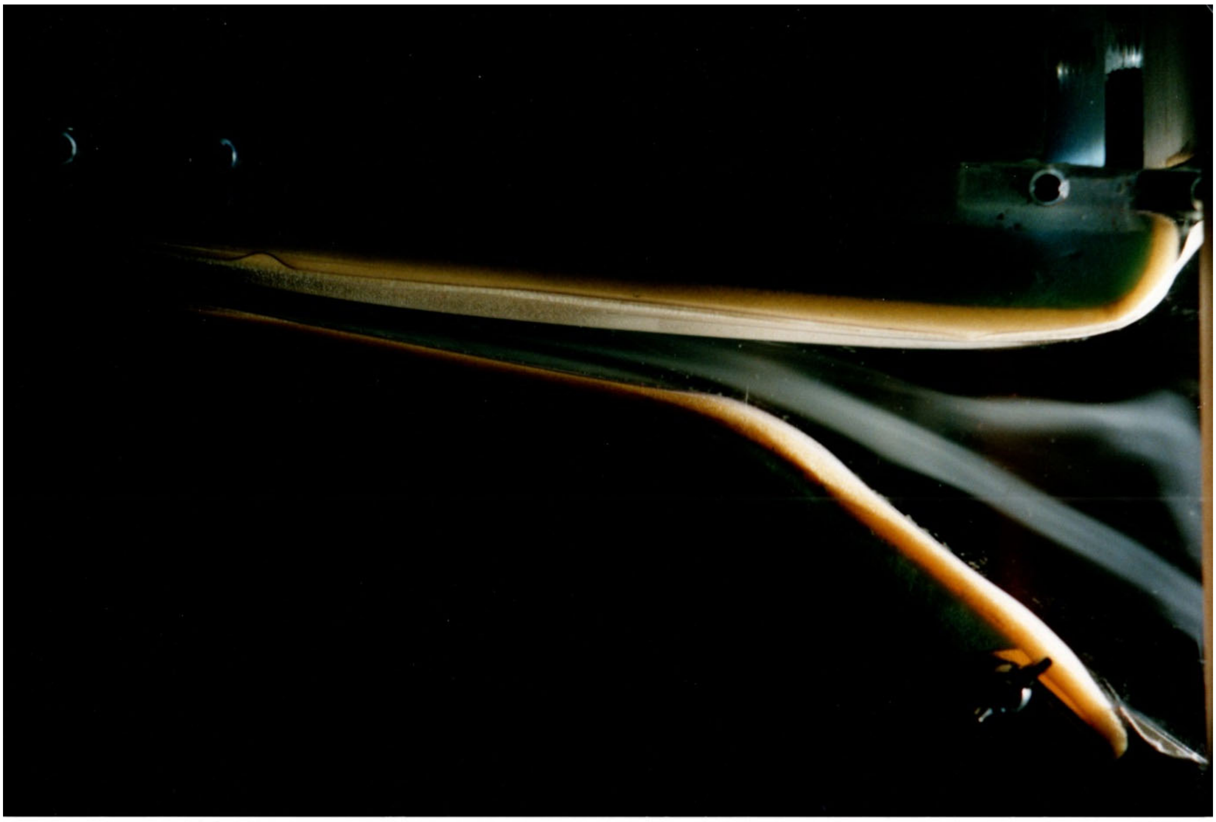
HYBRID VENTILATION – A DESIGN GUIDE

Peter J.W. van den Engel



Handbook, in development, version 1.01 / 17-04-2019

Front page: cross section of a special venture shaped trickle ventilator that produces a parabolic inlet profile. This results in a maximum turbulence near the inlet and a very low Draught Rate (Engel 1995).

Acknowledgements

I want to thank the following persons and organisations:

- Susan Roaf (Heriot-Watt university, Edinburgh) for giving continuous advice during the development of the handbook.

- Ceciel Sillevis and Kees van der Linden for their assistance to finish the first publication.

- Deerns for giving me the opportunity to work on this handbook and using their information.

