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
			×

Acoustics			
No effect	Normal	Good	Excelent
		×	

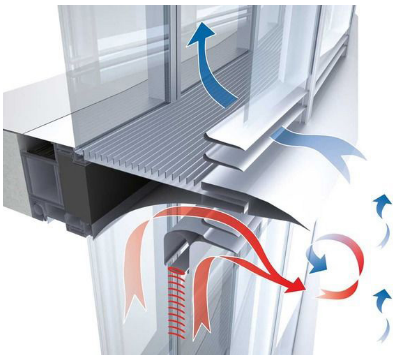
Operation			
Fixed	Manual	BMS	Hybrid
			×

Technology readiness level	
TRL 1	
TRL 2	
TRL 3	
TRL 4	
TRL 5	
TRL 6	
TRL 7	
TRL 8	
TRL 9	×

Sources:
- https://www.archdaily.com/231521/flashback-post-tower-murphyjahn
- Wood & Salib,2013

1 Bligh Street

The façade of the 1 Bligh Street building in Sydney, Australia is made of a double-skin corridor façade with a cavity of 60cm. The inner skin is made of a high insulated double-glazed glass, and the outer skin has laminated low-iron glass. Although the second-skin is used in this building, the offices do not use the fresh air of the cavity to ventilate. They are ventilated through mechanical means so the building could get Australia's Green Star certification. The cavity of the façade is ventilated through the fixed louvres placed at each floor level to prevent overheating in the cavity. These louvres have an aerodynamic shape to prevent high wind speed harming the blinds in the cavity, and to prevent re-enter of the exhaust air. Since the offices are not ventilated from the cavity in between the façade the purpose of the second skin is to protect the blinds from the harsh outdoor wind and to sustain a stable average temperature in the façade to reduce the reliance on the HVAC (Wood & Salib,2013).



Maintenance			
None	Basic	Easy	Hard
			×

Structural Impact			
None	Low	Acceptable	High
			×

Construction Impact			
None	Limited	Bulky	Very bulky
		×	

Effectivity			
Basic	Positive	Good	Very good
	×		

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
			×

Acoustics			
No effect	Normal	Good	Excelent
			×

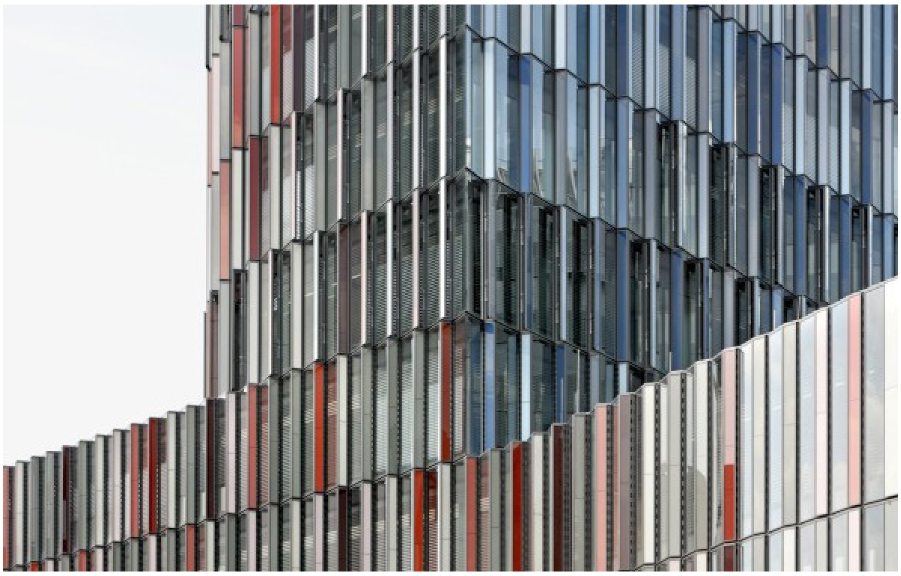
Operation			
Fixed	Manual	BMS	Hybrid
			×

Technology readiness level	
TRL 1	
TRL 2	
TRL 3	
TRL 4	
TRL 5	
TRL 6	
TRL 7	
TRL 8	
TRL 9	×

Sources:

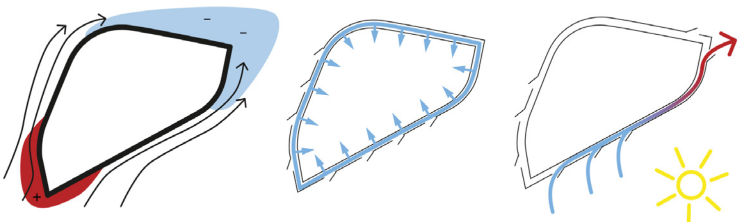
- https://www.archdaily.com/169173/1-bligh-office-tower-ingenhoven-architects
- Wood & Salib,2013

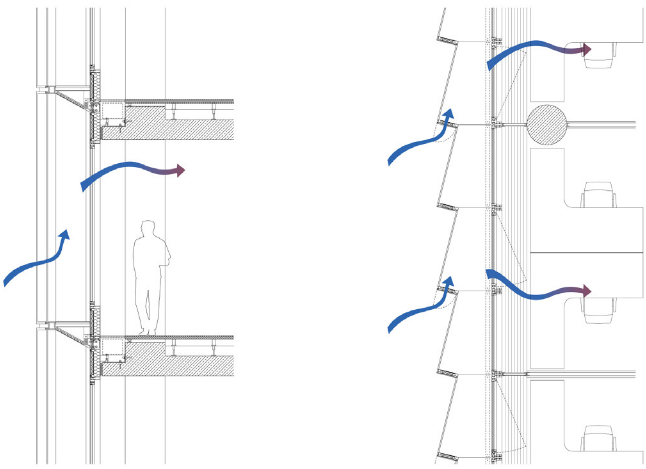
KfW Westarkade



The façade of the KfW Westarkade building in Frankfurt, Germany is made of a double-skin corridor façade. The depth of the cavity is 70 cm. The shape and the façade helps to build a pressure ring in the cavity, which makes a ring of uniform positive pressure around the building, making natural ventilation effective in all directions. The offices are ventilated from the cavity by BMS, ensuring that the cavity air pressure is higher than the internal pressure. The coloured glass panels of the outer skin get open depending on the outdoor conditions to ventilate the cavity. On hot summer days all of the panels on the façade could be opened to allow wind in the cavity. On winter a limited number of panels are opened to enable solar heating in the cavity.

The disadvantage is that the sound made in the neighbouring offices could transmit in the cavity, causing problems for the adjacent offices.





Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
			×

Construction Impact			
None	Limited	Bulky	Very bulky
		×	

Effectivity			
Basic	Positive	Good	Very good
			×

Visual field			
Limited	Obstructed	Good	Excellent
		×	

Cost			
Normal	Acceptable	High	Very high
			×

Acoustics			
No effect	Normal	Good	Excellent
		×	

Operation			
Fixed	Manual	BMS	Hybrid
			×

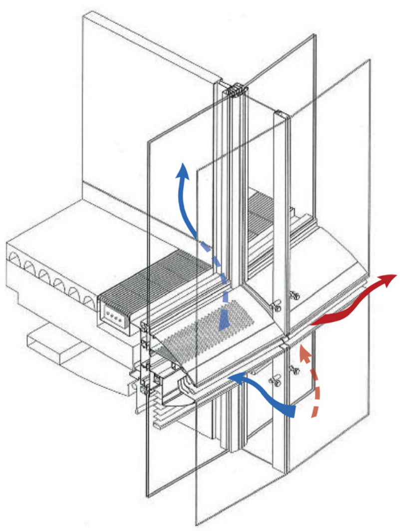
Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	×

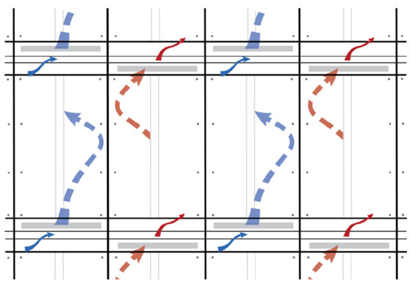
Sources:
- https://www.archdaily.com/316143/kfw-westarkade-sauerbruch-hutton
- Wood & Salib,2013

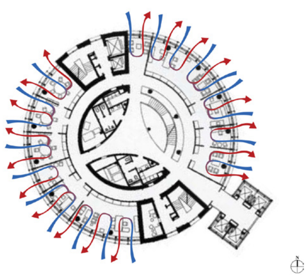
RWE Headquarters Tower

The façade of the RWE Headquarters building in Essen, Germany is made of window-box double-skin façade. The depth of the cavity of the skin is 50 cm. The windows of the inner skin could be opened to ventilate the offices from the fresh air in the cavity. Every office is in contact with two window-boxes. Each of these window-boxes has different fish mouth devices which one could be used for air intake and one for air exhaust. Besides ventilating the cavity, Fish mouth devices also regulate the ventilation rates through adjusting the passing airspeed. Since the wind pressure is higher at altitudes, there are two types of fish moth devices, one for the first 16 floors and the other for the floors above the 16th floor. For shading and reducing external gains blinds are used in the cavity.

Disadvantage: Double-skin façade is used in all directions with the same depth and design, causing to have window-boxes in orientations that second-skin is not necessary and causing different airflow patterns in offices in different orientations.







Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
			×

Construction Impact			
None	Limited	Bulky	Very bulky
		×	

Effectivity			
Basic	Positive	Good	Very good
		×	

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
			×

Acoustics			
No effect	Normal	Good	Excellent
			×

Operation			
Fixed	Manual	BMS	Hybrid
			×

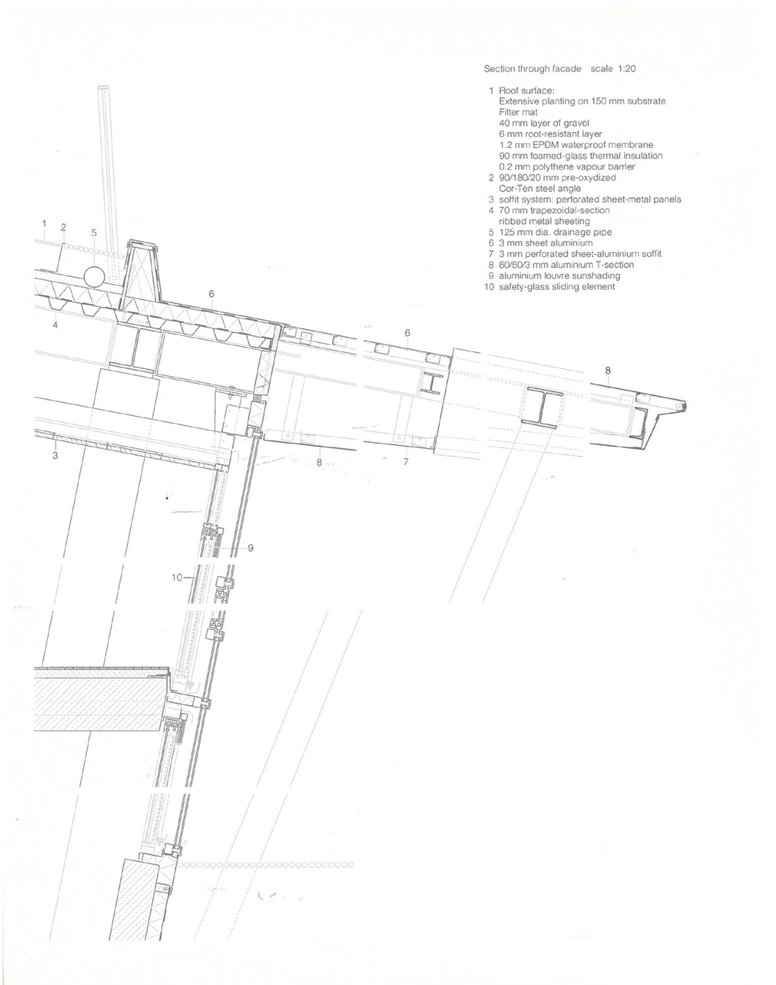
Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	×

Sources:
- https://www.archiweb.cz/en/b/rwe-hochhaus
- Wood & Salib,2013

TU Delft Library

The façade of the Library of the Delft university is made of an unsegmented double-skin façade with a double glazed outer skin, and the inner skin has single operable glazing. The depth of the cavity is 15cm, and it accommodates blinds for shading. The second skin is used for weather protection. In summer, the exhaust air goes through this façade to cool the cavity.

Disadvantage: The hybrid control for this building makes a lot of difficulties since the users does not know how to operate it usually the action they take is undesirable.



Maintenance			
None	Basic	Easy	Hard
			×

Structural Impact			
None	Low	Acceptable	High
			×

Construction Impact			
None	Limited	Bulky	Very bulky
	×		

Effectivity			
Basic	Positive	Good	Very good
		×	

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
			×

Acoustics			
No effect	Normal	Good	Excellent
		×	

Operation			
Fixed	Manual	BMS	Hybrid
		×	

Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	×

Sources:
- www.tudelft.nl
- Krippner, R., Lang, W., & Schittich, C. (2012). Building skins. Birkhäuser

Mercator I

The façade of the Mercator I building in Nijmegen, Netherlands is built from a single skin façade. To add the properties of a climate façade to this building, for glare and climate protection a thin, movable screen film in the inner side of the façade. Just like the double-skin facades, the cavity air is exhausted from the top of the façade. This way it allows for having a fully glazed building without the overheating risk.

Disadvantage: Since the screen is placed inside the building, most of the solar heat already enters the building and has a limited effect on reducing overheating.

Maintenance			
None	Basic	Easy	Hard
	×		

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
	×		

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
×			

Acoustics			
No effect	Normal	Good	Excellent
	×		

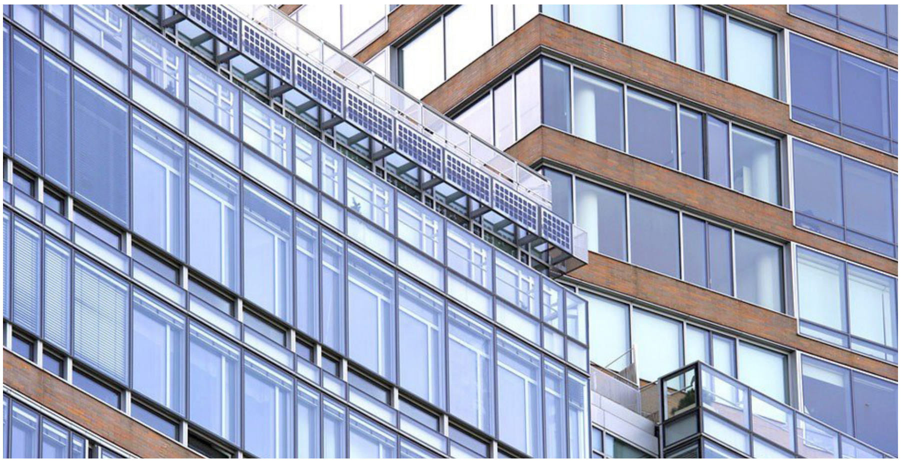
Operation			
Fixed	Manual	BMS	Hybrid
	×		

Technology readiness level	
TRL 1	
TRL 2	
TRL 3	
TRL 4	
TRL 5	
TRL 6	
TRL 7	
TRL 8	
TRL 9	×

Sources:

- https://www.e-architect.co.uk/holland/mercator-building

Riverhouse – One River Terrace



The façade of the Riverhouse residential high-rise in New York is made of window-box double-skin façade with a cavity of 11.5 cm. The vents and passive dampers on the skin regulate the ventilation in the cavity depending on the season. The inner skin windows are fully openable and are used for ventilation. For sun protection solar blinds are used in the cavity to prevent excessive heat getting inside the building.

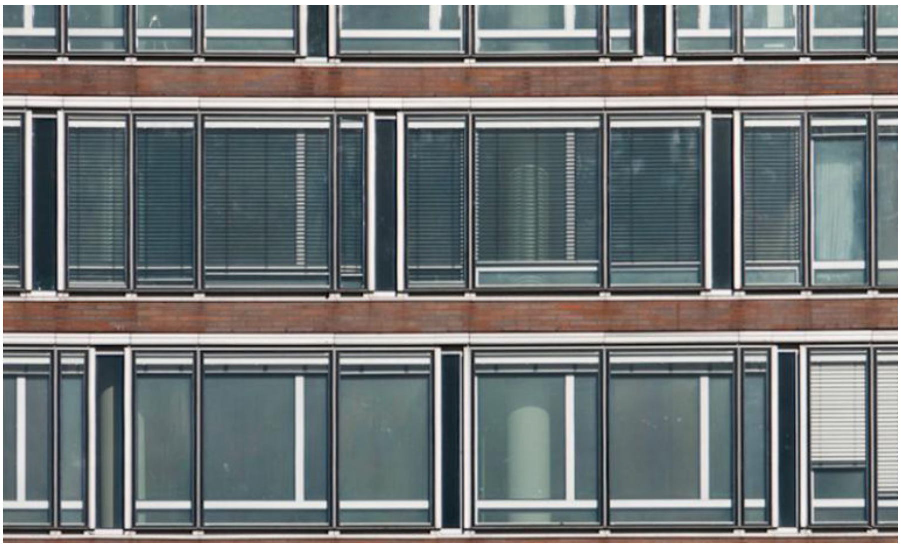


Figure: Unitized window-box facade of Riverhouse

Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
	×		

Effectivity			
Basic	Positive	Good	Very good
		×	

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
		×	

Acoustics			
No effect	Normal	Good	Excellent
		×	

Operation			
Fixed	Manual	BMS	Hybrid
	×		

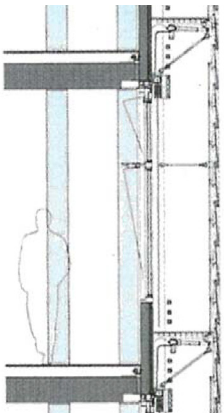
Technology readiness level	
TRL 1	
TRL 2	
TRL 3	
TRL 4	
TRL 5	
TRL 6	
TRL 7	
TRL 8	
TRL 9	×

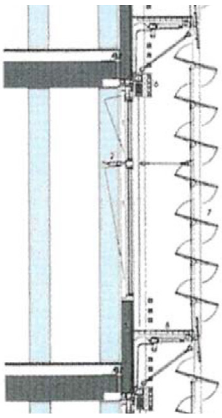
Sources:
- https://www.nynesting.com/
- www.streeteasy.com

Debis Headquarters

The façade of the Debis headquarters In Berlin, Germany is made of double skin façade. Between the skins there is a 70cm cavity which is segmented in each floor for easy access for fire protection and easy access for maintenance. The outer skin is made of segments of laminated glass louvers each connected to pivoting aluminium brackets.

The outer skin is made of eight glass louvers every story. Seven of these louvers can tilt up to 70 degree to allow air flow into the cavity (Figure). When closed there is a 1 cm gap between the louvers to allow air to penetrate. The louvers are controlled with a building management system which control the airflow into the cavity. This way building could benefit from natural ventilation 55% of the year. For sun control blinds are placed outside of the inner façade.





Sources:

- Vaglio, J. (2015). AEROPHYSICS OF DOUBLE-SKIN FACADES. UNIVERSITY OF SOUTHERN CALIFORNIA

Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
		×	

Construction Impact			
None	Limited	Bulky	Very bulky
		×	

Effectivity			
Basic	Positive	Good	Very good
			×

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
			×

Acoustics			
No effect	Normal	Good	Excellent
		×	

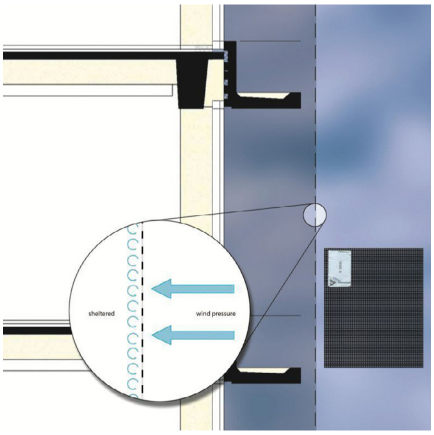
Operation			
Fixed	Manual	BMS	Hybrid
			×

Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	×

Westraven Building

Westraven high-rise office in Utrecht benefit from a innovative second-skin façade. In this building inorder to limit the solar gains and to decrease the wind pressure in order to make natural ventilation possible, a open-weave, teflon-coated glass fibre is used as a second skin. When wind hits the fabric small turbulences decreases the wind pressure, sheltering the balconies behind from wind speed at height. The offices then can open their windows which access the balconies for fresh air.

The first half of the second skin is made of the glass in order to both provide fall protection and provide a good transparent view to outside. The second half is made of the teflon-coated glass fibre.



Maintenance			
None	Basic	Easy	Hard
	×		
Structural Impact			
None	Low	Acceptable	High
×			
Construction Impact			
None	Limited	Bulky	Very bulky
×			
Effectivity			
Basic	Positive	Good	Very good
			×
Visual field			
Limited	Obstructed	Good	Excellent
		×	
Cost			
Normal	Acceptable	High	Very high
	×		
Acoustics			
No effect	Normal	Good	Excellent
	×		
Operation			
Fixed	Manual	BMS	Hybrid
×			

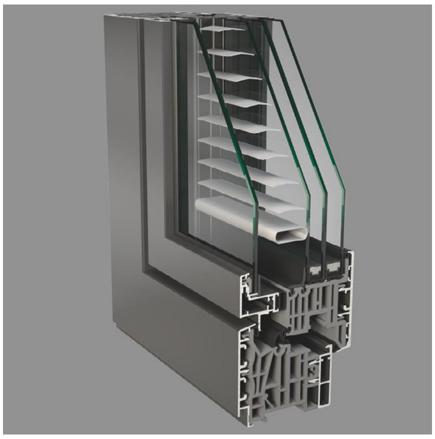
Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	×

Sources:
- https://archello.com/project/westraven

FIN-Project Twin-line Nova

The Fin-project has applied the concept of a climate façade in a building component scale by introducing Twin-line Nova windows. The window works as a triple glazing window with sun shading in the cavity. The inner glazing could be opened to provide access to the cavity for maintenance of the blinds. Having limited ventilation in the cavity eliminates the dust in the cavity therefore only two inner and outer surfaces has to be cleaned when needed.

Disadvantage: The outer glass does not provide the possibility of ventilation at high wind speed.



Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
		×	

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
		×	

Acoustics			
No effect	Normal	Good	Excellent
		×	

Operation			
Fixed	Manual	BMS	Hybrid
		×	

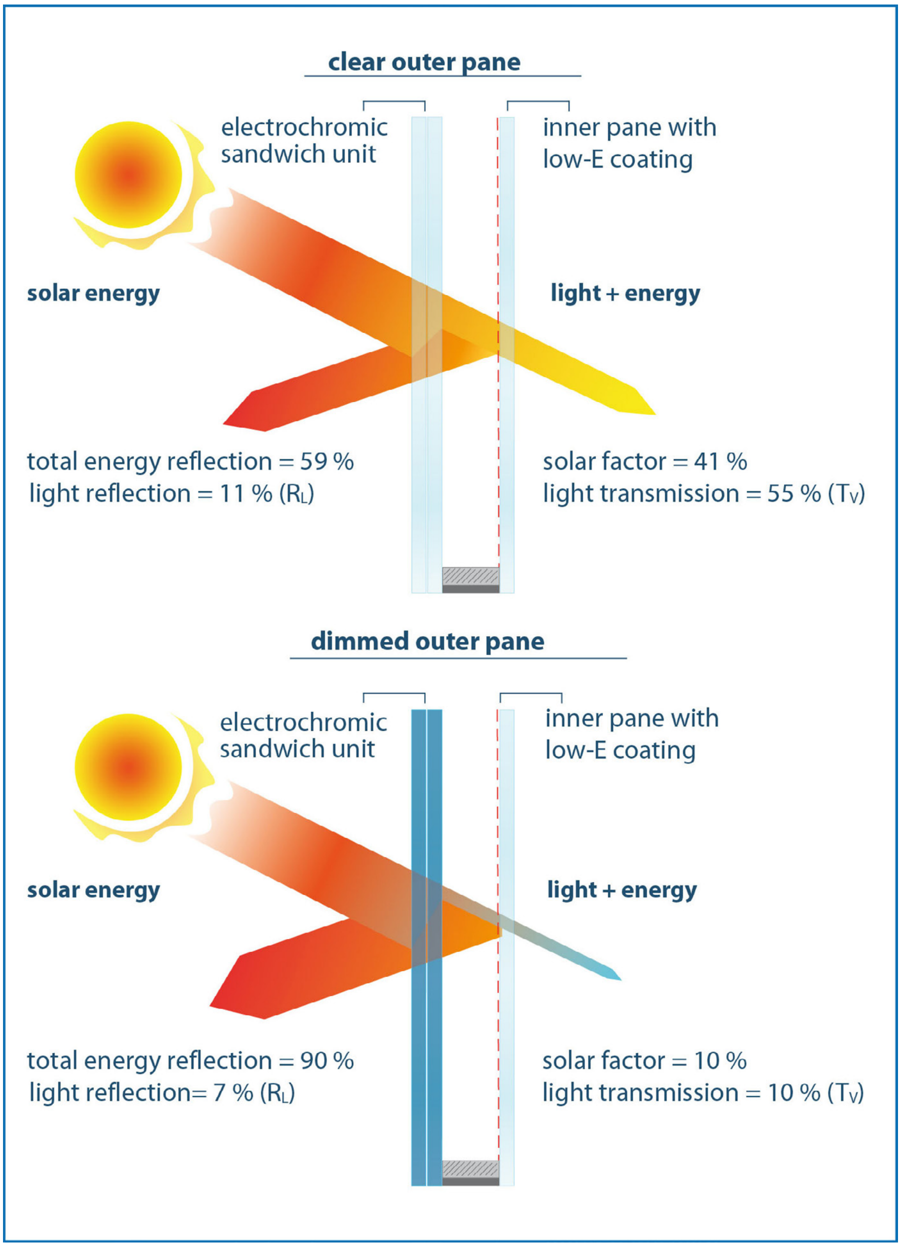
Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	×

Sources:

- https://www.bm-online.de/aktuelles/markt-branche/fin-project-twin-line-nova-moderne-optik-hoher-mehrwert/
- https://www.edilportale.com/news/2014/05/aziende/fin-project-twin-line-nova-di-finstral-estetica-slanciata-con-molti-valori-aggiunti_39264_5.html
- https://www.batirenover.com/produits-travaux/menuiserie-huisserie/huisserie/fenetre/finstral/la-fenetre-multi-fonction-tout-en-un-top-90-twin-line/

ECONTROL

The Econtrol glass developed by EControl-Glas GmbH uses an electrochromic coating to change the solar transmittance. The solar transmittance could be changed from almost 60% to 10% by applying a voltage to the glass. This helps to reduce the solar heat gain and therefore reducing the overheating risk. The benefit of this system is that it gives high architectural freedom since there is no need for the use of mechanical indoor-outdoor shading devices using this system.

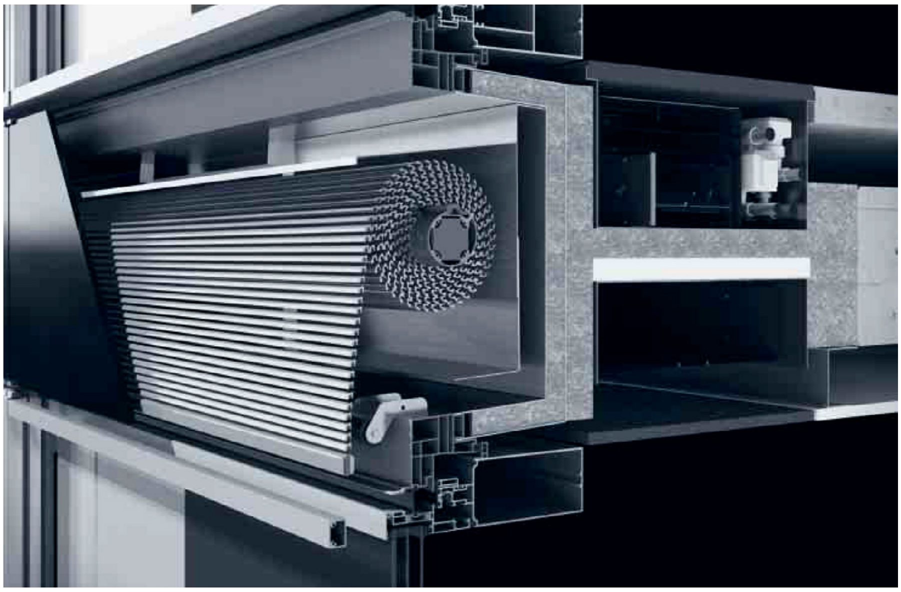


Maintenance			
None	Basic	Easy	Hard
		×	
Structural Impact			
None	Low	Acceptable	High
×			
Construction Impact			
None	Limited	Bulky	Very bulky
×			
Effectivity			
Basic	Positive	Good	Very good
	×		
Visual field			
Limited	Obstructed	Good	Excellent
			×
Cost			
Normal	Acceptable	High	Very high
		×	
Acoustics			
No effect	Normal	Good	Excellent
	×		
Operation			
Fixed	Manual	BMS	Hybrid
			×

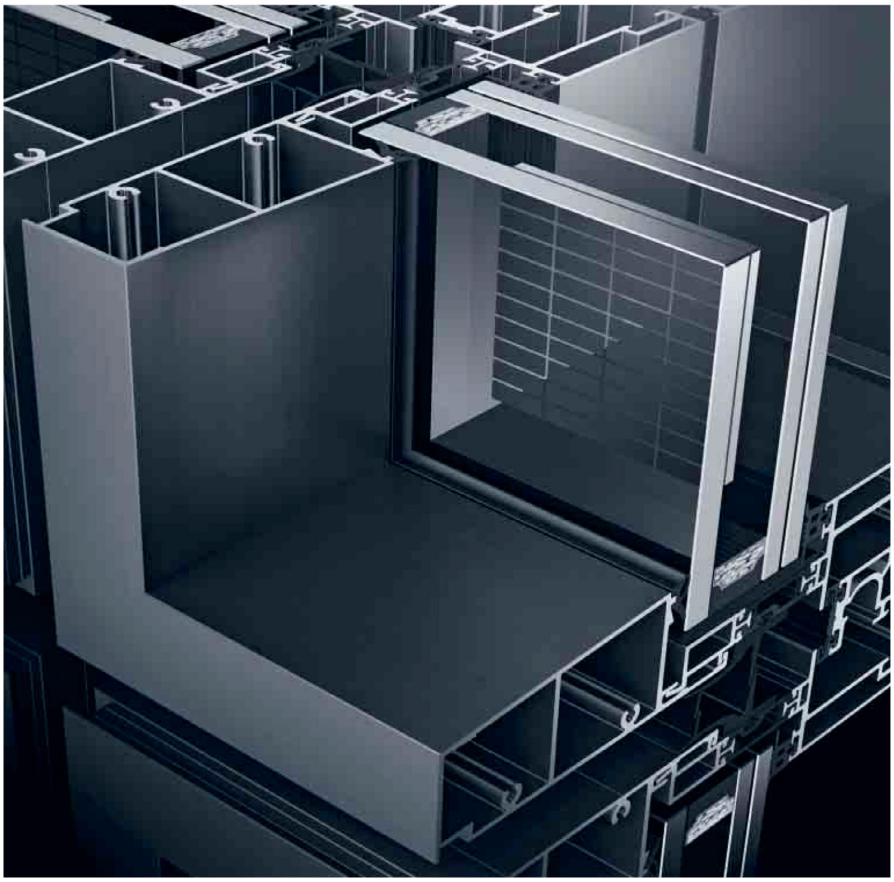
Technology readiness level	
TRL 1	
TRL 2	
TRL 3	
TRL 4	
TRL 5	
TRL 6	
TRL 7	
TRL 8	
TRL 9	×

Sources:
- https://www.econtrol-glas.de/en_

SCHÜCO E² FAÇADE



The E² FAÇADE developed by SCHÜCO incorporates the sun protection and energy generating devices in the façade module. The façade module uses semi-transparent photovoltaic cells in the façade for energy generation and for solar shading it uses a concealed sun screen that when needed could block the sun radiation to the glazing area. The windows are operable and can be opened for ventilation.



Maintenance			
None	Basic	Easy	Hard
			×

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
		×	

<table>
<tr><th colspan="4">Visual field</th></tr>
<tr><td>Limited</td><td>Obstructed</td><td>Good</td><td>Excellent</td></tr>
<tr><td></td><td colspan="2">×</td><td></td></tr>
</table>

Cost			
Normal	Acceptable	High	Very high
		×	

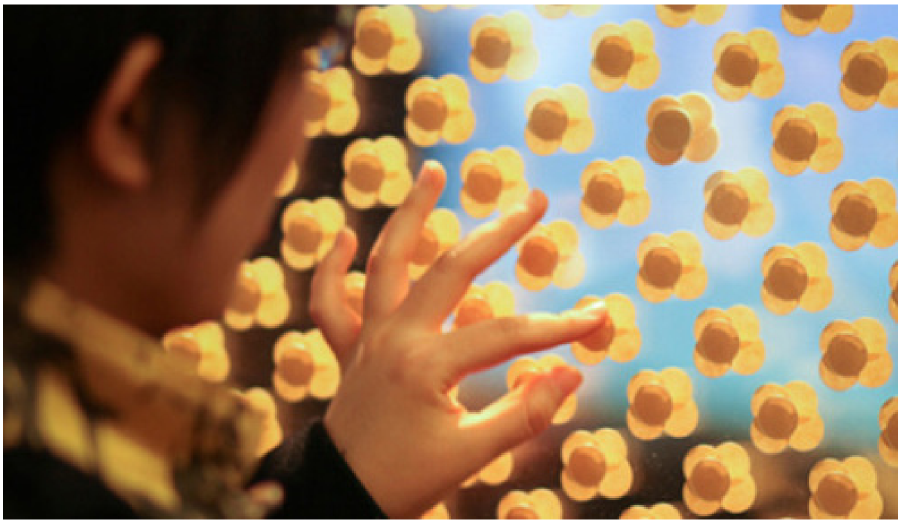
Acoustics			
No effect	Normal	Good	Excellent
		×	

Operation			
Fixed	Manual	BMS	Hybrid
			×

Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	×
	TRL 9	

Sources:
- http://www.geopetaluminium.com/E2.html

Interactive adaptive fritting Harvard GSD



Developed in Design school of Harvard, the adaptive fritting glass uses the motion of different layers of fritting glass relative to one another to control solar heat gain by making patterns.

Disadvantage: This product is in development level.

Maintenance			
None	Basic	Easy	Hard
			×

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
	×		

Visual field			
Limited	Obstructed	Good	Excellent
		×	

Cost			
Normal	Acceptable	High	Very high
		×	

Acoustics			
No effect	Normal	Good	Excellent
	×		

Operation			
Fixed	Manual	BMS	Hybrid
			×

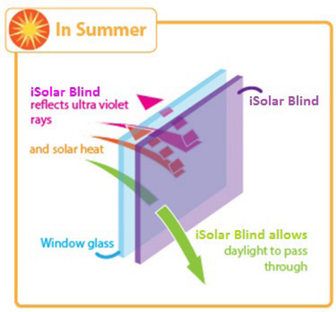
Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	×
	TRL 7	
	TRL 8	
	TRL 9	

Sources:

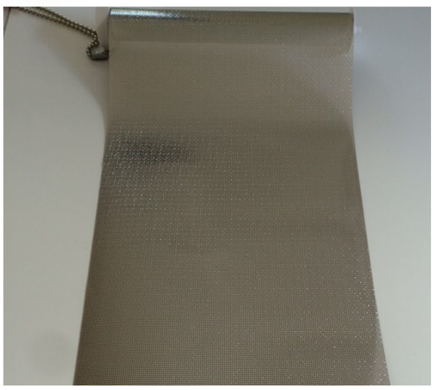
- http://code-collective.cc/interactive-adaptive-fritting-harvard-gsd/

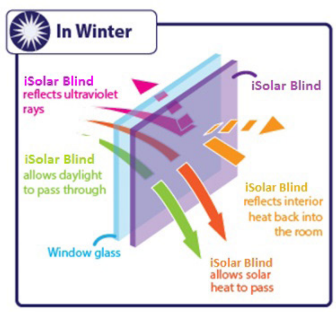
iSolar Blinds

First developed by NASA, iSolar blinds is made of perforated aluminium coated polyethylene laminated to carbon graphite. The blind is transparent, allowing for visual access to outside view when in use. The aluminium coated side works as a solar reflector in the summer while the graphite laminated side works as an absorber in the winter.



'The reflective side'
Aluminium reflects radiant heat out of the building in summer and back into the building in winter.





'The dark side'
Carbon graphite non-reflective side absorbs the sun's energy acting as a passive solar collector drawing heat into the building in winter.

Maintenance			
None	Basic	Easy	Hard
×			

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
×			

Visual field			
Limited	Obstructed	Good	Excellent
		×	

Cost			
Normal	Acceptable	High	Very high
×			

Acoustics			
No effect	Normal	Good	Excellent
×			

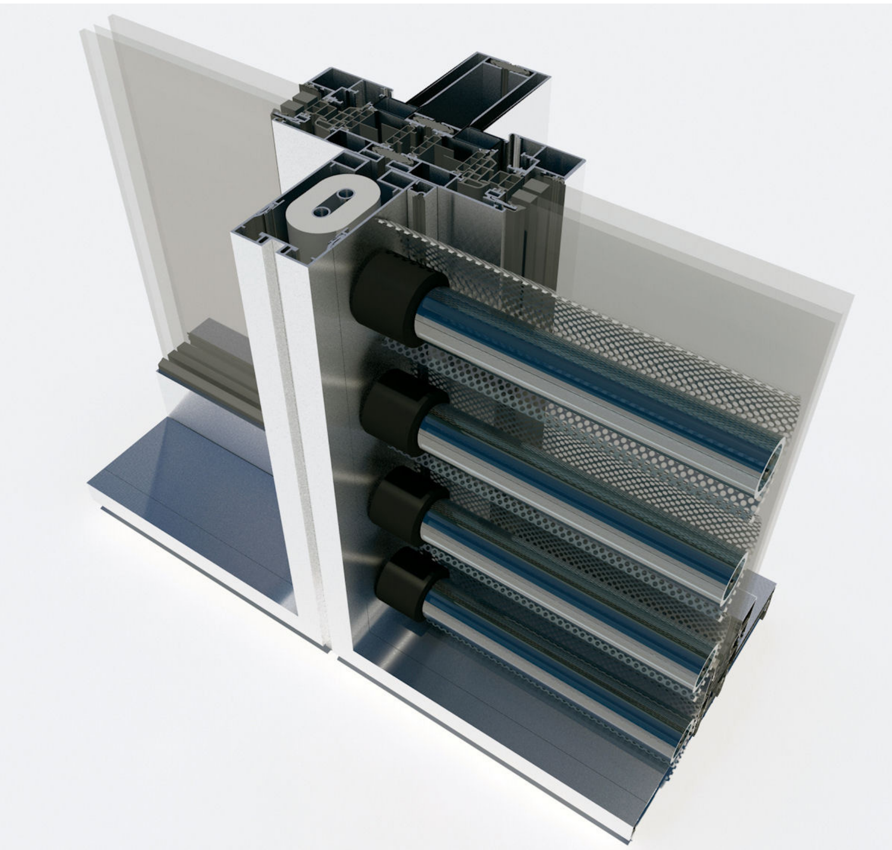
Operation			
Fixed	Manual	BMS	Hybrid
	×		

Technology readiness level	
TRL 1	
TRL 2	
TRL 3	
TRL 4	
TRL 5	
TRL 6	
TRL 7	
TRL 8	
TRL 9	×

Sources:
- https://www.arcthermalproducts.co.uk/all-products/cooling-products/isolar-blinds/

Facade collectors with perspective

Developed by university of Stuttgart, this system integrates evacuated tube collectors in window for both thermal and visual comfort. The solar collectors, stores solar radiation in high-temperature water which latter can be used on other means. These collectors are covered with perforated mirrors for energy redirection to the solar tubes. Also, this works as a solar shield to protect the indoor environment from excessive solar gain in summer, reducing the risk of overheating.



Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
	×		

Visual field			
Limited	Obstructed	Good	Excellent
		×	

Cost			
Normal	Acceptable	High	Very high
		×	

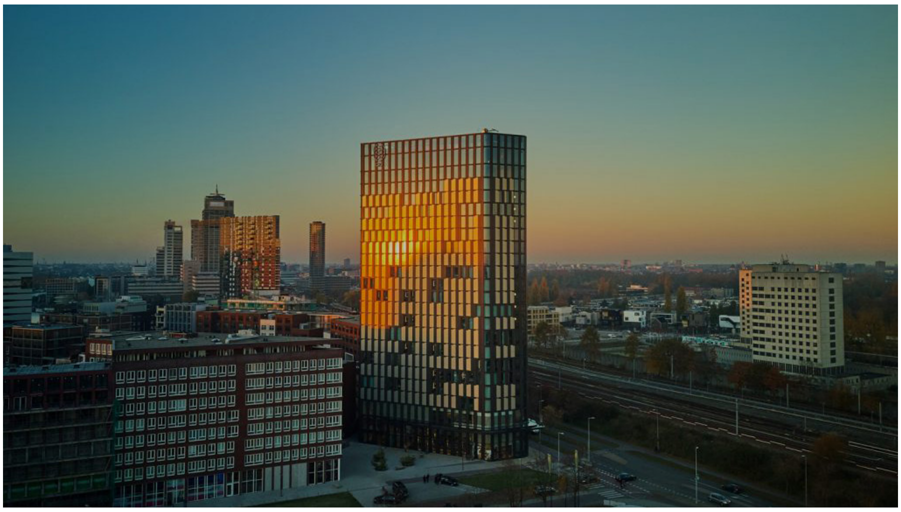
Acoustics			
No effect	Normal	Good	Excellent
×			

Operation			
Fixed	Manual	BMS	Hybrid
	×		

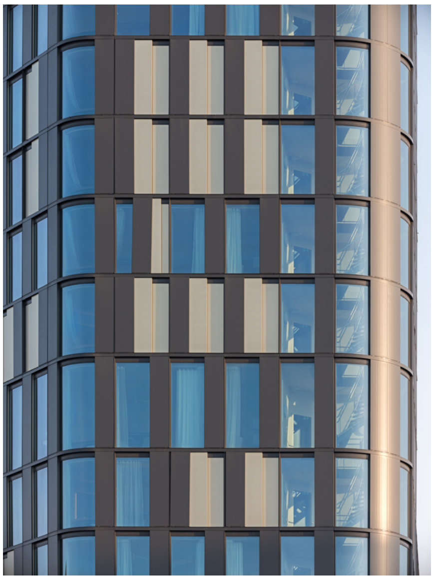
Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	×
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	

Sources:
- http://www.bine.info/en/publications/publikation/fassadenkollektoren-mit-durchblick/

Hotel Amstelkwartier



The hotel Amstelkwartier is made of a single skin façade with adaptable, moveable panels. The panels are controlled with a BMS system adapts the panels according to the occupancy and outside climate conditions. When the room is unoccupied, the panels are closed. The panels block the solar radiation in summer, preventing external heat gains. In winter the panels limit the heat loss through the façade.



