Natural & decentralised ventilation and climate concepts

Jeroen ter Haar

A research into existing ventilation and climate concepts, both natural and mechanical based, the advantages and disadvantages of decentralised concepts and a proposal for a new natural-decentralised hybrid concept.
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Abstract

This report tries to answer the question:

Can a hybrid system, combining the good air quality and low costs of a natural system with the user-adjustability, energy efficiency and small size of a decentralised mechanical system, offers a feasible, sustainable alternative to current ventilation concepts?

In an attempt to do so, the Climat Cavity facade concept has been developed, a facade that uses the glass cavity to either pre-heat supply air with thermal energy leaving the building through the facade and solar radiation, or uses the cavity to extract solar heat gain and room air by using the solar chimney effect.

The climate cavity facade concept aims to invest the same money that would otherwise be spend on a (central) ventilation system, into the facade which provides the ventilation, but simultaneously offers the advantages of a second skin facade, being reduced energy consumption in terms of heating and cooling and improving thermal comfort.

Apart from that, the concept offers a low maintenance and low fan-energy ventilation system, that always provides fresh air without the interruption of filters, heat exchangers or ducts. Also, the concept allows users to influence their climate and make decisions in terms of pre-heating and conditioning air, opening a window and solar heat/light entry.

Where the second-skin facade and climate facade concepts rely on mechanical ventilation for the interior, the climate cavity facade aims to be a natural alternative, providing air directly from the outside and using buoyancy and solar radiation to help provide ventilation.

The Climate cavity, a ‘natural ventilation - decentralised mechanical ventilation’ hybrid system, can offer improvement in terms of maintenance, fan energy, solar heat gain, user/room adjustability, space consumption and air quality. On the other hand, points of critique are the relatively low heat recovery at this moment, investment costs that could be higher, the uncertainty of cleaning frequency and acoustic comfort. These points will require further research and development before the concept can be applied to an actual building.
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1 Introduction

This first chapter gives an introduction to the outline of the research. Starting with the problem statement (§1.1) that lead to this subject, next the research question and scope of this research (§1.2), followed by the research framework (§1.3), the approach to this subject. Lastly the (sustainable) relevance of this research will be discussed (§1.4).

## 1.1 Problem statement

Every building has a ventilation system based on one out of two groups: natural based ventilation or mechanical ventilation. Hybrid concepts exist, adding mechanical extraction for example, but a ventilation concept always seems to have the problems of one of both groups.

- Natural based systems often experience discomfort, because air is not pre-heated, causing draft problems, the airflow is uncontrolled and can be unreliable. Apart from that there is usually no possibility for heat recovery, meaning high energy loss and external problems like sound, burglary and rain are often a problem.

- Mechanical systems are prone to air contamination due to poor design or a lack of maintenance because their are many elements the supply air has to pass before it reaches the interior. Also, they are usually not adjustable by individual users and don’t allow for purge ventilation (opening a window). Apart from that, investment, maintenance and operation energy costs can be very expensive and the system often consumes a lot of space.

Due to ever rising demands for energy efficiency, heat recovery, and therefore a mechanical system, has become the standard in non-residential buildings and is rising in popularity in houses too. Complaints about the sick building syndrome and lack of influence on the conditions seem to be the result of these systems. Even though the system are far superior in theory, practice often reveals a lot of problems.

A sub-group that’s slowly coming up, are the decentralized mechanical systems, offering ventilation and possibly heating and air conditioning, with heat recovery in a small unit. The advantage being that these are regulated per unit/room and don’t use a one-size-fits-all approach, and lack ducting which reduces energy costs and waste of space. However, at this point most of these system can’t cope with central mechanical HVAC systems in terms of costs. These systems are mostly confined to renovation projects, though exceptions definitely exist.

## 1.2 Research Questions & scope

The aim of this research is to first achieve knowledge of the existing situation and concepts of ventilation and climate systems. Research the differences between and identify the advantages and disadvantages or problems that all the systems have. Ultimately a new ventilation concept will be proposed, taking into account the findings from the analysis.

The research question for this new design is:

Can a hybrid system, combining the good air quality and low costs of a natural system with the user-adjustability, energy efficiency and small size of a decentralised mechanical system, offers a feasible, sustainable alternative to current ventilation concepts?

The advantages of a natural system being the good air quality, the feeling of a fresh breeze when opening a window, the understandable, fool-proof simplicity of the system and the low investment, maintenance and operation costs.

Sub questions in order to determine this are:

1. What is the current state of the art of ventilation systems? What concepts exist, how do they function?
2. What are the costs in terms of investment, maintenance and operation costs of current concepts?
3. How are these concepts integrated into the framework of a building?
4. Is the proposed new concept feasible in terms of (thermal/acoustic) comfort, energy efficiency, investment, maintenance and operation costs and in aesthetic value?
5. How does the new concept position itself towards existing concepts. What are the advantages?
1.3 Research framework

The following graph show the approach to this research on how to achieve the expected result:

- Literature
- Existing systems
- Reference projects
- Data of users/manufacturers
- New design
- Calculations
- Conclusions & feasibility

The first step would be literature research into the basics of ventilation, physical forces behind ventilation, regulations for buildings, the current situation and ongoing discussions.

The next step is an analysis of existing ventilation and/or climate solutions available on the market or in development by manufacturers. Apart from that a research into how these systems are applied into buildings, how they integrate into the facade and with other climate systems is part of this step. Also the statistics behind these systems are very important to get an overview of how they relate to each other in terms of energy consumption, capital costs, maintenance (costs), sound levels and damping, airflow etc. This data will also be necessary to determine the feasibility of the new design.

The third step is the new design. Based on the knowledge of the first two steps, a new concept that offers a new approach will be designed.

To estimate the performance of this new design in terms of energy usage, comfort etc. calculations and research models will be the next step. This will result in adaptations of the design and can eliminate unfeasible ideas in an early stage.

The last step are conclusions based on the calculations and data from existing solutions to determine whether the new design is feasible, in order to answer the research question.

1.4 Relevance of research/sustainability

The central mechanical ventilation concept is no longer the only option. Other approaches like naturally ventilated schools, houses and offices with hybrid ventilation instead of balanced mechanical ventilation and decentralized units like the Climarad are rising in popularity. There is an ongoing discussion into the benefits and disadvantages of natural, hybrid, mechanical and decentralized ventilation and climate systems.

Possible (sustainable) advantages of these developments include the following:

- Reduced energy costs by reducing fan power and heating and cooling costs by addressing local demands instead of the entire building as a whole.
- Reduced building costs and material use by eliminating the need for ducts, plant rooms and others.
- Improved user satisfaction by allowing users to influence their climate.
- Improved air quality by preventing the need for ducts, filters and other elements between the exterior and interior, which also reduces maintenance.
2 Introduction to ventilation

This chapter serves as an introduction to ventilation in general. It is an overview of necessary background information as well as information on groups on ventilation systems and when and how they are being applied, which together with chapter 3 and 4 aims to answer the first research question: ‘What is the current state of the art of ventilation systems? What systems exist and how do they function?’

This chapter gives an overview of ventilation in general at first (§2.1), followed by the regulation and the effects on the indoor comfort (§2.2). After that an overview of all different groups of ventilation concepts will be discussed (§2.3). These are four groups, some with sub groups, in which almost every ventilation system can be classified. Every group will be discussed separately, listing the advantages and disadvantages of every system. The following paragraph(§2.4) focuses on the discussion between natural and mechanical ventilation systems and why some are used in specific situations.

2.1 Ventilation basics

Ventilation is necessary in every building because of the following reasons:

- Provide fresh air for respiration, about 0.1 to 0.2 l/s per person
- Preserve the correct oxygen levels at about 21% 
- Control CO₂ levels to stay below 0.1% (above 2% is fatal)
- Control moisture levels, relative humidity should be between 30 and 70 %
- Remove excess heat from the space
- Dispose of odours, smoke, dust and other atmospheric contaminations
- Relieve stagnation and provide a sense of freshness, 0.15 - 0.5 m/s is adequate.

(Holl & Greeno, 2013)

Apart from that ventilation provides the psychological sense of ‘freshness’ and connection to the outside.

The driving force behind ventilation can be divided into two groups, namely natural ventilation, based on natural occurring forces, and mechanical ventilation, powered by electric fans.

2.1.1 Natural ventilation

Natural ventilation occurs due to two driving forces, buoyancy, the difference in weight between two substances, and due to wind creating a pressure difference between two openings (other sides of the facade for example). The most common form of natural ventilation is to simply opening a window or facade vent.

Buoyancy occurs due to a higher temperature inside a building than on the outside, decreasing the density and causing it to ‘float’ atop the colder ‘heavier’ air. An opening in the roof will allow air to flow out, forcing air to enter through a different opening. Alternatively, a temperature difference can be achieved by using the sun’s radiation to heat the air, in a solar chimney. An example of this of the building of the ROC Twente, in Hengelo. The building uses solar chimneys to extract air from atria.

The airflow as a result of buoyancy can be approximated by the following equation:

\[ Q = C_d \times A_e \times \frac{2 \times g \times h \times \Delta T}{T_e} \]

- \( Q \) resulting Airflow [m³/s]
- \( C_d \) discharge coefficient for opening = 0.8 [-]
- \( A_e \) equivalent opening area [m²]
- \( g \) gravitational acceleration = 9.81 [m/s²]
- \( h \) height difference between openings [m]
- \( \Delta T \) temperature difference inside - outside [°K]
- \( T_e \) outdoor temperature [°K]

The equivalent opening area is defined by:

\[ \frac{1}{A_e} = \frac{1}{A_{e1}} + \frac{1}{A_{e2}} + \ldots \]

- \( A_e \) equivalent opening area [m²]
- \( A_{e1} \) opening 1 [m²]
- \( A_{e2} \) opening 2 [m²]

2.1.1 Solar chimneys on the roof of the ROC Twente
The force of wind will force air to enter on the windward side and extract air on the leeward side. This can occur on two sides of the building (cross-ventilation) or in a single room/on one side of the building by opening windows in opposite direction. In some occasions ‘wind cowls’ have been used to guide air in and out through the roof as well, for example in the BedZED project near London. These wind cowls orient themselves automatically towards to wind because of the fin on top.

The airflow resulting from wind force can be approximated by:

\[ Q = C_d \cdot A_e \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho}} \]

\( Q \) resulting airflow \( [m^3/s] \)
\( C_d \) discharge coefficient for opening = 0.8 \([-]\)
\( A_e \) equivalent opening area \( [m^2] \)
\( \Delta P \) pressure difference \( [\text{kPa}] \)
\( \rho \) density of air = 1.2 kg/m^3 \( [kg/m^3] \)

The pressure difference can be approximated by:

\[ \Delta P = \left( C_{pw} - C_{pl} \right) \cdot \frac{\rho \cdot v^2}{2} \]

\( \Delta P \) pressure difference \( [\text{kPa}] \)
\( C_{pw} \) wind pressure coefficient windward side \([-]\)
\( C_{pl} \) wind pressure coefficient leeward side \([-]\)
\( \rho \) density of air = 1.2 kg/m^3 \( [kg/m^3] \)
\( v \) wind speed \( [m/s] \)

### 2.2 Regulations and comfort

Regulations in the Dutch building decree for non-residential buildings (utility sector) are based on the amount of people in a room. For residential buildings the regulations are based on floor area.

The regulations described in the Dutch building decree are as follows:

#### 2.2.1 Residential buildings

**Capacity**

The installations in a residential building must be able to achieve to following air changes per square meter floor area. This doesn't mean that this much ventilation is neccesary at all times, but it must be possible.

<table>
<thead>
<tr>
<th>Function</th>
<th>minimum capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupied space</td>
<td>&gt;0.9 l/s per m²</td>
</tr>
<tr>
<td>Toilet</td>
<td>&gt;7 l/s per m²</td>
</tr>
<tr>
<td>Bathroom</td>
<td>&gt;14 l/s per m²</td>
</tr>
<tr>
<td>Kitchen</td>
<td>&gt;21 l/s per m²</td>
</tr>
</tbody>
</table>

**Sound**

The maximum sound production of ventilation and heating installations in occupied space (living room, bedroom, not hallways etc.) should not exceed 30 dB

**Thermal comfort**

In an effort to improve thermal comfort, some regulation exist for air velocity and vent placement. The air velocity in ‘living area’ of occupied space should not exceed 0.2 m/s. The ‘living area’ is defined as the space that’s 1 meter apart from the facade, 0.2 meters from interior walls and up to 1.8 meters in height. Outside of the living space there are no regulations.

For the placement of supply vents exists no regulation, but a recommendation to place them above 1.8 meter from the floor. It is allowed to place the vent lower, but it must be proved that air speeds do not exceed 0.2 m/s.

These are the only regulations for thermal comfort in the Dutch building decree. However, thermal comfort is defined by much more than air speed and fan placement. According to Fanger, the following factors are to be taken into account:

- Air velocity
- Air temperature
- Surface temperature of facade, interior walls, floor and ceiling
- Humidity
- Activity-level of occupants
- Clothing

(\text{Innova-AirTech-Instruments, 2002})

**Controllability**

As far as controllability goes, there is a division between natural inlets and mechanical systems. For natural systems, the air supply (vent) should have a closed and a fully open configuration. Apart from that there should be at least two intermediary configuration between 0% and 30% of the maximum capacity, which should be 10% apart from each other. The closed configuration should not allow more than 10% of the maximum capacity through, in other words, it should close properly. Windows can often be opened stepless and therefore meet the demand.

### 2.2.2 Wind cowls on the roof of the BedZED pavilion
Air quality
For air quality there are two regulations, one for the mixing factor of air and one for the direct supply or extraction per function.

The mixing factor is the degree to which exhaust air leaving the building is mixed with outside air before it (possibly) enters the intake vent. The mixing factor is determined by the following equation:

\[ f = \frac{\sqrt{Q}}{C_1 + l + C_2 + \Delta h} \]

- \( f \): mixing factor [-]
- \( Q \): exhaust airflow [l/s]
- \( l \): distance between vents [m]
- \( C_1, C_2 \): mixing coefficients [-] To be found in table 3 of NEN1087, added in annex.
- \( \Delta h \): height difference vents [m]

The mixing required mixing factor depends on the type of exhaust:
- Ventilation exhaust 0,01
- Gas-fueled (heater) exhaust 0,01
- Other fueled exhaust 0,0015

Note that the mixing factor only applies to ventilation facilities on a single building lot. However, supply or exhaust fans should always be positioned at least 1 meter away from the lot boundary.

Certain functions require direct supply or exhaust, meaning air can’t come from or go to other rooms:
- Occupied space direct supply for at least 50%
- Kitchen direct exhaust for at least 21 l/s of capacity
- Toilet and bathroom direct exhaust

Apart from the regulations, air quality depends on other factors such as present humans and animals, emission from building materials, cleaning products, smoking and outdoor air quality.

Purge ventilation
Every occupied space in a residential building should have the facilities to purge a room, which usually means openable windows. The capacity of the purging facility should be at least 6 l/s per m² floor space.

## 2.2.2 Non-residential buildings

### Capacity
For non-residential building the maximum ventilation capacity should at least be capable of achieving the following air changes. Apart from that there is a minimum occupation for every room to be taken into account. This defines the minimum amount of ventilation.

<table>
<thead>
<tr>
<th>Function</th>
<th>minimum capacity</th>
<th>minimum occupation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meeting room</td>
<td>6,5 l/s per person</td>
<td>spectating sport 0,3 persons/m²</td>
</tr>
<tr>
<td>Childcare</td>
<td>6,5 l/s per person</td>
<td>other 0,125 persons/m²</td>
</tr>
<tr>
<td>Other</td>
<td>4 l/s per person</td>
<td>other 0,05 persons/m²</td>
</tr>
<tr>
<td>Cell function</td>
<td>12 l/s per person</td>
<td>for visitors 0,125 persons/m²</td>
</tr>
<tr>
<td>Cell</td>
<td>12 l/s per person</td>
<td>other 0,05 persons/m²</td>
</tr>
<tr>
<td>Healthcare</td>
<td>6,5 l/s per person</td>
<td>Industrial function 0,05 persons/m²</td>
</tr>
<tr>
<td>Hotel function</td>
<td>12 l/s per person</td>
<td>Office function 0,05 persons/m²</td>
</tr>
<tr>
<td>Educational function</td>
<td>8,5 l/s per person</td>
<td>Educational function 0,125 persons/m²</td>
</tr>
<tr>
<td>Sport function</td>
<td>6,5 l/s per person</td>
<td>Sport function - persons/m²</td>
</tr>
<tr>
<td>Retail function</td>
<td>4 l/s per person</td>
<td>Retail function - persons/m²</td>
</tr>
</tbody>
</table>

### Sound
The only regulations for sound for non-residential building are for educational and childcare functions. The maximum sound production of ventilation and heating installations in occupied space should not exceed 35 dB in these rooms.

### Thermal comfort
For non-residential building the same regulations apply as for residential buildings. Air velocity should not exceed 0,2 m/s inside the livings space of occupied spaces.

### Controllability
The same requirements for natural supply openings applies as for residential buildings. Vents/windows should have a closed, fully open and two intermediary configurations within the range of 0% - 30%, at least 10% apart.

### Air quality
The same regulations apply as for residential buildings, with the exception of the 50% rule for occupied space. Non-residential building should have 100% of the air supply directly from the outside.

### Purge ventilation
Educational buildings and childcare should have facilities to purge a room. For other building types there are no regulations.

(H. Valk. Praktijkgids Bouwbesluit Ventilatie (2013))
2.3 Ventilation concepts

Like mentioned before, ventilation is either natural-driven or mechanical. The combination of supply and extraction creates 4 different main groups to be distinguished:

<table>
<thead>
<tr>
<th>System</th>
<th>Supply</th>
<th>Exhaust</th>
<th>Also know as</th>
</tr>
</thead>
<tbody>
<tr>
<td>System A</td>
<td>Natural</td>
<td>Natural</td>
<td>Natural ventilation</td>
</tr>
<tr>
<td>System B</td>
<td>Mechanical</td>
<td>Natural</td>
<td>Overpressure ventilation</td>
</tr>
<tr>
<td>System C</td>
<td>Natural</td>
<td>Mechanical</td>
<td>Mechanical ventilation/natural ventilation</td>
</tr>
<tr>
<td>System D</td>
<td>Mechanical</td>
<td>Mechanical</td>
<td>Balanced ventilation</td>
</tr>
</tbody>
</table>

Other groups include

System C+ natural supply through demand-regulated vents, with mechanical extraction. Vents can be regulated through CO₂ or humidity sensors to vent only when necessary, reducing ventilation and heat loss to a minimum.

System E also know as system D (decentralized): Mechanical supply and exhaust through a decentralized ventilation unit (in the facade). Every room has its own ventilation unit.

System X anything outside of mentioned groups. Usually for a combination of different systems, for example system E for one room and C for others.

2.3.1 System A

The simplest of all the systems. System A consist of nothing more than adjustable inlets in the facades (windows or vents) and vertical exhaust shafts. Air enters the building through wind pressure and is extracted due to buoyancy through the vertical shafts (chimneys). The shafts are located in the 'wet' rooms to extract 'polluted' air and moisture. Mechanical extraction is often present in kitchens. Air flows between rooms through overflow vents or underneath doors.

Advantages:
- Low investment costs
- No operation costs (no fan energy consumption)
- No sound production (no fans)
- Supply air is always 'fresh'

Disadvantages:
- Highly dependent on external conditions
- High heat loss (no heat recovery)
- Possible noise problems from outside
- Exhaust shafts have to be almost vertical

In order to reduce problems, special vents are available. Silenced vents to damp outside sound levels are a common solution for noise. Wind-pressure regulated vents are also available to prevent excessive heat loss and draft during the winter.

System A is still present in a large portion of existing residential buildings, but is no longer being applied in new buildings, because proper ventilation cannot be guaranteed at all times and because of the high heat losses.

2.3.2 System B

System B consist of supply ducts to occupied spaces and (vertical) extraction shafts/ducts in 'wet' rooms. Unlike other systems, system B creates an overpressure inside the building, preventing air to enter through gaps and other accidental openings.

Advantages:
- Guaranteed air supply
- Sound damping usually easily possible

Disadvantages:
- Some investment costs
- Energy consumption by fan
- Sound production by fan
- High heat loss (no heat recovery)
- Possible draft problems (cold supply air)
- Proper cleaning is required to prevent contamination of supply air

System B is very oncommon in both residential and non-residential buildings. In some occasions this system has been used in combination with air-based heating systems (as opposed to using radiators and such). Apart from that, when overpressure is needed, for example because of odour problems due to industrial facilities, and when there are no high comfort demands, system B can be used.

2.3.3 System C

System C is quite common in modern houses. Vents in occupied rooms allow air to enter, whereas a central exhaust fan extracts air from kitchen, bathroom and toilet. Unlike system A, extraction ducts and shafts don't have to be vertical, which allows for more design options. Air moves from room to room through overflow vents or underneath doors.

Advantages:
- Guaranteed, regulated supply of fresh air
- Relatively simple and well-known system
- Supply air is always 'fresh'

Disadvantages:
- Some investment costs
- Energy consumption by fan
- Sound production by fan
- High heat loss (unless heat recovery through a heat pump is applied)
- Possible draft problems (cold supply air)

System C is the most applied ventilation concept in new build residential buildings. In non-residential buildings views on system C differ greatly. Some designers and companies embrace the idea of fresh air through natural inlets as opposed to dirty ducts and filters in system D. However in rooms with a high occupation (meeting rooms, schools) the large airflow will cause draft problems if the air is not pre-heated and enters through normal vents.

Jeroen ter Haar                    Natural & Decentralized ventilation and climate concepts
System C+
Subcategory C+ uses the same extraction principles, but uses automatically regulated vents in combination with the extraction fan to reduce heat loss by only venting as much air as needed. The extraction unit has CO₂ and/or humidity sensors to determine how much ventilation is necessary. An empty house requires no ventilation (CO₂), and someone using the shower requires more extraction (humidity). Compared to system C, system C+ saves quite some energy. For example: Renson claims on average 32% lower energy consumption for their Xtravent Modus, compared to a ‘normal’ system C.


2.3.4 System D
The fully mechanical system D is the standard for non-residential buildings and is also becoming more popular in residential buildings. By using a central ventilation unit for both supply and exhaust, system D is very suitable for using a heat exchanger. Supply vents lead from the central unit to the living room, bedroom etc, and exhaust vents extract air from bathrooms and kitchen. Apart from ducts through the building, system D also needs filters to keep the heat exchanger from clogging up. This makes system D the most complex of the systems and it requires the most maintenance.

Advantages
- Completely regulated ventilation
- Heat recovery allows up to 90% of heat to be recovered
- Pre-heated air prevents draft problems
- External sound is not a problem because the facade is closed

Disadvantages
- High investment costs
- Requires regular maintenance
- Filters and (supply) ducts prone to contamination
- High operation costs (heat recovery compensates for this)
- Sound production of fans in the system (especially in bedrooms)
- Ducting through the entire building is necessary
- A bypass is needed (and should be activated) in warmer periods
- Very little flexibility, system is regulated for specific room dimensions and functions. Small adaptations or wear can unbalance the system.

Even though system D offers the most regulated ventilation and saves a lot of energy through heat recovery, there has been some negative publicity lately for residential buildings. Many people have been complaining about poor air quality and noise problems. Even though most of these problems were caused by improper design or construction and a poor understanding of the system by users, it shows that a highly technical solution is more prone to problems. A well-designed, well-maintained and well-used system performs well, but most homeowners have little understanding of the system.


2.3.5 System E
Decentralized mechanical ventilation is exactly the same as system D, but has a ventilation unit in every room. Therefore no ducts are needed. The ventilation unit has supply and exhaust fans, a heat exchanger and filters just like the central units in system D.

The ventilation unit can be a separate box, to be mounted to the wall, an unit to be integrated with a radiator or an unit to be integrated into the floor, ceiling, windowsill, window frame etc. The ventilation boxes are usually fitted with CO₂ and/or humidity sensors to regulate the amount of ventilation. Because every room has it’s own unit, ventilation is regulated separately for every room, unlike (most) central systems. A central system would constantly ventilate every room with a fixed amount of fresh air. A decentralized unit in an unoccupied room would simply shut itself off.

System E is simpler than System D in terms of construction, because of the lack of ducting, which also eliminates pressure loss in the ducts and therefore saves on energy consumption for the fans. The system also offers more flexibility, but usually at an increased investment. Placing a single unit in a living room can be a good investment, but outfitting an entire office building with decentralized units instead of a central HVAC system tends to be more expensive.

Advantages (compared to system D)
- No need for ducting
- Regulated per room, eliminating unnecessary ventilation
- Allows for individual adjustment
- Possibly lower energy consumption
- Possibility for nighttime cooling where needed

Disadvantages (compared to system D)
- Higher investment cost (in new build)
- Higher maintenance costs

Because of the higher costs, system E is not very common yet. Units like the Climarad are increasingly being used in residential buildings, but as of this moment system E is mostly confined to renovation projects.
Discussion on Mechanical and Natural

There is an ongoing discussion between manufacturers, designers and users between two approaches of ventilation: natural ventilation and mechanical ventilation. In this case ‘natural ventilation’ means natural supply of air, not necessarily natural exhaust. In residential buildings there are mainly two options for ventilation: system C(+), allowing air to enter through the facade, or system D, guiding air in through filters and ducts.

System C in this case, is often referred to as hybrid ventilation, because it uses either natural forces to ventilate or the central exhaust fan when natural forces are unsufficient. The motto used for this system is ‘Hybrid ventilation, natural when possible, mechanical when necessary’ (A. van der Aa). The main arguments for both sides are that hybrid ventilation offers a healthy, efficient approach, whereas mechanical ventilation offers the best energy savings and comfort, due to heat recovery.