Table of contents page

1. Introduction/background

1.1 Aim

The aim of the book is to give an overview of the advantages, history and principles of hybrid and mixed mode ventilation. Natural ventilation plays a key role to improve comfort and reducing energy. In order to make natural ventilation successful, an early integration in the design-process is necessary. In the long term fully natural ventilated buildings are expected to become the standard, even in high rise buildings (Wood 2013). However, much more scientific development is necessary in order to guarantee that these buildings will behave as expected. The book is not an advertising book for natural ventilation. In many cases natural ventilation alone for climate control is not possible. However, in most of the cases hybrid or mixed mode types can be applied and these options need more attention. Adaptive thermal comfort is closely related to hybrid and mixed mode buildings in which a wide range of temperatures are possible, with substantial options of saving energy (Humphreys 2015).

A key success factor is always the degree of user satisfaction. This is not only related to dissatisfaction, but also to thermal satisfaction. The highest level of thermal satisfaction is called thermal delight. About thermal comfort, air quality and spaces there is still much to learn, especially because it is strongly related to psychology.

Knowledge about comfort is generally only available after the period in which the building is built. In some naturally ventilated buildings there have been more problems than expected, due to a lack of knowledge of physical reality or usage of the building. Mostly it could be solved by adaptations of the original concept. Nevertheless, many naturally ventilated buildings did not need significant adaptations. Moreover, many fully mechanical ventilated buildings have comfort-problems as well, which are generally not deeply analysed.

From both naturally as well as mechanical ventilated buildings we can learn. The development of insight in naturally and hybrid ventilation will also contribute to better mechanical ventilation, as to air quality, thermal comfort and energy consumption. For instance, at the moment the air resistance of mechanical systems becomes lower and the combination with (smart) operable windows is considered as a quality in building certification systems like LEEDS, WELL and BREEAM.

Designing natural, hybrid or mixed mode buildings requires a complete other way of thinking about design. It is partly a mixture of mechanical, building physical and architectural engineering, but it is also more. Knowledge about natural air flows and designing with natural air flows is in fact a new profession, for which this book gives a general, and sometimes detailed, outline.

1.2 Why do people like natural air flows?

- Link to weather
  Most people like natural ventilation, due to the experience that there is a connection with the weather.
- Link to scent of nature
  Especially being in contact with the pleasant scent of nature, such as from pine-trees, flowers or the freshness of the air after a thunderstorm, there can be a feeling of delight (Guzowski 2003).
- Link to adaptive comfort
  The better the connection to the outdoor climate is, the more people are able to adapt themselves to lower or higher temperatures. This is not only a comfort issue, but a health and energy issue as well.
- Increasing the robustness of the building in case of failure of the climate system
  In case there is a failure of the climate system of a building (ventilation and cooling), it is good to have an alternative solution with operable windows. A failure is also possible during a short fall-out of the grid.
- Personal control
  When occupants can control their environment individually, like windows, sunshade and heating elements they can easier adapt to the local climate and will have a higher appreciation of the climate. This will increase their appreciation of thermal comfort and improve productivity.

1.3. Why is ventilation necessary?

- Oxygen
  The concentration of oxygen in the air is 209 litre per m^3. A concentration lower than 190 litre per m^3 produces (without adaptation) concentration loss and lower than 180 litre per m^3 a choking hazard. However, adaptation plays a dominant role. People living in mountain-areas are accustomed to a lower level of oxygen per m^3. The average oxygen-consumption of a sleeping person is 18 l/h. Circa 10 m^3 air per day passes the lungs. The maximum oxygen consumption is 3 to 7 l/m (running very fast).
- CO_2
  CO_2-level is since long the main indication of the air quality (Pettenkofer 1858). Nevertheless it is a poor indicator because there are many other sources of air pollution (Sassi 2016).
  The general assumption is that a concentration higher than 1200 ppm CO_2 (1.2 litre per m^3) is noticed and is equivalent to a slight loss of concentration. Pettenkofer advised 1000 ppm as a healthy maximum. In his time CO_2-levels of more than 7000 ppm in classrooms or meeting rooms were not unusual. In submarines concentrations of 6000 ppm or more are possible without health risk. This is due to adaptation. Smell is generally the only indication that the air quality level is insufficient and will for instance be noticed by a visitor coming from a well ventilated space in a poorly ventilated occupied space.
- Moisture control
  Ventilation is also necessary to remove moisture. This depends on the moisture production which is, for instance, generally higher in houses (showering, cooking) and old buildings (via the fabric). A sufficient low air humidity will also decrease mite-development.