Sources:
- https://archello.com/project/hotel-amstelkwartier
- https://www.arup.com/projects/qo-amsterdam

Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
	×		

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
		×	

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
	×		

Acoustics			
No effect	Normal	Good	Excellent
		×	

Operation			
Fixed	Manual	BMS	Hybrid
			×

Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	×

Daylight-redirecting glass-shading system

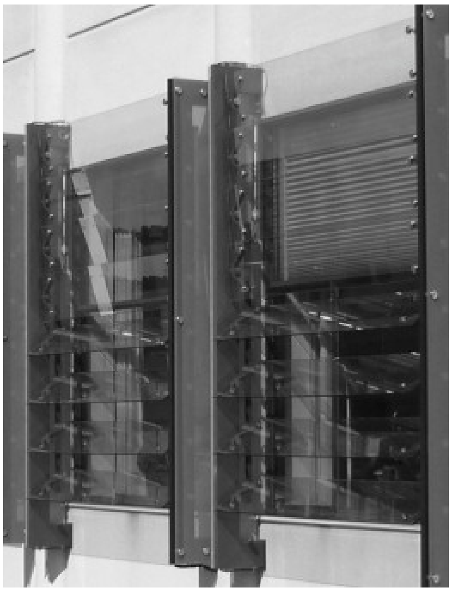
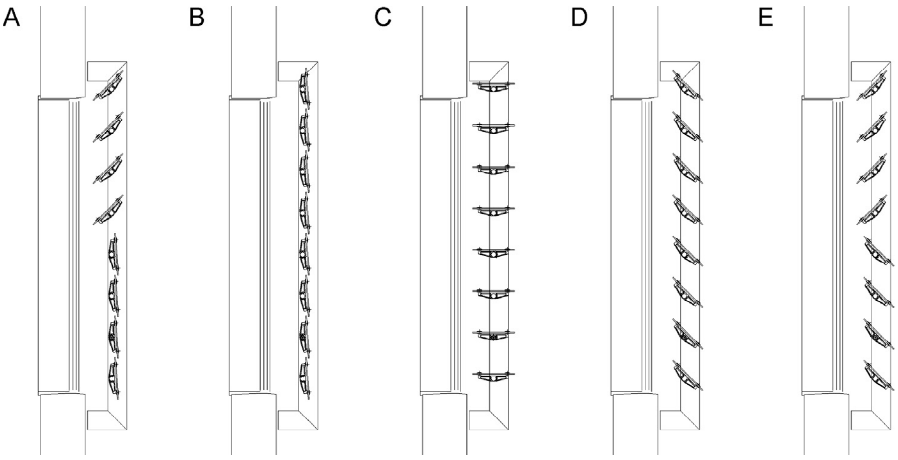


Figure: LRGSS system. The upper glass lamellas are positioned to block the sun gains and the lower ones are redirecting sun illumination deep into the building. Source: Appelfeld & Svendsen, 2013

Developed by technical university of Denmark the light-redirecting glass-shading system (LRGSS) works both as a shading device to control solar gains and as a light reflector to help in redirecting light deep into the building. The lamellas of the LRGSS is made of highly reflective coated glass for sunlight redirection. LRGSS has five shading configurating according to the occupants needs and outside conditions which could be seen in the figure. (Appelfeld & Svendsen, 2013)



Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
		×	

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
		×	

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
	×		

Acoustics			
No effect	Normal	Good	Excellent
		×	

Operation			
Fixed	Manual	BMS	Hybrid
			×

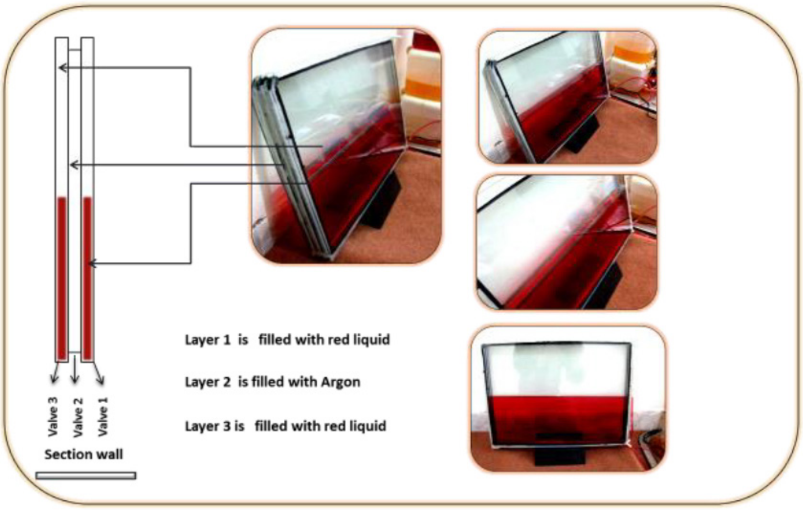
Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	×
	TRL 8	
	TRL 9	

Sources:

- Appelfeld, D. Svendsen,D. (2013).Performance of a daylight-redirecting glass-shading system.Energy and Buildings. Volume 64. Pages 309-316

Window variable layer system

First developed in Shahid Beheshti university in Iran, window variable layer system uses dyed water in a double glazed window to control sun gains. The water both works as a shader and a heat storage. The system is connected to several water tanks with different colours for shading control.



Maintenance			
None	Basic	Easy	Hard
			×

Structural Impact			
None	Low	Acceptable	High
	×		

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
	×		

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
		×	

Acoustics			
No effect	Normal	Good	Excellent
		×	

Operation			
Fixed	Manual	BMS	Hybrid
		×	

Technology readiness level	
TRL 1	
TRL 2	
TRL 3	
TRL 4	
TRL 5	
TRL 6	×
TRL 7	
TRL 8	
TRL 9	

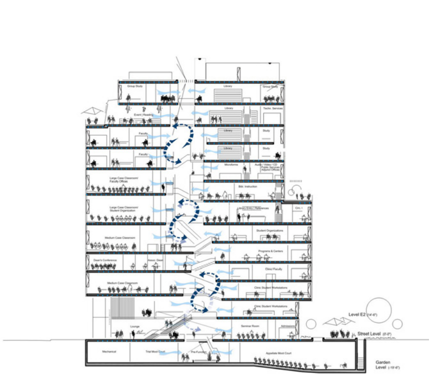
Sources:

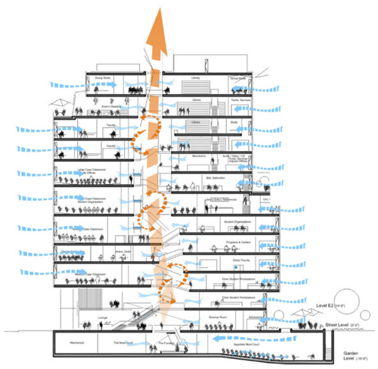
- basi M, Tahbaz M, Vafaee R. Introducing an Innovative Variable Building Layers System (V.B.L.S). BSNT. 2015; 5 (2) :43-54
- URL: http://journals.modares.ac.ir/article-2-4530-fa.html

University of Baltimore Angelos Law School

The façade of the University of Baltimore Angelos Law School is made of a unique double skin façade with 25cm deep cavity. The second skin primary works as a rain and wind screen. The purpose of the second skin is to make natural ventilation possible in high wind speed of Baltimore and to provide protection to the sun shading in the cavity. Beside that insulating the openings from external noises was also one of the key elements for choosing this façade. The second skin is attached to the building using capture clamps on vertical sides of the glazing. The gap between the glazing and the open top-bottom makes the cavity completely permeable to outside air.

Disadvantage: The open cavity makes it easy that glazing become dirty by dust while because of the narrow depth of cavity cleaning the inner side of the second skin and outer side of the inner skin is not easy.





Maintenance			
None	Basic	Easy	Hard
	×		

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
		×	

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
	×		

Acoustics			
No effect	Normal	Good	Excellent
		×	

Operation			
Fixed	Manual	BMS	Hybrid
	×		

Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	×

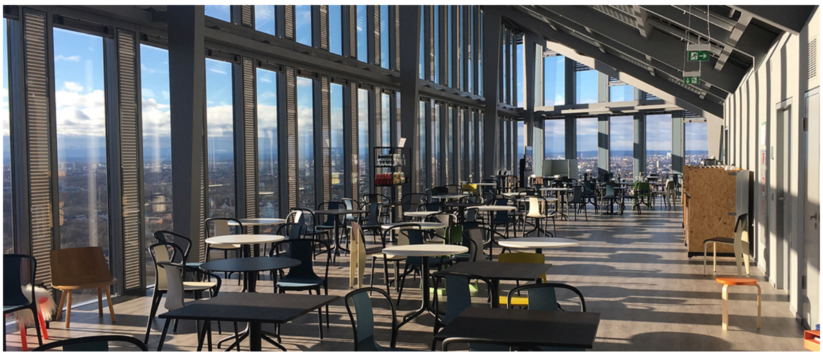
Sources:

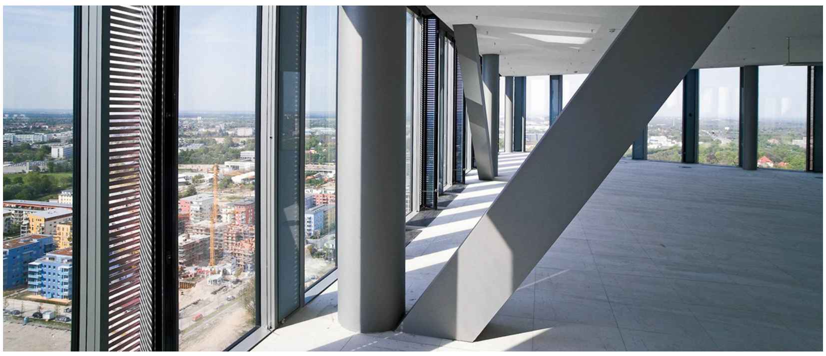
- https://www.archdaily.com/409062/john-and-frances-angelos-law-center-behnisch-architekten

Highlight Towers

The façade of the Highlight towers in Germany are made of single skin façade. The buildings are ventilated through openable windows protected by perforated steel panels which protects the air inlet from high wind speed and rain (Wood & salib, 2013). The perforated panel is also integrated with sound absorbing material protecting the indoor environment from outside noise. The windows are operated through electronical means allowing both the building management system and the user to control the ventilation (Wood & salib, 2013).

In addition, the low depth of the plan and good placement of the vertical circulation elements allow for flexible internal air movement (Wood & salib, 2013). The exhaust chimneys located on the centre of the plan further help the internal air movement and effectivity of natural ventilation.





Sources:

- https://www.designoffices.de/en/sites/muenchen-highlight-towers/
- Wood & Salib,2013

Maintenance			
None	Basic	Easy	Hard
	×		

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
		×	

Visual field			
Limited	Obstructed	Good	Excellent
			×

Cost			
Normal	Acceptable	High	Very high
	×		

Acoustics			
No effect	Normal	Good	Excellent
		×	

Operation			
Fixed	Manual	BMS	Hybrid
			×

Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	×

Solozip – Zip vertical awning

Solozip is a external shading product by Griesser. The zipping system used in this product allow for the screen to be welded to the rail, protecting it from the uplift force caused by the wind. Therefore, this product can withstand wind speeds up to 26 m/s. The fabric used in could allow for both ventilation and an unobstructed view to outside while limiting solar gains and glare.

Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
	×		

Visual field			
Limited	Obstructed	Good	Excellent
		×	

Cost			
Normal	Acceptable	High	Very high
×			

Acoustics			
No effect	Normal	Good	Excellent
×			

Operation			
Fixed	Manual	BMS	Hybrid
			×

Technology readiness level	
TRL 1	
TRL 2	
TRL 3	
TRL 4	
TRL 5	
TRL 6	
TRL 7	
TRL 8	
TRL 9	×

Sources:

- https://www.griessergroup.com/en/products/facade-awnings/zip-vertical-awning/solozip

Folie Divine

Design by Farshid Mousavi architects Folie Divine building benefits from balconies shading the windows below preventing excessive solar gain. To further prevent solar gains and protect the balconies and indoor spaces from the wind, curtains are placed at the balconies. This way both natural ventilation and solar protection is achieved protecting the indoor spaces from overheating.

Sources:

- https://www.archdaily.com/885516/folie-divine-farshid-moussavi-architecture?ad_source=search&ad_medium=search_result_projects

Maintenance			
None	Basic	Easy	Hard
×			

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
	×		

Visual field			
Limited	Obstructed	Good	Excellent
	×		

Cost			
Normal	Acceptable	High	Very high
×			

Acoustics			
No effect	Normal	Good	Excellent
×			

Operation			
Fixed	Manual	BMS	Hybrid
	×		

Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	×

Vitacon Itaim Building

Designed by Studio MK27, Vitacon Itaim Building benefits from perforated wooden panel working as shading and windscreen. The movable wooden screens could completely block the solar radiation hitting the windows. Also, the perforated panel works as a protection from high wind speeds, allowing for adequate natural ventilation during the day.

Sources:

- https://www.archdaily.com/575391/vitacon-itaim-building-studio-mk27-marcio-kogan-carolina-castroviejo?ad_source=search&ad_medium=search_result_projects

Maintenance			
None	Basic	Easy	Hard
	×		

Structural Impact			
None	Low	Acceptable	High
	×		

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
		×	

Visual field			
Limited	Obstructed	Good	Excellent
		×	

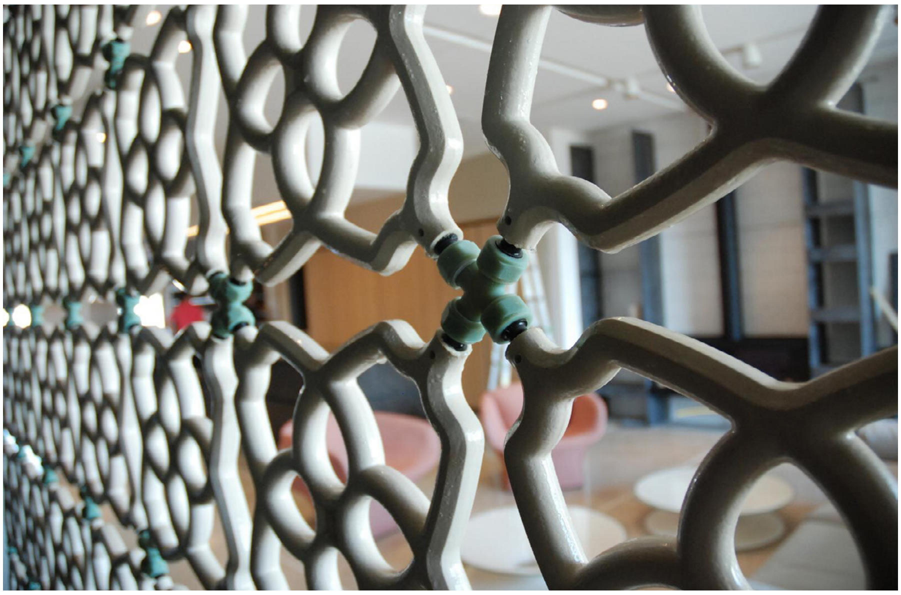
Cost			
Normal	Acceptable	High	Very high
	×		

Acoustics			
No effect	Normal	Good	Excellent
	×		

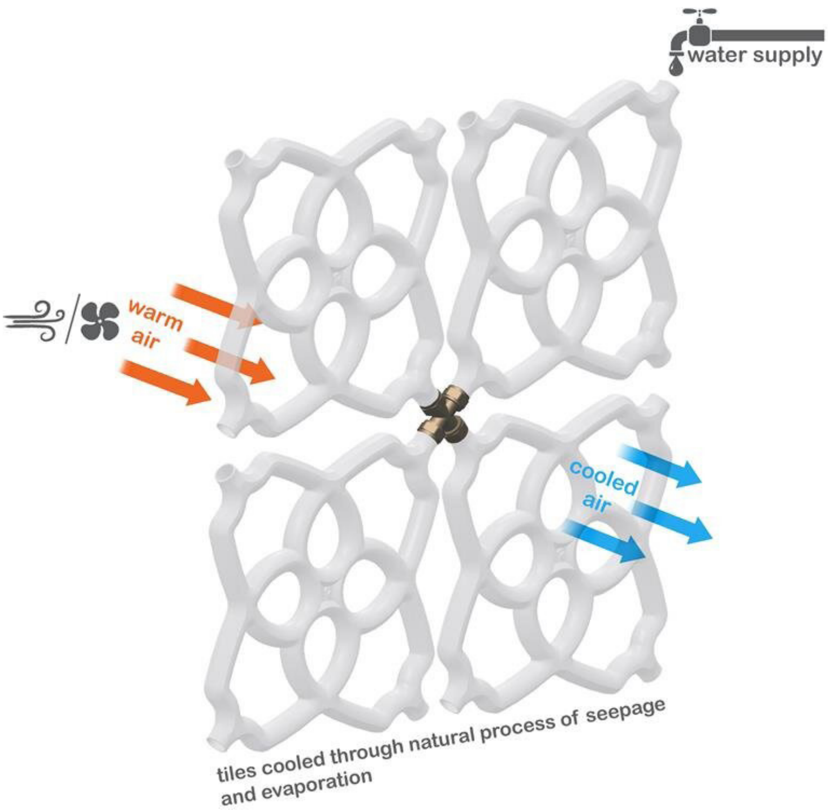
Operation			
Fixed	Manual	BMS	Hybrid
	×		

Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	
	TRL 8	
	TRL 9	×

Ecooler ceramics



Designed by Kahn studio, Ecooler uses the principle of clay pots for evaporative cooling. The water runs through the shaped ceramics making it to be trapped in the microstructures of the ceramic. Then, water trapped on the surface evaporates cooling the surrounding air. This system could be used inside or outside. Using the Ecooler on outside in addition to cooling could help in providing shading for the windows.



Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
×			

Construction Impact			
None	Limited	Bulky	Very bulky
	×		

Effectivity			
Basic	Positive	Good	Very good
		×	

Visual field			
Limited	Obstructed	Good	Excellent
		×	

Cost			
Normal	Acceptable	High	Very high
	×		

Acoustics			
No effect	Normal	Good	Excellent
×			

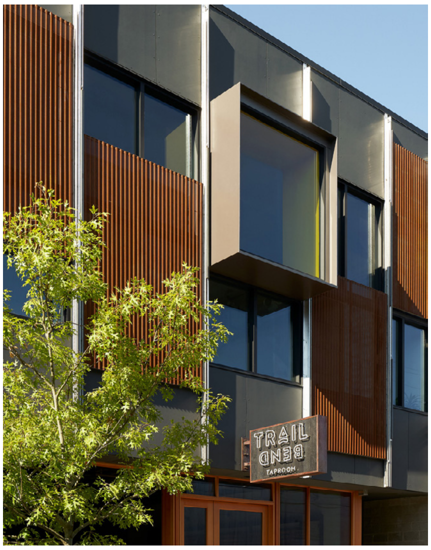
Operation			
Fixed	Manual	BMS	Hybrid
×			

Technology readiness level		
	TRL 1	
	TRL 2	
	TRL 3	
	TRL 4	
	TRL 5	
	TRL 6	
	TRL 7	×
	TRL 8	
	TRL 9	

Sources:
- https://studiokahn.com/ecooler

The Klotski Building

Designed by graham baba architects, the Klotski building uses perforated metal sheets for solar protection. These metal screens are mounted on a vertical rail which allow user to control the solar gains by sliding these elements up and down.



Maintenance			
None	Basic	Easy	Hard
		×	

Structural Impact			
None	Low	Acceptable	High
	×		

Construction Impact			
None	Limited	Bulky	Very bulky
×			

Effectivity			
Basic	Positive	Good	Very good
	×		

Visual field			
Limited	Obstructed	Good	Excellent
		×	

Cost			
Normal	Acceptable	High	Very high
	×		

Acoustics			
No effect	Normal	Good	Excellent
×			

Operation			
Fixed	Manual	BMS	Hybrid
	×		

Technology readiness level	
TRL 1	
TRL 2	
TRL 3	
TRL 4	
TRL 5	
TRL 6	
TRL 7	
TRL 8	
TRL 9	×

Sources:
- http://grahambabaarchitects.com/klotski-building

Appendix B. TOjuli assessment method

The TOjuli indicator was simplified in collaboration with a fellow student ***Prateek Wahi***. This method is derived from NEN 5128:2003, NEN 7120:2012 and NTA 8800 and converted into an excel calculation sheet. The TOJuli can be calculated by:

Equation 1

$TO_{juli;i}$	**zone I's overheating risk Indicator in the month of July calculated**	**K**
$Q_{beh;koud;juli;i}$	Zone I's Cooling Requirement for the month of July	MJ
$H_{T;koud;i}$	Heat Loss coefficient due to transmission of zone i	W/K
$H_{V;koud;i}$	Heat Loss coefficient due to ventilation of zone i.	W/K
t	Length of the month of July	Ms

$$TO_{juli;i} = \frac{Q_{beh;koud;juli;i}}{(H_{T;koud;i} + H_{V;koud;i}).t}$$

B.1. Heat Loss Coefficient due to Transmission [1068:2012]

Equation 2

$H_{T;koud;i}$	**Heat Loss coefficient due to transmission of zone i**	**W/K**
H_D	Direct heat loss coefficient between heated inner space and outside air with flat rate linear thermal bridge	W/K
H_g	Stationary heat loss coefficient through the floor	W/K
H_U	Heat Loss coefficient via adjacent unheated spaces.	W/K
H_A	Heat Loss coefficient via adjacent heated spaces.	W/K

$$H_{T;koud;i} = H_D + H_g + H_U + H_A$$

B.1.1 Direct Heat Loss Coefficient

Equation 3

H_D	**Direct heat loss coefficient between heated inner space and outside air with flat rate linear thermal bridge**	**W/K**
$A_{T;i}$	Area of the flat element of the zone i (opaque part of façade, transparent part, roof, etc)	m^2
$U_{C;i}$	U- value of the flat element of the zone i (opaque part of façade, transparent part, roof, etc)	W/m^2K
ΔU	Flat rate surcharge for calculation of linear thermal bridges	W/m^2K

$$H_D = \Sigma(A_{T;i} \times (U_{C;i} + \Delta U)$$

Equation 4

$A_{T;i}$	Area of the flat element of the zone i (opaque part of façade, transparent part, roof,etc) which is not a floor above a crawl space, directly on a surface or a plane	m^2
$U_{C;i}$	U-Value of flat element of the zone i (opaque part of façade, transparent part, roof, etc) which is not a floor above a crawl space, directly on a surface or a plane	W/m^2K

$$\Delta U = \max\left[0, 0.1 - 0.25\left(\frac{\sum_i (A_{T;i} \times U_{C;i})}{\sum_i (A_{T;i})} - 0.4\right)\right]$$

B.1.2 Stationary Heat Loss Coefficient due to ground

Equation 5

H_g	Stationary heat loss coefficient through the floor	W/K
$A_{T;fl}$	Area of the floor	m^2
$U_{C;fl}$	U- value of the floor	W/m^2K
P	Perimeter of the Zone	m

$$H_g = (A_{T;fl} \times U_{C;fl}) + 1.2 \times P)$$

B.1.3 Heat Loss Coefficient via adjacent heated and unheated spaces

Equation 6

The heat loss coefficient of adjacent heated and unheated spaces in a flat rate calculation is taken as zero .

$$H_U = 0, H_A = 0$$

B.2. Heat Loss Coefficient due to Ventilation [7120:2012, Simplified]

Equation 7

$H_{V;koud;i}$	Heat Loss coefficient due to ventilation of zone i	W/K
$q_{v;i}$	Air volume flow for cooling	dm^3/s
S	For rooms with single-sided ventilation: 1.2 For rooms with cross ventilation: 1.8	(-)

$$H_{V;koud;i} = S \times q_{v;i}$$

B.2.1 Air volume flow for cooling

Equation 8

q_f	Minimum Air flow rate or Design Air flow rate (combination of natural, mechanical and infiltration) per m^2	dm^3/s per m^2
A_g	Area of the zone	m^2
$t_{wind:h}$	Number of hours that wind speed is lower than 7m/s at the apartment at height h;	(-)

$$q_{v;i} = q_f \times A_g \times t_{wind:h}/740$$

B.3. Heat Loss due to transmission and ventilation [5128:2003]

Equation 9

Q_H	Total Heat loss due to Transmission and Ventilation	MJ
$H_{T;koud;i}$	Heat Loss coefficient due to transmission of zone I from eq 2	W/K
$H_{V;koud;i}$	Heat Loss coefficient due to ventilation of zone I from eq 7	W/K
$\theta_{i;koud}$	The indoor temperature averaged for a period. A value of 24 ˚C must be taken according to 5128:2003	˚C
θ_e	Average outside temperature over the period. A value of 17.5 ˚C must be taken for the month of July according to NTA8800	˚C
θ_{corr}	Correction factor for the outside temperature. A value of 2 ˚C must be taken according to 5128:2003	˚C
t	Length of the month of July. A value of 2.678 MS must be taken according to 5128:2003 and 7120:2012.	MS
H_a	The altitude of the apartment from the ground. (To find the temperature difference at height)	˚C

$$Q_H = [H_{T;koud;i} + H_{V;koud;i}] \times [\theta_{i;koud} - (\theta_e + \theta_{corr} + H_a/100)] \times t$$

B.4. Heat gain by solar radiation [5128:2003]

Equation 10

$Q_{sun;i}$	**Heat Gain by solar radiation in zone i.**	**MJ**
$Q_{Trans;i}$	Heat gain by transparent parts of the "zone I"'s facade.	MJ
$Q_{nontrans;i}$	Heat Gain by the opaque parts of the "zone I"'s façade.	MJ
$Q_{Roof;i}$	Heat Gain by the "zone I"'s roof.	MJ

$$Q_{sun;i} = Q_{Trans;i} + Q_{nontrans;i} + Q_{Roof;i}$$

B.4.1 Heat gain from the transparent part of façade.