The following paragraphs show important statements, facts and views presented in several articles and journals on ‘natural ventilation’.

Problems with balanced ventilation
Balanced ventilation systems often encounter problems as a result of poor design and/or construction, like:

- Poor design, improper placing of vents, resulting in shortcuts in the system or draft problems, ducts with too many curves, no air movement possible between rooms etc.
- Too low capacity of the system, because the system is not configured properly after construction
- Not accessible for the user, no switches available in the kitchen and bathroom to change the airflow
- Dirt and/or mold in the system because of poor construction quality or lack of maintenance and quality control
- The system is unclear to the users, they don’t use the right configurations, block vents, configure the system improperly
- No possibility to purge the room, because of a lack of openable windows or because of smell, noise and burglary problems. Resulting in overheating and poor air quality. Especially in the bedrooms.

The system only allows for ‘sufficient’ ventilation, no purging. Also, the heat recovery will trap heat inside, also in summer. Unless a bypass is installed, which is sometimes not the case or it’s not being used. As a result, the house and especially the bedrooms will get too hot. Because the entire house is treated as a single environment, there is no difference in temperature between the living room and the bed rooms. Also, rooms that are not in use will be ventilated even when no-one is present.

Advantages and disadvantages of natural ventilation
Natural ventilation requires no fan-energy, whereas 25% of the energy consumed by buildings is caused by fans.

- Occupants prefer to have control over their environment and not to be completely isolated from the external environment.
- Natural ventilation is cheaper both in building costs and maintenance
- Natural ventilation requires no space for plant rooms and networks of ducts, but space for chimneys and such might be necessary.
- Natural ventilation does not provide a constant airflow. The amount varies with wind speed, wind direction, temperature differences and opening areas.
- If the temperature outside is too hot and humid, natural ventilation provides no cooling. A cooling system will be required.

The direction of the airflow in naturally ventilated buildings has to be secured in some way.

Source:

Natural and hybrid ventilation systems
Natural and hybrid ventilation systems are often highly appreciated because of psychological and building physical reasons, because of:

- Good air quality
- Pleasant cooling in summer
- Air movement, a fresh breeze
- Lower electrical energy consumption

The fans in a mechanical system are one of the biggest consumers of energy, together with appliances and lighting.

Natural ventilation is possible under the following conditions:

- The airflow has to be controlled (preventing too much ventilation, draft)
- Allowing plenty of ventilation during the mild seasons
- Heat recovery is necessary, through for example a heat-pump

Economic issues are:

- If the airflow is not regulated, the loss of energy can be very high and draft can be an issue. Flow-regulations is expensive though.
- Ducts or other passages have to be bigger than for a mechanical system, because the air speed is lower.
- A mechanical backup-system will always be necessary.
- Openable windows are more expensive than fixed windows.

Source:
Hybrid ventilation in practice

Hybrid ventilation is often seen as the answer to the sick building syndrome caused by mechanical systems as a result of bad design and maintenance, filters and ducts. The idea is that there is as little as possible separating the outside air and the interior, to prevent contamination.

Natural air inlets have a few problems:
1. Draft
2. Energy loss
3. Uncontrollable airflow

There are modern techniques however to prevent these problems:
1. Draft-shielding, adding a ceiling in between the openable windows or vents and the workspace, possibly integrated with heating, cooling, lighting and acoustic damping.
2. Heat recovery in exhaust air and feeding the energy back through the heating system (low temperature underfloor heating)
3. Air-pressure regulated vents, to prevent too large airflows and draft problems. They can either be electrically regulated or mechanically by wind pressure. They also prevent air from flowing in the wrong direction.

Some important notices when applying natural or hybrid ventilation:
- Air-pressure regulated vents are a must.
- Vents should be distributed over the entire width of the facade.
- Prevent cross-ventilation, the (mechanical) extraction will create enough of a pressure difference.
- Every room needs extraction. Air should only be allowed to enter through the facade.
- The fresh air will only reach about 6-7 meters from the facade.
- The capacity is limited because of draft problems. Rooms with a high occupation (meeting room) will experience problems.
- Rooms that are not connected to the facade need overflow-vents.
- If 1 person opens a window, all air will flow through there instead of the vents. This window will ‘use up’ all the pressure difference, because this is the flow of the least resistance.

When using a ceiling to block draft, note that:
- The inlet vent should be at least 100mm above the ceiling and maximal 130mm away from it, to prevent a draft downwards. Also a 100mm margin at the edge.
- The Coanda effect will extend the flow, so a vent placed directly against the ceiling is best.
- The air-velocity at the inlet should at least be 2m/s. This may require a spout to accelerate the air.
- The maximum comfort temperature of the ceiling shouldn’t exceed 29 °C.

In general, as little ducts and vents that can get dirty. Also, a vent shouldn’t be above a lightweight structure because of overheating in summer. Above glass is ideal.

Buildings with Robust climate concepts

When surveying the demands for a new school building, the requirements where:
- good acoustic quality, for a productive working-environment and productivity.
- Clear and easy to clean.
- Nice, fresh air.
- Daylight and outside view without glare.
- Natural materials and vegetation inside and outside the building.

In earlier times building made optimal use of wind, shadow, ground temperature, solar orientation and daylight.

With the rise of mechanical climate systems, this was no longer necessary, because of system allowed for a completely regulated environment. At the cost of higher energy consumption of course. As a result, the sick building syndrome was born.

In present times, energy consumption is the primary issue. The indoor environment is completely conditioned in a mechanical way and heat recovery systems prevent heat losses. Sun shading is often left out because of maintenance issues however. The focus is on low energy consumption for a low budget, but not on the user. Over time, small interventions and user adaptations deregulate the system and complains are often: ‘it’s too hot in winter’ or ‘it’s too cold in summer’. Which indicates of course a waste of energy.

Concluded: High-tech mechanical systems to regulate the climate often don’t work in reality.

The solution:
Buildings with as little as possible installations, good building-physical qualities and high user-regulation. These buildings score best in user-satisfaction, energy consumption and building operating costs.

The simpler the installation, the better the users understand what’s happening and the less energy is wasted.

Therefore, a building should have:
- highly insulating skin.
- operable sun shading.
- adjustable heaters.
- adjustable vents.
- operable windows.

This results in a ‘what you see is what you get’ installation. Everyone understands what is happening and if something doesn’t work, it’s clear why. These are called Robust Buildings.


Robust Climate design combines efficiency with occupant health & comfort

Calculated energy performance and measured performance often differ greatly (in a negative way). Most of the time the actual performance is never measured, only predicted.

Setting a narrower PMV range for a building to increase comfort often does not result in a more comfortable environment, but does increase energy costs.

Problems often occur because of:

- Construction problems
- Changes in building use
- User interventions
- Budget cuts during design, construction or operation

These buildings often have a high-tech approach, which ignores external conditions. Robust buildings are more likely to score as predicted, e.g. are more reliable to work. Factors that affect robustness:

- Lack of individual control (ability to change indoor climate)
- Occupant consideration and tradeoffs (opening a window causes noise but improves air quality)
- Active versus passive design (mechanical systems are more prone to unexpected energy consumption and comfort issues)
- Sensitivity to deviations from design assumptions (small changes in construction and use, different manufacturer etc.)
- Maintenance (popular budget cut)
- Combined heating and ventilation (a broken fan results in poor air quality and thermal discomfort)
- Lack of transparency (occupants should understand what happens, also for service staff, systems are often not used to their full potentials because even staff doesn’t understand)

The goal is creating a comfortable and healthy environment at minimal energy costs. Mechanical ventilation with heat recovery is the only recommended solution.

Note that the indoor temperature for the Passivhaus standard is set at 21 degrees for the entire house. However, there is a linear correlation between the comfort temperature inside and the exterior temperature in free-running buildings. With conditioned buildings this is much more complicated. Also, the width of the accepted temperature band is much wider in naturally ventilated buildings.

Highly insulated houses also have a much higher surface wall temperature and as a result the body looses less heat through radiation (which can be as much as 45% of the body heat exchange). Therefore the room temperature can be lower than in houses with less insulation.

User adaptations provide a more comfortable environment and wider temperature band. Where there are no options for personal adaptation (blinds, fans, windows, clothing) the band may be as narrow as ±2°C

This research suggests that highly insulated and reasonably airtight but naturally ventilated buildings where occupants are in control of their environment and are able to make adjustments to maintain comfort would not need to achieve a fixed temperature of 21 °C to feel comfortable and occupants could tolerate lower and higher temperatures.

Desired temperatures according to the CIBSE Guide B1 Heating are:

- Bathrooms 26–27 °C
- Bedroorns 17–19 °C
- Hall stairs landing 19–24 °C
- Kitchen 17–19 °C
- Living rooms 20–23 °C
- Toilets 19–21 °C

Note that varying temperatures are perceived pleasant by some people, because you experience differences as you move through your home.

Source:
The Passivhaus-standard and natural ventilation (continued)

CO₂ levels are not dangerous themselves, but are measured because it’s assumed that these give a good indication of the amount of pollutant materials in the air (formaldehyde, benzene etc). This is not always right though. When designing a less polluted house (no glued wood products, no gas cooking or heating) less ventilation can be sufficient. Also, users can open a window when they feel it’s stuffy.

Notes from the research model:

- Reducing the set temperature by 1 °C reduces the energy consumption by approximately 10% in colder climates and up to 14% in milder climates.
- In colder climates (such as in Dresden), a building with MVHR uses less energy than a naturally ventilated building if uniform temperature throughout the building is assumed.
- If non-uniform temperature is assumed in the naturally ventilated option, then modest savings can be made in naturally ventilated buildings if the upper temperature is maintained at 18–19 °C.
- In warmer climates (such as in Plymouth and London), a building with MVHR and uniform temperatures throughout uses less energy than a naturally ventilated building with uniform temperature throughout, but more energy than a naturally ventilated building with non-uniform temperatures.

Installation costs for MVHR was 3% of the building costs in this research. Also, maintenance can be expensive and the system uses quite some space.

For new build housing the capital costs are a minor problem, but for refurbishment, leaving out the MVHR system and just insulating the house, allows occupants to stay in their home during the renovation, reducing disruption and costs. Also, this does not require specialist companies, but only mainstream construction companies.

Source:
3 Analysis of heat recovery techniques

Since heat recovery is a vital part of saving energy in modern ventilation and climate systems, this chapter focuses on different means of heat recovery, in order to understand how ventilation systems apply these techniques to answer the first research question:

What is the current state of the art of ventilation systems? What concepts exist and how do they function?

This chapter shows an overview of different types of heat exchangers used in ventilation systems. The first paragraph (§3.1) describes the following systems:

- Plate heat exchanger
- Thermal wheel
- Enthalpy exchanger
- Heat pipe
- Twin coil system
- Fine wire heat exchanger
- Heat pump

Paragraph §3.2 gives a comparison of the efficiency between these systems.

3.1.1 Plate heat exchanger

A plate heat exchanger or recupercator transfers heat through a plastic or aluminum surface (plate). These plates separate the exhaust and supply air from each other. The result is a box of layered plates, altering between supply and exhaust flow. The volume between to plates is often divided into smaller tubes to increase the surface area and therefore heat transfer of the heat exchanger. In order to maximize surface area, plates are only millimeters apart from each other. This does however make them prone to clogging up due to dust particles. For this reason, filters are a necessity.

Advantages and disadvantages:
+ Simple, reliable design
+ Low maintenance (except for cleaning filters)
+ Air flows are separated from each other
+ Scalable to very small or large applications
- Only sensible heat is transferred
- Condensation and freezing

The flows in a plate heat exchanger can flow in different directions:
- Parallel-flow (uncommon)
- Cross-flow
- Counter-flow

Cross flow heat exchangers can reach an efficiency of about 50-70%. Counter-flow heat exchangers are slightly more complicated in connecting the flows, but can get an efficiency of 70-90%*

*(DuurzaamMKB.nl, 2015)
3.1.2 Thermal wheel

A thermal wheel consists of a rotating set of tubes. Exhaust air passes through the tubes, transferring heat to the tubes. These tubes slowly rotate towards the intake vent and eventually, intake air passes through the heated tubes, transferring the heat. This cycle continues infinitely, indirectly transferring the heat from the exhaust air to the intake air. It is possible to use an absorbent material in the tubes to recover moisture as well (enthalpy wheel). Thermal wheels are the most common choice for large ventilation systems (office buildings and such). Their efficiency ranges from about 60-85%* *(AL-KO, 2012) *(DuurzaamMKB.nl, 2015)

Advantages and disadvantages
+ Can transfer both sensible and latent heat
+ Can recover moisture
+ Efficiency can be altered by changes rotation speed
+ Unlikely to have freezing problems
- Requires an electromotor (maintenance) and electricity
- Intake air can be contaminated by exhaust air

3.1.3 Enthalpy exchanger

An enthalpy exchanger is not an independent kind of heat exchanger, but rather a name for heat exchangers that transfer latent heat. Latent heat is the energy stored in the water vapor in the air.

An enthalpy exchanger allows water to condensate from the exhaust flow and to be vaporized into the intake air. A thermal wheel with an absorbent material uses this concept. A plate heat exchanger can do the same by altering the supply and exhaust flow, by using switches. This also prevents freezing in the heat exchanger. Enthalpy exchangers reach efficiencies of 80-95%* *(DuurzaamMKB.nl, 2015) *(smartfacade.nl)

3.1.4 Heat pipe

A heat pipe uses a container or tube that is connected to both the exhaust flow and supply flow. Inside the container is a liquid that evaporates on the warm end, extracting heat from the exhaust air. The vapor condenses on the cold end, supply heat to the supply air. This technique is also used for example inside computer components, using a copper tube. The efficiency of a heat pipe is 45-70%* *(DuurzaamMKB.nl, 2015) *(Prendergast & Erdtsieck, 2004)

Advantages and disadvantages
+ Low maintenance
+ Air flow are separated from each other
+ Scalable to very small sizes and different shapes
- Expensive
- Only sensible heat is transferred

3.1.5 Twin-coil system

A twin-coil system uses two heat exchangers and an intermediate substance to transfer the heat. Exhaust air is forced through a coil, heating water in the system, or a mixture of water and glycol to prevent freezing. The heated water is pumped to the coil in the supply air, where heat is transferred to the supply air. Therefore the systems consists of two air-liquid heat exchangers connected by pipes and a pump. The efficiency of twin-coil systems is about 40-70%* *(AL-KO, 2012)

Advantages and disadvantages
+ Supply air(vent) and exhaust air(vent) can be separated far apart.
+ Supply and exhaust air are perfectly separated
+ Low maintenance
- Requires a pump (electricity)
- Only recovers sensible heat
- Condensation and freezing
3.1.6 Fine wire heat exchanger

The FiWiHex is a specific kind of heat exchanger that uses thin copper wires to transfer heat from air to liquid or from air to air. Instead of a plate separating the two substances, these copper wires create a web through which air flows, transferring heat. This creates a low-resistance, high contact-surface heat exchanger, with efficiencies of up to 95%*(http://www.breathingwindow.org/)

Advantages and disadvantages
+ Very high efficiency
+ Low resistance
+ Low maintenance
- Still somewhat experimental

3.1.7 Heat pump

A heat pump uses a compressor to pressurize a gas, forcing it to condensate. This releases heat to the area. On the other side, and expansion valve relieves the pressure, allowing the liquid to return to its gaseous form, absorbing heat from the (second) area.

In some situations a heat pump is used for heat recovery. For example when natural ventilation is being used, a heat pump can be applied in the exhaust flow. By extracting heat from the air, water is heated which can be used in the central heating system.

The thermal efficiency of a heat pump in this application relies heavily on the conditions:
- Outside air: -10°C RH 63% Efficiency: 56%
- Outside air: 0°C RH 30% Efficiency: 87%*

*(Prendergast & Erdtsieck, 2004)

Advantages and disadvantages
+ Recovered heat can be used for the central heating system
+ Supply air(vent) and exhaust air(vent) can be separated far apart
- Very expensive
- Consumes relatively much electricity

3.2 Comparison

The following graph shows the typical efficiency of every mentioned heat recovery technique. Note that there will always be exceptions, falling outside of the mentioned range. For example a heat exchanger that is simply too small and has not enough surface area (time) to transfer all the energy.

There are of course other important aspects when choosing a type of heat exchanger. The air resistance, and therefore needed pressure and fan energy, varies greatly between systems. Apart from that, a heat pump and thermal wheel will need electrical energy, and some systems have the possibility to recover moisture as well. The size and price are important aspects as well of course. However, all these aspects will differ greatly depending on the specific application and are not easily comparable. Therefore these will not be elaborated on in this report.

Heat recovery in practice

In building construction, the vast majority of (non-residential) buildings uses a thermal wheel for heat recovery (Boonstra, 2015). The reason for this is the fact that a thermal wheel is capable of the high heat recovery rate and the possibility of recovering humidity. Also, the thermal wheel is applicable for large quantities of air and is a system that has been proved through time.

Twin-coil systems are only used in two situations:
- The extraction- and supply air must absolutely be separated for hygienic reasons
- The intake and exhaust are separated far apart from each other

Sales of different systems by AL-KO
The following life-cycle-costs calculation by Alko luchttechniek BV, for an airflow of 40,000 m$^3$/h, shows the differences between HVAC units with these heat recovery techniques over a lifetime of 15 years.

The graph shows the costs for a thermal wheel (81.9% heat recovery), Twin-coil (43%), HVAC unit without heat recovery and lastly a twin-coil with a higher heat recovery rate(70%), which also has a higher airflow resistance. The invest costs do not include ducts etc. just the HVAC unit.

Noticeable is that the twin-coil is favourable in maintenance (grey), electrical consumption (yellow) and capital costs (green). The big downside of course, is the lower heat recovery rate, resulting in much higher heating costs for the building.

The high-efficiency twin-coil, compared to the ‘normal’ one, is more expensive on all aspects but the heating, but for this case is favourable over the entire lifetime. Compared to the thermal wheel it’s still favourable in terms of maintenance and purchase. A last note is that twin-coils will need extra water pipes connecting the units, which also adds to construction costs.

Possibilities for twin-coil systems for a natural ventilation system
The big advantage of twin-coil system is the fact that the intake and exhaust can be separated, which is often the case with natural ventilation. Apart from that, the heat recovery rate of 80% might not be completely necessary at all times. In general a higher rate will of course be better, but with modern airtight buildings, with better and better insulation, internal heat load and positioning to the sun, a lower rate might be reasonable if ventilation is limited to a minimum and would be enough to prevent draft problems.

Apart from that, the lower costs for maintenance, energy and investment can be attractive to buyers. For these reason, a twin-coil system offers opportunities for adding heat recovery to natural ventilation as a new concept.
Chapter four gives an overview of different ventilation systems and their performance. The list includes many decentralised systems, as these tend to be very different from each other, whereas central systems are mostly the same. This overview, together with chapter 2 and 3, answers the research question:

What is the current state of the art of ventilation systems? What concepts exist, how do they function?

It also provides some insight in the integration of the systems into the facade, answering part of the question

How are these concepts integrated into the framework of a building?

This chapter shows an overview of different types of ventilation and climate concepts by different manufacturers. The first paragraph (§4.1) describes the following systems:

- Climasmart  Heycop Systemen BV
- Breathing window  Brink Climate Systems
- Brink Advance  Brink Climate Systems
- Ventotherm  Schüco
- Provent D-luxe  Profel
- Emcovent FLH  Emco
- Climarad  Climarad BV
- E’ Facade  Schüco
- Smartbox  Cepezed
- Coolphase  Monodraught
- Climatop  Duco
- Vent-Trex  Titon
- Ducobox WTW  Duco

Paragraph §4.2 gives a comparison of the energy-efficiency between systems. Paragraph §4.3 is an overview of other interesting ventilation or climate concepts, that will be referred to further on in the report.

4.1 Climasmart – Heycop Systemen BV

This ventilation concept is essentially a ‘starter pack’ for ventilation system C+. It consist of different, regulated vents, connected to a central exhaust fan which has CO₂ sensors to determine the necessary amount of ventilation.

The central computer receives signals from the CO₂ sensor and regulates the inlet vents to maintain proper air quality and prevent unnecessary ventilation.

This system has no heat recovery or heating/cooling options and has natural inlets.

### Specifications

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4.1.2 Breathing window – Brink Climate Systems

A relatively simple but effective solution. Using only fans, filters and a Fiwihex, the unit supplies and extracts air from the room in one box through the facade. The Fiwihex transfers heat from air to air through copper wires and has relatively little air resistance. As a result, the system uses little energy for the fans and has a high heat recovery rate.

The unit is rather visible in the façade though. Apart from that, the system focuses solely on ventilation, heating or cooling is not a part of it, so additional installations are still needed.

The system also has CO₂ sensors to limit ventilation to a minimum and uses filters in the inlet and exhaust to keep the heat exchanger clean. The system has a ‘boost’ setting for purging a room, but this makes a lot of noise.

### Specifications

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<tr>
<td>Price</td>
<td>1175 €</td>
<td></td>
</tr>
<tr>
<td>Price (without sensors)</td>
<td>900 €</td>
<td></td>
</tr>
</tbody>
</table>
4.1.3 Brink Advance – Brink climate systems

The Brink Advance is a similar concept as the Breathing Window, it uses a single box for supply and exhaust, with CO2 and moisture sensors, a heat- and moisture recovery system, filters and fans. Unlike the Breathing Window, the Brink Advance is designed for larger rooms and nighttime ventilation.

The heat exchanger is made of a special polymer-membrane that allows up to 60% of the moisture to be transferred from the exhaust air to the supply air.

The unit is rather big, and applicable for dwellings, offices, hospitals, hotels etc, for both renovation and new build projects. The large unit allows for bigger, quieter fans and is claimed to have high sound-damping qualities.

4.1.4 Ventotherm – Schüco

Essentially the same concept as the breathing window, but integrated into a window frame. This makes the system much less visible and better integrated into the facade.

For heat recovery, the Ventotherm uses an aluminum heat-sink (called a heat-hedgehog, because of the spikes), that transfers heat from one side to the other with a rate of 45%. The Ventotherm also has CO2 and moisture sensors and filters for cleaning the air, which require regular maintenance.

When using the low setting, the system is supposedly quiet enough to be used in bedrooms, though an airflow of 15 m³/h is very limited.

4.1.5 Provent D-luxe – Profel

The Provent D-luxe is practically the same as the Ventotherm, but uses a different kind of heat exchanger. It uses a plastic, cross-flow heat exchanger. This makes the box larger than the Ventotherm, at a higher heat recovery rate.

Apart from that, the system offers some special options for the user, for example a sleep modus (turns the system of for 2 hours), boost modus (15 minutes max. capacity) and a bypass for the heat exchanger.

Like other systems it uses filters to prevent dust from entering the heat exchanger, as well as an insect screen. The system has an indication LED that lights up when the filters need cleaning.

The system is nicely integrated with the window frame, preventing the need for ventilation ducts through the wall.

### Specifications

<table>
<thead>
<tr>
<th>Size (w<em>h</em>d)</th>
<th>Max airflow</th>
<th>Sound damping</th>
<th>Heat recovery rate</th>
<th>Energy consumption</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>500<em>1200</em>150 mm</td>
<td>150 m³/h</td>
<td>? dB (A)</td>
<td>90 %</td>
<td>6 - 102 W</td>
<td>? €</td>
</tr>
</tbody>
</table>

(Profel, 2015)  
(Livios, 2015)

4.1.6 Emcovent FLH – Emco

The Emcovent FLH is, again, the same concept as the Ventotherm and Provent, but this one is integrated into the windowsill. It uses a cross-flow heat exchanger.

The unit does have very good sound-damping qualities, because the relatively large box allows for plenty of sound damping material.

### Specifications

<table>
<thead>
<tr>
<th>Size (w<em>h</em>d)</th>
<th>Max airflow</th>
<th>Sound damping</th>
<th>Heat recovery rate</th>
<th>Energy consumption</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>1050<em>75</em>195 mm</td>
<td>(15) 30 m³/h</td>
<td>(26) 37.7 dB (A)</td>
<td>(40) 45 %</td>
<td>(5) 13 W</td>
<td>? €</td>
</tr>
</tbody>
</table>

(Emco, 2012)
4.1.7 Climarad – Climarad BV

The Climarad is again the same concept but combined with a radiator(convector) heater. It’s mounted on the wall and supplies and extracts air through the wall to the single unit for ventilation and heating. Inside the radiator has a heat exchanger, supply and exhaust fans and CO₂, humidity and temperature sensors. The standard configuration has no cooling option, but a convector can be installed that can use either hot or cold water.

The system is linked to the central heating system and can function either automatically through its sensors, or manually. The combination with a radiator makes the ventilation system ‘disappear’ into the already existing facilities.

The Climarad is meant to be used in the living room of houses, though other versions for offices are available too. It can be combined with an extraction fan in the bathroom (80m³/h).

Inlets and outlets go through the façade, ending in either a vent or integrated into a window frame.

4.1.8 schematic of the Climarad

4.1.9 the movair+ by ISC, a vent inside a window frame (ClimaRad, 2015a, 2015c, 2015e)

4.1.10 the ventilation and climate unit inside

(Diepen, 2010)

4.1.11 a view inside the smartbox

4.1.12 integration of the Smartbox into the floor

(Hoogendoorn, Veltkamp, Boer, Sijpheer, & Heijnis, 2007) (Diepen, 2010)

4.1.13 schematic of the Coolphase

4.1.14 schematic of the Coolphase

4.1.15 view of the Smartbox

4.1.9 Smartbox – Cepezed

The Smartbox is again a full HVAC system, but has an enthalpy heat exchanger, which changes the direction of the airflow in the heat exchanger and allows for humidity control. The system uses sliding flaps to guide the airflow through the heat exchanger and to bypass it.