- Removal of toxic gasses
  With ventilation it is possible to remove pollutants.
- Removal of stale air
  With ventilation stale air can be replaced by fresh air. Common practice is the opening of a window of a sleeping room in the morning.
- Temperature control
  When the inside temperature is too high it is possible to reduce this temperature when the outside temperature is lower. For an effective control enough information about the outside temperature is necessary.
- Comfort cooling
  When the inside temperature follows the outside temperature cooling by air movement is also an option. Depending on the air velocity, a decrease of comfort temperature of 3 ^{o}C or more is possible (NEN-EN 15251).
- Health and productivity
  Individual temperature and air quality control will improve health and productivity. However, there is no consensus yet how much this influence is.

1.4 Thermal sense

Ventilation is an integrated part of the experience of thermal comfort. It can increase or reduce the feeling of thermal pleasure. In winter air flows via cracks in the façade can have a negative effect. However, still air is seldom appreciated neither.

Thermal comfort is influenced by the following parameters:

- Air temperature
- Radiation temperature
- Clothing level
- Metabolism
- Air velocity, with
  - Turbulence intensity
  - Power spectral density
- Humidity

Adaptation plays an important role. People tend to adapt their preferred most optimal (neutral) temperature related to the average outside temperature. There is a big difference between buildings that follow the outside temperature (free running) and are (partly) natural ventilated and buildings in which the temperature is controlled between strict limits (Nicol 2012).

1.5 Harvesting and reduction of energy

One of the main driving forces behind an increased usage of natural ventilation in the future is the option of energy-reduction. The following parameters are relevant:

- Reduction of fan energy

In most of the climate zones in the world there is a period in which the outside temperature makes it possible to use natural ventilation. This are outside temperatures between 10 and 25 ^{o}C, or even below or above these temperatures depending on the kind of comfort that is required. At the moment there are already many hybrid ventilated buildings that can switch from mechanical to natural ventilation (mixed mode). In a period with very low or very high temperatures mechanical ventilation can take over the natural system. The most basic solution is a building in which mechanical air flows are reduced when windows are opened, but ducts that can transport mechanical driven as well as natural air flows are an option as well. Alan Short (2017) has made a very detailed description of this principle, based on several self-realized buildings (e.g. Judson building). Natural ventilation is possible during the whole year, but in winter more heating energy may be necessary and in a hot-spell in summer more cooling energy, compared to mechanical ventilation with heat recovery.

- Reduction of cooling energy

With smart natural ventilation it is possible to reduce or prevent mechanical cooling. In most of the climate zones in the world there are many days in which the inside temperature is too high and higher than the outside temperature. In these cases natural ventilation is often an option. Especially during the night the temperatures are lower. Ventilation during the night can cool down the building mass.

In buildings with a high occupancy combined with strict limitations on the humidity level and temperatures operable windows are not popular among building developers. Factors that make application of natural ventilation more difficult in periods with high outside temperature and humidity (enthalpy) are:

- a risk of condensation on cooled ceilings
- increasing the cooling energy in the air handling unit
- the fear of draught
- the fear of disturbance of the air flow distribution in the duct system.

Only with a smart design and control of natural ventilation systems these problems can be overcome. The high expectations of double skin façades with regard to energy savings and poor results (Leao 2016) make it clear that this is a serious point of attention for the future.