Equation 11

$Q_{Trans;i}$	Heat gain from the transparent part of the façade for zone i.	MJ
f_{sh}	Shading reduction factor	-
ZTA	g-value of the glass at façade for daylight opening	-
A_r	Area of the opening including frame	m^2
C_{corr}	Correction factor for solar radiation for the calculation of cooling requirement. To be taken as 1 according to 5128:2003	-
g_{sol}	Total incident solar radiation on the opening in an orientation.	MJ/m^2

$$Q_{Trans;i} = [f_{sh} \times ZTA \times A_r] \times 0.75 \times C_{corr} \times g_{sol}$$

B.4.1.1 Shading factor calculation (Standard Assessment Procedure, SAP:2012)

Equation 12

f_{sh}	Solar Shading Factor	-
f_{blinds}	Shading reduction factor for blinds or curtains. Values should be taken from SAP:2012, table P3.1	-
f_{access}	Solar Access factor. Values should be taken from SAP:2012, table 6d.	-
$f_{overhangs}$	Shading factor for overhang. Values should be taken from SAP:2012, table P4 and P5	-

$$f_{sh} = f_{blinds} \times [f_{acc} + f_{overhang} - 1]$$

B.4.2 Heat gain from the non-transparent part of façade or Roof. [NTA 8800]

Equation 13

$Q_{Trans;i}$, $Q_{roof;i}$	Heat Gain from the opaque part of the façade or from the roof for zone i.	MJ
α_{sol}	Dimensionless absorption coefficient for solar radiation. Should be taken as 0.6 according to NTA 8800	-
R_{se}	Heat transfer resistance of the outside air	m^2K/W
U_C	U-value of the non-transparent part of façade or roof	W/m^2K
A_t	Area of the non-transparent part of the façade or roof	m^2
$f_{sh,nt}$	Shading reduction factor for the non-transparent external façade element or roof	-
I_{sol}	Incident solar radiation on the non-transparent of the façade for an orientation. For Roof the value can be taken as 191 according to NTA 8800	W/m^2
t_m	Length of the month of July. The value should be taken as 744 according to NTA 8800	h

$$Q_{nontrans;i} = Q_{roof;i} = [\alpha_{sol} \times R_{se} \times U_C \times A_t \times f_{sh,nt} \times I_{sol} \times 0.001 \times t_m] \times 3.6$$

B.5. Heat Gain due to Internal Loads [5128:2003]

Equation 14

$Q_{int;i}$	Heat Gain due to internal loads for zone i.	MJ
$Q_{occ;i}$	Total Occupant Load in zone i per m^2	W/m^2
$Q_{equip;i}$	Total Equipment Load in zone i per m^2	W/m^2
$Q_{light;i}$	Total Lighting Load in zone i per m^2	W/m^2
$A_{g;i}$	Area of the zone i.	m^2
t	Length of the month of July	Ms.

$$Q_{int;i} = (Q_{occ;i} + Q_{equip;i} + Q_{light;i}) \times A_{g;i} \times t$$

B.6. Total Heat Gain due to sun and internal loads [5128:2003]

Equation 15

$Q_{G;i}$	Total Heat gain due to sum and internal loads for zone i.	MJ
$Q_{sun;i}$	Total heat gain due to sun from the transparent, non-transparent part of the façade and roof for zone i.	MJ
$Q_{int;i}$	Total internal heat gain due to occupants, equipment's and lighting loads for zone i.	MJ

$$Q_{G;i} = Q_{sun;i} + Q_{int;i}$$

B.7. Total Cooling Required [5128:2003]

Equation 16

$Q_{beh;koud;juli;i}$	Total cooling required for zone i in the month of July.	MJ
$\eta_{b;koud;i}$	Utilisation factor for the heat gain in zone i.	-
$Q_{G;i}$	Total Heat gain due to sum and internal loads for zone i. Calculated from eq. 15	MJ

$$Q_{beh;koud;juli;i} = (1 - \eta_{b;koud;i}) \times Q_{G;i}$$

B.7.1 Heat Gain utilisation factor [5128:2003]

Equation 17

$\eta_{b;koud;i}$	Utilisation factor for the heat gain in zone i.	-
γ_l	Ratio between total heat gain and total heat loss. Total heat loss is calculated using eq 9 Total heat gain is calculated using eq 15	-
a_{koud}	Dimensionless numeric parameter.	-
U_C	U-value of the non-transparent part of façade or roof	W/m^2K

$$\text{If } \gamma_l = 1 \; ; \; \eta_{b;koud;i} = \frac{a_{koud}}{1 + a_{koud}}$$

$$\text{If } \gamma_l \neq 1 \; ; \; \eta_{b;koud;i} = \frac{1 - \gamma_l^{a_{koud}}}{1 - \gamma_l^{a_{koud}+1}}$$

B.7.1.1 Dimensionless numeric parameter [5128:2003]

Equation 18

a_{koud}	**Dimensionless numeric parameter used in calculation of utilisation factor.**	-
a_o	Dimensionless constant. According to 5128:2003 following values must be used: Residential: 1 Utility buildings: 0.8	-
$\tau_{o;koude}$	Nominal time constant for calculation. According to 5128:2003 following values must be used: Residential: 0.0576 Utility Buildings: 0.252	Ms
τ_{koude}	Time constant in a relevant heated zone.	Ks

$$a_{koud} = a_o + (\tau_{koude} \ X \ \tau_{o;koude})$$

B.7.1.2 Dimensionless numeric parameter [5128:2003]

Equation 19

τ_{koude}	**Time constant in a relevant heated zone.**	**Ks**
$H_{T;koud;i}$	Heat Loss coefficient due to transmission of zone I from eq 2	W/K
$H_{V;koud;i}$	Heat Loss coefficient due to ventilation of zone I from eq 7	W/K
C_i	Thermal Capacity of the construction in the zone i.	KJ/K

$$\tau_{koude} = \frac{C_i}{H_{T;koud;i} + H_{V;koud;i}}$$

B.7.1.3 Thermal Capacity of the construction [5128:2003]

Equation 20

C_i	Thermal Capacity of the construction in the zone i.	KJ/K
D_i	Specific Effective Thermal Capacity of the construction of the zone i. The values can be taken from table 38 of 5128:2003	KJ/m^2.K
$A_{g;i}$	Area of the zone i.	m^2

$$C_i = D_i \times A_{g;i}$$

Simplified TOjuli validation

To validate the simplified TOjuli calculation method a statistical comparison with TOjuli calculated according to NEN-7120 were made.

First a apartment zone were assumed and TOjuli were calculated with the simplified method for different orientations, window wall ratios, U-value, and g-values. In figure 1 a sample calculation sheet for west orientation could be seen.

In order to calculate TOjuli in accordance with NEN-7120, Uneic2 software were used. Uniec2 is an online energy performance calculation tool in which EPC and building's energy performance is calculated according to NEN-7120.

The steps taken to calculate TOjuli according to NEN-7120 in Uniec2 software is as followed:

1. In the building layout tab an area of 40m2 for zone with mixed-light internal heat capacity were set (Figure 2).

—>*Figure 2: Building layout input data. In collaboration with Prateek Wahi*

Zone area [m2]	40
Roof area [m2]	0
Zone parameter [m]	0
Di [specific effectic thermal capacity] [Kj/m2K]	350
Wall area [m2]	16.9
WWR [-]	0.3
U-value of glass [w/m2k]	1.5
g-value of glass [-]	0.6
U-value of roof	0
U-value of opaque [w/m2k]	0.22
U-value of floor [w/m2k]	0
R (shading factor)	1
Ihorizontal [W/m2]	191
Isol [W/m2]	112.5
gsol [Mj/m2]	301.32
qv [dm3/s]	48
qv;natural [dm3/s]	48
qv;mechanical [dm3/s]	0
HD [W/k]	13.132145
Hg [W/k]	0
Hu [W/k]	0
HA [W/k]	0
ηb;koinde;I [-]	0.595434434
Qtotal heat loss [Mj]	833.5754995
Qtotal heat gain [Mj]	1399.023738
ɣI [-]	1.678340761
Qbeh;koude;juli;I [Mj]	565.9968309
Ht;koude;I [W/k]	13.132145
Hv;Koude;I [W/k]	57.6
Tojuli	2.987595074

Only if these spaces are on the ground

Δu	0.17305
Surcharge formula	0.17305

West

Natural supply and natural distcharge

Qsolar gain [Mj]	756.207738
Qinternal [Mj]	642.816

If (ɣI)=1	ηb;koinde;I [-]	0.92537735
If (ɣI)≠1	ηb;koinde;I [-]	0.595434434

Cthermal capacity [Kj/k]	14000
Tkoude	197.9298097
akoude	12.40075704

Figure 1: TO juli calculation with simplified model for West orientation. In collaboration with Prateek Wahi.

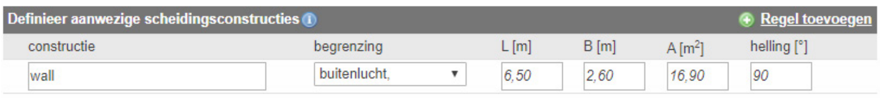
2. In infiltration tab 6.5m, 6.15m and 2.6m were set for building's width, length and height respectively. For building type "Meerlaags gebouw, tussenligging op bovenste (Multi-layered building, middle location on top)" were chosen.

—>*Figure 3: Infiltration tab inputs. In collaboration with Prateek Wahi*

3. In architectural tab the walls and openings input values were set as in figure 4.

—>*Figure 4: Architectural elements inputs. In collaboration with Prateek Wahi*

4. The exterior wall dimensions and area were set. For every orientations TOjuli were calculated by orienting the wall (Figure 5).



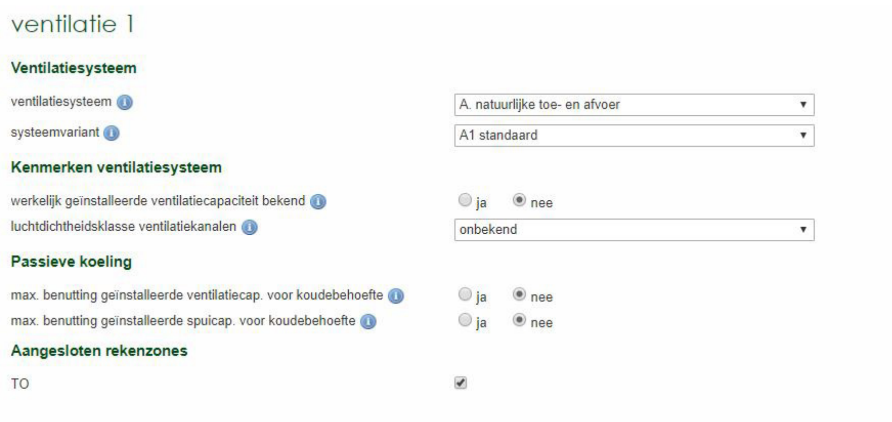
—>*Figure 5: Exterior wall data. In collaboration with Prateek Wahi*

5. The opaque elements and openings area were set considering different window to wall ratios of 65%,50% and 35%, (Figure 6).

—>*Figure 6: Opaque and transparent construction elements area for a WWR of 65% . In collaboration with Prateek Wahi*

6. For ventilation system, natural supply and discharge were chosen. Since TOjuli were needed so the spaces could be assessed according to their envelope and architectural layout a fixed natural ventilation rate according to NEN-5128:2003 were assumed. Therefore, to be able to compare Uniec2 results with simplified method all options in natural ventilation tab were set to "nee (No)"

so the software would calculate the TOjuli with known minimum natural ventilation rate from Bouwbelsuit.



—>Figure 7: Ventilation system settings. In collaboration with Prateek Wahi

After calculating TOjuli with Uniec2, the data were compared with the TOjuli values from simplified model (Figure 8).

			Uniec2	Simplified method
Glass h++- 0.35 g-value- 1.21 U-value	30% WWR	South	1.75	1.6
		North	1.00	0.7
		West	1.64	1.45
		East	1.80	1.64
	50% WWR	South	2.70	2.88
		North	1.39	1.3
		West	2.50	2.66
		East	2.80	2.97
	65% WWR	South	3.40	3.8
		North	1.67	1.76
		West	3.13	3.5
		East	3.50	3.9
Glass h+- 0.6 g-value- 1.5 U-value	30% WWR	South	3.06	3.22
		North	1.60	1.52
		West	2.85	2.98
		East	3.15	3.31
	50% WWR	South	4.93	5.4
		North	2.43	2.7
		West	4.56	5.03
		East	5.07	5.5
	65% WWR	South	6.23	6.89
		North	3.03	3.5
		West	5.78	6.43
		East	6.41	7.07

—>Figure 7: TOjuli values according to two calculation methods. In collaboration with Prateek Wahi.

In order to do an statistical validation on the results NMBE, CV(RMSE), and R2 validation methods were used. These methods are all used to indicate if a model is accurate enough.

NMBE (Normalized Mean Bias Error) in here indicates the global disparity of the Uniec2 values and the simplified model (Ruiz & Bamdera, 2017). The lower the absolute value of NMBE is the more accurate the model is.

CV(RMSE) (Coefficient of Variation of the Root Mean Square Error) in here indicates the inconsistency of the errors between the TOjuli values from Uniec2 and the simplified method (Ruiz & Bamdera, 2017). A value of less than 0.15 shows model could accurately calculate "the overall load shape that is reflected in the data" (Ruiz & Bamdera, 2017).

R2 (coefficient of determination) is a statistical index that is used to compare the closeness of the values of a data set to the regression line of the other data set and the values is between 0 and 1 (Ruiz & Bamdera, 2017). The higher the R2 values is the more similar the two data sets are.

As it can be seen in the figure xx the statistical indicators clearly show that the simplified model is accurate enough to represent the more complex TOjuli calculation of Uniec2.

NMBE	CV(RMSE)	R^2
-0.069	0.11	0.99

—>Figure 8: Results of statistical validation of the simplified models. In collaboration with Prateek Wahi.

Appendix C. Simulation Workflow

In this section, the building performance modelling workflow is reviewed.

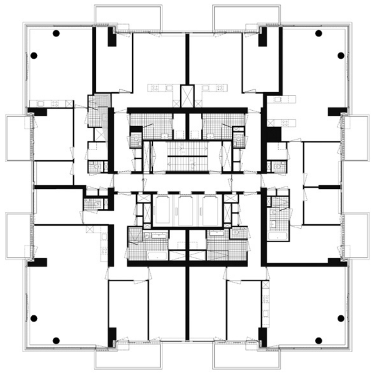
C.1. Geometry

As mentioned the selected layout were modelled in two representative levels in the tower with almost the same plan layout.

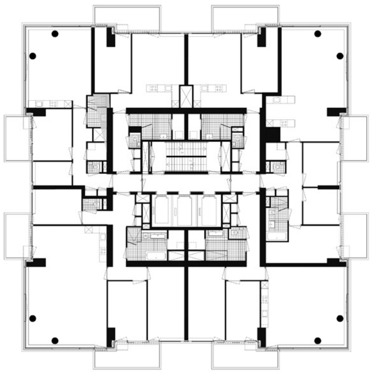
The geometries were modelled using "External measurement" geometry convention. Since the window-wall ratio between the walls facing balconies and exterior walls are different, all of the openings were drawn manually with the outer window frame as reference dimension. The balconies, overhands and railing guards were modelled using component blocks. The internal partitions and openings were modelled in order to include the effect of internal partitions in the airflow.

The preliminary analysis showed a marginal effect when heat exchange between different floors and heat exchange between staircase and apartments were included. Therefore to reduce the calculation time, the mention heat exchanges were not taken into account by modelling staircase and the adjacent floors as adiabatic zones.

Adiabatic component blocks were used in order to place the building at the correct height.



Level 9



Level 9

C.2. Materialization

The surfaces properties were provided by the construction plan from V8 architects. The surfaces specifications used in the simulation is presented in the table 1.

—>Table 1: Opaque surfaces properties

	Material layers	U-value
External wall	Concrete -Rockwool -Concrete	0.22 W/ m²K
Internal floor	Lime stone-Concrete Mortar- EPS insulation- Concrete	0.4 W/ m²K
Roof	Concrete tiles- polyurethane insulation- Concrete	0.17 W/ m²K
15cm Structural wall	Plaster- Dense concrete- plaster	2.4 W/ m²K
30cm Structural wall	Plaster- Dense concrete- plaster	1.9 W/ m²K
50cm Structural wall	Plaster- Dense concrete- plaster	1.5 W/ m²K
Ventilation panel	Aluminum- Rockwool- Aluminum	1.65 W/ m²K
Internal partitions	Plaster- Sand-lime brick- Plaster	1.2 W/ m²K

Four types of glazing unit with different U-value and g-value is used in Cooltoren. Since the window frame specifications were not given, the window were modelled without the frame. Further to include the effect of the frame on the g-value the mentioned formula were used:

Equation 1

g_{total}	**Total g-value of the fenestration**	-
g_{glass}	g-value of the glass	-
A_{glass}	Area of the glass	m^2
A_{frame}	Area of the frame	m^2

$$g_{total} = g_{glass} * ({}^{A_{glass}}/_{A_{frame}} - 1)$$

Therefore the façade openings were modelled with specifications as in table 2.

	U-value	g-value	VLT
Fixed and tilted windows on East, South and west	1.21	0.3	0.51
Fixed and tilted windows on North	1.21	0.51	0.51
Sliding doors on the North	1.58	0.51	0.51
Sliding doors on East, South and west	1.58	0.3	0.51

—>Table 2: transparent surfaces properties

C.3. Cooling, Heating and mechanical ventilation

The Cooltoren benefits from city heating combined with heat pumps and floor cooling based on the thermal storage. However, as mentioned before, this study is trying to investigate solutions that could eliminate the need of active cooling in these energy efficient high-rise residents. Therefore, cooling system were not included in the study. Further, since the overheating heating study is operated during the summer months there is no need to include heating in the modelling. Therefore, the “Natural ventilation – No heating/cooling” template were chosen in the Design Builder.

The Cooltoren provides the minimum needed fresh air for apartments using Brink Renovent Excellent 300 Plus ventilation. This system can provide maximum of 225 m3/h fresh air. During the winter the built in heat recovery system helps in reducing the energy needs and during the summer the summer by pass helps energy reductions by free cooling. The mechanical system works with CO2 sensor providing fresh air in the presence of occupants.

The mechanical ventilation unit where included to the modelling by providing the minimum fresh air for zones according to the bouwbesluit. The ventilation rates included for each zone can be seen in table xx. To include the effect of the CO2 sensor in the modelling, the modelling guideline in ISSO 32 were used. Therefore, the mechanical ventilation unit were scheduled to work by the zone’s occupancy schedule with 60% capacity.

Zone’s Function	**Ventilation rate**
Living room with kitchen	0.7 (l/s) per m2
Bedroom	0.9 (l/s) per m2
Bathroom	14 (l/s)
Toilet	7 (l/s)
Corridor	0.15 (l/s) per m2
Storage	7 (l/s)

—>Table 3: Ventilation rate of zones

C.4. Natural ventilation and infiltration

The openings were modelled according to the construction plans. Cooltoren benefits from bottom-hinged windows, ventilation flaps, sliding doors and side hung doors for ventilation. The opening were calculated based on the details. The corresponding openable percentage were included in the model. The minimum ventilation set point were set to 22˚C were in higher degree windows will be opened for natural ventilation. In order to study the full potential of the building in preventing overheating nigh ventilation were included in the window operation schedule.

According to the Design Builder guideline, for hybrid and naturally ventilated buildings, the natural ventilation calculation method should be set to “Calculated” to include the effect of the wind pressure and internal air flows into the thermal model.

The infiltration rate for Cooltoren at 10 pa is 0.241 dm3/s per m2 of façade according to Wolf+Dikken. Since in "Calculated" method the infiltration rate has to be calculated by the crack flow coefficient the formula were used to convert the infiltration rate to flow coefficient.

Equation 2

q_{v1}	Flow coefficient at a uniform pressure difference of 1 pa	Kg/s per m
q_{v10}	specific air permeability at a uniform pressure difference of 10 Pa	l/s per m^2
n	flow exponent (in this case: 0.67)	-
ρ	Air density	Kg/m3

$$q_{v1} = q_{v10} * \frac{1}{10^n} * 0.09 * \frac{1}{1000} * 1/\rho$$

Derived from NTA8800

Hence, the value of 0.000015 (Kg/s per m) were used for crack flow coefficient.