The box uses a heat pump for heating or cooling the air in the unit. The makes it again a very complete but also expensive system, as many small heat pumps are more expensive and require more maintenance than a single large one.

4.1.10 Coolphase – Monodraught

The Coolphase is a ventilation concept that uses ‘thermal batteries’, containing Phase Change Materials. The unit is mounted above or underneath the lowered ceiling and has a duct to the outside, a central unit and modular parts that can be added. The central unit contains fans, sensors and can circulate air. The mixture between fresh air and recirculated air is determined by the sensors. It uses no heat exchanger, but stores excess heat at the end of the day in the heating season.

The thermal batteries store ‘cold’ during the night to cool during the day, or store excess heat to heat in cold periods. Depending on the internal heat load, more thermal batteries can be added to provide enough cooling capacity. Multiple vents can be connected to divide fresh air over a larger room. The thermal storage is 6-10 kWh, dependent on the model.

The system is designed for larger rooms, like office floors, classrooms or retail space. The price is claimed to be lower than traditional mechanical ventilation system with air-conditioning.

(Monodraught, Coolphase Brochure) (Monodraught, Coolphase system types)
4.1.11 Climatop – Duco

The Climatop is not a so much a ventilation system, but an addition to a natural inlet vent for a façade. The Climatop is an automatically regulated vent, coupled to a central exhaust fan with sensors, but the vent additionally has an electric heating strip to pre-heat incoming air up to 12°C. The heating element has an efficiency of 99%, meaning 99% of electric energy is converted to thermal energy, but there is no heat recovery.

(Duco, Flyer Climatop 60 (AK(+)))

4.1.12 Vent-Trex - Titon

The Vent-Trex is little more than an extraction fan to be mounted above a window, to be used in either bathroom (small version) or a kitchen (larger version). The bathroom version runs at 15 l/s and the bathroom version at either 30 or 60 l/s.

Whereas most decentralised ventilation units use centrifugal fans or axial fans, the Vent-Trex uses a tangential fan, making it a wide, but very slender unit. The lack of a heat exchanger and filters and such, limits maintenance to a minimum.

(Titon, 2003)

4.1.13 Ducobox WTW – Duco

The Ducobox WTW is a central exhaust fan, for ventilation system C(+)luchttechniek BV for an HVAC system. The Ventilation box recovers heat from the exhaust air through a heat pump, cooling it to 5 °C. The heat is added to the return water flow of the central heating system, pre-heating it for the central boiler. In this way heat is recovered to be used for (low temperature) heating and hot water. In this way heat recovery is added to a ventilation system with natural supply.

This combination of a heat recovery unit and central extraction unit reduces the energy demand for heating. For a large part of the year, the Ducobox will provide enough energy by itself. Apart from that, the system can be combined with solar-boiler, shower heat recovery etc.

(Duco, 2015a, 2015c)

4.2 Comparisson

The following graphs show the airflow (m³/h) for all systems for every known power usage (W). For some this is an actual fan-curve, for others just one or two values. The higher the airflow the better. So a lower line means a high power usage for little airflow.

The Coolphase has by far the best fan performance and is included in a separate graph. The E¹ façade and Smartbox are unknown and therefore left out. The Climatop has no fan and is therefore also left out. The Ducobox WTW uses most of its power for the heat pump and not the fan. For reference, the ‘regular’ Ducobox (without heat pump, values for high air resistance in vents) has been added in this graph. Presumably, the performance will be somewhat similar to this curve.

* Based on calculation by AL-KO and Dr Nijs luchttechniek BV for an HVAC system for 40,000m³/h with a thermal wheel.

The graph can be divided into 3 groups:
- The large systems, with a high efficiency and large airflows: Coolphase, Climasmart, Ducobox
- The small systems, with a lower efficiency and smaller airflows: Vent-Trex, Emcovent FLH, Climarad, Breathing Window, Ventotherm
- The Brink Advance, which falls outside of both groups.
It is unclear why the Coolphase has such a great performance. The values claimed by the manufacturer are for the system including a weather grille, a 3 meter vent, a 90° bend and a G4 bag filter. It is possible that the PCM batteries don’t require as much contact surface as conventional heat exchanger, reducing the resistance of the system.

The larger systems use bigger fans that the smaller systems which are more efficient for larger airflows than small fans. Also, the larger systems in this group have no conventional heat exchangers like the small systems, which reduces air resistance.

This explains why the larger systems perform better than the small systems. But the huge difference between the Climasmart/Ducobox and the Coolphase are still unclear. The Climasmart and Ducobox both have no heat exchanger or other component that causes a large air resistance, whereas the Coolphase’s thermal batteries have some air resistance.

The Brink Advance on the other hand, has the worst performance of all mentioned systems, even though it’s quite a lot bigger than the small systems. It uses roughly the same components (a plate heat exchanger, filters, centrifugal fans) as the small systems both for some reason is very inefficient. It must be noted however, that there are only 2 values given for the system, standby power use (6W for 0 m³/h) and max power use/airflow (102W for 150 m³/h). The actual fan curve for the system would be more efficient than these two given values and would presumably be within the same range as the small systems.

The Brink Advance does however have almost the best heat recovery rate of all systems mentioned in the graph above, but the values for the Ducobox WTW and the Coolphase are unknown, because they don’t recover heat the way the other systems do.

The plate/enthalpy exchangers used by the Brink Advance and Smartbox allow for the best heat recovery. Apart from that, they also recover humidity. The counter flow recupercator and FiWHex follow closely. The FiWHex can recover as much as 95%, but this depends on the size on the heat exchanger. The one used in the breathing window does not perform that well. The cross-flow heat exchanger does not perform as well as the counter-flow exchanger but still allows for a decent amount of heat to be recovered. The recupercator in the Ventotherm has by far the worst heat recovery rate, because of its simple design. It is simply an aluminum plate with pins extending from both sides, so there is no cross- or counter-flow. Even though this is relatively little heat recovery, it can be enough to prevent draft problems.

<table>
<thead>
<tr>
<th>System</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climasmart</td>
<td>+ Simple, reliable</td>
<td>- No heat recovery</td>
</tr>
<tr>
<td>Breathing Window</td>
<td>+ Compact</td>
<td>- No integration with façade</td>
</tr>
<tr>
<td>Brink Advance</td>
<td>+ Very good heat recovery</td>
<td>- High fan energy consumption (unfinished product)</td>
</tr>
<tr>
<td>Ventotherm</td>
<td>+ Compact</td>
<td>- Poor heat recovery</td>
</tr>
<tr>
<td>Provent D-luxe</td>
<td>+ Well integrated into façade</td>
<td>- High fan energy consumption</td>
</tr>
<tr>
<td>Emcovent FLH</td>
<td>+ Well integrated into façade, little sound</td>
<td>- High sound production</td>
</tr>
<tr>
<td>Climarad</td>
<td>+ Integrated into radiator</td>
<td>- Limited airflow</td>
</tr>
<tr>
<td>E’ façade</td>
<td>+ Full climate façade concept</td>
<td>- Large unit</td>
</tr>
<tr>
<td>Smartbox</td>
<td>+ Full climate concept</td>
<td>- Radiator unit necessary (not integrated into façade)</td>
</tr>
<tr>
<td>Coolphase</td>
<td>+ Very good fan performance?</td>
<td>- Relatively more expensive</td>
</tr>
<tr>
<td>Climatop</td>
<td>+ Preheating in a natural inlet</td>
<td>- Poor heat recovery</td>
</tr>
<tr>
<td>Vent-Trex</td>
<td>+ Compact</td>
<td>- Expensive</td>
</tr>
<tr>
<td>Ducobox WTW</td>
<td>+ Heat recovery for ventilation (°C)</td>
<td>- Complicated maintenance</td>
</tr>
</tbody>
</table>

The plate/enthalpy exchangers used by the Brink Advance and Smartbox allow for the best heat recovery. Apart from that, they also recover humidity. The counter flow recupercator and FiWHex follow closely. The FiWHex can recover as much as 95%, but this depends on the size on the heat exchanger. The one used in the breathing window does not perform that well. The cross-flow heat exchanger does not perform as well as the counter-flow exchanger but still allows for a decent amount of heat to be recovered. The recupercator in the Ventotherm has by far the worst heat recovery rate, because of its simple design. It is simply an aluminum plate with pins extending from both sides, so there is no cross- or counter-flow. Even though this is relatively little heat recovery, it can be enough to prevent draft problems.
4.3 Other notable concepts

Ducowall
The ducowall is essentially a ventilation wall, a system of louvers covering the wall and protecting it from rain and burglary. The louvers can contain sound damping material to reduce the noise from the outside and can have bug screens to keep insects outside.

The main goal of the system is to allow burglar- and rainproof ventilation through a large opening, mainly for nighttime ventilation. By turning part of the wall into an ‘opening’, large airflows are possible. The opening can be closed with a door behind it.

Ventilation windows/vents
These systems are essentially openable windows or doors with louvers in front of them to protect them from rain and make them burglar-proof. This concept is becoming more common especially in Germany. This allows for plenty of ventilation in living rooms and offices.

Double skin facades or triple glazing with sun shading
These concepts use a cavity to integrate sun shading into the façade and extract the heat from solar radiation from the building before it even enters. The cavities are opened to the outside.

Floor-integrated heaters/coolers
These units contain a convector element, connected to the warm and/or cool water supply to heat or cool air. An optional fan is used to draw air through the system. These units are to be integrated into the floor. This element allows to cool and heat in a single heat exchanger in a decentralized system, with a central, efficient, heating or cooling system. This allows for personal adjustment without the expenses of abundant amounts of cooling and heating elements, such as adding a heat pump to decentralized ventilation units.
Integrated sun shading
Several examples of sun shading integrated into window frames with optional ventilation vents. This provides a way of adding vent openings without unaesthetic grilles and such.

Draft shielding
Ways of preventing draft, or allowing the incoming air to mix with indoor air, by the use of a lowered ceiling, with optional heating/cooling, lighting and acoustic damping integrated.

ComfoSchool by TNO
An alternative way of allowing air to enter, the ComfoSchool, or ‘gaatjesplafond’ (punctured ceiling) uses a supply fan above the ceiling, that allows air to enter through holes in the ceiling. This spreads out the supply air over a large surface, allowing for lower speeds and better mixing with the indoor air.

This system has been approved for use in schools.
5 Analysis of investment, maintenance & energy costs

Chapter 5 aims to answer the second research question:

What are the costs in terms of investment, maintenance and operation costs of current concepts?

This chapter compares the costs of natural, mechanical and decentralized systems according to different reports. The first paragraph (§5.1) discusses several sources on the investment costs of natural and decentralized systems compared to a central system. The second paragraph (§5.2) discusses the maintenance costs and the third (§5.3) the electrical (fan) energy. The conclusions (§5.4) relate the costs in general.

### 5.1 Investment costs

This paragraph aims to give an idea of the investment costs of natural and decentralized systems as opposed to central ventilation concepts. Two different reports discussing decentralized ventilation concepts will be discussed, one by Climarad and another by Trox.

#### 5.1.1 Climarad

Duinwijk Technisch Advies estimated the investment costs of the Climarad system as opposed to ventilation system C and D for a fictional residential building (with additional healthcare, assisted living) of 5,290m², for both new-build and renovations. The three scenarios described are:

- System C (Wind-pressure-regulated window vents, 18 mechanical exhaust fans on the roof)
- System D (2 central HVAC units with heat recovery and a bypass for the summer season)
- Climarad (sensor-regulated units with and heat recovery and an additional fan in the bathroom)

Cost calculations are based on rules of thumb for system C and D. The costs for Climarad are obtained from an installation construction company that has experience with the Climarad system. The additional building costs for renovation for system D are the installation costs for new-build with an additional 20% for adaptations in the existing structure.

Source:
These costs have been established as follows:

<table>
<thead>
<tr>
<th>System C</th>
<th>Amount</th>
<th>Costs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof fans (400m³/hr)</td>
<td>18</td>
<td>€1,000</td>
<td>€18,000</td>
</tr>
<tr>
<td>Ducts and vents (exhaust only)</td>
<td>5,290</td>
<td>20,80 m²</td>
<td>€110,072</td>
</tr>
<tr>
<td>Building costs installations</td>
<td></td>
<td></td>
<td>€128,272</td>
</tr>
<tr>
<td>Façadevents (Ducotop)</td>
<td>80</td>
<td>€100</td>
<td>€8,000</td>
</tr>
<tr>
<td>Space for exhaust shaft</td>
<td></td>
<td></td>
<td>€7,200</td>
</tr>
<tr>
<td>Additional building costs</td>
<td></td>
<td></td>
<td>€15,200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System D</th>
<th>Amount</th>
<th>Costs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVAC unit</td>
<td>5,290</td>
<td>9 m²</td>
<td>€47,610</td>
</tr>
<tr>
<td>Ducts and vents</td>
<td>5,290</td>
<td>41 m²</td>
<td>€216,890</td>
</tr>
<tr>
<td>Inflation since 2012</td>
<td></td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>Building costs installations</td>
<td></td>
<td></td>
<td>€268,468</td>
</tr>
<tr>
<td>30 cm additional floor height</td>
<td></td>
<td></td>
<td>€238,050</td>
</tr>
<tr>
<td>Space for main shafts</td>
<td></td>
<td></td>
<td>€3,200</td>
</tr>
<tr>
<td>Additional building costs</td>
<td></td>
<td></td>
<td>€241,250</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Climarad</th>
<th>Amount</th>
<th>Costs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climarad 2.0 Sensa</td>
<td>96</td>
<td>€1,925</td>
<td>€184,800</td>
</tr>
<tr>
<td>Climarad B-Fan</td>
<td>90</td>
<td>€280</td>
<td>€22,400</td>
</tr>
<tr>
<td>Building costs installations</td>
<td></td>
<td></td>
<td>€207,200</td>
</tr>
<tr>
<td>Space for exhaust shaft</td>
<td></td>
<td></td>
<td>€7,200</td>
</tr>
<tr>
<td>Additional building costs</td>
<td></td>
<td></td>
<td>€7,200</td>
</tr>
</tbody>
</table>


The graphs show a significant decrease in total investment costs for the Climarad system as opposed to system D in both renovation and new-build. System C has lower investment costs for both, but lacks heat recovery, which will increase heating costs (discussed later).

However, upon closer inspection it shows that the additional building costs for system D include a (very large) expense for an increased floor height. This suggests that any building requiring ventilation ducts always needs this extra floor height and a building with a decentralized system would never need this. However, in order to apply cooled ceilings, the concrete floor often has to be exposed and ventilation ducts can be placed outside of the functional space, in hallways or inside the floor etc. On the other hand, a building with decentralized ventilation might still need a lowered ceiling for lighting and other climate functions.

Without this expense the difference between system D and the Climarad become a lot smaller, but still favor the Climarad. The costs for ducts and vents really makes the difference.

### 5.1.2 Trox

The following calculation compares the costs for a decentralized system with system D for renovating a building with 6 floors for a total functional floor area of 3,600 m². It is unclear if this decentralized system is solely for ventilation or a full HVAC system. The expense for induction-units for the central system suggest the decentralized units also provide heating and cooling.

<table>
<thead>
<tr>
<th>Decentralized system</th>
<th>Amount</th>
<th>Costs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation units with HR Assembly/construction</td>
<td>30</td>
<td>€2,439</td>
<td>€73,170</td>
</tr>
<tr>
<td>Recirculation unit Assembly/construction</td>
<td>23</td>
<td>€1,128</td>
<td>€25,944</td>
</tr>
<tr>
<td>Building costs per floor</td>
<td></td>
<td></td>
<td>€127,654</td>
</tr>
<tr>
<td>Total building costs</td>
<td>5 floors</td>
<td></td>
<td>€765,925</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Central system</th>
<th>Amount</th>
<th>Costs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central/ventilationunit</td>
<td>1</td>
<td>€20/m²</td>
<td>€72,000</td>
</tr>
<tr>
<td>Ducting</td>
<td></td>
<td>€50/m²</td>
<td>€180,000</td>
</tr>
<tr>
<td>Induction units, heating/cooling</td>
<td></td>
<td>€32/m²</td>
<td>€115,200</td>
</tr>
<tr>
<td>Total building costs</td>
<td></td>
<td></td>
<td>€367,200</td>
</tr>
</tbody>
</table>

Source: Author-unknown. (Date unknown). Revitalisering kostenraming: commissioned by Trox.

In this estimate the decentralized system is over 2 times as expensive as the central system. This is probably because of the vast amounts of units, 30 units per floor of 600 m², one for every 20 m². The Climarad estimated for one unit every 55 m². Apart from that individual units are more expensive as well (€1,925 for a Climarad and €2,439 for Trox).

This difference is probably due to the different function. The Climarad (in this specific calculation) has an airflow of 6,5 l/s, which is enough for 1 person. In a house this will be sufficient. The calculation for Trox is probably for an office building, which means more ventilation is required due to the high occupation levels.

Apart from that, the calculation includes recirculation units, either to disperse fresh air or to provide additional heating / cooling. For total, an unit(ventilation or circulation) is needed for every 11 m², which does appear to be a lot, considering that decentralized units can easily achieve airflows of over 26 l/s, providing air for at least 4 persons. By using half the amount of ventilation units, the investment costs for decentralized and central would roughly be the same, but the specifics of this calculation are unclear.

Due to a lack of data and the many variables in an actual design situation, it’s hard to draw conclusions on the investment cost of decentralized systems as opposed to central systems. Judging from the calculation for the Climarad without the expense for additional floor height, and the Trox calculation with a ventilation unit for every 20 m² instead of every 11 m², the investment costs for a decentralized system would be somewhat equal to a central system, but there is no hard proof for this. However, it does give reason to believe that a decentralized system doesn’t necessarily have to be more expensive than system D. System C is of course a lot less expensive as it requires only half the amount of ducts or less.
5.2 Maintenance costs

This paragraph aims to give an idea of the maintenance costs of decentralized systems as opposed to central ventilation concepts. Two different reports discussing decentralized ventilation concepts will be discussed, one by ILK Dresden, and the same report on Climarad as mentioned in the investment cost.

5.2.1 ILK Dresden

The following graph shows a calculation for the maintenance costs of a decentralized system compared to the costs for a central system, by ILK Dresden (Institute for Air- und Cooling Technique). The estimate is for a central unit providing 9600 m$^3$/h and 96 facade units for 100 m$^3$/h each. The building has 30 floors of 20*20m each. This means 3.2 units per floor, or one unit every 125 m$^2$.

The estimates are specified as follows:

<table>
<thead>
<tr>
<th>Centralised air conditioning</th>
<th>Amount</th>
<th>Time</th>
<th>Costs</th>
<th>Frequency</th>
<th>Total annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleaning of ventilation units</td>
<td>1</td>
<td>120 min</td>
<td>35/h</td>
<td>Twice a year</td>
<td>€140</td>
</tr>
<tr>
<td>Change of filters (material)</td>
<td>1</td>
<td></td>
<td>520</td>
<td>Four times a year</td>
<td>€2,080</td>
</tr>
<tr>
<td>(labor costs)</td>
<td>30 min</td>
<td></td>
<td>35/h</td>
<td></td>
<td>€70</td>
</tr>
<tr>
<td>Inspection of fire dampers</td>
<td>18</td>
<td>5 min</td>
<td>35/h</td>
<td>Once a year</td>
<td>€53</td>
</tr>
<tr>
<td>350 m$^2$</td>
<td></td>
<td></td>
<td>10/m$^2$</td>
<td>Every two years</td>
<td>€1,750</td>
</tr>
<tr>
<td>Cleaning of air diffusers</td>
<td>48</td>
<td>5 min</td>
<td>40/h</td>
<td>Every two years</td>
<td>€90</td>
</tr>
<tr>
<td>Cleaning of return air devices</td>
<td>24</td>
<td>10 min</td>
<td>40/h</td>
<td>Every two years</td>
<td>€80</td>
</tr>
<tr>
<td>Annual maintenance costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>€4,263</td>
</tr>
</tbody>
</table>

Decentralised AC

<table>
<thead>
<tr>
<th>Amount</th>
<th>Time</th>
<th>Costs</th>
<th>Frequency</th>
<th>Total annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleaning of ventilation units</td>
<td>96</td>
<td>10 min</td>
<td>35/h</td>
<td>Twice a year</td>
</tr>
<tr>
<td>Sampling ventilation units</td>
<td>12</td>
<td>10 min</td>
<td>35/h</td>
<td>Twice a year</td>
</tr>
<tr>
<td>Change of filters (material)</td>
<td>96</td>
<td>2 min</td>
<td>7</td>
<td>Four times a year</td>
</tr>
<tr>
<td>(labor costs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inspection of fire dampers</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cleaning of air diffusers</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cleaning of return air devices</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual maintenance costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The estimates are specified as follows:

Source:

5.2.2 Climarad

The same report of Climarad includes an estimate of maintenance costs for system C, D and the Climarad for the residential building of 5,290 m$^2$. The estimates for system C and D have been provided by Blygold, an installation company.

The estimates are specified as follows:

<table>
<thead>
<tr>
<th>System C</th>
<th>Amount</th>
<th>Costs</th>
<th>Frequency</th>
<th>Total annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleaning of exhaust ducts</td>
<td>€3,510</td>
<td>Every five years</td>
<td>€702</td>
<td></td>
</tr>
<tr>
<td>Cleaning of exhaust vents</td>
<td>€3,150</td>
<td>Every five years</td>
<td>€530</td>
<td></td>
</tr>
<tr>
<td>Cleaning of roof fans</td>
<td>€22.22</td>
<td>Once a year</td>
<td>€400</td>
<td></td>
</tr>
<tr>
<td>Total annual costs</td>
<td></td>
<td></td>
<td></td>
<td>€1,732</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System D</th>
<th>Amount</th>
<th>Costs</th>
<th>Frequency</th>
<th>Total annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance of HVAC unit</td>
<td>2</td>
<td>€490</td>
<td>Once a year</td>
<td>€980</td>
</tr>
<tr>
<td>Change of filters</td>
<td>2</td>
<td>€425</td>
<td>Once a year</td>
<td>€850</td>
</tr>
<tr>
<td>Cleaning of exhaust ducts</td>
<td>€3,510</td>
<td>Every five years</td>
<td>€702</td>
<td></td>
</tr>
<tr>
<td>Cleaning of supply ducts</td>
<td>€3,510</td>
<td>Every ten years</td>
<td>€351</td>
<td></td>
</tr>
<tr>
<td>Cleaning of exhaust vents</td>
<td>€3,150</td>
<td>Every five years</td>
<td>€530</td>
<td></td>
</tr>
<tr>
<td>Total annual costs</td>
<td></td>
<td></td>
<td></td>
<td>€3,513</td>
</tr>
</tbody>
</table>

Climarad

Change of filters Climarad

<table>
<thead>
<tr>
<th>Change of filters</th>
<th>Amount</th>
<th>Costs</th>
<th>Frequency</th>
<th>Total annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bathroom fan &amp; cleaning ducts</td>
<td>96</td>
<td>€40.5</td>
<td>Every two years</td>
<td>€1,944</td>
</tr>
<tr>
<td>Total annual costs</td>
<td></td>
<td></td>
<td></td>
<td>€2,344</td>
</tr>
</tbody>
</table>

Source:

Chapter 5 - Analysis of investment, maintenance and energy costs
Jeroen ter Haar Natural & Decentralized ventilation and climate concepts
Notable is that in this report, the decentralised (Climarad) system has only about 2/3 the maintenance costs of system D. This is largely due to the fact that Climarad claims the filters only need to be changed once every two years, whereas system D requires annual changes. However, they also mentioned this depends on the internal and external air quality. ILK Dresden claimed as much as 4 filter changes per year are necessary for their decentralised systems.

Also the cleaning of ducts and vents for a central system are almost 50% of the total costs. Again, this is highly recommended but not always the case. Notable is that system C isn’t that much cheaper than the Climarad system. The costs for cleaning the exhaust vents and ducts are quite expensive.

For houses with balanced ventilation (system D), it is recommended that filters should be cleaned regularly (once a month) and replaced at least twice a year.*

*Source:  
http://www.milieucentraal.nl/energie-besparen/energiezuinig-huis/ventileren/balansventilatie/  
http://www.wtw-filters.nl/wtw-ventilatie/hoe-vaak-filters-vervangen  
http://www.ventilatienl.nl/service-algemeen.html

### 5.2.3 Vereniging eigen huis (home-owners association)

Vereniging eigen huis has set up an information sheet for residents of houses with balanced ventilation. They suggest the following maintenance measures:

- Cleaning filters once a month
- Replacing filters regularly, at the costs of €15 - €30 for a set
- Checkup and cleaning of the system every year by a professional
- Cleaning of the ducts once every five years

Source:  
Vereniging-eigen-huis. (Date unknown). Aandachtspunten balansventilatie met wtw. Published online

This suggests more maintenance would be necessary than once every two years as suggested by Climarad, but this will be different for every situation. The cleaning of ducts every five years supports the estimate by Climarad, although Trox suggest cleaning every two years for the central system.

If the estimate by ILK Dresden is changed to clean ducts once every five years instead of two, the decentralised design would be far more expensive than the central approach:

- Central ventilation (cleaning ducts every 2 years, original) €4,263
- Central ventilation (cleaning ducts every 5 years, adapted) €3,213
- Decentralised ventilation €4,396

The same can be said for the Climarad if filters have to be changed once a year, and especially if they have to be changed twice a year. However, the central design in this calculation suggests once a year as well:

- Central ventilation €3,513
- Decentralised ventilation (cleaning filters every two years, original) €2,344
- Decentralised ventilation (cleaning filters once a year, adapted) €4,288

The results will be different for every situation, but it doesn’t seem very likely that decentralised systems will be cheaper in terms of maintenance than central solutions. It’s likely that the costs will be somewhat equal or more expensive than central systems. However, it would be beneficial to have fewer decentralised units that supply large airflows instead of a larger number of smaller units. But personal adjustment is another factor.