- Harvesting and reduction of heating energy

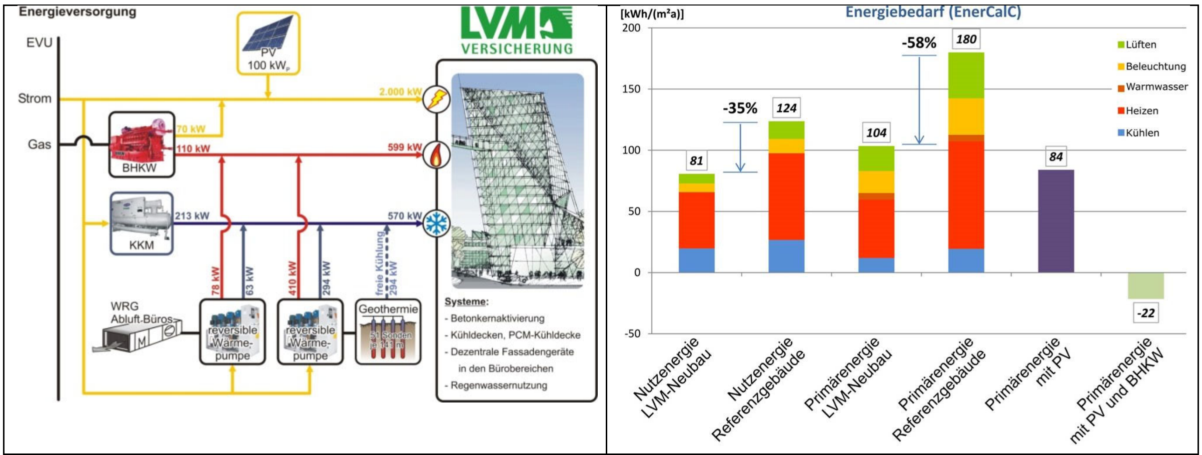
It is wise to use the heat such as from the sun, high occupancies and servers to zones in the building that are too cool. Before heating or cooling a building the internal energy flows can be used. This way of energy use is most effective in combination of the usage of the thermal mass and the acceptance of occupants that the indoor temperature can fluctuate. Smart usage of thermal mass inside the building can reduce heating energy. Other options to reduce heating energy are:

- Adapting the volume of fresh air supply to the outside temperature
- Heat recovery with a very low air resistance integrated in a natural ventilation system
- Usage of ground ducts

1.6 Economic issues

At the moment the energy performance of many new buildings is expressed in kWh/m^2 of primary energy. Related to climate this is generally for fan, heating and cooling energy. Some of the most advanced buildings have the following expected energy consumption for those parameters:

1	Post Tower	75 kWh/m^2 (Schuler 2005, Wood 2013)
2	LVM Münster	70 kWh/m^2 (with PV and bio-combined heat power generator (CHP) around 0 kWh/m^2)
3	Unipol Tower	hybrid ventilated building 20 kWh/m^2, conventional façade/air handling unit AHU 40 kWh/m^2 (design study Transsolar)



a. Installation concept with, among other equipment, PV, PCM ceilings, heat pumps, geothermal storage and bio-CHP.

b. Energy consumption and production LVM-building in kWh/m^2 compared to more conventional buildings, only cooling, heating, ventilation and lighting is considered.

Figure 1.6.1: Energy concept hybrid ventilated LVM Münster building (see also section 4.3), text in German.

The electricity demand for e.g. office equipment, lighting and elevators can more than double this energy consumption (Schuler 2005), making it more difficult to develop a building as a zero energy building. On top of that, measurements of buildings in use show generally higher energy values, so it seems that the ambition is often higher than what can be realized in practice.

Investment costs and pay-back times are important parameters during the design process. When designs are compared pay-back periods are generally used.

Sustainable buildings tend to have more and more complex installations which have the risk of less robustness, more failure of systems and maintenance. This is not always taken into account, so an overall judgement of climate systems in general should always be the starting point. Conventional, but smart designed single façades and climate systems can also have a rather low energy consumption for climate and a high degree of robustness. Changing a design culture into hybrid ventilated buildings requires a high feeling of responsibility, level of knowledge and skills of the designer.

Resilience against rising temperatures in the world is an important evaluation parameter. In many habited zones of the world rising temperatures will give more opportunities for passive cooling by natural ventilation (Short 2017).

Finally, user satisfaction, health and productivity should be the most important economic evaluation parameter, but is still difficult to assess in mechanical and hybrid ventilated buildings.