To include the effect of wind speed and rain on natural ventilation, it was set to close the windows in wind speed higher than 7 m/s and in the case of raining (Mărginean,2019). Since Design Builder does not include the wind speed at height for window operations, windspeed at height formula were used in order to include the corresponding wind speed at ground level (3.6 m/s), so window operation could operate correctly. Also, the min and max outdoor temperature control set points were set to 10 ˚C and 30 ˚C respectively for natural ventilation.

C.5. Weather file

Weather data files are files containing hourly or sub-hourly climatic data such as external temperature, solar radiation etc. of a specific location for a time period of a year. These files are used in building performance software for defining external conditions in the course of the building simulation (Crawley, 1998). For overheating study, the reference climate year with 1% chance of exceedance as described in NEN5060: 2008 were produced in a collaboration with Prateek Wahi and that weather file were used for simulations.

In addition, To enable assessment of overheating in projected future weather conditions, these weather projections should be included into weather data files. For which reason author in a collaboration with Prateek Wahi utilized KNMI Klimaatscenario transformation program and Design Builder in order to make future climate weather data files for performance simulation in 2050 and 2085 future reference climates.

The detailed weather data file transformation method can be found in appendix xx.

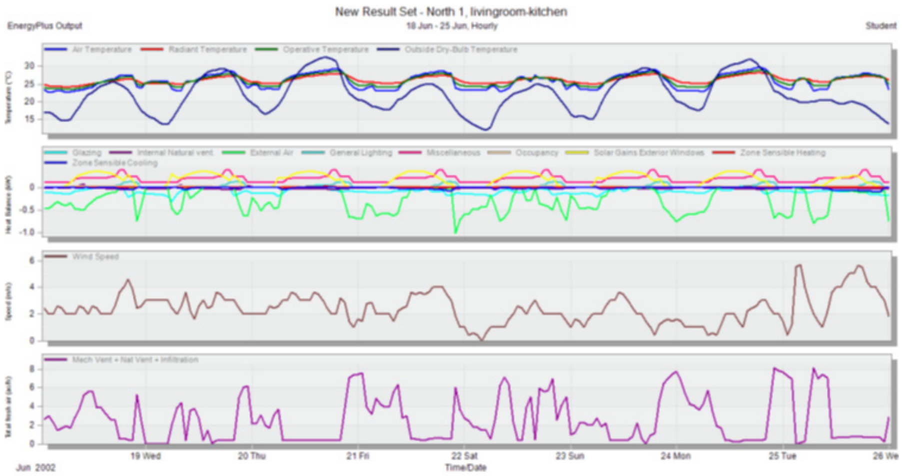
C.6. Internal loads

Internal loads are one of the most essential parameters in overheating analysis. To have an accurate thermal model, building internal parameters such as occupancy level, equipment load, lighting load and their corresponding schedule should be modelled correctly in the software.

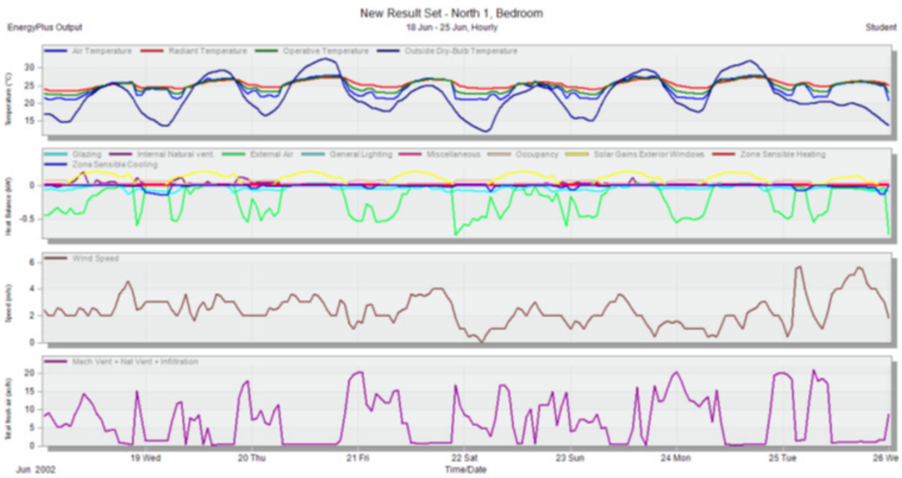
At the beginning, the internal load data given by Wolf+Dikken were used for simulation. However, since the equipment and lighting loads in Wolf+Dikken schedule were very overestimated compared to the average Dutch household consumption, it was decided to use equipment and lighting loads given in ISSO's "Thermisch Comfort" (2019) thermal modelling guideline. For occupancy loads and schedule the schedule given by Wolf+Dikken were used. The Internal loads and their representative schedule can be seen in the table:

<table>
<tr><th colspan="3">Hours</th><th>6-7 am</th><th>7-8 am</th><th>8-9 am</th><th>9-10 am</th><th>10-11 am</th><th>11-12 pm</th><th>12-13 pm</th><th>13-14 pm</th><th>14-15 pm</th><th>15-16 pm</th><th>16-17-pm</th><th>17-18 pm</th><th>18-19 pm</th><th>19-20 pm</th><th>20-21 pm</th><th>21-22 pm</th><th>22-23 pm</th><th>23-0 am</th><th>0-1 am</th><th>1-2 am</th><th>2-3 am</th><th>3-4 am</th><th>4-5 am</th><th>5-6 am</th></tr>
<tr><td rowspan="6">Livingroom</td><td rowspan="2">Equipm</td><td>load (W)</td><td colspan="24">100</td></tr>
<tr><td>Schedule (%)</td><td colspan="3">50</td><td colspan="7">75</td><td colspan="7">100</td><td colspan="7">50</td></tr>
<tr><td rowspan="2">Lighting</td><td>load (W/m2)</td><td colspan="24">5</td></tr>
<tr><td>Schedule (%)</td><td>0</td><td colspan="3">15</td><td colspan="7">0</td><td colspan="2">35</td><td>75</td><td colspan="2">100</td><td>75</td><td colspan="7">0</td></tr>
<tr><td rowspan="2">Occupanc</td><td>load (W/m2)</td><td colspan="24">8.3 W / m2 to 30 m2, above that 2 W / m2</td></tr>
<tr><td>Schedule (%)</td><td>0</td><td colspan="16">30</td><td colspan="7">0</td></tr>
<tr><td rowspan="6">Main Bedroom</td><td rowspan="2">Equipm</td><td>load (W)</td><td colspan="24">25</td></tr>
<tr><td>Schedule (%)</td><td colspan="24">100</td></tr>
<tr><td rowspan="2">Lighting</td><td>load (W/m2)</td><td colspan="24">3</td></tr>
<tr><td>Schedule (%)</td><td>0</td><td colspan="2">25</td><td colspan="14">0</td><td>25</td><td colspan="6">0</td></tr>
<tr><td rowspan="2">Occupa</td><td>load (W)</td><td colspan="24">100</td></tr>
<tr><td>Schedule (%)</td><td colspan="2">100</td><td colspan="15">50</td><td colspan="7">100</td></tr>
<tr><td rowspan="6">Bedroom</td><td rowspan="2">Equipm</td><td>load (W)</td><td colspan="24">25</td></tr>
<tr><td>Schedule (%)</td><td colspan="24">100</td></tr>
<tr><td rowspan="2">Lighting</td><td>load (W/m2)</td><td colspan="24">3</td></tr>
<tr><td>Schedule (%)</td><td>0</td><td colspan="2">25</td><td colspan="14">0</td><td>25</td><td colspan="6">0</td></tr>
<tr><td rowspan="2">Occupanc</td><td>load (W/m2)</td><td colspan="24">6 W / m2, with a minimum of 50 W and a maximum of 100 W</td></tr>
<tr><td>Schedule (%)</td><td colspan="2">100</td><td colspan="15">50</td><td colspan="7">100</td></tr>
<tr><td rowspan="6">Kitchen</td><td rowspan="2">Equipm</td><td>load (W)</td><td colspan="24">300</td></tr>
<tr><td>Schedule (%)</td><td>10</td><td colspan="11">15</td><td colspan="2">100</td><td colspan="3">15</td><td colspan="7">10</td></tr>
<tr><td rowspan="2">Lighting</td><td>load (W/m2)</td><td colspan="24">5</td></tr>
<tr><td>Schedule (%)</td><td>0</td><td colspan="3">15</td><td colspan="7">0</td><td colspan="2">35</td><td>75</td><td colspan="2">100</td><td>75</td><td colspan="7">0</td></tr>
<tr><td rowspan="2">Occupa</td><td>load (W)</td><td colspan="24">8.3 W / m2 to 30 m2, above that 2 W / m2</td></tr>
<tr><td>Schedule (%)</td><td>0</td><td colspan="16">30</td><td colspan="7">0</td></tr>
<tr><td rowspan="4">Toilet</td><td rowspan="2">Equipm</td><td>load (W)</td><td colspan="24">15</td></tr>
<tr><td>Schedule (%)</td><td colspan="24">100</td></tr>
<tr><td rowspan="2">Lighting</td><td>load (W/m2)</td><td colspan="24">5</td></tr>
<tr><td>Schedule (%)</td><td>0</td><td colspan="17">5</td><td colspan="6">0</td></tr>
<tr><td rowspan="4">Storage</td><td rowspan="2">Equipm</td><td>load (W)</td><td colspan="24">500</td></tr>
<tr><td>Schedule (%)</td><td colspan="24">Weekends from 22pm to 0 am: 100%- other times: 5%</td></tr>
<tr><td rowspan="2">Lighting</td><td>load (W/m2)</td><td colspan="24"></td></tr>
<tr><td>Schedule (%)</td><td colspan="24">Weekends from 22pm to 0 am: 10%</td></tr>
<tr><td rowspan="6">Bathroom</td><td rowspan="2">Equipment</td><td>load (W)</td><td colspan="24">150</td></tr>
<tr><td>Schedule (%)</td><td>8.5</td><td>100</td><td colspan="11">8.5</td><td colspan="2">100</td><td colspan="9">8.5</td></tr>
<tr><td rowspan="2">Lighting</td><td>load (W)</td><td colspan="24">5</td></tr>
<tr><td>Schedule (%)</td><td>0</td><td colspan="2">25</td><td colspan="10">0</td><td colspan="2">25</td><td>0</td><td>25</td><td></td><td colspan="6">0</td></tr>
<tr><td rowspan="2">Occupancy</td><td>load (W)</td><td colspan="24">50</td></tr>
<tr><td>Schedule (%)</td><td>0</td><td colspan="3">100</td><td colspan="2">0</td><td colspan="2">100</td><td colspan="5">0</td><td colspan="2">100</td><td>0</td><td>100</td><td colspan="7">0</td></tr>
</table>

Appendix D. Results of building performance simulation

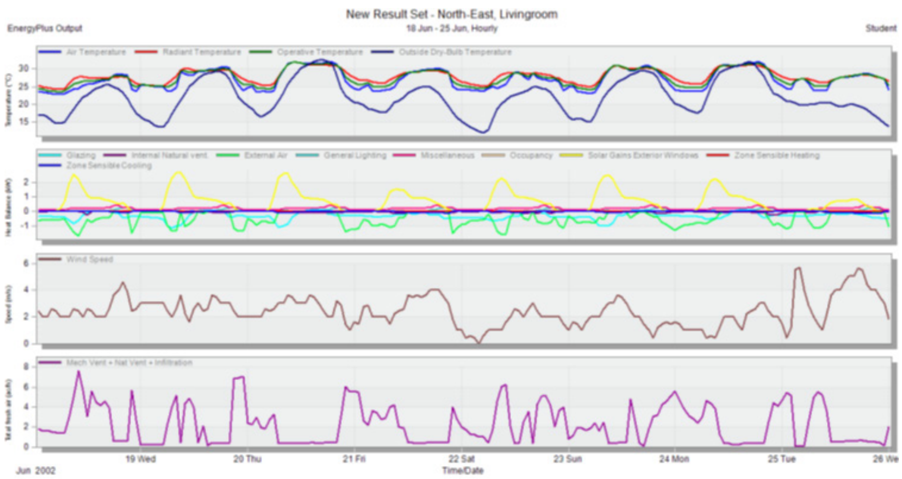


—>*Figure 1: Livingroom "E1"*

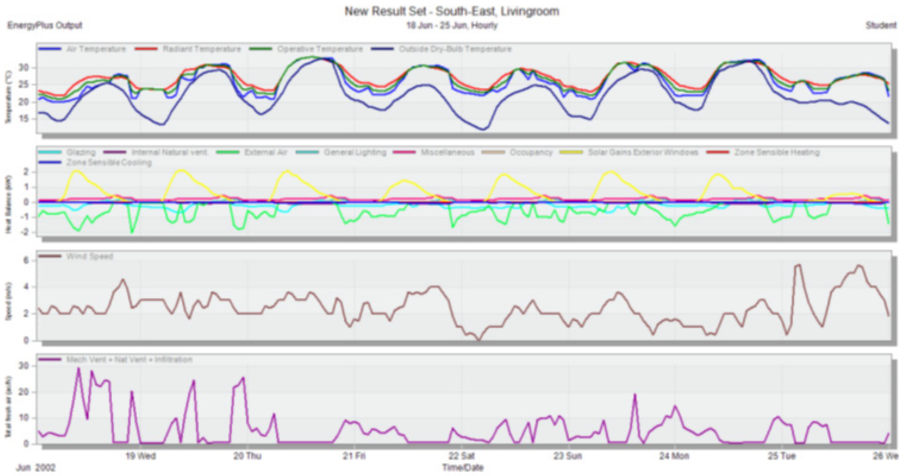


—>*Figure 2: Bedroom "E1-1"*

As can be seen in figure 1 and 2, despite the outdoor temperature swings, the indoor environment in occupied zones of single-sided apartment on North is stable. As the graph shows during the high outdoor temperature the ventilation becomes limited allowing to maintain the indoor temperature on the comfort range with the help of thermal mass. During the night when the temperature start to drop and the indoor temperature hit the peak, the windows become open again allowing for natural ventilation and regeneration of thermal mass.



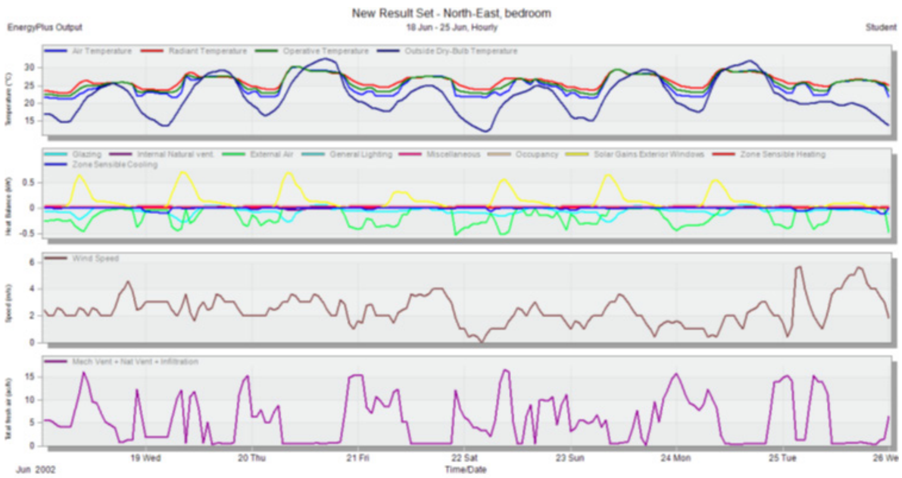
—>*Figure 3: Livingroom "E6"*



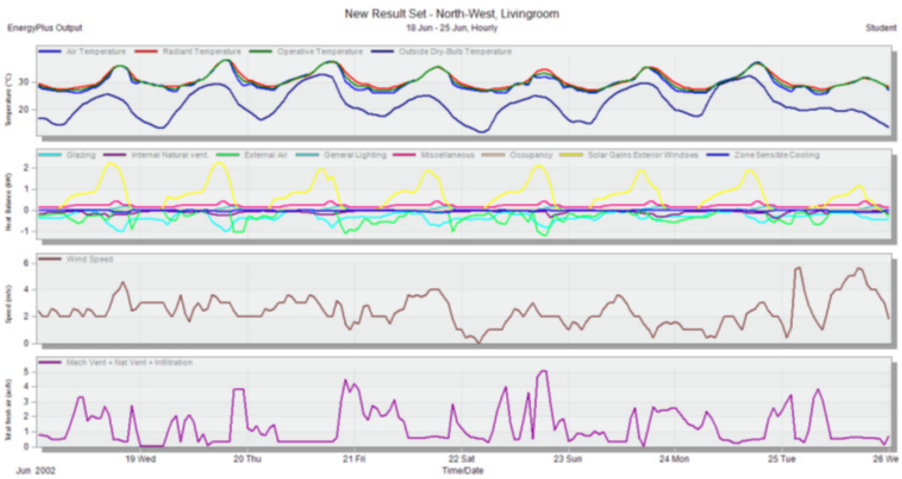
—>*Figure 4: Livingroom "E5"*

The East facing double-sided zones in apartment E5 and E6 have almost similar conditions. As can be seen, the peak solar gain of these zones is during the morning, when the outdoor temperature is low, therefore allowing for effective ventilation cooling as green lines show. During the hot mid-day hours then, the ventilation becomes limited, allowing thermal mass to maintain a stable environment during the day. Also, as can be seen during the 21st to 23rd of June the ventilation becomes limited due to the unfavorable direction of the wind, reducing the natural ventilation rate.

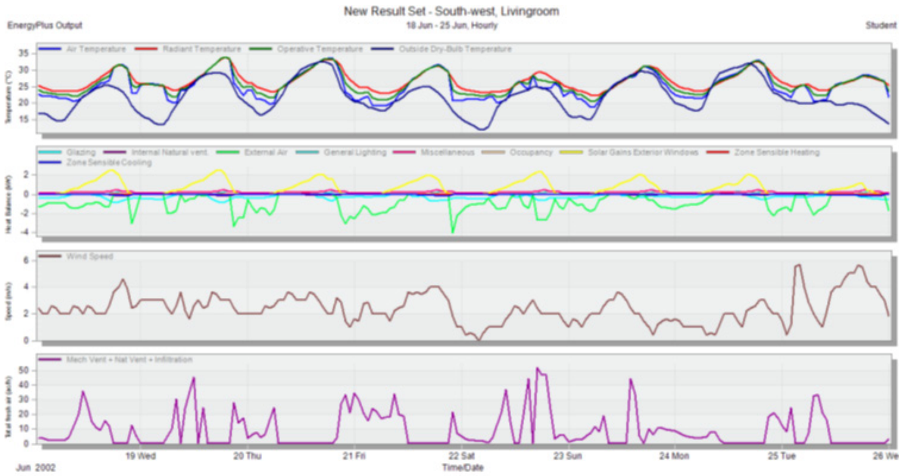
The East facing bedroom too demonstrate similar behavior, as evident the peak solar radiation but also the heat dissipation by ventilation is during the early morning hours, preventing heat accumulation in the room and protecting the indoor space from high temperature swings.



—>*Figure 4: Bedroom "E6-1"*



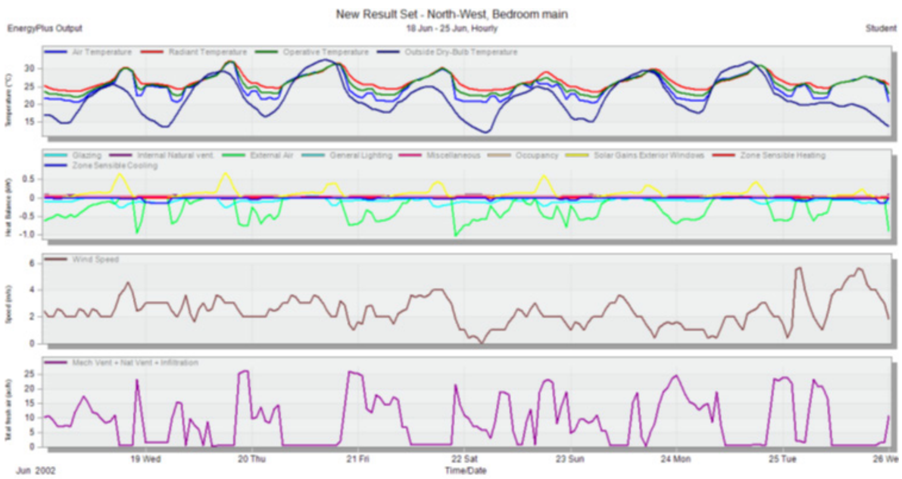
—>*Figure 5: Livingroom "E3"*



—>*Figure 7: Livingroom "E4"*

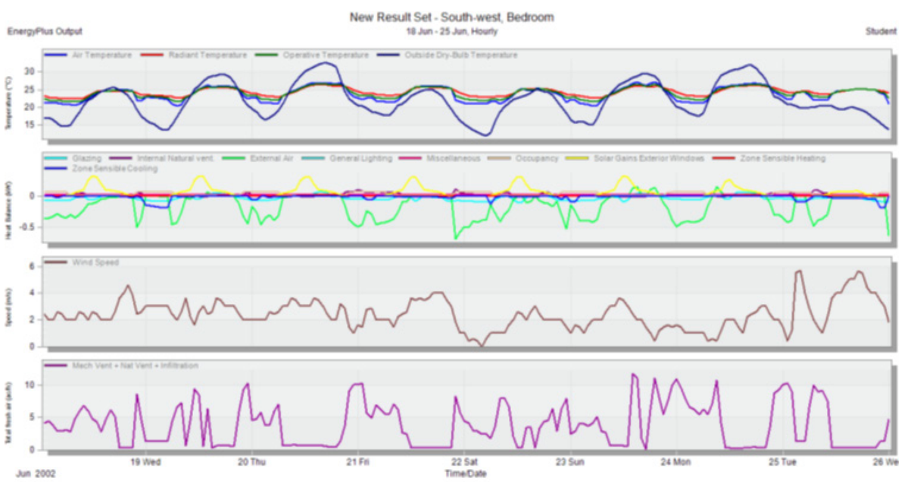
As illustrated, the double sided zones facing west have high overheating problem, the reason for that is when the solar radiation peaks at after noon the heat already have accumulated in the thermal mass allowing solar radiation to overheat the space. Moreover, since the heat is already accumulated and the outdoor temperature is high the effectivity of natural ventilation becomes lower.

As evident in figure 7, the same happens for west facing bedrooms.



—>*Figure 7: Bedroom "E3-1"*

Looking at the south facing bedrooms in figure 8, it can be seen that through out the day, they have very low temperature fluctuations. The balconies shade these bedrooms from high altitude noon solar radiation and thermal mass ensure a stable indoor environment throughout the day.