### 5.3 Energy consumption

This paragraph aims to give an idea of the energy costs of decentralized systems and natural systems as opposed to central ventilation concepts. Reports by Climarad and ILK Dresden are discussed, as well as a rough estimate by Trox.

#### 5.3.1 Climarad

The same report by Duinwijck Technisch Advies also includes an estimate for energy costs of the Climarad system opposed to system C and D.

Estimated fan power for the Climarad is based on graphs measured by TNO. Fan power for system C and D is calculated through the following equation (as mentioned in §2.1.2):

\[
\Sigma P = \frac{Q \times \Delta P}{\eta}
\]

The desired amount of ventilation is estimated as follows: 22/24 hours an airflow of 6,5 l/s will be necessary, for 2/24 hours an increased airflow of 14 l/s will be needed for the bathroom. The Climarad system switches automatically, system C will provide additional airflow for 10/24 hours. System D provides constant airflow, normal in the living room, higher in the bathroom.

The assumed fan efficiency for system C and D is estimated as: \(\eta = 0.65\).

Annual electrical consumption and gas consumption are based on EPC calculations, which will not be discussed.

![Energy consumption](image)

Source:  
The estimated fan power is specified as follows:

<table>
<thead>
<tr>
<th>System C normal ventilation (14/24)</th>
<th>Airflow (l/s)</th>
<th>Amount</th>
<th>Total (l/s)</th>
<th>Increased (10/24)</th>
<th>Airflow (l/s)</th>
<th>Total (l/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedroom</td>
<td>6.5</td>
<td>94</td>
<td>611</td>
<td>14</td>
<td>1316</td>
<td></td>
</tr>
<tr>
<td>Bathroom</td>
<td>6.5</td>
<td>58</td>
<td>442</td>
<td>7</td>
<td>952</td>
<td></td>
</tr>
<tr>
<td>Washing room</td>
<td>7</td>
<td>18</td>
<td>126</td>
<td>24</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Miva (wheelchair/accessible)</td>
<td>24</td>
<td>2</td>
<td>48</td>
<td>22.5</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>22.5</td>
<td>2</td>
<td>45</td>
<td>22.5</td>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>

| Amount of systems                   | 18           | -      |
| Duct length                         | 16           | m      |
| Air resistance                      | 2            | Pa/m   |
| Additional units                    | 0.2          | -      |
| $\eta$ fan                          | 0.65         | -      |

| Air resistance per system           | 38           | Pa     |
| Air resistance roof vent            | 50           | Pa     |
| Total air resistance                | 884          | Pa     |

| Power air side                      | 112          | W      |
| Fan power                           | 173          | W      |
| Average fan power                   | 242          | W      |

<table>
<thead>
<tr>
<th>System D</th>
<th>Airflow (l/s)</th>
<th>Amount</th>
<th>Total (l/s)</th>
<th>Increased (10/24)</th>
<th>Airflow (l/s)</th>
<th>Total (l/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedroom</td>
<td>6.5</td>
<td>94</td>
<td>611</td>
<td>14</td>
<td>1316</td>
<td></td>
</tr>
<tr>
<td>Bathroom</td>
<td>6.5</td>
<td>58</td>
<td>442</td>
<td>7</td>
<td>952</td>
<td></td>
</tr>
<tr>
<td>Washing room</td>
<td>7</td>
<td>18</td>
<td>126</td>
<td>24</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Miva (wheelchair/accessible)</td>
<td>24</td>
<td>2</td>
<td>48</td>
<td>22.5</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>22.5</td>
<td>2</td>
<td>45</td>
<td>22.5</td>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>

| Average duct length                 | 60           | m      |
| Air resistance                      | 2            | Pa/m   |
| Additional units                    | 0.2          | -      |
| $\eta$ fan                          | 0.65         | -      |

| Air resistance ducts                | 144          | Pa     |
| Air resistance vents, HEX, etc.     | 280          | Pa     |
| Total air resistance                | 424          | Pa     |

| Power air side                      | 756          | W      |
| Fan power (supply/exhaust)          | 2325         | W      |

These calculations show the advantage of the lack of ducts in the Climarad system, although the ducts themselves are not the biggest problem. The heat exchanger, vents and filters are the biggest source of resistance in system D. System C requires less fan energy than the Climarad system, because of the short ducts and the lack of heat exchangers and such.

The annual consumptions are based on EPC calculations, involving a lot of different factors and calculations. To summarize, the lower electrical consumption compared to both system C and D is the result of sensor-regulated ventilation, which limits the amount of ventilation and heat lost to the outside.

This is also the cause for the lower gas consumption. By ventilating only the occupied rooms, the total amount of ventilation is reduced by about 40%, reducing heat loss. Apart from that, the Climarad recovers as much as 95% of the heat, whereas system D in this calculation recovers only 80%, and system C none.

### 5.3.2 Trox

An estimate from a presentation by Trox on the NEXT Active Facades concept gives no detailed description, but mentions the following ranges of specific fan power for systems:

<table>
<thead>
<tr>
<th>Specific Fan Power</th>
<th>Central</th>
<th>Decentralised</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>250 - 600 W/(m³/s)</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>1500 - 3000 W/(m³/s)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System D central</th>
<th>Airflow (l/s)</th>
<th>Power (W)</th>
<th>Amount</th>
<th>Total (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climarad (decentralised)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>877.6 l/s at 516 W = 588 W/(m³/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.487 l/s at 886 W = 356 W/(m³/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

System D (central)

1.782 l/s at 2.325W = 1305 W/(m³/s)

Another estimate as given by AL-KO luchttechniek (as mentioned in §3.2) gives the following values for a central system with a thermal wheel:

40,000 m³/h at 26.430 W = 2.379 W/(m³/s)

This matches the range as given by Trox.

The decentralised systems mentioned in chapter 4 mostly have a SPF of about 700 W/(m³/s), which is just inside the mentioned range. Although this differs from system to system and depends on the airflow.
The same report by ILK Dresden, for an office tower of 12,000 m² with either a central system or 96 facade units, also contains an estimate for the fan power for both solutions.

<table>
<thead>
<tr>
<th>Central system</th>
<th>Decentralised system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure difference(_{eT})</td>
<td>500 Pa</td>
</tr>
<tr>
<td>Pressure difference(_{axm})</td>
<td>450 Pa</td>
</tr>
<tr>
<td>Total Airflow</td>
<td>3600 m³/h</td>
</tr>
<tr>
<td>Fan efficiency(_{fan})</td>
<td>0.6</td>
</tr>
<tr>
<td>Total amount of units</td>
<td>1</td>
</tr>
<tr>
<td>Fan power</td>
<td>4.200 W</td>
</tr>
<tr>
<td>Pressure difference(_{eT})</td>
<td>220 Pa</td>
</tr>
<tr>
<td>Pressure difference(_{axm})</td>
<td>0 Pa</td>
</tr>
<tr>
<td>Total Airflow</td>
<td>100 m³/h</td>
</tr>
<tr>
<td>Fan efficiency(_{fan})</td>
<td>0.15</td>
</tr>
<tr>
<td>Total amount of units</td>
<td>96</td>
</tr>
<tr>
<td>Fan power</td>
<td>3.900 W</td>
</tr>
</tbody>
</table>

The conclusion being: the energy consumption (fan energy) is generally similar, because the lower fan efficiency of decentralised systems is compensated for by the resistance of the ducts in a central system. Compared to the values given by Trox, the decentralised system falls outside the given range:

Central system:

- 9600 m³/h at 4.200 W = 1.575 W/(m³/s)

Decentralised system:

- 9600 m³/h at 3.900 W = 1.462 W/(m³/s)

The specific fan power of the decentralised unit is (very) high in this case. The specific fan power is defined as:

\[
SFP = \frac{\Delta P}{\eta} \quad \text{(mentioned in §2.1.2)}
\]

Therefore, the high SFP is caused by either the pressure difference or the fan efficiency. The efficiency is assumed at 0.15, which is somewhat low, but considering the size of the fans not unrealistic. The pressure difference of 220 Pa seems somewhat high though, considering the lack of ducts. It is unknown what kind of filters and heat exchanger are applied, but these would possibly be the cause.

Even though all sources offer different values, they all seem to agree that decentralised system have a lower electrical energy consumption than the central systems. All sources mentioned above combined suggest the fan energy for central systems is about 2-3 times as high as decentralised systems, but, of course, depend on a lot of design parameters.

System C uses by far the least energy, as it has little ducts, no filters and no heat exchanger.

Source:

### 5.4 Conclusions

Other factors to determine the feasibility of decentralised systems are important as well, but are not described further in this report. These include:
- Heating/cooling load of buildings, these are claimed to be lower for decentralised systems because of the individually adjusted units. These provide an alternative for the ‘one size fits all’ approach of central systems, cooling and heating wherever is needed. Also, loss in transport is cancelled as well.
- Increased flexibility, because the units provide supply and exhaust and service a given floor area. Interior walls are not a factor, whereas a central system has specifically placed supply and exhaust vents.
- Occupied space, decentralised units have no ducting, plant rooms, lowered ceiling etc. This increases the effectively used volume by over 20% (provided a lowered ceiling would otherwise be necessary).

Considering the three mentioned aspects, the following (general) conclusions can be drawn:

**Investment costs**

The investment costs of decentralised system are somewhat equal to central systems. The extra costs for fans, heat exchanger and such in decentralised systems is within the same range as the costs for vents and ducts in a central system. Depending on the effective use of the building volume, a decentralised system can offer a less expensive ventilation concept, although there are possibilities to prevent a lowered ceiling even with central systems. System C has the lowest investment costs, as it requires only a small amount of elements.

**Maintenance costs**

Provided that the ducts and such in central system will have to be cleaned (every five years), a decentralised system would probably be slightly more expensive than an central system, somewhere around 25%. This all depends on the frequency of maintenance of course. However, without the cleaning of the ducts of a central system, which is not advised but does occur, a decentralised system would be far more expensive, up to 2-4 times more expensive. System C is again the favourable solution as it only requires exhaust ducts to be cleaned, no supply ducts, filters or heat exchangers.

**Electrical energy consumption**

The lack up ducts in decentralised system more than makes up for the lower efficiency of the smaller fans. Very small decentralised system might perform worse, but generally, a decentralised system uses only 50%-33% of the electrical energy of a central system. System C uses even less energy, as there are no filters or heat exchangers and little ducts that provide air resistance.
6 Reference projects

This chapter shows three reference projects, two for decentralised ventilation systems and a naturally ventilated school. Together with chapter 4 and 7, these answer to third research question:

How are these concepts integrated into the framework of a building?

6.1 Sigmax Building - Enschede

The Sigmax office building in Enschede is an exceptionally transparent building, partly because of the decentralised HVAC system with heat recovery. The building uses the Trox Schoolair-D, a box to be integrated into the ceiling. Apart from that, the building has a floor heating system.

In this case, openings have been left out in the concrete floor to provide room for the ventilation units. As a result, there is no need for a lowered ceiling and the floors remain very thin. The same design with a central system would require ducts to be hidden on the outside of the building (in the overhang?), as well as a large unit on the roof. Apart from that vertical shafts would be necessary. Alternatively, a central vertical core would be needed. A central system with the same aesthetic quality would be very complicated.

Every unit has two ducts leading through the facade into the overhang, were the supply and exhaust vent are located. On the inside a two vents supply and extract air from the inside (one along the facade, the other into the room). Apart from that, a shading system has been integrated into the overhang.

This building gives a great example of the flexibility in design of decentralised ventilation systems.
6.2 Traungasse - Vienna

The Traungasse building in Vienna is a office and retail complex, that has recently been renovated to improve energy performance and comfort inside. Amongst other things, the buildings now has a decentralised HVAC system with heat recovery.

The system used is the FSL-B-ZAB by Trox, an unit to be integrated into the parapet. The building now has a proper heating and cooling system, as well as comfortable ventilation, without the need for a lowered ceiling. The steel box is integrated into the existing parapet.

A single unit can provide up to 120 m³/h, has a heating capacity of up to 1788 W and a cooling capacity of up to 781 W, through a central heating and cooling system that supplies water to the individual units.

Fresh air is enters underneath the windowsill, while exhaust air leaves through perforations in the windowsill.

This project shows a good example of the easy integration of decentralised ventilation in a restoration project.

6.3 De Schakel - Utrecht

The primary school building De Schakel in Utrecht is an example of a modern building using ventilation system C, for rooms with a high occupation. In order to provide 'natural' ventilation, the design goal was to allow air to enter directly through the facade, without ducts, filters etc.

In order to allow a natural supply of air without draft and external noise problem, the supply vents are fitted with sound damping material and a directional flap to guide air along the ceiling. The 'flap' also narrows the airstream, accelerating it, to supply fresh air in the entire room and prevent downfall of cold.

Apart from that, the vent has a heating element (a water pipe) to pre-heat air by 10-15 °C if the outside temperature is - 5 °C. Air is extracted through a mechanical system on the other side of the room.

In order to get permission to supply fresh air in this way, a study was necessary to prove there would be no draft problems. Through CFD-analysis, WTB-Buro proved that natural ventilation in schools is possible.
7 Ventilated facades

Chapter 7 gives an overview of facade systems that handle ventilation and climate control. These provide other ways of integrating ventilation into the facade, completely or in addition to a central ventilation system. This adds to the answer to the third research question:

How are these concepts integrated into the framework of a building?

§7.1 Discusses the climate facade- and second-skin facade concepts and other similar concepts. §7.2 provides two examples of modern buildings with a climate facade and §7.3 gives two examples of second-skin facades.

7.1 Facade types

Because of the ever rising popularity of glass facades in the late 20th century, new facade concepts were being developed that would allow for fully glazed facades without sun-reflective coatings without enormous costs for air conditioning. These facade concepts focussed on shading systems that would extract most of the sun's heat to the outside preventing it from ever reaching the interior of the building. In general, two groups can be divided:

- Climate facade, with a narrow cavity (10-20cm) and ventilated with interior air
- Second skin facade, with a wide cavity (50-100cm) and ventilated with exterior air

(Voorden, 2000)

Another (sub)group is the climate window, which is the climate facade concept applied to a single window, often by adding an additional plane of glass behind the existing facade, for example in older buildings to improve energy efficiency and comfort.

These two groups provide only a limited division in existing designs. Variables in the design include:

- Cavity width
- Vertical compartmentalisation (over the facade height, for every floor)
- Natural or mechanical (cavity) ventilation, using either:
  - Interior or exterior air, and extracting it either:
    - To the interior or exterior
  - Openable windows

(Renskens, 1996)

Climate facade

7.1.1 Climate facade

The climate facade concept was developed in the seventies in order to allow for fully transparant glazing in the facade. But because external shading was not an option in higher buildings, shading would have to be located on the inside. In general, the 'normal' facade consist of insulating double glass, with additional shading (blinds) and a plane of single glass behind it. Exhaust air from the interior is mechanically being extracted through the newly formed cavity, removing heat from the blinds and reducing heat gain. In this way, only about 15% of the sun's heat enters the building, which is roughly equal to external sun shading. (Renskens, 1996)

During the winter on the other hand, the inner (single) glass plane is kept at a pleasant temperature, because interior air is constantly extracted past it, improving thermal comfort in terms of radiant temperature. Because of this, it is not necessary to apply perimeter heating (convector-heaters at the facade) and underfloor heating or other concepts can be applied instead.

'The climate facade can best be described as a defensive separation between the outdoor and indoor environments - keeping out the influence of the outdoor climate.'

'The climate facade is reactive to the indoor climate.' (Roelofsen, 2002)

原则 of a climate facade

(Roelofsen, 2002)
7.1.2 Second skin facade

In the end of the eighties the second skin facade was developed, with the idea that primarily the facade would provide and regulate climate functions. Other climatic systems would only assist when necessary. Natural forces would be utilised as much as possible to minimize energy consumption.

Contrary to the climate facade, the second skin facade usually has insulating glazing in the inside and a single glazed panel on the outside, whereas the cavity is connected directly to the outside. The cavity is therefore naturally ventilated and functions as a solar chimney to extract its own air and cool itself. Because the cavity is connected to the outside, windows in the interior facade can be opened to provide indirect natural ventilation in the mild seasons. The external glass acts as a shield to protect against the harsh winds in high-rise buildings. The windows are usually either sliding doors or tilting windows.

In order to prevent the air in the cavity from getting too hot, the cavity is usually compartmentalised over the height of the facade. In order to allow for maintenance, second skin facades often have a catwalk in the cavity to allow for cleaning of the windows and maintenance of the (automated) shading systems.

The double-skin facade acts in a totally opposite manner, as it is an active separation between the outside- and inside environments, that endeavours to utilise the outdoor conditions as much as possible. The double-skin facade is reactive to the outdoor climate. (Roelofsen, 2002)

7.1.3 Differences and advantages

Like mentioned above, the main difference between the climate facade and second skin facade is that the climate facades is oriented inwards while the second skin facade is oriented outwards. Compared to a ‘regular’ (single skin) facade, both these facade have the following advantages:

- Better insulative properties
- Better solar regulation
- Better sound-damping qualities
- Well-protected shading system

The costs of a ventilated facade will however be higher and it will consume more space, especially the second skin facade.

The advantages and disadvantages between the climate facade and second skin facade as mentioned by Roelofsen are:

Climate facade as opposed to second-skin
- Internal climate is less subjective to external conditions
- No perimeter/convective heating required
- Requires less space
- Better sound insulation
- Less possibilities of sound flashing through the facade
- Less dust and air pollution and therefore less maintenance

Second-skin as opposed to Climate facade
- Openable windows in rooms at great height
- Less energy consumption for cooling and ventilation
- Inner windowpane does not shield inside heat capacity of the building
- For renovation: the entire building is warmly wrapped up

(Roelofsen, 2002)

7.1.4 Other ‘double’ facades

Apart from ‘conventional’ double facade structures, new concepts using triple glazed window frames are being introduced, effectively making a second skin facade with sun shading in a single window frame.

An example of this is the Twin-line by Finstral B.V. By adding an additional plane of single glass the blinds in the newly formed cavity are protected from dust and rain. This triple-glazed configuration offers a U-value of between 1,00 and 0,91 W/m²K. Quadruple glazing variants achieve a U-value of as little as 0,83 W/m²K. Different options for glazing include regular (g-value 0,50), solar-receptive (g-value 0,62) and solar resistant (g-value 0,26). With the blinds closed, the g-value would be 0,10.

(finstral.com) (Finstral, 2014)

The cavity with blinds in this design is unlike the climate facade and second-skin facade, not being ventilated (except for minor openings to allow for expansion of heated air). This prevents the blinds from collecting dusts and limits cleaning of the windows to the inner and outer side. If maintenance of the blinds is neccessary however, the window frame can be split apart through the middle, to open up the cavity.

In order to reduce visibility of the window frame, the twin-line concept includes various design options, mostly using a glass plane glued or screwed to the front of the frame, making it less visible from that side, as opposed to a ‘regular’ frame with the glass on top.
7.2 Climate facade reference projects

The following paragraph includes examples of two different climate facade designs in modern buildings, showing the differences in design.

7.2.1 TU Delft - Library (1997)

The library of the Delft university of technology aims to be a ‘green’ building, boasting a green roof, underground cold-storage and a climate facade. While the green roof offers thermal mass and natural cooling through evapotranspiration and the cold-storage in underground aquifers allows for energy-efficient cooling, the large glass facade still posed a problem for the summer situation.

In order to allow for a fully-glazed facade, and achieve the desired ‘transparency’, a climate facade was applied. The facade consist of a double glazed outer panel, blinds in the cavity which extracts indoor air and single glazed interior panels. The interior panels are sliding windows, allowing for maintenance of the blinds.

The extraction of indoor air through the facade offers a warm facade surface in winter, eliminating the need for perimeter heating, and extracts solar heat in summer. Apart from that the facade offers improved thermal insulation and sound damping qualities compared to ‘regular’ facades.

Source:
FMVG. TU Delft Library fact sheet

7.2.2 Mercator I (1996)

The Mercator I building provides office space and laboratoria for multiple companies in Nijmegen. The design aims to be a transparent, high-tech and sustainable building. In order to allow for this glass facade, again a climate facade was applied.

The climate facade in the Mercator I building is a different, simplified version of the ‘regular’ climate facade concept though. The so called ‘vlakdoek klimaatgevel’ (flat-screen climate facade) does not have an interior glass panel, but uses a screen(fabric) for both shading and as an interior ‘panel’. The screen has a layer of aluminum damped onto the exterior side to reflect the sun light. Like a regular climate facade, interior air is extracted above the shading.

Compared to a regular climate facade, with to layers of glass, the flat-screen climate facade reduces investment costs and facade depth and makes maintenance access easier. Solar gain however, will be higher and highly dependent on the configuration of the screen (halfway down, all the way down). It must also be noted that this concept only works with screens, not with blinds or other shading systems. Therefore visibility will be reduced heavily compared to blinds that can be rotated towards the sun’s angle.

Source:
Nieuwenhuizen, J. v., & Renckens, J. (2004). De ontwikkeling van vlakdoek klimaatgevels voor kantoorgebouwen
7.3 Second-skin facade reference projects

The following paragraph includes examples of two different second-skin facade designs in modern buildings, showing the differences in design.

7.3.1 ING house (2002)

Much like the previous buildings, the ING house in Amsterdam aims to be a futuristic, high-tech building. The buildings utilises underground thermal energy storage for heating and cooling, as well as a second-skin facade.

The second-skin facade on the south side consists of a single glazed exterior panel, a naturally ventilated cavity with screens or blinds and a double glazed interior panel. The cavity vents are closed in winter to increase insulation and can be opened in summer to reduce solar gain by ventilating the cavity by using the chimney effect.

The north side, which faces the highway, has no vents. This facade provides excellent sound damping qualities as well as increased insulation for the heating season.

Shading systems are operated automatically, lowering shading and rotating it towards the angle of the sun. Additional curtains to keep the heat inside in winter can be lowered as well.

Source: http://nl.wikipedia.org/wiki/ING_House

7.3.2 LVM building (2014)

The LVM building in Münster is a so called Positive energy building, a building that produces more energy than it consumes for building services (on a yearly basis). This includes the energy for HVAC, lighting, water, plumbing etc, but not computers and such.

The buildings aims to use natural forces when possible, and use energy-efficient methods otherwise. The design includes a heat pump with underground thermal storage, PV cells, a bio-fueled combined heat and power system and a second skin facade.

The facade has a triple glazed inner panel and a single glazed outer panel, with blinds in the facade. The facade has vents on the top and bottom, horizontally altering between supply and exhaust vents, to allow for sufficient mixing with outdoor air before air (possibly) re-enters the cavity.

For ventilation, the building uses decentralised supply units with a fan and a heating/cooling element. A central exhaust system extracts air from every floor and uses a heat pump to retrieve thermal energy from the exhaust air, to use in the underfloor heating system. Alternatively, users can open a window to the cavity, which deactivates the decentralised unit.

The ventilation unit is integrated into the raised floor system, which also allows for electrical and data wiring. The intake is located directly behind the supply vent of the cavity, to allow for fresh, unheated air.

Sources:
When designing a new concept, the following properties have been taken into account. This list is made up of characteristics of a ventilation system, based on the regulation, complaints etc. described in this report and good qualities of existing systems. Ideally, a system would meet all these demands in a positive way.

This checklist does not use exact numbers on energy consumption, price etc. but compares systems to other system based on a good, neutral, or bad rating, in order to determine how it performs in relation to other systems.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>Air quality / comfort</td>
<td>Filters, heat exchangers and ducts can cause poor air quality. An unobstructed opening is best</td>
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<tr>
<td>No contamination</td>
<td>Direct openings to the outside can cause too large and variable airflows due to the wind</td>
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<tr>
<td>Pre heated air</td>
<td>Proper ventilation should be ensured at all times, fans will be necessary in almost any case</td>
</tr>
<tr>
<td>Controlled airflow</td>
<td>If users can choose, the consequences are more acceptable. I.e. opening a window might cause more noise, but improves air quality. If people are in control, they will accept it.</td>
</tr>
</tbody>
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<thead>
<tr>
<th>Interaction</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>User adjustment</td>
<td>Users should have influence on their (individual) climate, to improve satisfaction</td>
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<tr>
<td>Purge ventilation</td>
<td>Purging a room should be possible, which usually means openable windows are a must</td>
</tr>
<tr>
<td>Understandable</td>
<td>An open window (psychologically) means fresh air. A vent/button-panel is incomprehensible</td>
</tr>
<tr>
<td>Consideration/trade-offs</td>
<td>If users can make choices, the consequences are more acceptable. I.e. opening a window</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermal properties</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>Nighttime cooling</td>
<td>(Burglar and rain-proof) nighttime ventilation reduces the cooling load in summer</td>
</tr>
<tr>
<td>Dispose of heat</td>
<td>During summer, heat must be disposed of, through a bypass for a HeX, or cross ventilation</td>
</tr>
<tr>
<td>Creating a nice breeze</td>
<td>A breeze (from a window) allows for higher temperatures and improves comfort in summer</td>
</tr>
<tr>
<td>No unnecessary venting</td>
<td>An unoccupied room should not vent air, reducing heat loss and fan energy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs</th>
<th>Explanation</th>
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</thead>
<tbody>
<tr>
<td>Low energy consumption</td>
<td>The lower the fan energy, the better</td>
</tr>
<tr>
<td>Low heat loss</td>
<td>Heat recovery is desirable, but limiting ventilation (CO2 controlled) helps too</td>
</tr>
<tr>
<td>Low capital costs</td>
<td>A decentralised full-HVAC system might perform very well, but the costs shouldn't be too high</td>
</tr>
<tr>
<td>Low maintenance costs</td>
<td>High maintenance costs make a system unfeasable. Low-maintenance also increases reliability</td>
</tr>
<tr>
<td>Flexible system</td>
<td>The layout and function of a building can change over time. A flexible system has an advantage</td>
</tr>
<tr>
<td>No waste of space</td>
<td>Ducts, plant rooms and unit in the facade are all effectively a waste of space an unaesthetic</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>External/safety</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burglar proof</td>
<td>Ventilation should be burglar-proof to allow ventilation at all times</td>
</tr>
<tr>
<td>Rain/condensation proof</td>
<td>Ventilation should be rain-proof and prevent condensation (thermal bridges)</td>
</tr>
<tr>
<td>Sound proof</td>
<td>External noise is a problem for many locations. Sound damping material is often necessary</td>
</tr>
</tbody>
</table>

8 Design concepts

This chapter describes some of the different design concepts formulated throughout the project. 4 different concepts will be described, divided into two groups.