1.7 Considerations in relation to well-being and health

Ventilation is only a part of a total building concept. The architectural environment, feelings of safety, privacy, psychological and social background and environment have also effect on how well human beings feel and how productive they can be. These feelings are often dominant, so the effect of ventilation can only be assessed taken also this into consideration.

2. The design process related to ventilation

2.1 Functional requirements

The function of the building, program of requirements, the architectonic expression and the characteristics of the site are main parameters to start with. The initial ventilation system is only chosen after the first design decisions. Depending on the function, access of daylight into and view out of the rooms might be one of the most important starting points.

The site gives the boundary conditions for natural ventilation, but also for the best position of air inlets for mechanical ventilation. The question what kind of natural ventilation is possible depends for instance on the outdoor air quality, noise, temperature, humidity and wind velocity. These might be highly time-dependent.

Natural ventilation cannot be seen as a goal in itself. Low or zero energy architecture is highly dependent on the design of the façade. The ultimate goal is that buildings can keep its internal temperature and air quality on the required level (almost) without installations, mainly due to the right physical, architectural and control measures.

Daylight, lighting and solar radiation

It is also essential to reduce heating and cooling energy as much as possible, together with promoting the access of natural daylight. At the moment energy of lighting is one of the highest parts of the energy balance, even with high efficient LED lighting with capacities of 1 W/m^2 per 100 lux. The access of daylight is influenced by parameters such as the percentage of glass, the LT-value of the windows, the position of the windows, the height of the space and the internal colours of the space (reflection). Due to the highly variable level of daylight, up to more than 100.000 lux outside, controllable sunshade is necessary. At the moment there are low energy mixed mode buildings like the Post Building in Bonn and the ING headquarters in Amsterdam with a very high percentage of glass. It seems as if the amount of glass doesn't matter, because of the very good sunshade in an effective ventilated second skin façade. However, a fully glaze façade still has disadvantages like more energy loss, a higher diurnal temperature swing of the rooms behind the façade and more glare risk. On top of that, occupants will tend to use more lighting in the spaces deeper in the office in order to counterbalance the high illumination level near the façade. Although a fully glazed façade is still an important architectural ambition, this should always be compared with other solutions. Maybe new technical solutions like PCM in the glass and controllable g-values can reduce disadvantages. Up to now the results are not convincing enough.

A façade that has a lower glass percentage has the additional option to integrate PV-systems as well, for instance as a sunshade element and as a covering of the parapet. This will increase the level of energy neutrality (Gonçalves 2012).

A façade that reflects heat can keep the space behind cool. A negative effect is that this will increase the heat island effect of the surroundings: the problem is partly removed. Options to prevent this are, for instance, green façades of balconies with enough water supply.

Occupancy

The amount of persons per m^2 is an important starting point for the choice of ventilation. Spaces with a low occupancy, say lower than 1 person per 10 m^2, have the best opportunities for natural ventilation. Spaces with a high density, like classrooms, meeting rooms and auditoria, are much more difficult to ventilate naturally. Of course, this also depends on the time of the year and the amount of additional control options.

Zoning

In order to control the air flows the most effective strategy is to divide the building into compartments that can be ventilated separately from each other. In this way air flows, temperature and energy consumption can be better controlled.

Combi-offices

Large offices landscapes are more difficult to ventilate in an only natural way. There are successful hybrid examples like the Commerzbank (Wood 2013) and the GSW and Bang and Olufsen headquarters (Kleiven 2003). Combi offices seem to be best appreciated. These also give the option to avoid sound nuisance of colleague office workers. However, the importance of boundary conditions like enough privacy and view to outside are also personal and not very well evaluated up to now, although there is already much research been executed in this field (Vroon 1990).