—>*Figure 7: Bedroom "E4-2"*

Level 45 (132 m) overheating simulation results: Present

Zone	Function	Temperature Exceedance hours of ATG	Temperature Exceedance hours of CIBSE static	Average Mean Temperature	Maximum temprature	AGT condition	CIBSE static(% of occupied hours over temprature thereshold)
E1	Livingroom	266	357	25.3	30.5	Very good	6.1
E1-1	Bedroom	20	662	23.6	29.5	Very good	7.5
E1-2	Bathroom	-	-	26.5	29.7	-	-
E1-3	Storage	-	-	26.8	34.1	-	-
E1-4	corridor	-	-	25.4	28.4	-	-
E2	Livingroom	296	391	25.3	30.6	Very good	6.7
E2-1	Bedroom	24	832	23.8	29.9	Very good	9.5
E2-2	Bathroom	-	-	26.3	29.6	-	-
E2-3	Storage	-	-	26.8	34.2	-	-
E2-4	corridor	-	-	25.6	28.6	-	-
E3	Livingroom	1220	1113	26.2	37.5	Overheated	19.0
E3-1	Bedroom	272	815	23.2	32.8	Overheated	9.3
E3-2	Bedroom	318	918	23.7	32.9	Overheated	10.4
E3-3	Bathroom	-	-	25.6	31.6	-	-
E3-4	Storage	-	-	25.3	33.7	-	-
E3-5	WC	-	-	25.1	30.0	-	-
E3-6	corridor	-	-	24.5	30.5	-	-
E4	Livingroom	470	522	23.5	35.0	Good	8.9
E4-1	Bedroom	148	641	22.9	31.8	Very good	7.3
E4-2	Bedroom	0	256	22.1	28.7	Very good	2.9
E4-3	Bedroom	0	193	22.0	28.4	Very good	2.2
E4-4	WC	-	-	23.9	29.8	-	-
E4-5	corridor	-	-	23.3	29.4	-	-
E4-6	Bathroom	-	-	24.2	28.7	-	-
E4-7	Storage	-	-	25.0	33.7	-	-
E5	Livingroom	801	772	24.6	35.2	Acceptable	13.2
E5-1	Bedroom	0	166	22.1	28.9	Very good	1.9
E5-2	Bedroom	2	218	22.5	29.5	Very good	2.5
E5-3	corridor	-	-	23.7	28.5	-	-
E5-4	Bathroom	-	-	24.3	28.6	-	-
E5-5	Storage	-	-	25.1	34.1	-	-
E6	Livingroom	782	744	25.1	33.0	Good	12.7
E6-1	Bedroom	143	838	23.4	31.6	Very good	9.5
E6-2	Bedroom	23	575	22.9	30.6	Very good	6.5
E6-3	Bedroom	2	540	23.1	29.9	Very good	6.1
E6-4	Bathroom	-	-	24.3	28.8	-	-
E6-5	Corridor	-	-	24.1	29.1	-	-
E6-6	WC	-	-	24.8	29.1	-	-
E6-7	Storage	-	-	25.2	32.7	-	-

Level 45 (132 m) overheating simulation results: 2050

Zone	Function	Temperature Exceedance hours of ATG	Temperature Exceedance hours of CIBSE static	Average Mean Temperature	Maximum temprature	AGT condition	CIBSE static(% of occupied hours over temprature thereshold)
E1	Livingroom	320	868	26.2	32.3	Very good	14.8
E1-1	Bedroom	28	1290	24.5	31.7	Very good	14.7
E1-2	Bathroom	-	-	27.5	31.6	-	-
E1-3	Storage	-	-	28.0	36.1	-	-
E1-4	corridor	-	-	26.4	30.4	-	-
E2	Livingroom	383	910	26.2	32.4	Very good	15.5
E2-1	Bedroom	58	1450	24.8	31.9	Very good	16.5
E2-2	Bathroom	-	-	27.3	31.5	-	-
E2-3	Storage	-	-	27.9	36.2	-	-
E2-4	corridor	-	-	26.7	30.5	-	-
E3	Livingroom	1378	1443	27.4	40.1	Overheated	24.6
E3-1	Bedroom	454	1338	24.3	35.3	Good	15.2
E3-2	Bedroom	416	1523	24.9	35.0	Good	17.3
E3-3	Bathroom	-	-	26.7	33.6	-	-
E3-4	Storage	-	-	26.5	36.1	-	-
E3-5	WC	-	-	26.3	31.8	-	-
E3-6	corridor	-	-	25.7	32.6	-	-
E4	Livingroom	594	787	24.6	37.7	Good	13.4
E4-1	Bedroom	247	1162	24.0	33.9	Very good	13.2
E4-2	Bedroom	0	772	23.3	31.3	Very good	8.8
E4-3	Bedroom	10	728	23.2	30.9	Very good	8.3
E4-4	WC	-	-	25.0	32.0	-	-
E4-5	corridor	-	-	24.4	31.5	-	-
E4-6	Bathroom	-	-	25.4	31.0	-	-
E4-7	Storage	-	-	26.4	36.0	-	-
E5	Livingroom	939	1088	25.8	38.1	Acceptable	18.6
E5-1	Bedroom	3	961	23.3	31.4	Very good	10.9
E5-2	Bedroom	31	1197	23.7	32.2	Very good	13.6
E5-3	corridor	-	-	24.9	30.8	-	-
E5-4	Bathroom	-	-	25.6	30.8	-	-
E5-5	Storage	-	-	26.4	36.5	-	-
E6	Livingroom	925	1132	26.2	35.5	Good	19.3
E6-1	Bedroom	260	1414	24.6	34.2	Very good	16.1
E6-2	Bedroom	65	1180	24.0	33.2	Very good	13.4
E6-3	Bedroom	54	1173	24.2	32.4	Very good	13.3
E6-4	Bathroom	-	-	25.4	31.2	-	-
E6-5	Corridor	-	-	25.2	31.5	-	-
E6-6	WC	-	-	26.0	31.3	-	-
E6-7	Storage	-	-	26.3	34.7	-	-

Level 45 (132 m) overheating simulation results: 2085

Zone	Function	Temperature Exceedance hours of ATG	Temperature Exceedance hours of CIBSE static	Average Mean Temperature	Maximum temprature	AGT condition	CIBSE static(% of occupied hours over temprature thereshold)
E1	Livingroom	562	1153	26.8	33.9	Very good	19.7
E1-1	Bedroom	92	1688	25.2	33.4	Very good	28.8
E1-2	Bathroom	-	-	28.2	33.2	-	-
E1-3	Storage	-	-	28.8	37.6	-	-
E1-4	corridor	-	-	27.1	32.0	-	-
E2	Livingroom	632	1189	26.9	34.1	Very good	20.3
E2-1	Bedroom	146	1821	25.5	33.7	Very good	31.1
E2-2	Bathroom	-	-	28.0	33.0	-	-
E2-3	Storage	-	-	28.7	37.7	-	-
E2-4	corridor	-	-	27.4	32.1	-	-
E3	Livingroom	1525	1781	28.2	41.8	Overheated	30.4
E3-1	Bedroom	558	1693	25.1	37.0	Good	28.9
E3-2	Bedroom	595	1883	25.7	36.7	Good	32.2
E3-3	Bathroom	-	-	27.5	35.2	-	-
E3-4	Storage	-	-	27.3	37.8	-	-
E3-5	WC	-	-	27.1	33.5	-	-
E3-6	corridor	-	-	26.5	34.3	-	-
E4	Livingroom	695	993	25.4	39.5	Good	17.0
E4-1	Bedroom	350	1556	24.8	35.7	Very good	26.6
E4-2	Bedroom	39	1271	24.1	33.1	Very good	21.7
E4-3	Bedroom	18	1208	24.0	32.7	Very good	20.6
E4-4	WC	-	-	25.8	33.7	-	-
E4-5	corridor	-	-	25.2	33.3	-	-
E4-6	Bathroom	-	-	26.3	32.7	-	-
E4-7	Storage	-	-	27.3	37.6	-	-
E5	Livingroom	1070	1642	26.5	39.8	Acceptable	28.0
E5-1	Bedroom	28	1231	24.1	33.1	Very good	21.0
E5-2	Bedroom	73	1410	24.5	33.9	Very good	24.1
E5-3	corridor	-	-	25.7	32.6	-	-
E5-4	Bathroom	-	-	26.4	32.5	-	-
E5-5	Storage	-	-	27.3	38.2	-	-
E6	Livingroom	1101	1375	27.0	37.3	Good	23.5
E6-1	Bedroom	455	1800	25.4	35.9	Very good	30.7
E6-2	Bedroom	164	1595	24.8	35.0	Very good	27.2
E6-3	Bedroom	115	1567	25.0	34.2	Very good	26.8
E6-4	Bathroom	-	-	26.2	32.9	-	-
E6-5	Corridor	-	-	26.0	33.2	-	-
E6-6	WC	-	-	26.8	33.0	-	-
E6-7	Storage	-	-	27.1	36.5	-	-

Level 9 (28 m) overheating simulation results: Present

Zone	Function	Temperature Exceedance hours of ATG	Temperature Exceedance hours of CIBSE static	Average Mean Temperature	Maximum temprature	AGT condition	CIBSE static(% of occupied hours over temprature thereshold)
E1	Livingroom	0	70	24.1	29.5	Very good	1.2
E1-1	Bedroom	0	213	22.8	28.1	Very good	2.4
E1-2	Bathroom	-	-	25.9	29.1	-	-
E1-3	Storage	-	-	26.6	34	-	-
E1-4	corridor	-	-	24.7	27.8	-	-
E2	Livingroom	1	74	24.1	29.5	Very good	1.3
E2-1	Bedroom	0	236	23	28.3	Very good	2.7
E2-2	Bathroom	-	-	25.8	29.1	-	-
E2-3	Storage	-	-	26.6	33.9	-	-
E2-4	corridor	-	-	24.9	27.6	-	-
E3	Livingroom	737	747	26	34.4	Overheated	12.8
E3-1	Bedroom	57	355	21.9	32.4	Good	4.0
E3-2	Bedroom	66	402	22.3	32	Good	4.6
E3-3	Bathroom	-	-	24.7	30.3	-	-
E3-4	Storage	-	-	24.9	32.4	-	-
E3-5	WC	-	-	24.1	28.7	-	-
E3-6	corridor	-	-	23.6	29.2	-	-
E4	Livingroom	59	108	22.2	32.3	Good	1.8
E4-1	Bedroom	5	244	21.7	30.5	Very good	2.8
E4-2	Bedroom	0	68	21.2	28.1	Very good	0.8
E4-3	Bedroom	0	63	22.1	27.9	Very good	0.7
E4-4	WC	-	-	22.9	28.4	-	-
E4-5	corridor	-	-	23.3	27.8	-	-
E4-6	Bathroom	-	-	23.5	28	-	-
E4-7	Storage	-	-	24.7	33.3	-	-
E5	Livingroom	95	170	23.5	31.9	Acceptable	2.9
E5-1	Bedroom	0	76	21.5	28.4	Very good	0.9
E5-2	Bedroom	0	123	21.2	28.4	Very good	1.4
E5-3	corridor	-	-	22.8	27.2	-	-
E5-4	Bathroom	-	-	23.7	27.9	-	-
E5-5	Storage	-	-	24.8	33.7	-	-
E6	Livingroom	71	222	24.6	30.4	Acceptable	3.8
E6-1	Bedroom	7	362	22.7	30.1	Very good	4.1
E6-2	Bedroom	0	233	22	28.9	Very good	2.6
E6-3	Bedroom	0	176	22.3	28.3	Very good	2.0
E6-4	Bathroom	-	-	23.7	28	-	-
E6-5	Corridor	-	-	23.4	27.9	-	-
E6-6	WC	-	-	24.3	28.4	-	-
E6-7	Storage	-	-	24.8	31.9	-	-

Level 9 (28 m) overheating simulation results: 2050

Zone	Function	Temperature Exceedance hours of ATG	Temperature Exceedance hours of CIBSE static	Average Mean Temperature	Maximum temprature	AGT condition	CIBSE static(% of occupied hours over temprature thereshold)
E1	Livingroom	9	384	24.8	31.8	Very good	6.6
E1-1	Bedroom	0	590	23.5	30.7	Very good	6.7
E1-2	Bathroom	-	-	26.7	31.1	-	-
E1-3	Storage	-	-	27.5	36.2	-	-
E1-4	corridor	-	-	25.5	29.9	-	-
E2	Livingroom	15	394	25.0	32.0	Good	6.7
E2-1	Bedroom	0	635	23.8	30.8	Very good	7.2
E2-2	Bathroom	-	-	26.6	30.9	-	-
E2-3	Storage	-	-	27.5	36.3	-	-
E2-4	corridor	-	-	25.7	29.8	-	-
E3	Livingroom	875	975	26.8	37.3	Overheated	16.6
E3-1	Bedroom	122	640	23.0	35.1	Acceptable	7.3
E3-2	Bedroom	135	736	23.4	34.6	Acceptable	8.4
E3-3	Bathroom	-	-	25.8	32.6	-	-
E3-4	Storage	-	-	25.6	35.1	-	-
E3-5	WC	-	-	25.1	31.1	-	-
E3-6	corridor	-	-	24.5	31.8	-	-
E4	Livingroom	142	334	23.2	35.1	Acceptable	5.7
E4-1	Bedroom	36	547	22.7	33.3	Good	6.2
E4-2	Bedroom	0	373	22.2	30.6	Very good	4.2
E4-3	Bedroom	0	379	22.2	30.6	Very good	4.3
E4-4	WC	-	-	23.9	31.3	-	-
E4-5	corridor	-	-	23.3	30.6	-	-
E4-6	Bathroom	-	-	24.6	30.6	-	-
E4-7	Storage	-	-	26.0	36.1	-	-
E5	Livingroom	228	429	24.3	35.0	Overheated	7.3
E5-1	Bedroom	0	379	22.3	31.0	Very good	4.3
E5-2	Bedroom	0	460	22.6	31.2	Very good	5.2
E5-3	corridor	-	-	23.9	29.7	-	-
E5-4	Bathroom	-	-	24.8	30.3	-	-
E5-5	Storage	-	-	26.0	36.5	-	-
E6	Livingroom	213	514	25.4	33.6	Overheated	8.8
E6-1	Bedroom	52	750	23.7	33.8	Good	8.5
E6-2	Bedroom	14	647	23.0	32.3	Good	7.4
E6-3	Bedroom	0	598	23.3	31.2	Very good	6.8
E6-4	Bathroom	-	-	24.5	30.6	-	-
E6-5	Corridor	-	-	24.4	30.5	-	-
E6-6	WC	-	-	25.2	30.9	-	-
E6-7	Storage	-	-	25.7	34.1	-	-

Level 9 (28 m) overheating simulation results: 2085

Zone	Function	Temperature Exceedance hours of ATG	Temperature Exceedance hours of CIBSE static	Average Mean Temperature	Maximum temprature	AGT condition	CIBSE static(% of occupied hours over temprature theresheld)
E1	Livingroom	65	631	25.4	33.5	Good	10.8
E1-1	Bedroom	17	988	24.1	32.5	Good	11.2
E1-2	Bathroom	-	-	27.3	32.7	-	-
E1-3	Storage	-	-	28.2	37.8	-	-
E1-4	corridor	-	-	26.1	31.4	-	-
E2	Livingroom	67	643	25.5	33.7	Good	11.0
E2-1	Bedroom	21	1072	24.4	32.7	Good	12.2
E2-2	Bathroom	-	-	27.2	32.6	-	-
E2-3	Storage	-	-	28.2	37.9	-	-
E2-4	corridor	-	-	26.3	31.4	-	-
E3	Livingroom	1015	1180	27.5	39.2	Overheated	20.2
E3-1	Bedroom	213	1106	23.8	36.9	Overheated	12.6
E3-2	Bedroom	224	1217	24.2	36.4	Overheated	13.8
E3-3	Bathroom	-	-	26.4	34.4	-	-
E3-4	Storage	-	-	26.3	37.0	-	-
E3-5	WC	-	-	25.7	32.8	-	-
E3-6	corridor	-	-	25.2	33.5	-	-
E4	Livingroom	205	515	23.9	37.0	Overheated	8.8
E4-1	Bedroom	89	991	23.5	35.1	Acceptable	11.3
E4-2	Bedroom	18	751	23.0	32.4	Good	8.5
E4-3	Bedroom	8	732	23.0	32.3	Very good	8.3
E4-4	WC	-	-	24.6	33.1	-	-
E4-5	corridor	-	-	24.0	32.4	-	-
E4-6	Bathroom	-	-	25.3	32.3	-	-
E4-7	Storage	-	-	26.7	37.7	-	-
E5	Livingroom	295	628	25.0	36.9	Overheated	10.7
E5-1	Bedroom	10	744	23.1	32.7	Good	8.5
E5-2	Bedroom	20	845	23.3	32.9	Good	9.6
E5-3	corridor	-	-	24.6	31.5	-	-
E5-4	Bathroom	-	-	25.5	32.0	-	-
E5-5	Storage	-	-	26.8	38.2	-	-
E6	Livingroom	290	789	26.0	35.5	Overheated	13.5
E6-1	Bedroom	161	1168	24.4	35.6	Acceptable	13.3
E6-2	Bedroom	46	1033	23.8	34.2	Good	11.7
E6-3	Bedroom	31	1004	24.0	33.0	Good	11.4
E6-4	Bathroom	-	-	25.2	32.3	-	-
E6-5	Corridor	-	-	25.1	32.4	-	-
E6-6	WC	-	-	25.9	32.6	-	-
E6-7	Storage	-	-	26.4	36.1	-	-

Appendix E. Incorporating Future climate into weather data file

Weather data files are files containing hourly or sub-hourly climatic data such as external temperature, solar radiation etc. of a specific location for a time period of a year. These files are used in building performance software for defining external conditions in the course of the building simulation (Crawley, 1998). To enable assessment of overheating in projected future weather conditions, these weather projections should be included into weather data files. For which reason author in a collaboration with Prateek Wahi utilized KNMI Klimaatscenario transformation program and design builder in order to make future climate weather data files for performance simulation. KNMI Klimaatscenario transformation program uses past recorded weather data time series and translates them to selected future weather scenario. After obtaining future temperature data for worst predicted scenarios then Design Builder software were used in order to produce weather data file used in the building performance simulator software.

In order to do building's comfort and energy simulations for future climate conditions, first hourly weather data of future weather conditions has to be produced. To do so, Dutch climatic reference data standard (NEN-5060) were transformed to the future climate data. For transformation, the KNMI transformation program was used. This online program transforms the past recorded climate data between 1981-2010 to future weather scenarios on a daily basis. Since this program does not support the weather data after 2010, NEN-5060:2008 were used instead of NEN:5060:2018 for data transformation. The future climate weather file transformation method is derived from the work of Van der Spoel & Van den Ham (2012).

The steps taken to make the projected weather data file is as below:

1. In the KNMI'14 Klimaatscenario transformation program, first the reference period 1981-2010 recorded daily average temperature data were downloaded. Then the files were converted to a spread sheet and the data for code 260 which represent "De Blit" weather station were selected and recorded on a separate spread sheet.

2. The 'Wh' scenario which is the worst case scenario for global warming were chosen and the data were downloaded for 2050 and 2085 time series. The transformation program translates each day between 1981-2010 to future climate predictions. For 2050 time horizon case it translate each year to 55 years later so it contains years between 2036 and 2065, and for 2085 case the time series is between 2071 and 2100. The data were then separated for 'De Blit' station similar to the previous step.

3. To find the increase in average daily temperature, the difference between two future time series and the reference file is taken.

4. The temperature difference then is chosen and separated for the months between 1981 and 2010 according to NEN-5060:2008 on a spread sheet. The selected time series for energy and 1&5 percent exceedance chance can be seen in the Table 1.

5. From KNMI the hourly weather data for same months and years as NEN-5060:2008 were obtained. Then for each hourly temperature value in a day, the relevant daily temperature increases were added to obtain the temperature increases according to the future climate scenario.

Month	Selected years for the reference climate		
	Energy	**1% excedence**	**5% excedence**
January	2003	1987	2003
February	2004	1986	1994
March	1992	1991	1989
April	2002	2003	1991
May	1985	1992	1988
June	2000	2005	1989
July	2002	1995	2003
August	2000	2004	1995
September	1992	1991	2004
October	2004	1995	2001
November	2001	1996	2005
December	2003	1996	1989

—>Table 1: Selected months for the reference climate year for energy and chance of exceedance calculation.

6. To make the data file used by simulation software design builder's weather data convertor was used. First, the weather data file for Amsterdam was transferred to .csv format. Then the temperature values obtained in the previous step and the wind speed and direction, vertical, horizontal and diffuse solar radiation and humidity obtained from KNMI hourly weather data according to NEN-5060:2008 were copied to the .csv file.

7. Last step, the transformed weather file was converted to the energy plus weather data file (.epw) using Design Builders weather data convertor.

Sources:

- Crawley, D. 1998. Which Weather Data Should You Use for Energy Simulations of Commercial Buildings?. ASHRAE 1998 TRANSACTIONS
- Van der Spoel, W.H, & Van den Ham, E.R. 2012. Pilot effect klimaatverandering op energiegebruik en besparingsconcepten bij woningen. TU Delft, Faculteit Bouwkunde, afdeling Architectural Engineering + Technology, groep Bouwfysica

Appendix F. Design variations simulation workflow

In this section, the building performance modelling workflow for design variations is reviewed.

F.1. Materialization

Same procedure and values as in Appendix C, only the g-value of the North facing windows were changed as in bellow.

	U-value	*g*-value	VLT
Fixed and tilted windows on North ,East, South and West	1.21	0.3	0.51
Sliding doors on North, East, South and west	1.58	0.3	0.51

—>Table 1: Transparent surfaces properties

F.2. Internal loads

Similar to the values presented in appendix C. The only difference in lighting load of living rooms and bedrooms which were reduce to 3 W/m2.

F.3. Cooling, Heating and mechanical ventilation:

1. *Rescheduling mechanical ventilation & Group A*

The ventilation rate for each living space were rescheduled considering maximum capacity of mechanical ventilation. The new rates for each living space can be seen in the table.

The mechanical ventilation were rescheduled to work in maximum power in nights from 11 PM. to 6 AM. and with 100% capacity during the occupied hours.