The first two are based on the idea of a twin-coil system for decentralised inlets in the form of openable windows, allowing for a conditioned-openable-window.

The third and fourth concept are based on the idea of using the cavity and area of the glass in the facade for ventilation and climate purposes.

These designs are attempts at concepts to answer the main research question:

Can a hybrid system, combining the good air quality and low costs of a natural system with the user-adjustability, energy efficiency and small size of a decentralised mechanical system, offers a feasible, sustainable alternative to current ventilation concepts?

The feasability will be tested in the following chapters.
8.1 An openable window for all seasons

The first concept was to make a natural-based system, that would allow users to open a window regardless of the outside conditions. In order to do so, a 'standard' openable window would be used, but the window would have three different configurations:

- Window closed for an unoccupied room
- Window in tilt-position conditioned air
- Window in turn-position free flowing air

This would provide an understandable way for users to influence their climate.

The 'climate box' above the window would have a small heat exchanger element, that provides heat recovered from a central, mechanical exhaust. In a way, the system functions as a twin-coil system, but instead of a single element in the supply air, smaller elements are placed above every window; whereas the heat recovery from the exhaust stays the same. Because of the mechanical extraction, no fans are needed in the facade. The box could also contain sound damping material, in order to reduce noise from the outside.

Alternatively, other designs, such as a sliding window, could be made.

Advantages and disadvantages

Advantages:
- The advantages of ventilation system C, but without draft and heat-loss problems
- Possibility to open a window regardless of the outside conditions (psychological effect)
- Allow users to choose between 'conditioned' air or opening a window, and close the window when leaving the room
- Provide rain- and burglar proof ventilation
- Simple, understandable, user-friendly, reliable, decentralized

Disadvantages:
- Perhaps costly, but the simplicity of the decentralized unit reduces costs, as opposed to complex units
- Maintenance, the heat exchanger, or filters protecting it, will need cleaning.
- Air-tightness and thermal insulation of the window, especially in tilt-position during winter
- 'Clean' air is not guaranteed, because a filter will probably be needed in the heat exchanger.
### 8.2 A conditioned ventilation vent

The second concept is the same idea of the first, but combined with a ventilation vent (as described in chapter 4.3). This would provide a much simpler detailing of the window and ‘ventilation box’, by separating the two from each other. Also, the ‘ventilation vent’ would allow for the entire window to be opened in a rain-proof and burglar-proof way, whereas the first concept only provided this in the tilt-position, with a limited airflow.

The system uses the same ‘ventilation box’, but mounted vertically, in the side-frame of the window. The openable window would therefore be placed slightly backward, allowing for the ventilation box on the side, and the louvers in the front (for burglar and rain-proof ventilation).

Instead of the tilt- and turn- configurations, the user now either opens the hatch on the side for conditioned air, or the window for free airflow.

On a building scale, this system would be the same as the first concept.

**Advantage and disadvantages, as opposed to concept 1**

**Advantages:**
- No thermal bridges and proper air-tightness can be achieved
- Allows for rain-proof and burglar-proof ventilation, even when opening the entire window
- Sound damping material can be integrated into the louvers and sides of the window frame

**Disadvantages:**
- Very visible element, even though similar concepts (chapter 4.3) are being applied, it reduces the freedom of the facade design and limits the transparency of the facade

**Optional heat pump**

Additionally, it would be possible to integrate a heat pump into the window frame, to provide heating and cooling without the central system. This would eliminate the water circuit throughout the building.

A small heat pump is possible, like in the smartbox, or like the DucoBox WTW, described in Chapter 4, but would make the system very costly.
8.3 Climate cavity window

The third concept focuses on using the cavity and the area of the glass surface of the facade for ventilation and climate purposes. The concept is a glass surface with openable vents on the top and bottom of the cavity, that can be directed either inwards or outwards. The cavity contains sun-shading. Additionally, a ventilation box containing a fan and heat exchanger can be mounted above the cavity. This allows for the following configurations:

Winter (heating season)
- Pre-heat air using:
  - Solar radiation
  - Heat leaving through glass
  - Waste heat from exhaust (HeX)

Mid-season
- Use the cavity to:
  - Dispose of excess solar heat
  - Extract air (solar chimney) Supply air goes only through HeX

Summer (cooling season)
- Use the cavity to:
  - Dispose of excess solar heat
  - Extract air (solar chimney) Supply air bypasses the system

Without the heat exchanger, the system could function as an inlet or outlet, with a central exhaust system or supply system, depending on the function of the facade at that point. That would require a full duct system throughout the building though, and it would be possible that one side of the building require the system to cool, whereas the other side requires heating.

The ventilation system would not be necessary on the entire width of the facade, but only for as much as would be needed to achieve enough ventilation, for example, 1 meter for every person in the room. The rest of the facade could have a simplified version of the system, that only allows the solar heat to either enter or to keep it outside.

Advantages and disadvantages

Advantages:
- Effective use of solar radiation for either (pre)heating air or for extraction
- Heat lost through the facade is recovered by ventilation air
- Different configurations allow for different climatic conditions
- Reduced fan energy
- User-adjustable, simple, understandable

If no heat exchanger is used:
- No obstruction between outside air and the inside (filters etc, no contamination)
- Completely transparent

Disadvantages:
- Openable windows require further attention, needed for purge ventilation
- Costs of a double skin facade are high
- No cooling integrated into the system, will require additional climate systems
- Windows will need to be cleaned often, similar to double skin facades

If no heat exchanger is used:
- Limited heating capacity, dependent on solar radiation

By doing so, the system uses solar radiation either for (pre)heating or for extraction. Heat that would otherwise leave the building through the glass can be recovered in the supply air. The (optional) heat exchanger can further heat the incoming air if necessary. In summer, air enters either through a bypass or through an openable window.

The cavity with shading essentially makes this system a double-skin facade, or a climate facade, but in this way, the shading system provides heating in winter and extraction in summer, in addition to the shielding from solar radiation and visual comfort.

Unlike the first two concepts, this system provides both supply and exhaust, making it a decentralised ventilation concept. It is unclear at this point if the heat exchanger and fan are necessary. Buoyancy will provide some extraction in winter and the cavity will function as a solar chimney, providing additional airflow in all seasons, but it is unclear if this will be enough. It is most likely that a fan will be necessary to ensure proper ventilation under all conditions.

As far as the heat exchanger goes, it will depend on the heating in the cavity through recapturing air leaving the building and solar radiation.
Chapter 8 - Design concepts

8.3.1 Climate cavity as opposed to Climate- & Second skin facade

Climate facade

Summer situation
Mechanical extraction of interior and cavity through cavity to reduce solar gain
Mechanical supply

Winter situation
Mechanical extraction of interior and cavity through cavity to reduce solar gain and prevent need for perimeter heating
Mechanical supply

Second-skin facade

Summer situation
Natural ventilation of cavity to reduce solar gain
Mechanical supply and exhaust of interior

Open window
Natural ventilation of interior and cavity.
Shielding against wind by exterior facade.

Climate cavity

Summer situation
Mechanical extraction aided by buoyancy (solar chimney) of interior and cavity through cavity to reduce solar gain
Natural supply

Winter situation
Natural supply through cavity to pre-heat air
Mechanical extraction

Open window
Natural supply
Mechanical/natural extraction along shading to reduce solar gain

Differences
A climate facade combines extraction of the interior with extraction of the cavity, but requires mechanical supply.

A second skin facade allows for natural ventilation of the cavity but requires mechanical supply and exhaust of the interior.
Opening a window is only possible if the cavity is not heated by the sun to prevent overheating of the interior.

The climate cavity concept combines extraction of interior with extraction of the cavity in summer and allows for natural supply in all situations, reducing fan energy.
Opening a window is possible, even with some amount of solar gain, because hot air from the shading is extracted above the shading. Supply is limited because of narrow openings along the width of the facade.

For short, a climate facade and second-skin facade are ventilation system D (mechanical supply and exhaust), while the climate cavity concept is a hybrid of ventilation system C (natural supply, mechanical exhaust) and system E (decentralised), combining natural supply (no ducts, no maintenance, no fans) with decentralised mechanical extraction (no ducts, no conventional HeX, guaranteed airflow).
8.4 Glass cavity heat exchanger

Whereas the previous concept uses one cavity for either supply or exhaust, it is also possible to use two adjacent cavities, for supply and for exhaust, to create a heat exchanger out of glass. Like the previous concept, one of the cavities could include a shading system. This would provide the following configurations:

- **Parallel flow HeX**
  - can recover 50% of heat at max

- **Counter flow HeX**
  - can potentially recover more heat, but counters buoyancy effect

---

**Advantage and disadvantages, as opposed to concept 3**

**Advantages:**
- Increased heat recovery rate
- Additional (ventilated) barrier between the shading/supply cavity and the indoor space, like in a climate facade

**Disadvantages:**
- Very complex

This system will most likely need a fan to drive the air. The forced airflow will increase to rate of heat transfer to and from the glass separating the streams. However, this would effectively create a triple skin facade. It might eliminate the need for a conventional heat exchanger, but the additionally needed glass, window frames and the increased overall weight of the facade will increase costs a lot.

Apart from that, since windows need to be cleaned regularly, especially when air flows through the cavity, every panel should be accessible from both sides. This would mean that the there should be an openable window inside an openable window.

Lastly, in order to allow for openable windows within this system, the system would be even more complex:
## 8.5 Review

This table shows the rating according to these demands for ventilation system A, C, D and E as well as the 4 concepts mentioned before. Again, these are not measured facts, but more of an indication how these system relate to each other.

<table>
<thead>
<tr>
<th>Properties</th>
<th>System A</th>
<th>System C</th>
<th>System D</th>
<th>System E</th>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
<th>Concept 4</th>
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<tr>
<td>Air quality / comfort</td>
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<td>Pre heated air</td>
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<td>Thermal properties</td>
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<td>Dispose of heat</td>
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<td>Creating a nice breeze</td>
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<td>No unnecessary venting</td>
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<td>Low energy consumption</td>
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<td>Low maintenance costs</td>
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<tr>
<td>External/safety</td>
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<td></td>
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<tr>
<td>Burglar proof</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Rain/condensation proof</td>
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<td></td>
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<td></td>
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<tr>
<td>Sound proof</td>
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</tr>
</tbody>
</table>

| System A and C - natural ventilation | | | | | | | | |
| provides clean air | + | | | | | | |
| user-friendly, understandable | + | | | | | | |
| allows for cooling in summer (cross-ventilation) | + | | | | | | |
| inexpensive | + | | | | | | |
| uncomfortable (does not apply to system C) | - | | | | | | |
| unreliable (unless system C is sensor-regulated) | - | | | | | | |
| high heat loss (unless system C is sensor-regulated) | - | | | | | | |

| System D and E - Fully mechanical ventilation (E is decentralised) | | | | | | | | |
| reliable, controlled and comfortable airflow | + | | | | | | |
| Low heat loss | + | | | | | | |
| perfectly shielded from external problems | + | | | | | | |
| Prone to poor air quality | - | | | | | | |
| Not user-friendly and understandable | - | | | | | | |
| ‘One size fits all’ for the entire building | - | | | | | | |
| Costly in terms of fan energy, capital costs, maintenance and space consumption | - | | | | | | |

| Concept 1 - All-season window | | | | | | | | |
| reliable, controlled and comfortable airflow | + | | | | | | |
| user-friendly, understandable | + | | | | | | |
| allows for cooling in summer (cross-ventilation) | + | | | | | | |
| Low heat loss | + | | | | | | |
| Filters require cleaning, similar to system E, but no ducts like system D | - | | | | | | |
| Costly in terms of capital costs | - | | | | | | |
| External factors can be a problem | - | | | | | | |

| Concept 2 - Conditioned ventilation vent | | | | | | | | |
| reliable, controlled and comfortable airflow | + | | | | | | |
| user-friendly, understandable | + | | | | | | |
| allows for cooling in summer (cross-ventilation) | + | | | | | | |
| Low heat loss | + | | | | | | |
| Rain and burglar proof (nighttime ventilation) | + | | | | | | |
| Filters require cleaning, similar to system E, but no ducts like system D | - | | | | | | |
| Costly in terms of capital costs | - | | | | | | |
| Occupies facade space | - | | | | | | |

| Concept 3 - Climate cavity | | | | | | | | |
| reliable, controlled and comfortable airflow | + | | | | | | |
| user-friendly, understandable | + | | | | | | |
| allows for cooling in summer (shading) | + | | | | | | |
| Limited/low heat loss | + | | | | | | |
| Limited capital costs, considering the combination with shading and climate advantages | + | | | | | | |
| Reduced fan energy | + | | | | | | |
| maintenance of filters and HeX (unless the HeX is left out) | - | | | | | | |
| does not allow for burglar proof large airflows (nighttime ventilation) | - | | | | | | |
| Occupies facade space (if a HeX is needed) | - | | | | | | |

| Concept 4 - Glass cavity heat exchanger | | | | | | | | |
| provides clean air | + | | | | | | |
| reliable, controlled and comfortable airflow | + | | | | | | |
| user-adjustable | + | | | | | | |
| allows for cooling in summer (shading) | + | | | | | | |
| Low heat loss | + | | | | | | |
| Reduced fan energy | + | | | | | | |
| no filters or conventional HeX | - | | | | | | |
| fan will probably be necessary | + | | | | | | |
| optionally combined with openable windows | + | | | | | | |
| depending on HeX or just the cavity | + | | | | | | |

For short:

- comfortable
- reliable
- perfect

- Comfortable
- user-friendly
- understandable

- High heat loss
- unreliable
- maintenance of filters and HeX
- burglary
- sound proof
9 Preliminary calculation models & estimates for the all-season window (concept 1 & 2)

This chapter provides calculation models and estimate in support of the first two concepts mentioned before, focussing on a facade vent with a heat exchanger element and a twin coil system in the building, in a first attempt at answering the fourth research question:

Is the proposed new concept feasible in terms of (thermal/acoustic) comfort, energy efficiency, investment, maintenance and operation costs and in aesthetic value?

Chapter 8.1 describes the temperate and comfort feasibility of the concept
Chapter 8.2 describes the investment-, maintenance-, and energy-costs

9.1 Temperature and comfort

The heat transfer coefficient for convective heat transfer \((\alpha_c)\) is defined as:

\[
Nu = \frac{(\alpha_c * d) / \lambda}{[\text{-}]} \quad \Rightarrow \quad \alpha_c = \frac{(Nu * \lambda)}{d} \quad [\text{W/(m}^2\text{K)}]
\]

\(Nu\) Nusselts number, relation between heat transfer with and without convection (conduction) for purely conductive heat transfer, \(Nu = 1\). Nu is the 'improvement' of heat transfer in relation to conduction

\(\alpha_c\) heat transfer coefficient for convection \( [\text{W/(m}^2\text{K)}] \)

\(d\) defining dimension \( [\text{m}] \)

\(\lambda\) heat transfer coefficient for the flowing medium \( [\text{W/(m}^2\text{K)}] \)

For air of \(20\degree C\), \(\lambda = 0.026 \text{ W/(m}^2\text{K)}\)

Nusselts number for an airflow between two parallel surfaces for a forced airflow is defined as:

\[
Nu = 3.66 \quad \text{(for Re < 2.300, laminar flow)}
\]

\[
Nu = 0.027 \ast Re^{0.80} \ast Pr^{0.33} \quad \text{(for Re > 10.000, turbulent flow)}
\]

\(Re\) Reynolds number

\(Pr\) Prandtels number, defining for physical properties of a flowing medium

Reynolds number is defined as:

\[
Re = \frac{(v \ast d)}{\nu} \quad [\text{-}]
\]

\(v\) Average speed of the forced airflow \( [\text{m/s}] \)

\(d\) Defining dimension \( [\text{m}] \)

\(\nu\) kinematic viscosity \( [\text{m}^2/\text{s}] \)

For air of \(20\degree C\), \(\nu = 1.517 \ast 10^{-5} \text{ m}^2/\text{s}\)

Prandtels number is defined as:

\[
Pr = \frac{\nu}{a} \quad [\text{-}]
\]

\(\nu\) kinematic viscosity \( [\text{m}^2/\text{s}] \)

For air of \(20\degree C\), \(\nu = 1.517 \ast 10^{-5} \text{ m}^2/\text{s}\)

\(a\) thermal diffusivity \( [\text{m}^2/\text{s}] \)

(Dutch: temperatuurvereffeningscoëfficiënt)

Thermal diffusivity is defined as:

\[
a = \frac{\lambda}{(\rho \ast cp)} \quad [\text{m}^2/\text{s}]
\]

\(\lambda\) heat transfer coefficient for the flowing medium \( [\text{W/(m}^2\text{K)}] \)

For air of \(20\degree C\), \(\lambda = 0.026 \text{ W/(m}^2\text{K)}\)

\(\rho\) density, \( [\text{kg/m}^3] \)

For air of \(20\degree C\), \(\rho = 1.2 \text{ kg/m}^3\)

\(cp\) specific heat \( [\text{J/(kg} \cdot \text{K}] \)

For air of \(20\degree C\), \(cp = 1010 \text{ J/(kg} \cdot \text{K} \))

Source:
9.1.2 Finite element method

By using these equations, the convective heat transfer in the heating element can be estimated.

For:
\[ d = 0.01 \text{ m} \]
\[ v = 0.1 \text{ m/s} \]
the resulting heat transfer coefficient for convection for a laminar flow is:
\[ \alpha = 9.516 \text{ W/m}^2\text{K} \]

In order to determine the temperature of the air inside the heat exchanger, a simple model using a finite-element approach has been made, that functions as follows:

The air in between two plates in divided in smaller volumes (100 in this model). For every volume, the heat transfer from the plates is determined by the temperature difference, the heat transfer coefficient, the contact surface for that volume, and the time that air would be inside that given volume:

\[ Q = \alpha \cdot 2 \cdot A \cdot \Delta T \cdot t \quad [J] \]

\[ \Delta T = T_{plate} - T_{air} \]
\[ A = \text{area of the plate for the given volume (total area)/100} \quad [\text{m}^2] \]
\[ t = \text{time period during which air would be in the volume} \quad [\text{s}] \]

The energy added through convection is determined as follows:

\[ Q_{\text{conv}} = \alpha \cdot 2 \cdot A \cdot \Delta T \cdot t \quad [J] \]

\[ T_{plate} = 13.2^\circ C \]
\[ T_{air} = 5^\circ C \]

The efficiency of this heat exchanger in the facade would then be \( (10.5-(-5))/(13.2-(-5)) = 85\% \)

Notes:
Two assumptions can have a huge impact on this estimate:
1. The fact that the temperature of the plates is equal to the water temperature of the system. In reality the temperature of the plates would be lower.
2. The temperature of the water in the system, estimated at 70% of the difference between indoor and outdoor temperature. This highly depends on the kind of heat exchanger used in the central exhaust, as well as the pipes between this exchanger and the facade elements. The estimated value of 70% is for two heat exchangers combined, one in the exhaust flow and one in the supply, whereas in this case it is used solely for the one in the exhaust. As far as the pipes go, they would probably be heated up, because the water temperature is lower than the indoor temperature.

Conclusion
There is no way to determine the exact temperature of the supply air without testing an actual mockup, but the model suggest that a decent temperature could be achieved with a relatively small element, provided that the airspeed is limited. So for short, the width and depth of the element have to be limited, but a higher height allows for sufficient airflow at low airspeeds, which gives the air more time to heat up. This would require a wind-pressure regulated vent to prevent gusts of wind blowing through at high speeds and therefore cold air.

Additional heating or cooling would be possible, but the pipes leading through the entire building would need to be insulated.
9.2 Costs of concept 1 & 2

To get an idea of the feasibility of the concept, an estimate will be made for the investment cost, maintenance costs and energy costs of the concept, based on data from chapter 3, 4 and 5.

9.2.1 Investment costs

The investment costs for a twin-coil system as opposed to a thermal wheel as estimated by AL-KO luchttechniek for an airflow of 40,000 m$^3$/h (chapter 3.2) are as follows:

- Twin-coil system (70% efficiency) €86,708
- Thermal wheel (81.9% efficiency) €93,934

Ventilation of office buildings is typically about 5m$^3$/m$^2$*h
That would mean that the floor area of this building (not mentioned in AL-KO's calculation) would be 8,000m$^2$

The costs for ducting as estimated in chapter 5.1 is about €45/m$^2$ floor area.

The costs for ducting in this building, in addition to the costs for the HVAC unit, would then be €360,000 for both supply and exhaust, and halve that for just extraction.

This matches the ratio between costs for the HVAC unit and the ducts/vents in the calculation by climarad in chapter 5.1.1:

<table>
<thead>
<tr>
<th>Component</th>
<th>Climarad</th>
<th>Mentioned above</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVAC unit</td>
<td>€47,610</td>
<td>€90,000</td>
</tr>
<tr>
<td>Ducts</td>
<td>€216,890</td>
<td>€360,000</td>
</tr>
<tr>
<td>Ratio</td>
<td>1/4.56</td>
<td>1/4</td>
</tr>
</tbody>
</table>

The costs for the decentralized unit are hard to estimate, but compared to the other decentralised concepts it includes mostly the same components, without the fans. Since the other decentralised concepts range from about €1,000 - €2,000, the costs for the ventilation box for the first two concepts is estimated at €1,000 for now.

The airflow through a single unit as estimated in 8.1 would be 10 l/s, but could possibly be higher. Judging from the 10 l/s, a total of 1,111 decentralised units would be required. This would however be one unit for every 7,2 m$^2$. The units described in chapter 5.1 used 1 unit for respectively every 20 and 55 m$^2$. Therefore a single unit for every 20 m$^2$ will be assumed for this estimate.

According to this estimate the investment costs for the system would be about 37% higher than a conventional central system. It must be noted though that like mentioned before, the elements used for this ventilation system could also be used for (limited) heating and cooling of the building, which would reduce costs for additional climate systems.

9.2.2 Maintenance costs

By using the same values given in chapter 5.2, the following maintenance costs can be estimated:

<table>
<thead>
<tr>
<th>System</th>
<th>info</th>
<th>costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>for 9,600 m$^3$/h</td>
<td>€4,263</td>
</tr>
<tr>
<td>Example building</td>
<td>for 4,000 m$^3$/h</td>
<td>€17,763</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>info</th>
<th>costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>All season window</td>
<td>costs of system D</td>
<td>€8,882</td>
</tr>
<tr>
<td>Extraction system</td>
<td>€46/year</td>
<td>€30,25/year</td>
</tr>
<tr>
<td>Climarad single unit</td>
<td>€20,25/year</td>
<td>€33,200</td>
</tr>
<tr>
<td>400 units total</td>
<td>€13,200</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>€22,082</td>
<td></td>
</tr>
</tbody>
</table>

According to this estimate, the maintenance costs of the system would be about 24% higher than a conventional system. Again, this is primarily caused by the fact that the system requires decentralised unit as well as the central extraction system, effectively adding 50% of the costs of system D to the costs of a decentralised system. The maintenance costs for a single unit could however be lower, as it only functions as a supply unit, and therefore has no exhaust filter. If this is assumed, the maintenance costs could be slightly lower.

9.2.3 Energy costs

The energy costs for the system would be the same as for system C with the additional resistance of filters and heat exchangers in the inlet vents.

Considering the fact that the duct length is significantly shorter than system D, but that the biggest pressure difference is caused by heat exchangers, filters and vent, the system would probably be slightly more efficient. Additionally, the wind pressure on a facade would aid the system, whereas system D has little advantage of the wind.
10 Preliminary calculation models & estimates for the climate cavity (concept 3 & 4)

This chapter provides calculation models and estimates in support of the second two concepts mentioned before, focussing on facade element using the cavity as an supply or exhaust vent, in a first attempt at answering the fourth research question:

Is the proposed new concept feasible in terms of (thermal/acoustic) comfort, energy efficiency, investment, maintenance and operation costs and in aesthetic value?

Chapter 9.1 describes the temperare and comfort feasability of the concept. Chapter 9.2 describes the investment-, maintenance-, and energy-costs.

### 10.1 Temperature and comfort of concept 3

In order to determine the temperature of the supply air when it enters the room, equations for the temperature of every element of the facade will be set up. The following assumptions will be made:

- The facade is assumed as an endless, flat surface, consisting of a homogeneous, isotropic material.
- The temperature of a surface is equal for the entire surface and the thermal resistance is neglected.
- If sunshading is applied, it is assumed it will be complete closed towards the sun.
- Heat transfer occurs perpendicular to the surfaces.
- The temperature of any element is stationary.
- Air flowing through the cavity moves linear with an equal speed for every ‘particle’.
- The temperature of the air in the cavity is the average of the temperatures of air entering and leaving the cavity.

**Used variables:**
- $T_e$: Exterior temperature
- $T_i$: Interior temperature
- $T_{cavity}$: Cavity temperature (average value for entire cavity)
- $T_{inlet}$: Temperature of the air at the exterior vent, where fresh air enters
- $T_{supply}$: Temperature of the air at the interior vent, when entering the room
- $T_{glass1}$: Temperature of exterior glass plane
- $T_{glass2}$: Temperature of interior glass plane

#### Convection

Convective heat transfer is defined as:

$$q_c = \alpha_c \times \Delta T$$

$q_c$: Convective heat transfer [W]

$\alpha_c$: Heat transfer coefficient for convection [W/m²*K]

$\Delta T$: Difference in temperature [K]

For interior surfaces and closed cavities, $\alpha_c$ is assumed as:

$$0,5 \text{ W/m}^2\text{K} < \alpha_c < 3 \text{ W/m}^2\text{K}$$

For exterior surfaces, $\alpha_c$ is assumed as:

$$\alpha_c = 19,5 \text{ W/m}^2\text{K}$$

#### Radiation

Radiation heat transfer is defined as:

$$q_r = \alpha_r \times \Delta T$$

$q_r$: Radiation heat transfer [W]

$\alpha_r$: Heat transfer coefficient for radiation [W/m²*K]

$\Delta T$: Difference in temperature [K]

For most materials, $\alpha_r$ can be assumed as:

$$\alpha_r = 5,5 \text{ W/m}^2\text{K}$$

This does not apply to materials such as aluminum and to high temperatures.
10.1.1 Energy-balance equations model

In order to determine the temperature of the given elements of the facade, the following equations can now be established:

**Temperature of air in the cavity**

\[ T_{cavity} = \frac{T_{inlet} + T_{supply}}{2} \]

The temperature of the air in the cavity is the average temperature of the air entering and leaving the cavity.

**Temperature of the air entering the cavity**

\[ T_{inlet} = T_e \]

The temperature of the air entering the cavity is equal to the exterior temperature.

**Temperature of the exterior glass plane**

\[ \alpha_e \cdot (T_{e} - T_{glass1}) = \alpha_c \cdot (T_{glass1} - T_{cavity}) + \alpha_r \cdot (T_{glass1} - T_{glass2}) \]

Energy lost to the outside = energy gained/lost through convection from the cavity + energy gained through radiation from the interior glass plane.

In which \( \alpha \) is the heat transfer coefficient for the outside.

\( \alpha_e = 25.0 \text{ W/m}^2 \text{K} \)

**Temperature of the interior glass plane**

\[ \alpha_i \cdot (T_{cavity} - T_{glass2}) + \alpha_r \cdot (T_{glass1} - T_{glass2}) = \alpha_i \cdot (T_{glass2} - T_i) \]

Energy lost through convection to the cavity + energy lost through radiation to the exterior glass plane = energy gained from the inside.

In which \( \alpha \) is the heat transfer coefficient for the interior.

\( \alpha_i = 7.8 \text{ W/m}^2 \text{K} \)

**Temperature of the supply air**

\[ \alpha_c \cdot (T_{glass1} - T_{cavity}) \cdot A_{facade} + v \cdot A_{air} \cdot (\rho c)_{air} \cdot T_{inlet} = \]

\[ \alpha_c \cdot (T_{cavity} - T_{glass2}) \cdot A_{facade} + v \cdot A_{air} \cdot (\rho c)_{air} \cdot T_{supply} \]

Energy gained/lost over the entire surface of the facade from/to the exterior glass plane + energy added to the cavity through ventilation =

Energy gained/lost over the entire surface of the facade from/to the interior glass plane + energy removed from the cavity through ventilation.

Since \( T_{inlet} \) is known, there are now 4 equations with 4 unknown variables. These equations can be solved either by hand or by entering them in a software tool to solve them. The tool used for this report is the LInear Solver by WIMS (http://wims.unice.fr/wims/en_tool~linear~linsolver.en.html)

The following values are being used to solve the equations:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_e )</td>
<td>21 °C</td>
</tr>
<tr>
<td>( T_i )</td>
<td>-5 °C</td>
</tr>
<tr>
<td>( \alpha_e )</td>
<td>25.0 W/m²K</td>
</tr>
<tr>
<td>( \alpha_c )</td>
<td>3.0 W/m²K</td>
</tr>
<tr>
<td>( \alpha_r )</td>
<td>5.5 W/m²K</td>
</tr>
<tr>
<td>( \alpha_i )</td>
<td>7.8 W/m²K</td>
</tr>
<tr>
<td>( A_{facade} )</td>
<td>1 m²</td>
</tr>
<tr>
<td>( A_{air} )</td>
<td>0.1 m²</td>
</tr>
<tr>
<td>( v )</td>
<td>0.065 m/s</td>
</tr>
<tr>
<td>( \rho c )</td>
<td>1,22 kg/m³</td>
</tr>
</tbody>
</table>

The results in the following values:

Note that the ‘cavity’ value is the average temperature in the cavity. The temperature of the air entering the building is listed as ‘supply air’ on the right.

**Conclusions**

For a winter situation, where the outside temperature is -5 °C, the air inside the cavity will heat up by almost 5 degrees, resulting in a temperature of -0.5 °C. This is only a small improvement, but this model assumes there is only single glazing on both sides of the cavity. Apart from that, the longer the air will be in the cavity, the more it will heat up. The wider the ‘vent’ in the facade, the lower the speed in the cavity can be in order to achieve sufficient airflow for the amount of people inside.

10.1.2 Finite element method

An alternative calculation to estimate the temperature of the air inside the cavity, is to divide the volume into smaller parts (100 in this model). Then the energy flows can be calculated for every volume:

- Energy entering the volume through the inner plane of the facade, determined by the U-value for glass panels (single glazed, double glazed, HR++)
- Energy leaving the volume through the outer plane of the facade, determined by the U-value
- Energy entering the volume as air with a given temperature
- Energy leaving the volume as air with a given temperature.

The temperature of the first volume is assumed to be equal to the exterior temperature. The energy-flows for the first volume determine the temperature of the second volume. In other words:

\[ T_{\text{volume} 2} = T_{\text{volume} 1} + \frac{(\text{energy added to volume 1} - \text{energy removed from volume one})}{\text{heat capacity of a volume}} \]

The first volume will therefore only receive energy through the facade planes. The second volume will then have a slightly higher temperature. The air leaving this volume for volume 3, will therefore contain more energy than the air entering volume 2, which equals \( T_e \). In other words, energy leaves the volume, because warm air is replaced by cold air.

The 'time' during which energy is added and removed is defined by the airflow and the cross-section of the cavity. Because the model assumes that the energy-transfer remains constant during this time period, the step-size should be very small, because in reality, energy transfer decreases with the decrease in \( \Delta T \).

To achieve as high a temperature as possible the inner panel should insulate poorly (single glazing) and the outer panel should be highly insulating (HR++ glazing), but even then the temperature would only rise to 2,72 °C. However, this would leave the inner glass panel very cold, which will have a negative effect on the thermal comfort. In order to achieve a higher temperature the airflow in the cavity should be decreased (making the 'vent' wider) or alternative sources of heating are necessary, such as solar heating or a heat exchanger.

The same models for the following measures (a bigger window element) give the following results:

<table>
<thead>
<tr>
<th>Energy-balance method</th>
<th>Facade height 1,50 m</th>
<th>Facade width 2,00 m</th>
<th>Cavity depth 0,15 m</th>
<th>Airflow 6,5 l/s</th>
<th>Airspeed 0,022m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature over height</strong></td>
<td><strong>Interior</strong></td>
<td><strong>Exterior</strong></td>
<td><strong>Cavity (single glazing)</strong></td>
<td><strong>Cavity (double glazing)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Temperature per element</strong></td>
<td>EXTERIOR</td>
<td>OUTER GLASS</td>
<td>CAVITY</td>
<td>INNER GLASS</td>
<td>INTERIOR</td>
</tr>
<tr>
<td><strong>single glazing</strong></td>
<td>( T_{\text{supply}} = 1,82 ) °C</td>
<td>( T_{\text{supply}} = -0,83 ) °C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>double glazing</strong></td>
<td>( T_{\text{supply}} = 3,90 ) °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Additional solar radiation

The previously mentioned models did not take any solar radiation into account, just the energy flows through the facade. However, solar radiation can have a huge impact on the temperature inside the cavity.

Three factors are important for solar radiation:
- \( A \) Absorption assumed as 0,1 for glass [-]
- \( r \) Reflection assumed as 0,1 for glass [-]
- \( \tau \) Transmission assumed as 0,8 for glass [-]

The total of the three should always be 1.

For the energy-balance method, this gives the following new equations:

#### Temperature of the left cavity

\[
T_{\text{cavity-left}} = \frac{T_{\text{inlet}} + T_{\text{supply-left}}}{2}
\]

The temperature of both cavities is the average temperature of the air entering and leaving

#### Temperature of the air entering the cavity

\[
T_{\text{inlet}} = T_e
\]

The temperature of the air entering the cavities is equal to the exterior temperature

#### Temperature of the outer glass plane

\[
A_{\text{glass1}} \cdot q_{\text{conv}} + a_e \cdot (T_o - T_{\text{glass1}}) = a_c \cdot (T_{\text{glass1}} - T_{\text{cavity-left}}) + a_r \cdot (T_{\text{glass1}} - T_{\text{shading}})
\]

Absorbed solar energy and energy lost to the outside = convective heat to the outer cavity + radiation from the shading

#### Temperature of the outer side of the cavity

\[
a_c \cdot (T_{\text{glass1}} - T_{\text{cavity-left}}) \cdot A_{\text{facade}} + v_{\text{air}} \cdot A_{\text{cavity-left}} \cdot (\rho c)_{\text{air}} \cdot T_{\text{inlet}} = a_c \cdot (T_{\text{shading}} - T_{\text{cavity-left}}) \cdot A_{\text{facade}} + v_{\text{air}} \cdot A_{\text{cavity-left}} \cdot (\rho c)_{\text{air}} \cdot T_{\text{supply-left}}
\]

Convective heat from the outer glass and energy from the incoming air = convective heat from the shading and energy in the air leaving the cavity

#### Temperature of the sun shading

\[
A_{\text{shading}} \cdot \tau \cdot q_{\text{conv}} + a_e \cdot (T_{\text{shading}} - T_{\text{glass1}}) + a_r \cdot (T_{\text{glass1}} - T_{\text{shading}}) = a_c \cdot (T_{\text{shading}} - T_{\text{cavity-right}}) + a_r \cdot (T_{\text{shading}} - T_{\text{glass1}})
\]

Absorbed solar energy through the outer glass plane and convective heat to the outer cavity and radiation to the outer glass plane = convective heat to the inner cavity and radiation from inner glass

#### Temperature of the inner side of the cavity

\[
a_c \cdot (T_{\text{shading}} - T_{\text{cavity-right}}) \cdot A_{\text{facade}} + v_{\text{air}} \cdot A_{\text{cavity-right}} \cdot (\rho c)_{\text{air}} \cdot T_{\text{inlet}} = a_c \cdot (T_{\text{glass2}} - T_{\text{shading}})
\]

Convective heat from the shading and energy from the incoming air = convective heat from the inner glass and energy in the air leaving the cavity

#### Temperature of the inner glass plane

\[
a_c \cdot (T_{\text{cavity-right}} - T_{\text{glass2}}) + a_r \cdot (T_{\text{glass2}} - T_i) = a_i \cdot (T_{\text{glass2}} - T_i)
\]

Convective heat to the inner cavity and radiation to the shading = heat gained from the inside

---

The amount of solar radiation will obviously differ from day to day and hour to hour, but to establish a representative value, the following charts have been made using data from climate consultant:

**Average hourly solar radiation for every day of December**

**Average hourly solar radiation for every day of July**

**Source:**
Climate consultant. Downloadable from: http://www.energy-design-tools.aud.ucla.edu/

According to the data from Climate Consultant, these are the months with the least and most solar radiation. Note that these values are for a horizontal surface, which is not representative for the vertical surface of the facade. During the winter, when the sun is at a low inclination, the radiation on a vertical surface is slightly more intense, about 20%. During summer the inclination of the sun will differ greatly over the day, it is best to assume the ‘worst case scenario’ and apply the same values as given for a horizontal surface in the midst of the afternoon.

By doing so, the representative values used further in this report are:
- Winter 50 W/m²
- Summer 800 W/m²

These values will be used in order to determine the increased temperature in winter, which will aid in preheating the air in the cavity, and the (average) temperature inside the cavity in summer, to determine how much of the sun’s heat is being kept outside.
Adding 50 W/m² of solar radiation to the energy-balance model results in the following data for the winter situation:

**Small window**

<table>
<thead>
<tr>
<th>Without radiation</th>
<th>With 50 W/m² radiation</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small window</td>
<td>-0.52 °C</td>
<td>3.43 °C</td>
</tr>
<tr>
<td>Large window</td>
<td>4.00 °C</td>
<td>10.50 °C</td>
</tr>
</tbody>
</table>

This shows that even with a little solar radiation a large increase in temperature can be achieved. Compared to the model without solar radiation, the values have increased by:

**Conclusion**

Provided that the element is wide enough to allow for low airspeeds, the facade element can decently pre-heat the air, especially with the addition of solar radiation. As a reference for comfort, the Duco Climatop as mentioned in paragraph 4.1.11 pre-heats air up to 12 °C.

For unfavourable conditions, a heat exchanger might be necessary or other ways to prevent draft problems. However, heat loss would still be a problem.
10.2 Temperature and comfort of concept 4

Similar to the finite element method in chapter 9.1, a similar model has been made for concept 4. However, in order to determine the amount of convection, the convective heat transfer coefficient has to be determined for transfer between every layer. Apart from that, radiation has been integrated as well. The model functions as follows:

Similar to the finite element methods mentioned before, the height of the facade element is divided into 100 equal elements. The different layers are the exterior, at -5 °C, a double glass panel for insulation, the supply cavity, another glass panel, the exhaust cavity, the inner glass plane and the interior, at 21 °C.

The temperature for every layer except the supply and exhaust is assumed to be equal over the entire height. For every 1/100th step, the heat transfer to the outside, convective heat transfer from layer to layer, radiative heat transfer from glass to glass and energy lost through ventilation is determined. The equations are described on the next 2 pages. It is assumed that the outer glass panel is a HR++ panel with a radiative coating, that prevents radiation loss to the exterior. Therefore radiative heat exchange only takes place between glass 2 and 3, glass 3 and 4, glass 4 and the interior.

The size of the facade panel is again 2 meters wide and 1.5 meters high. The depth of a cavity is assumed as 0.10 meters.

Temperature and comfort of concept 4

Convection for a natural flow (when Re << Gr)

The heat transfer coefficient for convective heat transfer \( \alpha_c \) is defined as:

\[
Nu = \frac{(\alpha_c * d)}{\lambda} \quad [-] \quad \Rightarrow \quad \alpha_c = \left(\frac{Nu * \lambda}{d}\right) \quad \text{[W/(m}^2\text{K)]}
\]

- \( Nu \) Nusselts number [-]
- \( \alpha_c \) heat transfer coefficient for convection \([\text{W/(m}^2\text{K})]\)
- \( d \) defining dimension [m]
- \( \lambda \) heat transfer coefficient for the flowing medium \([\text{W/(m}^2\text{K})]\)
- for air of 20 °C \( \lambda = 0.026 \text{ W/(m}\cdot\text{K}) \)

Nusselts number for an airflow between two horizontal parallel surfaces for a natural airflow is defined as:

\[
Nu = 0.55 \cdot Ra^{0.25} \quad \text{(for} \ Ra < 10^{10}, \text{laminar flow)}
\]

\[
Nu = 0.13 \cdot Ra^{0.33} \quad \text{(for} \ Ra > 10^{10}, \text{turbulent flow)}
\]

- \( Ra \) Rayleigh’s number [-]
- \( \text{Rayleigh’s number is defined as:} \)
  \[
  Ra = Gr \cdot Pr
  \]
- \( Gr \) Grashof’s number [-]
  \( Gr = \frac{L^3 * g * \beta * \Delta T}{\nu^2} \)
  \( L \) defining dimension (known as D for tubes and such) [m]
  \( g \) gravitational constant, 9.81 m/s\(^2\) [m/s\(^2\)]
  \( \beta \) cubical expansion coefficient, 1/293 for 20°C [1/K]
  \( \Delta T \) temperature difference between surface and air [K]
  \( \nu \) kinematic viscosity \([\text{m}^2/\text{s}]\)
  for air of 20 °C, \( \nu = 1.517 \cdot 10^{-5} \text{ m}^2/\text{s} \)

- \( Pr \) Prandtl’s number [-]
  \( Pr = \frac{\nu}{a} \)
  \( a \) thermal diffusivity \([\text{m}^2/\text{s}]\)
  (Dutch: temperatuurvereffeningscoëfficient)

Prandtl’s number is defined as:

\[
Pr = \frac{\nu}{a} \quad [-]
\]

\[
\nu \quad \text{kinematic viscosity} \quad \text{[m}^2/\text{s}]\]

\[
a \quad \text{thermal diffusivity} \quad \text{[m}^2/\text{s}]\]

Prandtl’s number is defined as:

\[
Pr = \frac{\nu}{a} \quad [-]
\]

\[
\nu \quad \text{kinematic viscosity} \quad \text{[m}^2/\text{s}]\]

\[
a \quad \text{thermal diffusivity} \quad \text{[m}^2/\text{s}]\]

Thermal diffusivity is defined as:

\[
a = \frac{\lambda}{(\rho * cp)} \quad \text{[m}^2/\text{s}]\]

- \( \lambda \) heat transfer coefficient for the flowing medium \([\text{W/(m}^2\text{K})]\)
  for air of 20 °C \( \lambda = 0.026 \text{ W/(m}\cdot\text{K}) \)
- \( \rho \) density, \([\text{kg/m}^3]\)
  for air of 20 °C, \( \rho = 1.2 \text{ kg/m}^3 \)
- \( cp \) specific heat \([\text{J/(kg}\cdot\text{K}]\)
  for air of 20 °C, \( cp = 1010 \text{ J/(kg}\cdot\text{K}) \)

Source:

Jeroen ter Haar

Natural & Decentralized ventilation and climate concepts
Radiation
Radiative heat transfer from one surface to another is defined as:

\[ \Phi_{2\rightarrow1} = \Psi_{2\rightarrow1} \times A_2 \times \varepsilon_2 \times \sigma \times (T_2^4 - T_1^4) \]  

- \( \Phi \) netto heat transfer  
- \( \Psi \) exchange ratio  
- \( A \) surface area of surface  
- \( \varepsilon \) emission coefficient of surface  
- \( \sigma \) Stefan-Boltzmann constant  
- \( T \) temperature of surface

Ventilation of the cavity
Energy transfer through ventilation is calculated the same way as the other models mentioned before.

Results
This model results in the following temperatures per element, over the height of the facade panel. The temperature of the supply air, with a exterior temperature of -5 °C, would be just over 6,5 °C, which is slightly higher than the climate cavity for supply only. However, in this model, supply and exhaust are separated only by a single plane of glass, whereas in the supply-only, a double glazed panel separated supply and interior.

The 'heat exchanger' used in this concept uses a parallel flow, which means that the efficiency can never be higher than 50%. Using the cavities for a counter-flow heat exchanger would require the air stream to flow against the force of buoyancy, either the supply would have to flow down, which would make it an exhaust chimney, or the exhaust should flow downwards, against the buoyancy. A counter-flow heat exchanger could achieve much higher heat recovery rates though.

The temperatures according to this model result in an efficiency of:

\[ \mu_t = \frac{(t_2 - t_1)}{(t_3 - t_1)} \times 100 \]  
- \( t_1 \) external temperature  
- \( t_2 \) supply air temperature  
- \( t_3 \) internal temperature

\[ \mu_t = \frac{(6,52 - (-5))}{(21 - (-5))} = 44\% \]

Notable is that the average temperature of the supply and exhaust air is higher than the average temperature of the interior and exterior, respectively 10,02 °C and 8,00 °C. This is caused by the single glazing on the inside and the double glazed panel on the outside, causing more 'heat' to come in than go out through the glass.
10.3 Costs of concept 3&4

To get an idea of the feasibility of the concepts, an estimate will be made for the investment cost, maintenance costs and energy costs of the concept, based on data from chapter 3, 4 and 5.

10.3.1 Investment costs

The climate cavity concept with a single cavity (concept 3) is little more than an additional glass plane in from of the ‘normal’ facade, provided that there is no ‘ventilation box’ used, but just the cavity and vents. In order to determine the costs of this additional facade area, estimates for buildings costs per square meter have been used.

The costs of a facade of an office building according to BOAG are:

<table>
<thead>
<tr>
<th>Façade Building</th>
<th>High</th>
<th>Average</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Façade costs</td>
<td>€623</td>
<td>€550</td>
<td>€512</td>
</tr>
</tbody>
</table>

(BOAG, 2013)

A more detailed definition by Bouwplus is as follows:

<table>
<thead>
<tr>
<th>Façade costs</th>
<th>€100/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brickwork (+ insulation)</td>
<td></td>
</tr>
<tr>
<td>Window (+ glass)</td>
<td></td>
</tr>
<tr>
<td>Wooden frame</td>
<td>€275</td>
</tr>
<tr>
<td>Aluminum frame</td>
<td>€290</td>
</tr>
<tr>
<td>PVC frame</td>
<td>€225</td>
</tr>
<tr>
<td>Aluminum curtain wall</td>
<td>€350</td>
</tr>
<tr>
<td>Sun shading (screen, electric)</td>
<td>€90</td>
</tr>
<tr>
<td>Sun shading (blinds)</td>
<td>€300</td>
</tr>
</tbody>
</table>

(Bouwplus, 2014)

Additionally, the costs for self-regulating window vents from Duco are about €100 / m (Ducotop 50 ZR)

(Deu, 2012)

To summarize, the costs of the additional glass and window frames would be about €300/m². For the larger window variant used in the calculation above, 2,00 meters wide and 1,50 meters high, the costs would be:

<table>
<thead>
<tr>
<th>Climate cavity</th>
<th>Info</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window frame &amp; glass</td>
<td>€300/m² at 3m²</td>
<td>€900</td>
</tr>
<tr>
<td>Window vents</td>
<td>€100/m at 4m (top &amp; bottom)</td>
<td>€400</td>
</tr>
<tr>
<td>Shading (screen)</td>
<td>€50/m² at 3m²</td>
<td>€270</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>€1,570</td>
</tr>
</tbody>
</table>

Additional costs for a fan and sound damping material would increase the costs by about €100 extra. A ‘ventilation box’ would cost at least €1,000, as suggested by the analysis in chapter 4.

For the double cavity variant, the costs highly depend on the detailing, but it will be necessary to have a plane of double glazed glass and two single planes of glass, all with window frames. Additional vents will be needed as well for the second cavity. Therefore the costs for the double cavity could be much higher than the costs of the single cavity.

Compared to the costs of decentralised ventilation concepts, €1570 is about average. Therefore the investment costs for the climate cavity are about the same as investment costs for a central ventilation solution (chapter 5.4). It must be noted though that apart from a ventilation solution, this also transforms the facade into a double skin facade, provide climate and shading functions.

10.3.2 Maintenance costs

The lack of filters or a conventional heat exchanger would effectively reduce the maintenance costs to zero. However, the additional glass will need to be cleaned, and might require cleaning more often because of the function as a ventilation duct.

Costs for a window cleaner are about €0.45/m²

(Source: http://schoonmaak.startpagina.nl/prikbord/14835762/14836423/re-prijs-per-m2-ramen-wassen-en-hoeveel-m2-per-uur)

For the glass area of 3m² this would be €1.35 per unit. For cleaning once a month, this would be €16.20 per unit per year. Compared to for example the Climarad, this would be relatively cheap, considering that the Climarad costs €20.25 a year for changing filters every two years. The example from ILK dresden costs about €38.5 a year per unit. Compared to a central solution, the Climarad claim to be less expensive, but this takes into account the cleaning of ducts for a central solution.

10.3.3 Energy costs

The energy costs (fan energy) of the concept highly depends on the effect of the solar chimney (supply or exhaust) and buoyancy (exhaust). In the worst case scenario, when all airflow has to be provided by fans, the energy costs would be within the same range as other decentralised solutions, which are generally more energy efficient as central solutions, minus the resistance of a conventional heat exchanger and filters.
11 Final design

This chapter provides an overview of the final design of the chosen concept, concept 3, the Climate Cavity facade (single cavity), in an attempt at answering the fourth research question:

Is the proposed new concept feasible in terms of (thermal/acoustic) comfort, energy efficiency, investment, maintenance and operation costs and in aesthetic value?

11.1 Final concept

Out of the 2 concept groups and the four individual concepts, the Climate Cavity concept, with a single cavity for either supply (pre-heating) or exhaust (solar chimney) is deemed the most feasible.

The first group, consisting of an openable window with alternative ‘conditioning’ modus and central extraction might improve user comfort and satisfaction, but the heat exchanger, which requires filters to prevent it from clogging and a box to contain it, is almost a full decentralised ventilation unit, but it also requires a central extraction system and the twin coil system, making it more expensive in terms of investment than both system D and E. The same goes for maintenance, required for both both the facade unit and the central ducting. As far as energy consumption goes, there wouldn’t be a significant improvement either.

The difference between the first two concepts would be that the second, the ventilation vent, would allow for rain- and burglar proof ventilation, but would drastically limit facade design by requiring the vent.