Zone	Function	Ventilation rate (l/s per m2)
E1	Livingroom	1.3
E1-1	Bedroom	1.5
E2	Livingroom	1.3
E2-1	Bedroom	1.5
E3	Livingroom	1.3
E3-1	Bedroom	1.4
E3-2	Bedroom	1.4
E4	Livingroom	0.7
E4-1	Bedroom	0.9
E4-2	Bedroom	0.8
E4-3	Bedroom	0.8
E5	Livingroom	0.75
E5-1	Bedroom	0.9
E5-2	Bedroom	0.9
E6	Livingroom	0.7
E6-1	Bedroom	0.9
E6-2	Bedroom	0.9
E6-3	Bedroom	0.85

Table 2: Living zones new ventilation rates

2. *Increasing natural ventilation & Group B:*

Scheduled as in table 3 in appendix C.

F.4. Natural ventilation and infiltration

1. *Rescheduling mechanical ventilation:*

Settings as in appendix C.

2. *Increasing natural ventilation & Group B:*

In order to include the wind and rain protection effect of the wind breaker fabric and ventilation grills into the simulation, first the new windows and opening were modelled. Then for windows that were connected to the windbreaker shutters or ventilation flaps a virtual partition as in the figure were made. Making a new zone by virtual partition allows for changing the natural ventilation settings. The HVAC settings for other zones and windows are as the ones in the Appendix C.

The new settings for virtual zones were set to allow for ventilation when is raining. In addition, since the wind fabric allowed for ventilation at higher speed because of the wind reducing effect, the ventilation wind speed threshold were increased to 5.2 m/s for level 45 and 10.5 m/s for level 9. In order to include the effect of the wind speed reduction, the wind factor were reduced to 0.5 (-).

3. *Group A:*

New openings were introduced to the model by including the openable area. For areas with windows the same ventilation settings as in Appendix C were used. For rooms with ventilation flap the same procedure as in the previous section were used.

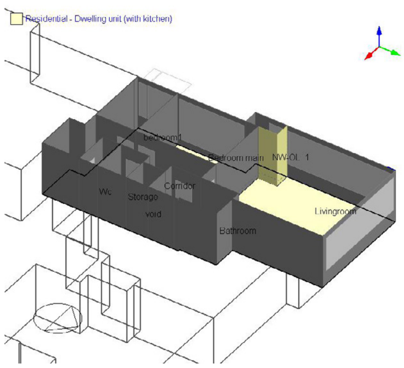


Figure 1: Using virtual zones for defining seprate ventilation settings in one room.

F.5. Shading

Overhang shading were placed using “local shading” command in Design Builder. Overhangs were placed with 30 cm “vertical projection from the window” and 1.2m “projection”.

For screens, “Low reflectance, low transmittance” shade in “window shading” option of the Design Builder were utilized. Because of the weaving structure of the Solo zip, the air permeability of the screen were set to 0.35 to represent the fabric. The control type were set to “Solar” with solar set point of 120 W/m2.

Vertical shading elements where modelled using component blocks. Then the transmittance value of the component where set to 0.2 (-) with “always on” schedule.

Level 45 (132 m) proposed design overheating simulation results: Present

Zone	Function	Temperature Exceedance hours of ATG	Average Mean Temperature	Maximum temprature	AGT condition
E1	Livingroom	0	22.5	28.4	Very good
E1-1	Bedroom	0	21.4	27.4	Very good
E1-2	Bathroom	-	22.7	27.7	-
E1-3	Storage	-	23.8	33.0	-
E1-4	corridor	-	22.7	27.8	-
E2	Livingroom	0	22.3	28.2	Very good
E2-1	Bedroom	0	21.1	26.9	Very good
E2-2	Bathroom	-	23.5	28.2	-
E2-3	Storage	-	24.0	32.9	-
E2-4	corridor	-	22.9	30.3	-
E3	Livingroom	14	23.1	33.9	Good
E3-1	Bedroom	0	21.8	29.8	Very good
E3-2	Bedroom	4	22.0	30.2	Very good
E3-3	Bathroom	-	22.8	28.5	-
E3-4	Storage	-	23.8	31.7	-
E3-5	WC	-	23.2	27.4	-
E3-6	corridor	-	22.5	27.1	-
E4	Livingroom	30	21.8	31.1	Good
E4-1	Bedroom	0	21.6	29.2	Very good
E4-2	Bedroom	0	21.2	26.7	Very good
E4-3	Bedroom	0	21.0	26.5	Very good
E4-4	WC	-	22.4	27.2	-
E4-5	corridor	-	21.9	26.3	-
E4-6	Bathroom	-	22.2	27.1	-
E4-7	Storage	-	23.5	32.4	-
E5	Livingroom	0	21.7	29.9	Very good
E5-1	Bedroom	0	21.4	28.5	Very good
E5-2	Bedroom	0	21.8	28.4	Very good
E5-3	corridor	-	22.4	28.1	-
E5-4	Bathroom	-	22.8	29.7	-
E5-5	Storage	-	23.4	32.5	-
E6	Livingroom	0	22.9	29.5	Very good
E6-1	Bedroom	0	22.0	29.5	Very good
E6-2	Bedroom	0	21.6	28.7	Very good
E6-3	Bedroom	0	21.6	28.1	Very good
E6-4	Bathroom	-	22.5	28.7	-
E6-5	Corridor	-	22.4	28.2	-
E6-6	WC	-	23.2	31.8	-
E6-7	Storage	-	23.1	31.2	-

Level 45 (132 m) proposed design overheating simulation results: 2050

Zone	Function	Temperature Exceedance hours of ATG	Average Mean Temperature	Maximum temprature	AGT condition
E1	Livingroom	0	23.2	31.3	Very good
E1-1	Bedroom	0	22.4	29.6	Very good
E1-2	Bathroom	-	24.5	30.4	-
E1-3	Storage	-	24.7	36.4	-
E1-4	corridor	-	23.7	27.9	-
E2	Livingroom	0	23.2	31.4	Very good
E2-1	Bedroom	0	22.4	29.7	Very good
E2-2	Bathroom	-	24.5	29.9	-
E2-3	Storage	-	25.6	36.5	-
E2-4	corridor	-	23.8	28.2	-
E3	Livingroom	62	23.3	34.5	Acceptable
E3-1	Bedroom	14	22.6	32.7	good
E3-2	Bedroom	25	23.0	34.5	good
E3-3	Bathroom	-	23.9	32.2	-
E3-4	Storage	-	24.9	36.3	-
E3-5	WC	-	24.4	30.2	-
E3-6	corridor	-	23.9	29.2	-
E4	Livingroom	76	22.6	34.2	Acceptable
E4-1	Bedroom	7	22.3	32.0	Very good
E4-2	Bedroom	0	22.2	29.6	Very good
E4-3	Bedroom	0	22.0	29.7	Very good
E4-4	WC	-	23.7	30.3	-
E4-5	corridor	-	23.1	28.8	-
E4-6	Bathroom	-	23.7	30.5	-
E4-7	Storage	-	25.2	37.1	-
E5	Livingroom	18	23.2	33.4	Good
E5-1	Bedroom	0	22.2	30.0	Very good
E5-2	Bedroom	0	22.1	29.9	Very good
E5-3	corridor	-	23.8	34.0	-
E5-4	Bathroom	-	24.3	33.9	-
E5-5	Storage	-	25.2	37.3	-
E6	Livingroom	12	23.4	32.8	Good
E6-1	Bedroom	6	22.8	32.2	Very good
E6-2	Bedroom	0	22.9	31.4	Very good
E6-3	Bedroom	0	22.5	29.8	Very good
E6-4	Bathroom	-	23.8	31.8	-
E6-5	Corridor	-	23.6	29.0	-
E6-6	WC	-	23.9	29.8	-
E6-7	Storage	-	24.8	35.9	-

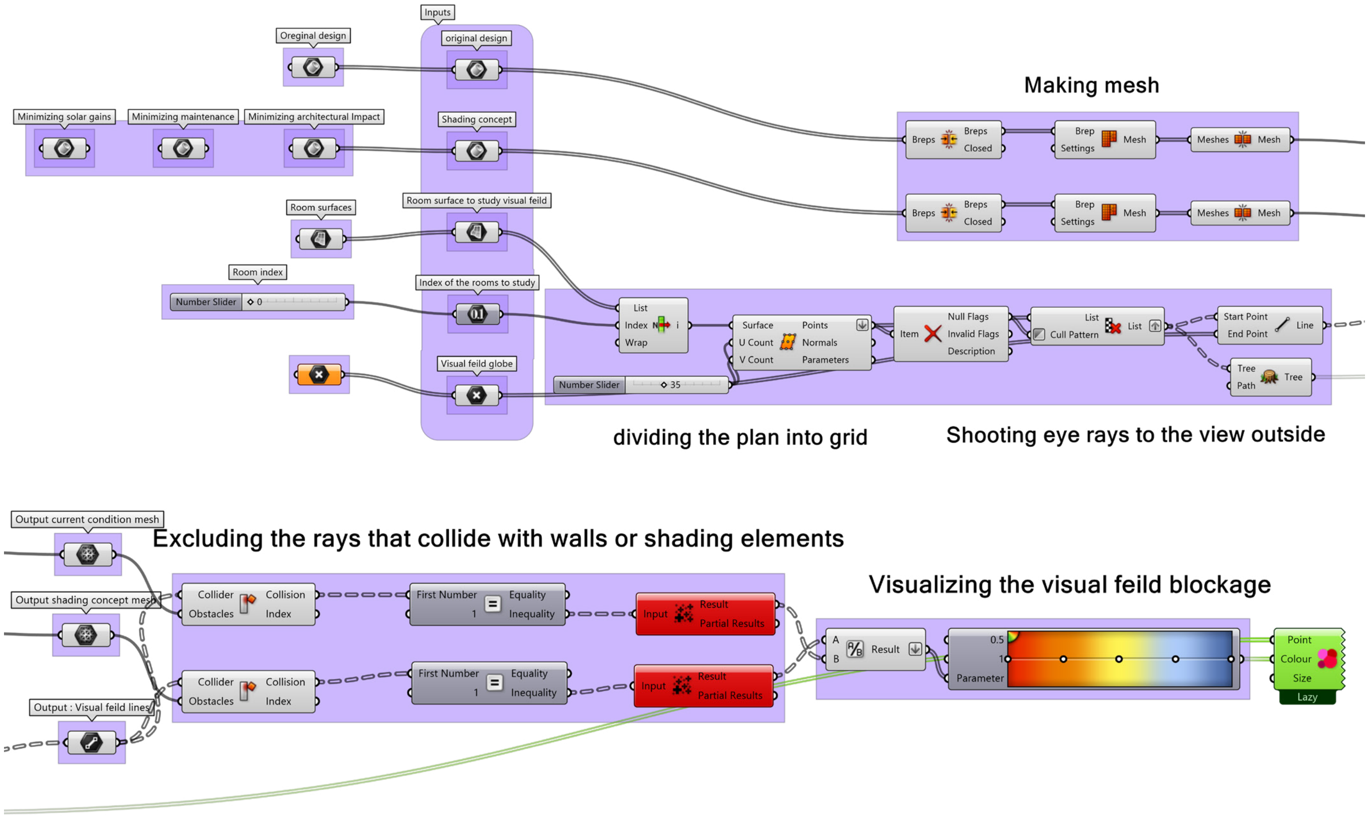
Level 45 (132 m) proposed design overheating simulation results: 2085

Zone	Function	Temperature Exceedance hours of ATG	Average Mean Temperature	Maximum temprature	AGT condition
E1	Livingroom	2	24.1	32.1	Very good
E1-1	Bedroom	0	23.3	31.0	Very good
E1-2	Bathroom	-	25.4	31.8	-
E1-3	Storage	-	25.9	35.3	-
E1-4	corridor	-	24.9	29.5	-
E2	Livingroom	3	24.8	34.0	Very good
E2-1	Bedroom	0	23.7	33.0	Very good
E2-2	Bathroom	-	25.6	31.3	-
E2-3	Storage	-	26.2	35.4	-
E2-4	corridor	-	25.4	33.9	-
E3	Livingroom	123	24.4	35.3	Acceptable
E3-1	Bedroom	52	23.6	34.4	Good
E3-2	Bedroom	80	24.1	34.7	Acceptable
E3-3	Bathroom	-	24.9	32.8	-
E3-4	Storage	-	25.7	35.4	-
E3-5	WC	-	25.6	32.9	-
E3-6	corridor	-	24.5	30.9	-
E4	Livingroom	144	24.0	35.6	Acceptable
E4-1	Bedroom	21	23.4	33.6	Good
E4-2	Bedroom	0	23.5	31.1	Very good
E4-3	Bedroom	0	23.3	31.2	Very good
E4-4	WC	-	24.3	31.3	-
E4-5	corridor	-	24.0	30.5	-
E4-6	Bathroom	-	24.7	31.2	-
E4-7	Storage	-	26.0	36.0	-
E5	Livingroom	53	23.9	34.4	Good
E5-1	Bedroom	0	23.0	31.5	Very good
E5-2	Bedroom	0	23.1	31.4	Very good
E5-3	corridor	-	23.9	29.4	-
E5-4	Bathroom	-	24.7	30.9	-
E5-5	Storage	-	26.0	36.2	-
E6	Livingroom	46	25.0	34.0	Good
E6-1	Bedroom	18	23.7	33.9	Good
E6-2	Bedroom	4	24.0	33.1	Very good
E6-3	Bedroom	0	23.8	31.5	Very good
E6-4	Bathroom	-	24.0	31.0	-
E6-5	Corridor	-	24.2	30.5	-
E6-6	WC	-	24.6	30.7	-
E6-7	Storage	-	25.4	35.0	-

Appendix G. Visual access analysis workflow

In order to find the visual field blockage by each design variations, the interior spaces and the static shading elements were modelled in a Rhino. The metal mesh which does not entirely block the visual access was modelled as a surface with 50 % porosity.

Each living zone was modelled and was divided by a grid in human eye level. Then The visual field of each grid point was compared with the visual field of the original design in order to find the percentage of visual blockage at each point. The grasshopper algorithm can be seen in the bellow.



Appendix H. Innovative solution concepts

PCM integrated internal shading

This concept suggests using a combination of PCM integrated shading and ventilation inlets in order to make a decentralized ventilation unit. As can be seen in the figure during the day the PCM curtain could be used in order to store the solar energy in the thermal storage and slow down the heat built up in between the shading and the window. This allows for ventilating the cavity before the heat built up. So in summer fresh air could come inside from the opening in the ventilation box and the heat in the cavity can be ventilated by the openings in the window. Then during the summer nights, when the shading is closed the PCM could be regenerated by ventilating the ventilation box. Also, during the winter nights, it could be used as a decentralized ventilation unit by preheating the incoming air. This also helps to prevent overheating during the sunny winter days which additional solar gains could increase the temperature, especially in apartments with a floor heating system.

However, this concept was not used for this project because of the following disadvantage:

Since in the future because of the climate change the diurnal temperature is higher than the indoor temperature, ventilating the cavity could bring additional gains by letting the hot outdoor air inside.

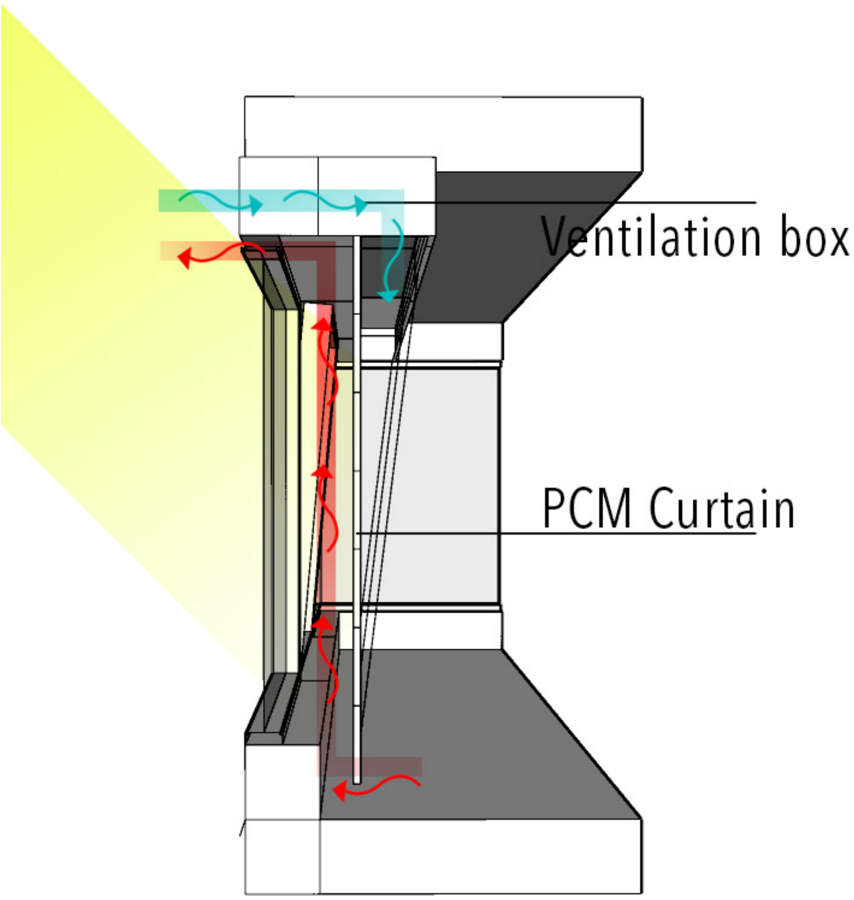


Figure H.1: During the day PCM stores the solar gains.

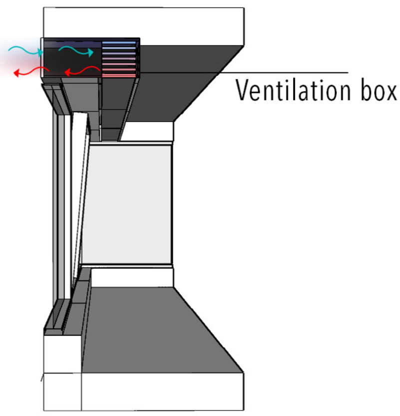


Figure H.2: Summer nights

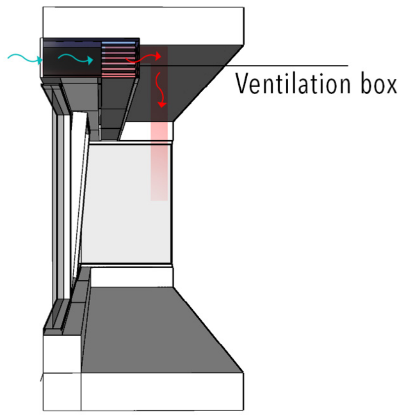


Figure H.3: Winter nights

Vertical sliding shutter

In this concept, a combination of verticaly sliding shutters with openable windows were suggested for both ventilation and shading. Since Cooltoren benefits from wide horizontal opaque strips between the floors, these strips could be used for placing the vertical shutters (Figure 4). Then during the sunny days or when there is too much wind these shutters could be closed in order to provide shading and wind protection (Figure 5).

However, Since the system railing system is positioned verticaly the uplift force of the wind could cause problems for operation of the system. Also, Very high cost of the system makes it economically unfeasible to use.

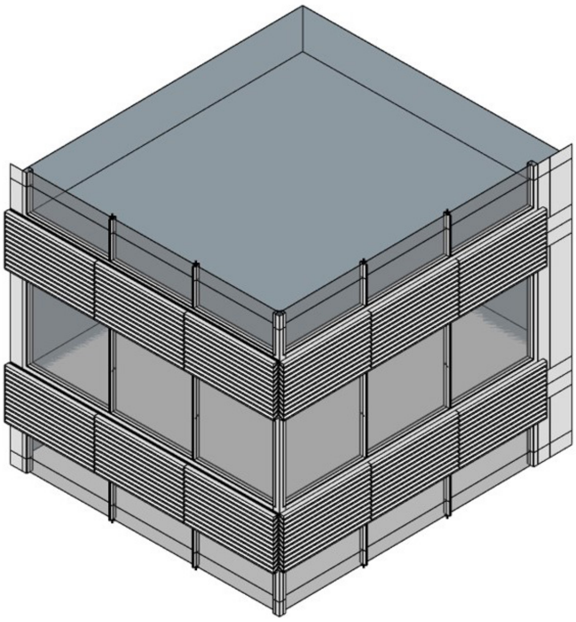


Figure H.4: Verticaly sliding shutters place on the opaue parts of the facade

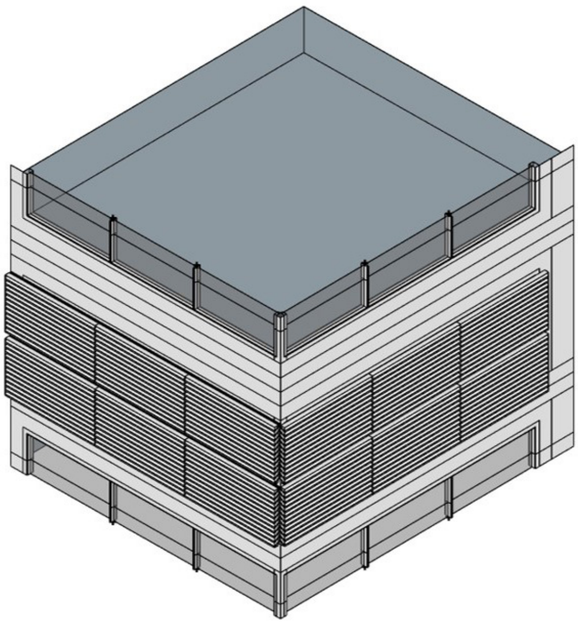


Figure H.5: Shutters in close position

Folding shutter

In this concept sliding folding shutters were considered for shading and ventilation. The motorized floding shutters were used in order to shade a percentage of the windows. The shutters are connected to the sliding windows in order to be used as wind and fall protection when the windows are open for ventilation. Polorized coating were considered for the window, so when sliding window is open the solar gains further is reduced by the dimming effect of the polorized coating on the windows.

Although wind stable, these system could make loud rattling noise because of the high wind speed at high-rise buildings making this concept to not meet the acoustic requirments.