The second group, the use of the cavity in a double skin facade or glass panel is deemed more feasible because it provides both supply and exhaust, eliminating the need for an additional ventilation system or ducts. Investment costs for the single cavity variant would be reasonable, compared to decentralised ventilation concepts, and also includes other climatic benefits. The double cavity variant would provide some improvement over the singel cavity design at significantly increased investment costs and complexity.

The lack of a conventional conventional heat exchanger (provided that would allow for comfortable ventilation) would reduce maintenance costs both in terms of labour and materials and also eliminates the possibility of contaminated air. Energy consumption would either be equal to or lower than decentralised units and therefore also probably lower than most central systems, as the system is practically ventilation system C with some resistance from the ‘duct’ through the facade.

Because of these opportunities, concept 3, the Climate cavity with a single cavity, has been developed further.

As preliminary models in chapter 9 showed, the concept can provide a reasonable amount of pre-heating without a conventional heat exchanger, provided that the airspeed is low enough. The following design will therefore not have a heat exchanger integrated. An additional heat exchanger might be optional, but the ‘default’ design will not use one, as this fits the research goal of a ‘natural’, low maintenance/investment/energy system.
11.2 First design

Heating season
- Supply through cavity
- Mechanical extraction
- Pre-heating through waste heat and solar radiation

Cooling season
- Supply through bypass
- Extraction through chimney
- Solar-powered extraction and reduced cooling load

Open window
- Freeflowing supply
- Mechanical extraction
- Extraction above sunshading extracts most of the sun's heat

Similar to concept 3 as presented in chapter 7, the facade element has different configurations for different external conditions. A new addition is the 'openable window' configuration, which provides an unobstructed airflow for as much as possible, while still extracting air and solar heat at the top. This can either be mechanically or naturally, if natural forces provide enough airflow.

The extraction fan, paired with a CO₂ sensor, can provide the adequate amount of airflow, without unnecessary ventilation.

In addition to the three configurations mentioned above, other configurations are possible, such as:
- Supply through bypass (bottom), extraction through bypass (top), eliminating the resistance of the cavity, when there is no sun.
- Ventilating the cavity with outside air (either naturally or mechanically), when the room is unoccupied, to keep heat outside without ventilating the room.

Glazing
As mentioned in chapter 9, the single-glazed variant performed better, but naturally, single glazing is no longer and option with modern insulation standards. However, in order to achieve maximum pre-heating, the inner panel should have poor insulation qualities and the outer panel should have the best possible insulation qualities. It must be noted that heat 'lost' through the inner panel is in fact mostly not lost, but is being recovered by the supply air. The only heat 'lost' is through the outer panel and through radiation.

However, since the air entering the cavity can be below freezing point, single glazing would be unacceptable, as it would cause condensation on the inside. In order to achieve the best performance, the inner panel should therefore be a regular double glazed panel, providing sufficient insulation to prevent condensation, and the outer panel should be a double glazed HR++ panel. This combination allows for a decent amount of heat to be 'recovered', but highly reduces heat loss to the outside, through both convection and radiation. It should be noted that the temperature of the cavity increases over the height, as will the temperature of the inner glass plane, so the average radiant temperature is not as low as just above freezing point.

Fan
In general, there are three groups of fans commonly used:
1. Axial-flow fans
   The air enters an axial fan through the side in the center of the fan and flows out perpendicular to the axis. Axial fans are mostly used for high pressure applications, such as leafblowers. They typically have a low flow rate and high pressure difference.

2. Centrifugal fans
   The air enters a centrifugal fan through the side in the center of the fan and flows out perpendicular to the axis. Centrifugal fans are mostly used for high pressure applications, such as leafblowers. They typically have a low flow rate and high pressure difference. Centrifugal fans typically produce less sound than axial fans.

3. Cross-flow fans
   Cross-flow or tangential fans can produce a wide stream of air perpendicular to the axis of the fan and are commonly used for HVAC applications such as convector heaters and tower fans. Tangential fans typically have a low pressure difference, low energy consumption and are relatively quiet.

For this design, the cross-flow fan is most suited, because of the wide stream of air along the facade. Apart from that, the (very) low airspeed at a low pressure difference, low noise and low energy consumption make the fan very suitable for this application.

Sources:
http://www.sofasco.com/dc_cross.html
http://en.wikipedia.org/wiki/Mechanical_fan
The first design is based mostly on existing elements, such as windows frames and vents. In order for the cavity to change between supply and exhaust flow, two vents are needed both at the top and bottom. One to access the cavity and one to bypass the cavity.

The inner glass panel has to be an openable window in order to access the cavity and to allow the user to 'open a window.' In this detail drawing this is a casement window (opens like a door), however, for larger planes a sliding window might be more suitable. The outer plane is a fixed window, though if desired, the outer plane could also be substituted by a sliding window or casement opening to the outside.

The supply vent at the bottom is a larger, more open vent that the bypass, which is a 'regular' sound damping window vent. This allows for a larger freeflowing airstream when opening a window. For this vent, a system such as the DucoWall, as mentioned in chapter 4.3, would be suitable and would reduce external noise.

In order to use the cavity for either supply or exhaust, the 'bottom cavity vent' is connected to an additional grate in the cavity, so that either the bottom is open (exterior) or the side (interior). This vent is disconnected from the 'bypass supply vent' below, because one is attached to the openable window frame and the other to the fixed window frame. This means that both have to be operated separately. In order to operate both separately (by hand), both would have to be attached to the same frame.
The top part of the facade is mostly a reflected version of the bottom. Additions are the tangential fan and the ‘frame cover’, which also serves as housing for the fan, directing the flow.

The dimensions of the fan are roughly the same as the cavity, so for a 100mm cavity, a fan with a diameter of 100mm is possible. Note that the Vent-Trex system in chapter 4.1.12 uses a fan with a diameter of only 40mm.

The flow direction in a tangential fan is determined by the vortex wall, or vortex builder: ‘The vortex separates the intake and discharge side of the fan at the narrowest point between the impeller and the vortex builder’ (LTG- Aktiengesellschaft, 2011). In this case, the ‘frame cover’ functions as the vortex wall, as well as a rain cover for the window frame and cavity. The intake of the fan is either the cavity or the bypass exhaust vent at the top.

The shading can be any type of shading that fits into the (limited) space of the cavity, since it’s shielded from rain and wind. In this drawing blinds are used, but other solutions like screens, vertical louvers etc. are possible as well. The shading should be mounted to the fixed window frame, in order to allow for sun shading with the windows open. Therefore they are attached to the outer window frame, screwed into the profile.

For this design, it is not possible to lift the shading up out of vision, because this would clog the cavity and obstruct airflow. For a wider cavity or narrower shading this would be possible, but for this design the shading is mounted just below the window frame.
11.2.1 Top of the facade with the window open

Opening a window in this way may not be as effective as completely opening a regular window, since the outer glass plane still covers most of the facade. The vents at the top and bottom do however provide a wide strip that will allow for some increased airflow. The fan at the top can help provide additional airflow and extract solar heat above the shading.

The concept works best if applied to the entire facade, allowing for lower airspeed in the cavity (and providing shading for the entire facade), but like mentioned before, for larger panels a casement is not suitable.

A sliding window provides a solution, which is often applied for narrow second skin facades to acces the shading for maintenance.

However, since one of the panels slides behind the other, this cause problems with the cavity vent switch system, which is located between the (inner) window frame and the outer plane. An option would be to limit the vent size to half of the width of the facade (the panel closest to the cavity) and close the other part at the top and bottom. Alternatively, the vent switch has to be attached to the fixed window frame, to the supply bypass vent for example.

11.2.2 Bottom of the facade with the window open

11.2.3 Bottom of the facade with a sliding window, which limits ventilation to 1/2 of the facade

11.2.4 Top of the facade with an additional HeX(black)

Since the concept functions best at low airflows, it is not suitable for room with a high occupation (to facade ratio), such as a meeting room. In order to provide comfortable ventilation in this scenario, a conventional heat exchanger will be neccesary.

In order to make this possible with the same facade concept, the vents have to be attached to the fixed parts of the frame, to allow for a ‘ventilation box’ to be connected to both supply and exhaust flow.

This ‘ventilation box’ would be similar to any of the decentralised concepts mentioned in chapter 4. This would allow larger airflows over a small width of the facade with proper heat recovery. Needless to say, this would increase the costs, as the box, heat exchanger, filters and possibly additional fans would be more expensive in terms of investment costs, maintenance, fan energy consumption. Apart from that, the ‘box’ would be a visible element in the facade.

Reflection

After assessing this design, the following points of critique have been established:

- The ‘window frame’ in this design would be too thick and visible as compared to regular window frames. This could result in architects finding the design unacceptable as it limits facade design too much and is rather bulky, whereas slim and transparent are usually desired qualities.
- The amount of heat recovery is too limited, compared to central and decentralised systems with a heat exchanger. The system is positioned somewhere in between natural and mechanical systems, offering some amount of heat recovery (at possible reduced fan energy, maintenance and investment costs) but not as much as mechanical systems. Especially for room with a higher occupation this is a problem.
- Possible draft problems due to vents that have been positioned rather low. Especially the ‘bypass supply vent’ at the bottom.
- Thermal bridges an insulation problems in the design. All the vents would offer poor insulative qualities compared to modern standards, where triple HR++ glazing and high insulative window frames are bcomming the standard.
- Possible noise problems caused by the fan, which is hardly separated from the interior. This depends on the exact fan used, the fan speed and turbulence in the system. Since the ventilation is spread out over a wide strip, the speed would be relatively low. Still, the noise caused by fans is a common problem in decentralised systems.

11.2.5 A regular fixed window frame

11.2.6 A regular openable window frame
11.3 Final iteration of the design

Since these problems severely reduce the feasibility of the concept, the system has been redesigned several times over in order to improve upon the mentioned criteria. The following design has been the result of this.
Contrary to the first design, this one does not confine to using existing profiles and elements, but uses modified or entirely new profiles. Instead of using casement windows, which is not practical for the example size of 2.00 by 1.50 meters, for the interior plane, this design uses sliding windows to limit the thickness and visibility of the window frame.

**Sliding window frame**

This design is based on the facade of the Library of the Delft University of Technology, as described in chapter 7.2.1. This facade uses no window frame for the inner panel, but simply rests the glass planes in a groove in the aluminium profile, with a glazing bead at the top. The glass planes are free to move sideways, effectively making it a sliding window. However, since this glass panel does not separate interior and exterior, it has poor insulative qualities. The designed profile uses plastic parts to separate the two sides in both the lower and upper profile and in the vertical profiles.

The profile allows for the exhaust flow at the bottom and exhaust and supply flows at the top to pass through, preventing the need for the openable vents. The glass panels are lowered into a groove at the bottom and fixed with glazing beads at the top.

**Fixed window frame**

The fixed window frame on the exterior side is much like a regular window frame, with perforations to allow the air to flow through, much like the Movair+ profile mentioned in chapter 4.1.7. The frame at the top has been shortened to make room for the fan and other elements in the cavity, and has a second compartment to allow for the supply and exhaust flow to pass each other. In addition, the frame has shutters to close the openings when not in use and a self-regulating flap in the exhaust flow, that closes the vent when the system is turned off.

**Supply vent**

Contrary to the first design, the supply vent is located all the way at the top for all situations. The ‘duct’ separates the supply and exhaust vent and guides the air towards the ceiling, improving circulation through the room and allowing air to mix with the interior air before reaching a person to prevent draft problems. In addition, the ‘duct’ allows for sound damping material to reduce external noise levels.

**Flow switch profile**

In order to improve insulation, this design no longer has a big opening at the bottom and top, but smaller vents. The flows are directed by the flow-switch elements, which open to one side, while closing the other with a layer of insulation. This functions much like the sliding shutter in conventional facade vents, only it opens and/or closes several openings instead of one.

The elements at the top also allows the exhaust and supply flow to cross each other. Apart from that, the internal slider has curved elements to reduce air resistance and direct the flows.

**Previous points of critique**

- Profile thickness
  - The new profile has the same thickness of a ‘regular’ window frame at the bottom, minus the glazing bead. The top side is also roughly the same size, depending on the fact if the supply ‘vent’ is regarded as window frame or as ‘window sill’ at the top, covering the side of the wall
- Limited heat recovery
  - The amount of heat recovery is still the same, but the design allows for variation, as mentioned further on. Also, the size can of course be increased.
- Draft problems
  - The supply vent has been moved to the ceiling, reducing the probability of draft problems. Optional variations are mentioned further on.
- Thermal bridges
  - All thermal bridges have been removed and vents can be shut to reduce heat loss. The insulative qualities of the profiles (at the top and bottom) are still lower than a ‘regular’ profile with filled cavities, like the side profile in the image to the left. The profiles have to be hollow in order to allow for the airflow. This is the same as a vent opening in any other ventilation system, but the opening is much wider in this case. It must be noted though that heat lost through the inner layer is ‘lost’ to the incoming supply air, so is in fact recovered in the winter situation, when heat loss is a problem.
- Noise levels
  - The final design does allow for some sound damping material in the ducts and openings in the profiles. It is unclear however if this will be enough, which depends on the exact situation.
11.4 Design variations

The facade system has been designed from a modular approach, where parts can be adapted or swapped out to allow for design variations. By making minor changes, the same system can allow for different situations and demands. Some examples are listed below. These designs rely on the same parts except for specifically changed elements.

1. Relocated supply and/or exhaust duct
The standard design features supply and exhaust vents directly on the window frame, however, by moving these away from the window frame, the (top side) can be even slimmer and this also sets the flows further apart, reducing the chance of recirculating used air. The bypass supply vent is still located directly above the glass, which is favourable in summer.

This also allows for an inlet directly against or even above the ceiling. Like the perforated ceiling in chapter 4.3, this allows the air to enter over the entire surface of the ceiling, reducing the risk of draft problems and allowing for a proper spread of fresh air over the entire room.

This variation is achieved by replacing the fixed window frame at the top by the same one used at the bottom and by using different perforations in the fan housing and sliding window profile, as well as a different vortex wall for the fan.

2. Additional heating/cooling
Since heating and air conditioning are usually necessary, it is possible to add additional climate systems, like underfloor heating or convectors and cooled ceilings. It is also possible to use the ventilation system for conditioning purposes, by exchanging the supply vent for a vent with an integrated convector element.

Since the vent is very wide and the speed is low, a narrow convector will suffice. The unit can be applied over the entire width of the facade or a limited length, depending on the desired heating/cooling load.

Unfortunately, a convector will collect dust and require regular maintenance. A central heating/cooling system will be required, and a double pipe system to provide cooling and heating simultaneously.

3. Conventional heat exchanger
In order to supply larger airflows over a limited facade width, for rooms with a higher occupation such as a meeting room, a regular heat exchanger will be necessary.

To allow for the same facade system, the fan housing and flow-switch can be exchanged for a ‘regular’ decentralised ventilation box. This unit will extract supply air from either the cavity or directly from the outside through a bypass and extract exhaust air from the interior or through a bypass through the cavity, depending on the climatic situation.

A counter-flow plate heat exchanger will provide heat recovery, in addition to the glass cavity, and centrifugal fans provide the airflow. Filters on both ends of the heat exchanger prevent the exchanger from clogging up and can be exchanged from the bottom.

4. Air filters
Some locations have more dust or a poorer air quality than others. In order to reduce the amount of dust in the cavity or to prevent dust from entering the optional convector element or heat exchanger box, an optional filter can be added at the bottom of the cavity.

Since this will greatly increase the air resistance, an additional supply fan will be necessary. This is achieved by using a shortened profile like the framing above and by replacing the flow-switch.

The replaceable filter filters the supply or exhaust air before entering the cavity and can be exchanged by accessing the cavity through the sliding windows.
5. Openable window

Since the standard design offers a very limited airflow in the ‘open window’ position, some buildings might require a different solution. The standard design has a narrow vent over the width of the entire facade, which might be enough for highrise office buildings, but for other buildings, the following offers a solution.

The same window frame can be modified to fit a casement window that holds both the interior and exterior glass plane and the shading system, much like the Twin-line system by Finstral as discussed in chapter 7.1.2. Needless to say, like any casement window, the frame will be thicker than a regular window frame, as the openable part will need additional framing, which can’t be hidden behind the facade structure.

This openable window functions in the same way as the normal facade design, except when it’s opened of course. For most situations, it would be most logical to use the standard design for the entire width of the facade, minus a small part to fit the openable window, in the same way that most houses and small office buildings have.

This variation is achieved by changing the rubber strips and insulation material for alternative rubber strips and adding frame extension profiles. The window standard profiles are still the same as used in the standard design.

Combinations

Since these variations affect different (modular) parts, they can be combined at will. If it would be necessary, one could add a heat exchanger, additional heating/cooling, additional air filters and fit it all in an openable window frame. The system can be modified to fit the demands of the architect and user.

Previous points of critique

- Profile thickness
  The thickness of the profile already has been severely reduced, but when moving the supply and exhaust vent at the top, as in the first variation, the thickness is reduced to the size of the glazing bead at both the top and the bottom, the interior and the exterior. The depth of the facade will of course be deeper than a facade with a single plane of glass. From up close this will be notable, but it is unlikely this will be much of a problem, since second skin facade can be meters wide. Whereas the climate cavity facade has a depth of about 150 mm.

- Limited heat recovery
  Like mentioned before, the amount of heat recovery in the standard configuration is limited (also depending on the intensity of the sun). When additional heat recovery is required, the heat exchanger variant can be applied, a larger window can be used or additional heating can be applied.

- Draft problems
  The high position of the supply vent, with an airflow distributed over the width of the facade will provide a solution in most scenarios. Additionally, heating can be applied or the supply can be positioned above the ceiling.

- Thermal bridges
  No other variants have been designed. If necessary, it could be possible to design a variant with even better insulation. The system already offers HR++ glazing over double glazing, which severely reduces the heat loss to the outside. The only heat ‘lost’ is heat from the (cooler) supply cavity, through the HR++ glazing, to the outside.

- Noise levels
  No specific variant has been designed, but the variant with the moved supply and exhaust vent (variant 1) offers plenty of space for sound damping material in the supply duct and also in the exhaust duct above the inner glass plane (inside the window frame), which can be extended like the supply duct in the default design, to allow for even more sound damping material.

Air mixing/use of facade space

The exact size of the part of the facade that will be used for ventilation will differ for every building design. The more facade is covered by the climate cavity, the more heat can be recovered into the supply air. So a fully glazed facade would perform best. It would however not make sense to have a 4 meter wide vent for an office with a single person in it, as the speed in the vent is not so relevant. The speed inside the cavity and the total surface area are what determine how much the air heats up. So for a facade of 4 meters wide, maybe one meter of it would be perforated for ventilation purposes. In order to still use the entire surface area, air would have to travel diagonally through the facade.

Apart from utilising the entire facade surface, this also allows for proper mixing of exhaust air with exterior air before it possibly re-enters as supply air. With a high parapet, proper mixing shouldn’t be much of a problem, however with a fully glazed facade, this will be a necessity.
12 Feasability of final design

This chapter aims to test the feasibility of the final design concept in terms of thermal comfort, investment costs, maintenance costs, energy consumption, in order to answer the fourth research question:

Is the proposed new concept feasible in terms of (thermal/acoustic) comfort, energy efficiency, investment, maintenance and operation costs and in aesthetic value?

12.1 Thermal comfort

In order to determine the temperature of the supply air inside the cavity, for the winter situation, the same model has been used, but for regular double glazing on the inside (U = 3.00 W/m²K) and HR++ glazing on the outside (U=1.20 W/m²K). The results with and without 50W/m² solar radiation are plotted in the following graph.

The temperature of the air without solar radiation is about 5°C, which would translate to approximately 40% heat recovery is the same equation is applied as for heat exchangers. Of course the heat being recovered is not from exhaust air, but from heat escaping through the facade. Applying the same equation to the temperature with radiation would translate to about 65% heat recovery. Of course, the heat from solar radiation added to the supply air would otherwise simply enter through the facade into the building, so this is no improvement in terms of ‘recovered’ heat compared to a regular facade. Unless of course the regular facade would utilize a shading system that keeps the heat outside, even in winter.

The same energy balance model as used in chapter 10 has been modified for the final design. Both window planes now consist of double glazing with a cavity in between. The shading separates both sides of the middle cavity. Like in the design drawing, supply air is drawn from the interior side. Since the exterior panel is a HR++ panel, no radiation passes through the inner glass plane to the outer glass plane because of the reflective coating, which reflects radiation back inside (to the shading).

Apart from that, the same equations have been used, only layers have been added.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facade height</td>
<td>1.50 m</td>
</tr>
<tr>
<td>Facade width</td>
<td>2.00 m</td>
</tr>
<tr>
<td>Cavity depth</td>
<td>0.10 m</td>
</tr>
<tr>
<td>Airflow</td>
<td>6.50 l/s</td>
</tr>
<tr>
<td>q_{sun}</td>
<td>50.00 W/m²</td>
</tr>
<tr>
<td>U_{outer glass panel}</td>
<td>1.20 W/m²K</td>
</tr>
<tr>
<td>U_{inner glass panel}</td>
<td>3.00 W/m²K</td>
</tr>
</tbody>
</table>
Adding 50 W/m² in the same way as in chapter 10, results in the following graph.

### Temperature per element

<table>
<thead>
<tr>
<th>Element</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior Glass</td>
<td>10.0</td>
</tr>
<tr>
<td>Cavity Glass</td>
<td>12.8</td>
</tr>
<tr>
<td>Cavity Supply</td>
<td>14.0</td>
</tr>
<tr>
<td>Glass</td>
<td>15.0</td>
</tr>
<tr>
<td>Cavity Glass</td>
<td>16.0</td>
</tr>
<tr>
<td>Glass Interior</td>
<td>17.2</td>
</tr>
<tr>
<td>Supply</td>
<td>18.7</td>
</tr>
<tr>
<td>Ceiling</td>
<td>19.8</td>
</tr>
<tr>
<td>Supply</td>
<td>20.0</td>
</tr>
<tr>
<td>Ceiling</td>
<td>22.3</td>
</tr>
<tr>
<td>Airflow</td>
<td>22.5</td>
</tr>
<tr>
<td>Supply</td>
<td>23.6</td>
</tr>
<tr>
<td>Ceiling</td>
<td>25.0</td>
</tr>
</tbody>
</table>

So according to the both models used, the temperature of the supply air when leaving the cavity at the top, with or without radiation, in the winter situation ($T_i = 21, T_e = -5$) will be:

**Finite element method**
- No radiation: 11.81°C
- 50.00 W/m²: 11.81°C

**Energy balance equations**
- No radiation: 10.99°C
- 50.00 W/m²: 11.40°C

**Average of the two**
- 11.15°C

### Other window sizes

In theory, there is no limit to the size of the window. The bigger the better, as more of the ‘lost heat’ will be recaptured. Ultimately, the entire façade of a one-person office could be used (diagonally or vertically) for a single person, making the speed of the air next to nothing and using the whole surface area.

To give an indication, the finite element model has been adapted to a fully glazed façade of 3 meters high and using 2 meters width for a single element (for a 2 person office of 4 meters wide, every two meters would service one person). This shows the continued heat-up of the supply air.

### Temperature over height

#### Summer situation

For the summer situation, the goal is of course to keep as much heat outside as possible. The cavity, which extracts interior air, can either be ventilated mechanically or naturally through buoyancy.

Since the airflow as a result of buoyancy is a function of the temperature difference between air in the chimney and on the outside (chapter 2.1.1), and the temperature of the cavity is determined by the airflow through it, an equilibrium will be achieved where the two are stable for the following airflow and average cavity temperature:

**Temperature over height**

This airflow has been estimated by:

\[
Q = C_d \times A_e \times \sqrt{\frac{2 \times g \times h \times \Delta T}{T_e}}
\]

Where:
- $Q$: Airflow rate (m³/s)
- $C_d$: Drag coefficient (approx. 0.8)
- $A_e$: Equivalent opening area (m²)
- $g$: Gravitational acceleration (m/s²)
- $h$: Height (m)
- $\Delta T$: Temperature difference (K)
- $T_e$: Average cavity temperature (K)

**Average cavity temperature**:

\[
T_e = \frac{1}{A_e} \times \left( \frac{1}{A_1} + \frac{1}{A_2} + \cdots \right)
\]

*2,00 meters wide, 0,02 meters high, * 0,7 for opening to profile ratio, * 0,5 because only half the openings are in use at a time.

This means the average temperature inside the cavity is 32.4 °C, when the temperature outside is 30°C. As a result, the convective heat entering the interior will be slightly higher than it would be without the façade system, because the exterior temperature is now effectively 32.4 °C instead of 30 °C. However, the 800 W/m² solar radiation is kept out.

Regardless, this is based solely on natural buoyancy. The extraction fans can mechanically extract the heat from the cavity, lowering the temperature far below 30 °C. This would of course increase the air changes in the room as well. Should this provide too much heat gain through ventilation (which is only the case if the exterior temperature if far above a comfortable interior temperature), it is possible to ventilate the cavity with exterior air and allow a limited amount of ventilation through the bypass.
12.1.2 Additional design possibilities

The ‘glass cavity heat exchanger’ concept (concept 4) from chapter 8.4, has been discarded at first, because at that point it seemed too complex for only limited gain in heat recovery. In retrospect however, the concept has quite some improvement too offer.

The current design features double glazing on the interior side of the supply cavity, as single glazing would lead to too low temperature on the interior side of the glass. Also, heat being recovered from double glas is being recovered, but when applying HR++ glas instead, less heat would be lost to the cavity. So only part of the heat is actual recovery, the other part (the difference between double glazing and HR++) is rather ‘mixing’ of supply air with interior heat.

The double cavity variant however, would subtract heat from the exhaust flow and would only require single glazing separating warm and cold air, as the exhaust cavity separates the supply cavity and interior.

As the graphs show, a significant improvement can be achieved over the default design with a double glazed inner panel. Event though this data is more optimistic than the actual results, a further improvement is possible. The newly formed exhaust duct would of course increase air resistance of the system, but this would be very limited, as mentioned further in this chapter. The increased maintenance would require further attention though, where the investment costs would hardly change.

The current design features double glazing on the interior side of the supply cavity, as single glazing would lead to too low temperature on the interior side of the glass. Also, heat being recovered from double glas is being recovered, but when applying HR++ glas instead, less heat would be lost to the cavity. So only part of the heat is actual recovery, the other part (the difference between double glazing and HR++) is rather ‘mixing’ of supply air with interior heat.

The double cavity variant however, would subtract heat from the exhaust flow and would only require single glazing separating warm and cold air, as the exhaust cavity separates the supply cavity and interior:

Adaptions to facade design profiles

The adaptations to the current design would be very limited, the interior double glazed plane would have to be split up, an openings at the top and bottom (perforation in window frame) would be required. Apart from that, in order to provide a counter flow heat exchanger, with supply still up top (to prevent possible draft problems) the exhaust flow would have to flow from the top op the glass to the bottom, where it’s exhausted to the exterior. This would require the extraction fan to be relocated to the bottom.

This new cavity would have to be accessible for cleaning though.
12.2 Investment, Maintenance & Energy costs

The case study to compare costs of different systems in this scenario is an office room of 5*4*3m (depth*facade width*height) for 2 persons. The facade has windows of 1500mm high over the entire width of four meters.

12.2.1 Investment costs

In order to make a more detailed comparison of the costs for the facade, the calculator of Creon ramen is used, as well as the estimates by www.kozijnen-weetjes.nl, to provide investment costs for the additional facade elements required for the Climate Cavity. Note that these values are based on estimates and don’t include delivery and assembly.

As mentioned below: Source 1 (http://www.creon-ramen.be/ramen/aluminium.html)

Reference situation

Openable windows on both ends, with a fixed window in the middle
width: 4000 mm
height: 1500 mm
Price source 1: €1578,97 (fixed window + 2 times tilt/turn window)
Price source 2: €1837,50 (extrapolated from given examples)
Average total: €1708,24

Vents are optional but left out for the reference situation, as ventilation is handled by the central system.

Climate cavity inner layer (sliding windows)

2 sliding windows next to each other, aluminium window frames
width: 4000 mm
height: 1500 mm
Price source 1: €2472,62 (3500*1725mm as width was limited)*
Price source 2: €2100,00 (extrapolated from given examples)
Average total: €2055,13

Additional vents (flow-switch vents, the window frames are just perforated)

Price source 1: €291,16 (both windows, *2 for top/bottom: €582,32)
Price source 2: €100,00 /m (*4 meters wide, *2 for top/bottom: €800,00)
Average total: €691,16

Climate cavity outer layer (fixed window)

width: 2000 mm
height: 1500 mm
Price source 1: €477,68 (*2 for full width: €955,36)
Price source 2: €750,00 (*2 for full width: €1500,00)
Average total: €1227,68

Note: The difference in costs between sliding windows and tilt/turn windows differs greatly for every source. Both sources used claim higher prices for sliding windows (almost twice the price), while others claim tilt/turn windows are slightly more expensive. Furthermore, P Roelofsen (chapter 7.1.3) claims second skin facades are only 136% the costs of regular facades.

Tangential fan

The price of tangential fans can differ greatly depending on the manufacturer, order size, fan diameter etc. Most prices range from 55-20 for a fan of about half a meter long. Because the fans in the design will run at (very) low speeds, a single electric motor could probably run at least two fans (not uncommon), which would reduce costs. As an estimate for this calculation, a price of €20/m will be used. The total price will therefore be €60 for the width of the facade.


Sunshading

For the price of sunshading, the estimate provided by Bouwplus(§9.3.1) set a price of €90/m² for screens and €300/m² for blinds. For the entire facade this will be 4*1.5=6m². The cost of shading (for either the standard situation or the climate cavity concept) would be:

Screens €540
Blinds €1800

Alternatively, zonwering-weetjes.nl provides the following price:

Size: 2000*1500 mm
Screen €300 (€600 for full width)

Additionally, the controls for the screen cost:

Manual €30
Electric €160
Remote controlled €230

http://www.zonwering-weetjes.nl/zonwering-prijzen/screens-prijzen/

Total average: €650 (€540 and €600 + €160)

Central ventilation system

For the standard situation several different estimates can be compared:

Climarad €50/m² for central HVAC unit and ducts
Trox €70/m² for central HVAC unit and ducts
BOAG/Deerns €32/m² for heating/cooling units
(BOAG, 2013)
BOAG/Deerns €200/m² - average costs
(BOAG, 2013)
BOAG/Deerns €272/m² - high costs
(BOAG, 2013)
BOAG/Deerns €147/m² - low costs
(BOAG, 2013)

Climarad (Vasters & Okken, 2014)
Trox (Author-unknown. (Date unknown)
BOAG (BOAG, 2013)
BOAG/Deerns (BOAG, 2013)
BouwkostenKompas.nl (BouwkostenKompas.nl, 2012)
Unfortunately, these estimates do not all include the same elements. The last three estimates do somewhat match, with all additional elements included. Since both design scenarios will require additional heating and cooling systems, only the ventilation system is taken into account. The first, second and last estimate respectively set €50, €70 and €111/m² for ducts and a central unit, €77 for average. This will therefore be used as a price per square meter functional area for an office building for a central ventilation system.

For the example office room, this would therefore be:

\[20 \text{ m}^2 \times €77/\text{m}^2 = €1540\]

### Total sum

The total costs of both solutions mentioned above are shown in these tables, as well as an option with the Climarad system, based on the calculation in chapter 5.1

#### Central system

<table>
<thead>
<tr>
<th>Element</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facade</td>
<td>1,708.24</td>
</tr>
<tr>
<td>Shading (screens)</td>
<td>650.00</td>
</tr>
<tr>
<td>Ventilation system</td>
<td>1,540.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3,898.24</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>With extra floor height</td>
<td>4,796.24</td>
</tr>
</tbody>
</table>

#### Climate cavity

<table>
<thead>
<tr>
<th>Element</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner facade</td>
<td>2,472.62</td>
</tr>
<tr>
<td>Outer facade</td>
<td>1,227.68</td>
</tr>
<tr>
<td>Window vents</td>
<td>691.16</td>
</tr>
<tr>
<td>Fans</td>
<td>80.00</td>
</tr>
<tr>
<td>Shading (screens)</td>
<td>650.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5,121.46</strong></td>
</tr>
</tbody>
</table>

If the building costs for additional floor height are taken into account, like in the Climarad calculation in chapter 5.1, this would add another €45/m² for 30cm extra height, so €900 extra, making for €4,743.89 total for the central system case.

Note that the total facade costs (glass and frame for the climate cavity are €3,700, whereas the costs for the regular facade are only €1,700. This does not quite match the estimate by P. Roelofsen of 136% for a second skin facade, but is rather 220%. It is quite possible that the construction costs for example are much lower, as the same scaffolding, crane etc. can be used, and the whole element could probably be installed as a single, prefabricated unit. Apart from that, the costs of regular double glazing as opposed to HR++ glazing would be lower as well. An exact estimate can therefore not be made, but it’s reasonable to believe that the difference between the three solutions isn’t that big.

### 12.2.2 Maintenance costs

Since the default design has neither a heat exchanger, nor filters, maintenance is severely reduced. The only maintenance required will be to clean the windows and ‘ducts’ of dust. As established in chapter 5.2, cleaning ducts out of sanitary reasons should occurs once every five years.

The cleaning of the glass will however be required out of aesthetic reasons, as accumulated dust on the glass will be visible. It is unclear how fast dust will accumulate, as this depends on a lot of factors, amongst which the local air quality and materials used inside the building. It is unlikely that large dust particles will travel far upwards in the cavity, as the airspeed inside is very low (because airflow is spread out over the entire width of the facade). Due to these low air speeds, most dust will settle down and not travel upwards.

Alternatively, regular filters or electrostatic filters could provide additional help. At this point there are no well-founded conclusions to be made, except that it would be similar to the maintenance of a second skin-facade or climate facade.

### 12.2.3 Energy consumption

Based on the calculations in chapter 5.3.1 for the Climarad report, the same have been made for this situation, using rules of thumb from www.isso-kenniskaarten.nl for the air resistance of the climate cavity.

#### Fan power consumption for ventilation system D

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow (m³/s)</td>
<td>0.09</td>
</tr>
<tr>
<td>Duct resistance (Pa/m)</td>
<td>0.20</td>
</tr>
<tr>
<td>Additional resistance factor (curves etc)</td>
<td>0.20</td>
</tr>
<tr>
<td>Resistance of ducts (Pa)</td>
<td>144</td>
</tr>
<tr>
<td>Resistance of vents, filters, Hex</td>
<td>280</td>
</tr>
<tr>
<td>Total resistance (Pa)</td>
<td>424</td>
</tr>
<tr>
<td>Power of single fan (W)</td>
<td>8.48</td>
</tr>
<tr>
<td>Supply &amp; Exhaust fans (W)</td>
<td>16.96</td>
</tr>
</tbody>
</table>

#### Air resistance of elements

- Duct (circular or rectangular): 45° curve 2 Pa/m, 90° curve 3 Pa
- Supply/ exhaust vent 20-40 Pa

#### Fan power consumption for Climate cavity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow (dm³/s)</td>
<td>1.05</td>
</tr>
<tr>
<td>Duct resistance (Pa/m)</td>
<td>0.20</td>
</tr>
<tr>
<td>Additional resistance (Pa/m²)</td>
<td>75</td>
</tr>
<tr>
<td>Resistance of ducts (Pa)</td>
<td>3.00</td>
</tr>
<tr>
<td>Total resistance (Pa)</td>
<td>7.90</td>
</tr>
<tr>
<td>Fan power (W)</td>
<td>2.57</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duct length (cavity height) (m)</td>
<td>1.55</td>
</tr>
<tr>
<td>Duct resistance (Pa/m)</td>
<td>0.20</td>
</tr>
<tr>
<td>Additional resistance (Pa/m²)</td>
<td>75</td>
</tr>
<tr>
<td>Resistance of ducts (Pa)</td>
<td>0.50</td>
</tr>
<tr>
<td>Total resistance (Pa)</td>
<td>45.50</td>
</tr>
<tr>
<td>Fan power (W)</td>
<td>1.48</td>
</tr>
</tbody>
</table>

**Total power: 4.05 W**

*Note: All calculations are based on the performance curve provided by Dukers & De Cock Consult B.V.*

### Data sources

- Climarad, 2015c
- Dukers & De Cock Consult B.V.
- (Dukers & De Cock Consult B.V., 2003)
- Jeroen ter Haar, Natural & Decentralized ventilation and climate concepts
The estimated value for the resistance of vents, of 30 Pa, seems somewhat high though, especially considering that a climarad system, which also has supply and exhaust fans, but also filters in the supply and exhaust flow, as well as a heat exchanger through which both flows have to pass.

In the article 'Hybride ventilatie in de praktijk', J. Veerman states that vent openings 'shouldn't be designed too small' so that the pressure loss over the vent is 5-10 Pa at max. (Veerman, 2012)

In other words, a vent that is big enough has a low pressure loss. When assuming that the openings (vents) in the climate cavity are 'big enough' and the pressure loss over a vent is set at 10 Pa, the power consumption is lowered drastically.

**Fan power consumption for Climate cavity**

<table>
<thead>
<tr>
<th>Supply through cavity</th>
<th>Exhaust through bypass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow</td>
<td>13,0 dm³/s</td>
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<tr>
<td>Duct length (cavity height)</td>
<td>1,5 m</td>
</tr>
<tr>
<td>Duct resistance</td>
<td>2,00 Pa/m</td>
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<tr>
<td>Additional resistance</td>
<td>36 Pa</td>
</tr>
<tr>
<td>$\eta$ fan</td>
<td>0,40 -</td>
</tr>
<tr>
<td>Resistance of ducts</td>
<td>3 Pa</td>
</tr>
<tr>
<td>Total resistance</td>
<td>39 Pa</td>
</tr>
<tr>
<td>Fan power</td>
<td>1,27 W</td>
</tr>
<tr>
<td>Total power</td>
<td>2,10 W</td>
</tr>
</tbody>
</table>

Since the initial design proved far too thick and visible, much effort has been put into limiting the thickness and hiding parts of the framing. In order to show the difference, the following 3D images show a regular window frame and several variants of the climate cavity in the setting of an office.

**12.3 Aesthetic value**

Since the initial design proved far too thick and visible, much effort has been put into limiting the thickness and hiding parts of the framing. In order to show the difference, the following 3D images show a regular window frame and several variants of the climate cavity in the setting of an office.

*Regular Aluminium window frame*

*Climate cavity default design*

*Climate cavity with openable window*

*Climate cavity with relocated vents*
13 Reflection & Conclusions

This chapter contains the final conclusion and answers all the research questions:

Main research question:
Can a hybrid system, combining the good air quality and low costs of a natural system with the user-adjustability, energy efficiency and small size of a decentralised mechanical system, offer a feasible, sustainable alternative to current ventilation concepts?

The advantages of a natural system being the good air quality, the feeling of a fresh breeze when opening a window, the understandable, fool-proof simplicity of the system and the low investment, maintenance and operation costs.

Sub research questions:
1. What is the current state of the art of ventilation systems? What concepts exist, how do they function?
2. How are these concepts integrated into the framework of a building?
3. What are the costs in terms of investment, maintenance and operation costs of current concepts?
4. Is the proposed new concept feasible in terms of (thermal/acoustic) comfort, energy efficiency, investment, maintenance and operation costs and in aesthetic value?
5. How does the new concept position itself towards existing concepts. What are the advantages?

1 What is the current state of the art of ventilation systems? What concepts exist and how do they function?

Ventilation concepts can be divided into 5 different groups, based on mechanical or natural-driven supply and exhaust flows, and decentralised systems. At this point, only two concepts are commonly used:
System C natural supply and mechanical exhaust (hybrid ventilation), mostly for residential buildings
System D mechanical supply and exhaust, used for almost any non-residential building and sometimes also in residential buildings.

Decentralised concepts (system E) are sometimes used in residential buildings and in renovation projects.

The main argument for system C is the fresh air and low investment, operation and maintenance costs. The main argument for system D being the perfectly regulated environment and central heat recovery.

The main argument for system E is the room/user specific conditioning and the duct-less building design

Ventilation systems use several different heat recovery techniques. The most common being the thermal wheel. Plate heat exchangers are also common and the usual choice for decentralised systems. The twin-coil is sometimes used, mainly when the supply and exhaust duct are separated of when the flows absolutely have to be separated because of hygienic reasons. Heat pumps offer a way of recovering heat from exhaust air in a natural system, to be used in the heating system. Efficiency differs per technique and per specific heat exchanger design. The FiWiHex, enthalpy heat exchangers and counter-flow plate exchangers generally offer the highest heat recovery rate.

Specific designs in any of these categories are available from many different manufacturers. Some important developments are the introduction of sensor regulated ventilation, possible in system C,D and E, but not yet very common in system D. Many different decentralised units exist, either as a separate box or to be integrated into a window sill, above the window frame into the facade, into the floor or into existing elements such as a radiator. In general, the larger units are more efficient and can provide a larger airflow.

2 What are the costs in terms of investment, maintenance and operation costs or current concepts?

Investment costs

The investment costs of decentralised system are somewhat equal to central systems. The extra costs for fans, heat exchangers and such in decentralised systems is within the same range as the costs for vents and ducts in a central system. When the cost for additional building height in system D as opposed to system E are taken into account, system D can be as much as twice as expensive. System C has the lowest investment costs by far, as it requires only a small amount of elements. If a single extraction unit is applied, exhaust ducts will be required, making it about half the costs of system D, but with multiple local exhaust fans the costs can be much lower.

Maintenance costs

Provided that the ducts and such in central systems will have to be cleaned every five years, a decentralised system would probably be slightly more expensive than an central system, somewhere around 125% the costs. This all depends on the frequency of maintenance of course. However, without the cleaning of the ducts of a central system, which is not advised but does occur, a decentralised system would be far more expensive, up to 2-4 times more expensive. System C is again the favourable solution as it only requires exhaust ducts to be cleaned, no supply ducts, filters or heat exchangers. Like the investment costs, depending on the amount of units, the costs can be 50% of system D or even less.

Operation costs/Electrical energy consumption

The lack up ducts in decentralised system more than makes up for the lower efficiency of the smaller fans. Generally, a decentralised system uses only 1/3 to 1/2 of the electrical energy of a central system. System C uses even less energy, as there are no filters, heat exchangers and generally shorter ducts, making the costs almost negligible compared to system D and E.
3 How are these concepts integrated into the framework of a building?

System C consist of either a single extraction fan, for example in houses with a heat pump, or for larger (residential or non-residential) building, with multiple extraction fans. Some ducting is usually required and extraction fans are often placed on the roof.

System D uses central HVAC units, often placed on the roof, and require supply and exhaust ducts throughout the building, often placed between a floor and lowered ceiling. They also perforate walls and fire-safety requires some attention.

System E comes in many forms. They can exist as a separate box or can be integrated into the windowsill, above the window frame into the facade, vertical units in, in front or behind the facade, into the floor or into existing elements such as a radiator. In general, visible units in the facade are not desired as they put limitations on the aesthetics of a building.

4 Is the proposed new concept feasible in terms of (thermal/ acoustic) comfort, energy efficiency, investment, maintenance and operation costs and in aesthetic value?

Thermal comfort
The climate cavity facade concept applied to a small window (1m²) offers only very limited pre-heating of the supply air, for a winter situation of -5°C without sun, the supply air will still be below the freezing point, which is absolutely unacceptable.

For a winter situation of -5°C, the climate cavity facade concept for a window of 2,00 * 1,50m can pre-heat air up to almost 5°C without radiation, and over 11°C and further with solar radiation and the shading system lowered. This is still somewhat low, but an improvement over a regular facade vent. With the vent located up high by the ceiling and optionally additional measures in the form of a perforated ceiling with supply above, or additional heating (which can be used whenever temperatures drop too low) it can be acceptable.

When the concept is applied to even larger surfaces, like a fully glazed facade, the pre-heating is improved further. For an element of 2,00 meters wide and 3,00 meters high, for the same winter situation, the supply air can heat up to 10°C without radiation and up to the interior temperature of 21°C with solar radiation.

Further developments with the glass cavity heat exchanger concept can improve performance further, as the single glazed separation between supply and exhaust allows almost double as much thermal energy to pass as opposed to a regular double glazed window. Instead of just recovering heat lost through the facade, this would recover heat from the exhaust air.

As a last note, the supply vent for summer, is located above the window, which provides cooler air than vents located in walls or on roofs, as they heat up in the sun. The system can also offer additional heating/cooling.

Acoustic comfort
There is no factual information on the acoustic comfort of the system. There is some room for sound damping material and design variations that allow for even more sound damping material, but only testing an actual mockup will provide valuable information. The fact that a very wide fan, running at low speed produces less sound than a small fan running at high speeds (most decentralised units) suggests this shouldn't be a huge problem.

Energy efficiency/operation costs
Like mentioned under thermal comfort, the amount of heat recovery depends on a lot of factors. Most likely the amount of heat recovered will be less than conventional heat exchangers. The fan energy is significantly lower than system D and E though. Depending on air resistance of the system, the fan energy can be as little as 12.5% - 25% of system D and 33% - 66% of the climarad system. Heat loss through the facade will also greatly be reduced, as the only heat that's actually lost is heat that travels through the inner double glass plane to the supply air, and then from the (cold) supply air, through the HR++ glazing.

Investment costs
The estimates in this report suggest the climate cavity facade costs about 130% the costs of the same building with system D (where the Climarad system costs about 110% of system D). When taking the additional floor height required for system D into account, system D is only slightly less expensive than the climate cavity concept, and the Climarad system is slightly less expensive than system D. It must be noted though that the climate cavity also offers a second-skin facade/climate facade design, that can keep most of the solar radiation outside, severely reducing heat gain.

The actual costs depend on more factors, construction, for example will be cheaper when applying the climate cavity as a single facade element instead of constructing two facades after each other. As a second source, P. Roelofsen claims the costs of a second-skin facade are 136% the costs of a regular facade, whereas in the calculation in this report, the costs for the facade (without the climate systems) would be over 200% the costs of a regular facade.

Maintenance costs
Since the default climate cavity design has neither a heat exchanger, nor filters, maintenance is severely reduced. The only maintenance required will be to clean the windows and 'ducts' of dust. As established in chapter 5.2, cleaning ducts out of sanitary reasons should occurs once every five years.

The cleaning of the glass will however be required out of aesthetic reasons, as accumulated dust on the glass will be visible. It is unclear how fast dust will accumulate, as this depends on a lot of factors, amongst which the local air quality and materials used inside the building. It is unlikely that large dust particles will travel far upwards in the cavity, as the airspeed inside is very low (because airflow is spread out over the entire width of the facade). Due to these low air speeds, most dust will settle down and not travel upwards.

Alternatively, regular filters or electrostatic filters could provide additional help. At this point there are no well-founded conclusions to be made, except that it would be similar to the maintenance of a second skin-facade or climate facade.

Aesthetic value
There is little difference in the thickness of a regular window frame, and the window frame of the climate cavity facade. The only noticeable difference is the depth of the facade, which is about 20 cm. When looking at window frames from the side (where both the outer and inner panel have a vertical element) this depth will be visible. Compared to a regular facade when looking at the facade from up close this will be notable.

Compared to an actual second-skin facade or climate cavity the depth of the cavity will be very little.

5 How does the new concept position itself towards existing concepts. What are the advantages?

The climate cavity facade concept aims to invest the same money that would otherwise be spend on a (central) ventilation system, into the facade which provides the ventilation, but simultaneously offers the advantages of a second skin facade, being reduced energy consumption in terms of heating and cooling and improving thermal comfort.

Apart from that, the concept offers a low maintenance and low fan-energy ventilation system, that always provides fresh air without the interruption of filters, heat exchangers or ducts. Also, the concept allows users to influence their climate and make decisions in terms of pre-heating and conditioning air, opening a window and solar heat/light entry.

Where the second-skin facade and climate facade concepts rely on mechanical ventilation for the interior, the climate cavity facade aims to be a natural alternative, providing air directly from the outside and using buoyancy and solar radiation to help provide ventilation.
Main research question:
Can a hybrid system, combining the good air quality and low costs of a natural system with the user-adjustability, energy efficiency and small size of a decentralised mechanical system, offers a feasible, sustainable alternative to current ventilation concepts?

The Climate cavity facade concept, an attempt at designing the mentioned hybrid system achieves some of the mentioned criteria. The system is a 'natural' system in the same way that system C is 'natural', with the addition of buoyancy and the solar chimney effect, to provide fresh, clean air with no elements that could reduce air quality like filters or heat exchangers.

The costs of the system are not completely sure, but the system is definitely more expensive than ventilation system C in terms of investment costs. The low operation costs and maintenance costs are similar to those of a natural system. Compared to a central ventilation system, the climate cavity concept provides a feasible alternative in all terms of costs except for heat recovery, as achieving the same amount of heat recovery (up to 90%) is impossible at this point. It is almost impossible to put all costs in terms of investment, maintenance, fan energy, energy savings from a second-skin facade concept, energy savings from using buoyancy and a solar chimney for ventilation and reduced heat recovery into perspective. If further developments on the glass-cavity heat exchanger concept allow for more heat recovery, the system could definitely provide a feasible alternative upon further development.

The 'user-adjustability' of the system is definitely better than that of a central system where the user has no influence at all. The two options of the winter and summer situation seem more like something for the building management system to handle, though adjustable vents and openable window give the users more of a choice. The options for the facade would allow for some changes in the room temperature though.

The 'small size' of decentralised systems are achieved in the way that no ducts or ventilation box are required. The thickness of the facade is of course increased.

The system is sustainable in the way that it reduces fan-energy consumption as well as heat gain in summer, but a lower heat recovery rate opposes this. The concept does reduce building material usage, as no ducts or additional building height is required. Lastly, user satisfaction and air quality can be improved.

Some points of attention are the maintenance (cleaning) of the facade, acoustic comfort and operation control of the system. At this point it is unclear how these work out.

To answer the main question, a 'natural ventilation - decentralised mechanical ventilation hybrid' system, like the climate cavity concept, can provide a feasible alternative upon further development. The exact improvement or decrease over a central ventilation system can only be proved by applying the concept in an actual building. But certain advantages are definitely possible. How they relate to the disadvantages can only be proved in practice.
Illustration sources (continued)


7.1.3 Roelofsen, P. (2002). Ventilated facades; Climate facade versus Double-Skin Facade. Published online: https://www.google.nl/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCIQFjAA&url=http%3A%2F%2Fwww.top-e.com%2Fdownload%2Ftop%2F52%2520%2520%2520%2520%2520%2520%2520%2520ventilated%2520facades.php&file=J3vNhP0y6WD7ya9vIPwAYwUgfAFQrCFHOGH4W3sKefpWzdHNjT5QnGb6&bvm=bv.9199022,d.ZGU:Top E.


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7.1.16 7.1.15 http://mw2.google.com/mw-panoramio/photos/medium/17222771.jpg

7.1.17 http://www.paulderuiter.nl/projecten/mercator-i-3/


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7.1.21 http://www.architectenweb.nl/Bin/Products/201503/238654.jpg

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7.1.24 http://www.architectenweb.nl/Bin/Products/201503/238654.jpg

15 Appendix

BEPALEN VAN DE VERDUNNINGSCOEFFICIENT S 1 EN S 2

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<thead>
<tr>
<th>SITUATIE</th>
<th>COEFFICIENT</th>
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Illustration sources (continued)