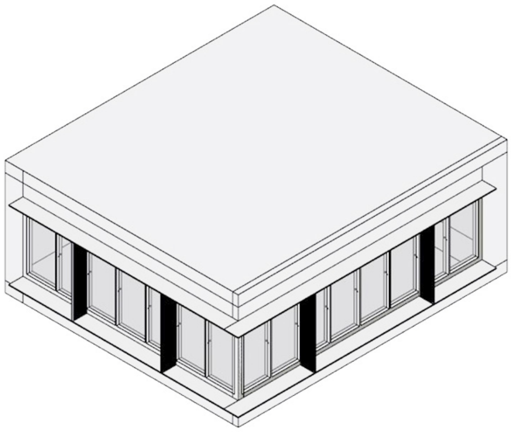


Figure H.6: Folding Shutters in close position

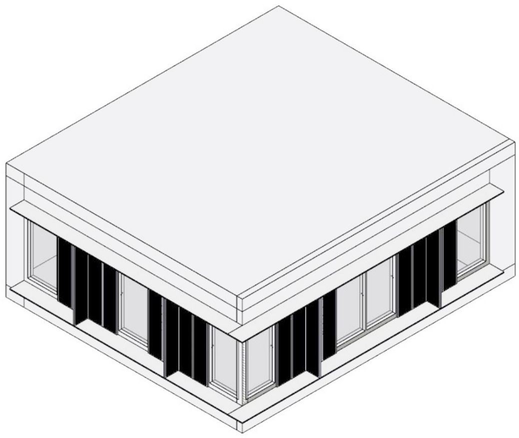


Figure H.7: Folding Shutters in open position

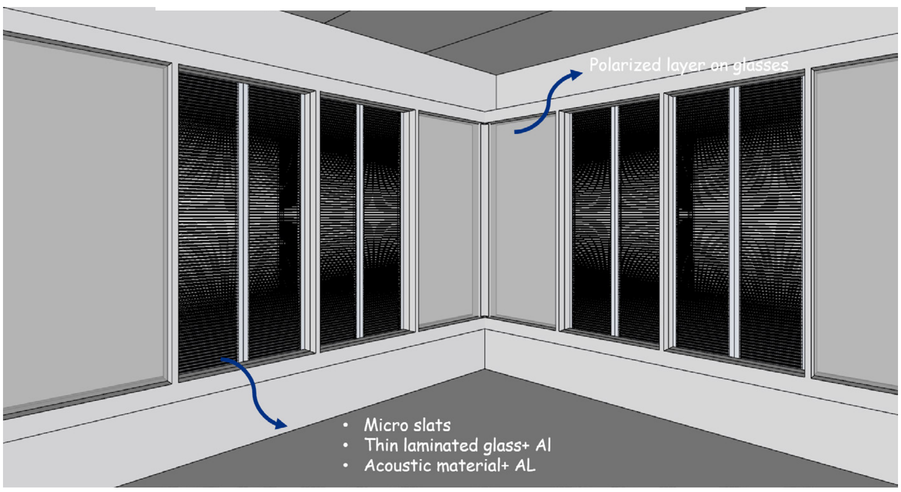


Figure H.8: Inside view of the folding shutters.

Forward oepnings window with ventilation grills

In this concept, top or bottom hunged forward opening window is connected to a ventilation grill (Figure 9). When the window is tilted outward the ventilation grill connected to the edge is placed on the opening to protect the opening from high wind speed (Figure 10). Also, the fins on the sides of the windows and the weather protecting overhangs help to shade the indoor space and to structuraly support the window so the wind could not rip it from the façade.

However, this concept was not used for this project because of the following disadvantage:

Additional moving part on the window makes it hard to maintain and mechanicaly complex. These results in for this conept to become not robust for residential use.

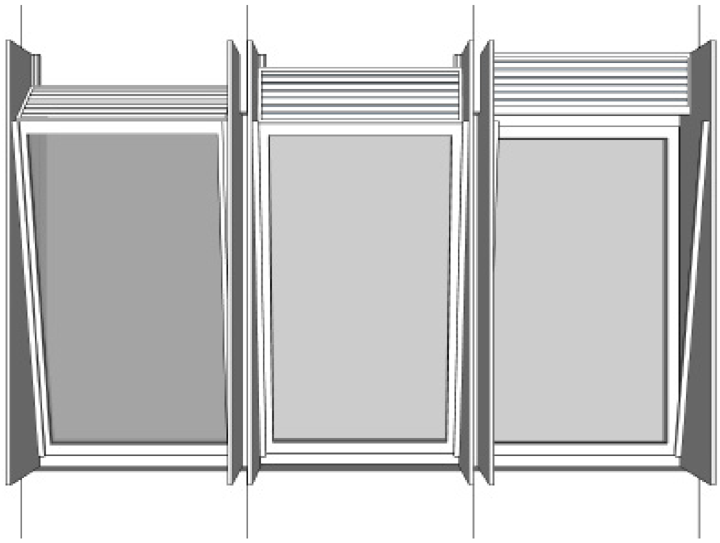


Figure H.9: The ventilation grill is positioned on the opening when the window is open.

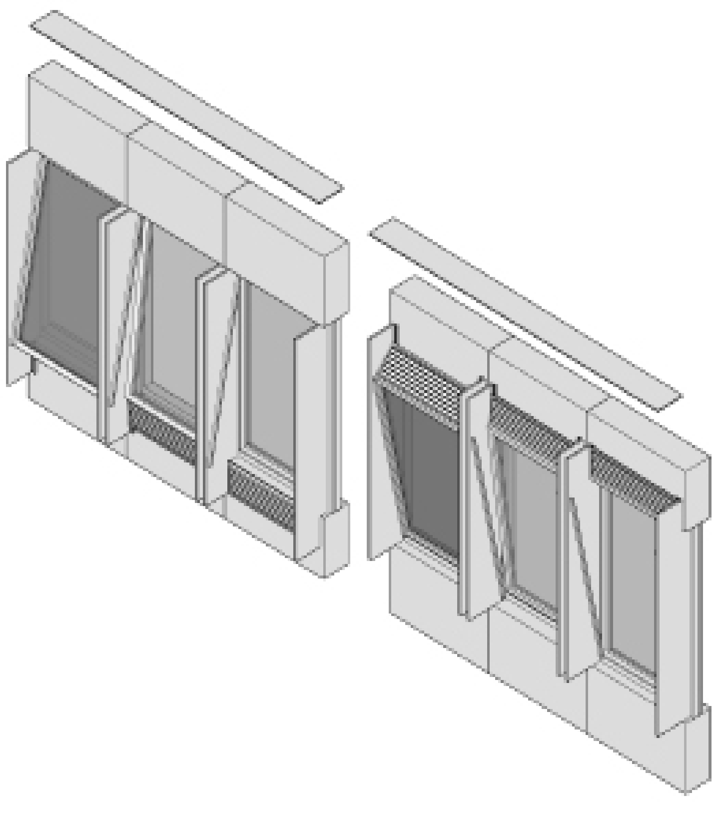


Figure H.10: The fins positioned on the sides of the openings could work as a shading beside structural support for the window.

Ventilation box with solar chimney

In this concept a ventilation box is positioned on top of the window openings. In corner rooms the ventilation box could harvest wind from different direction allowing for wind speed control and air pressure control. In addition harvesting wind from windward sides help to maintain positive air pressure in the box. With outward windows opening in the box the air then could be directed inside for ventilation. The solar chimney is used as the exhaust and to help air circulation in the rooms.

The other benefit of the box and outward tilting window is that the box could provide shading for the glazings. Also, when the window is tilted outward the solar incident degree increases allowing for more reflection and thus less solar gains.

However, the mechanical complexity of the ventilation box makes it unfeasible for residential buildings.

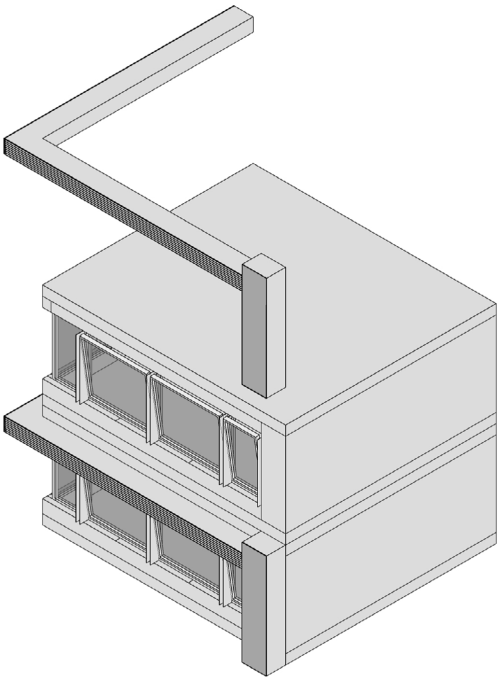


Figure H.11: Positioning ventilation box on facade on top of the windows

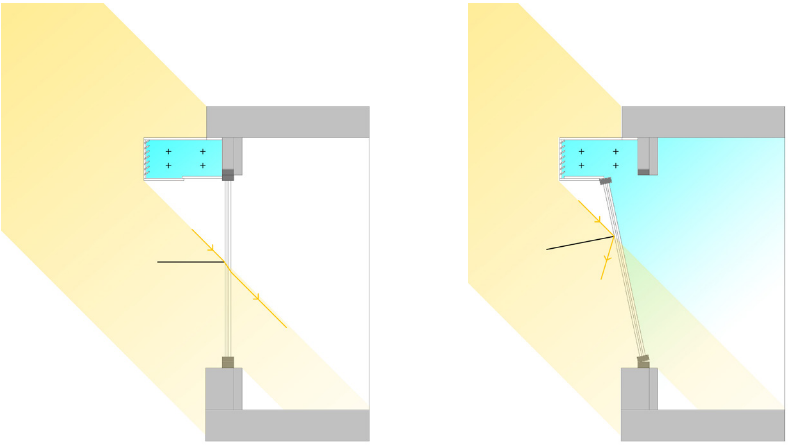


Figure H.12: Working principle of the ventilation box with the window system.

Shading ventilation flap

In this concept the ventilation flap with pressure control system is positioned outside. When the window is closed the ventilation flap and its supports work as shading elements. When ventilation is required the window could open in the flap. The falp then could work as wind protection. Also, wingwall shape positioning of the flaps helps in effective air circulation inside the building espicaly in calm days.

However, this concept was not used for this project because of the following disadvantage:

The outter positioned window sill/support becomes dirty due to weather exposure. When the window is opened in the flap the dirt from the sill could be transferred inside and cause health problems.

Figure H.13: In closed position. The flap elements and its horizontal supports provide exteranl shading.

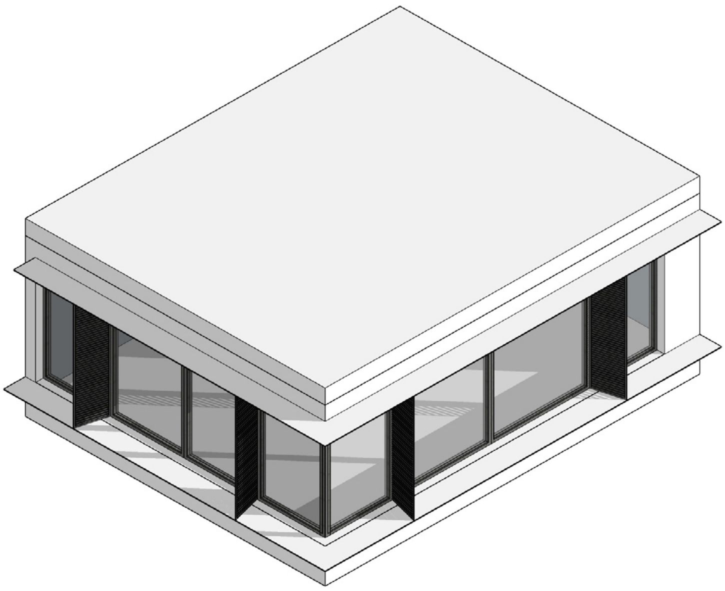
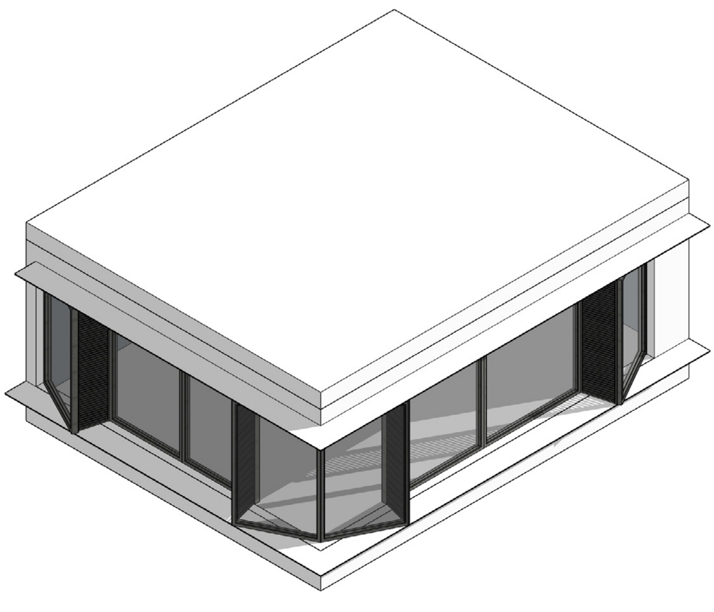


Figure H.13: In open position.



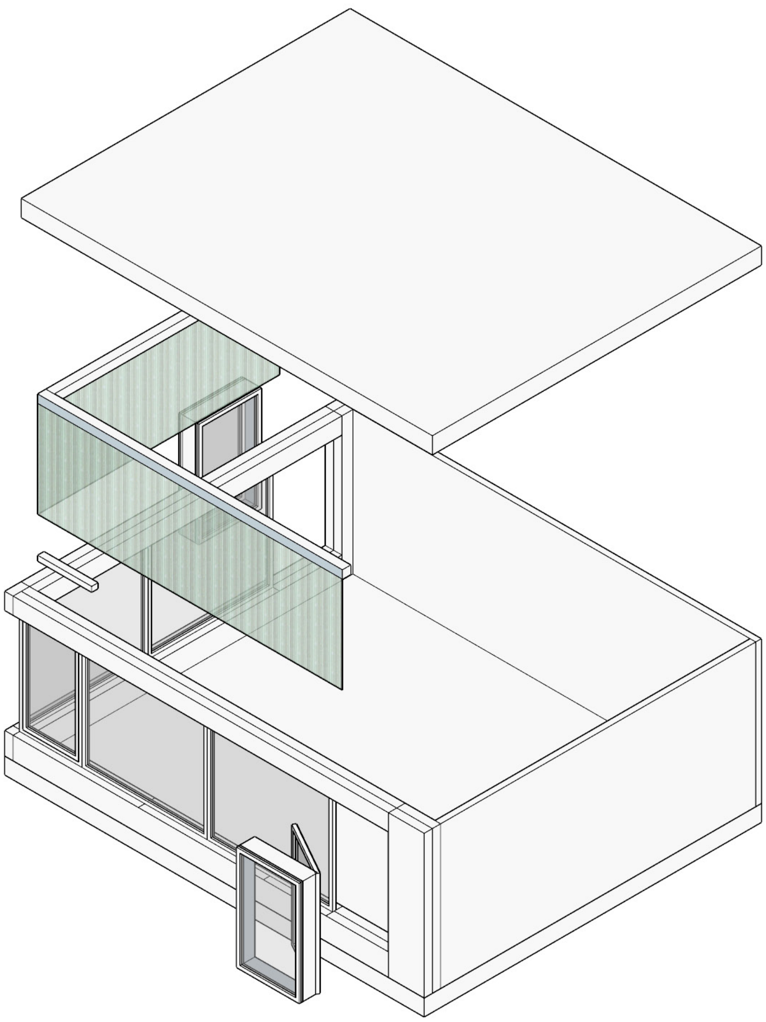
Climate facade

In this concept the principles of climate façade were considered for overheating protection. In order to make an alternating façade, double skin box windows with cavity shading were considered on the corners of the zones for effective ventilation and air circulation even with high wind speed.

For solar protection an reflective fabric were considered for the single skin part of the façade. The fabric rolls down when the solar radition is high to protect the indoor space from the solar gains. The hot air traped in the cavity between the glass and the fabric then is exhausted using fans to prevent heat built up in the cavity.

However, Since in the future the diurnal temperature is higher than the indoor temperature because of the climate change, ventilating the cavity could bring additional gains by letting the hot outdoor air inside. Also, the convection and radition of the hot surface of the fabric brings additional solar gains inside. Because of these reason it was decided to not apply this concept.

Figure H.14: Alternating facade concept.



Solar chimney for rooms in between balconies

The simulations showed that the smaller bedrooms facing West and East are at higher risk of overheating in lower levels. The reason for this is the low air exchange rate of this single-sided rooms in calmer days. To solve this problem, small solar chimnies were considered for these rooms. First analytical calculations showed that this method is good enough to induce ventilation for the smaller rooms. However, later the numerical experiments showed that since the chimney is placed in the location in between balconies, it does not perform well during the times it was needed to induce natural ventilation.

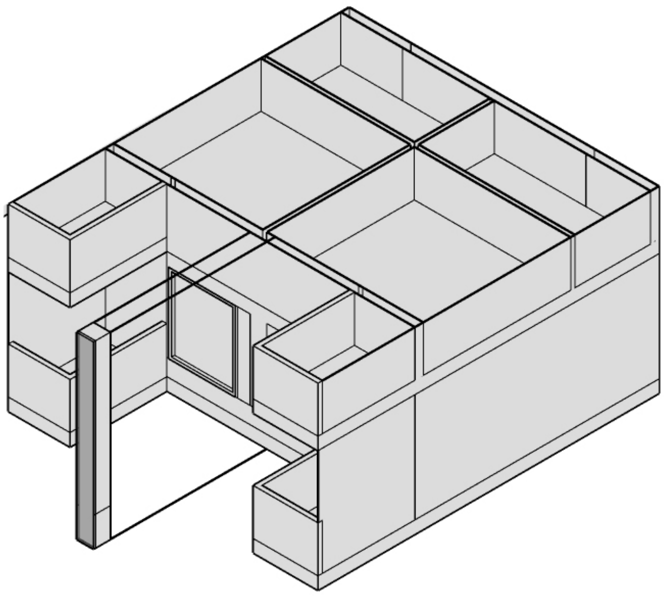


Figure H.14: Placing solar chimnies for small West & East facing bedrooms.

Appendix I. Simulation workflow of the innovative design

I.1. Modelling window-box modules

Using outline blocks the module where modelled where it has to be placed on the façade and was merged with the apartment block in order to define the new block as an apartment zone. The activity of the new zone then was set to "Cavity". Cavity's ventilation openings at the bottom and top and the one at the side were modelled as "vents". The internal window was set to operate with "Residential-Occ" schedule.

For in-between shading, "Low transmittance, high reflective" screen with g-value of 0.1 were used. The control type of the shading was set to "Solar" with a set point of 120 W/m2

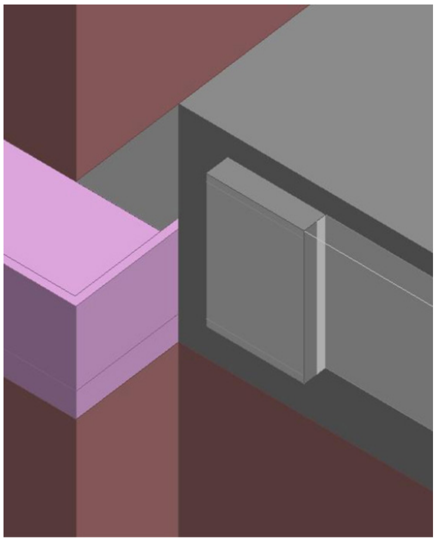


Figure 1: The position of the double-skin module on facade

	U-value	g-value
Internal window	1.21 w/ m2k	0.6 (-)
External glass	1.21 w/ m2k	0.5 (-)
Frame	2.7 w/m2k	-

Table 1: Box-window's surface properties

I.2. Modelling ventilation flaps

To model the modulating effect of the flap due to the wind, the area behind these openings were separated with virtual partitions. Then using "opening factor function wind speed" tool a quadratic curve with constant maximum and minimum values were made for the apartment at level 45 to define the effect of the wind speed on the modulation of the windows (Figure 3). The modulation effect was simplified by averaging the opening factor of the self-regulating flaps in different conditions.

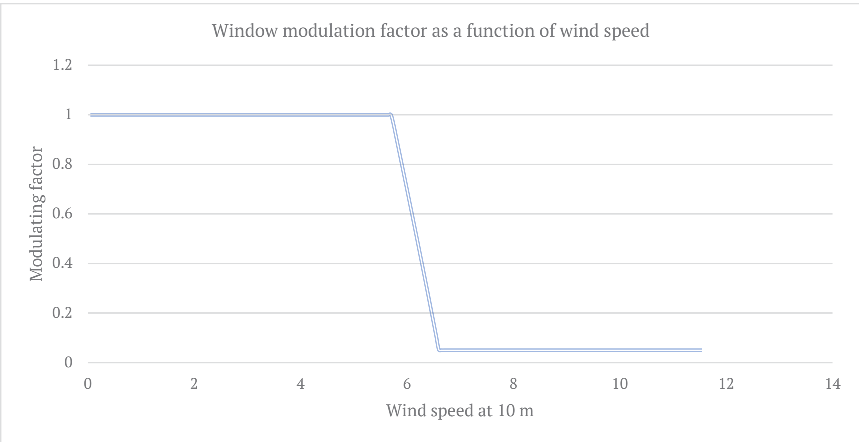


Figure 3: Window opening factor curve

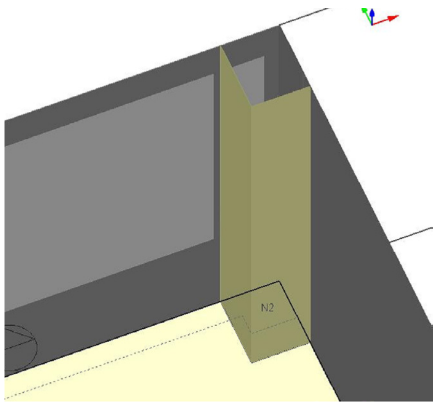


Figure 2: Using virtual zones for defining seprate ventilation settings in one room.

I.3. Shading devices

Vertical shadings were modelled using component blocks. To include the effect of the smart glass to be opaque on the effect of solar radiation, the transmittance value of the component block was set to 0.8 (-). Then using grasshopper's "Ladybug" tool the hours in which the solar radiation on the defined surfaces was higher than 120 w/m2 for a typical summer day were found and from that, the transmittance schedule of the components was defined.

I.4. Mechanical ventilation

Same ventilation values as in Appendix C were used for the rooms. In order to include the effect of the heat recovery, the "Heat recovery" was set to "on" with sensible heat recovery effectiveness of "0.9".