2.2 Typologies, shape of buildings

Buffer zones

Buffer zones will decrease heat losses from façades. In case solar transmission is possible overheating of these spaces should be avoided by enough ventilation facilities or sunshades.

a. Atria, light-wells, halls

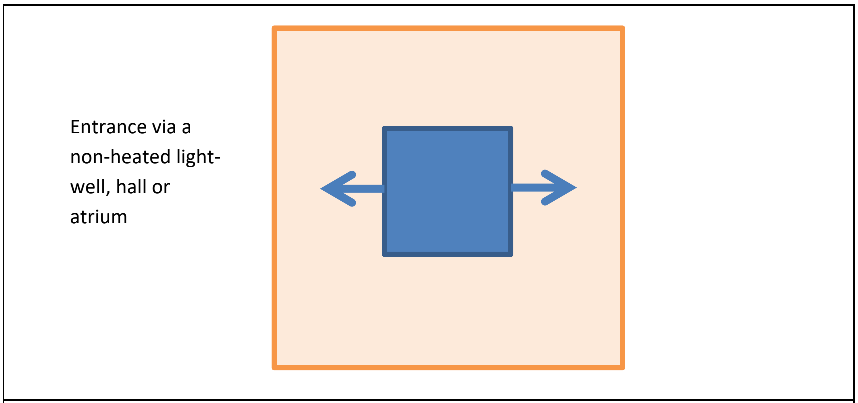


Figure 2.2.1: Scheme of a central atrium.

b. Adjacent glass-houses and entrances

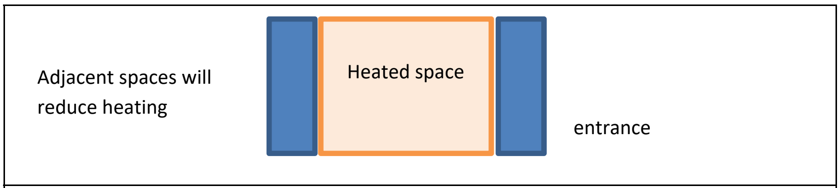


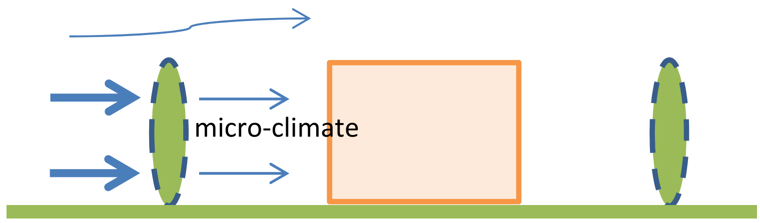
Figure 2.2.2: Scheme of an adjacent glass house.

Heat loss can also be reduced by adjacent glasshouses via which air can be preheated by the sun. These zones have also the capacity to improve comfort for occupants, and for visitors when these spaces are used as entrance, for instance as protected galleries.

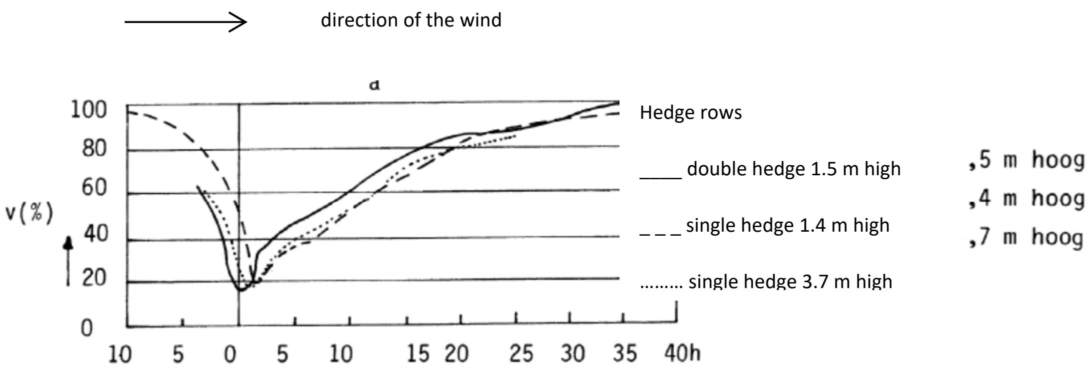
2.3 Microclimate, influence of the surroundings

The direct surroundings of a building like trees, hedges and fences can reduce the wind velocity. This can also partly be achieved by a rough shape (roughness) of the façade (Vongsingha 2015).

c. Protection against wind



a



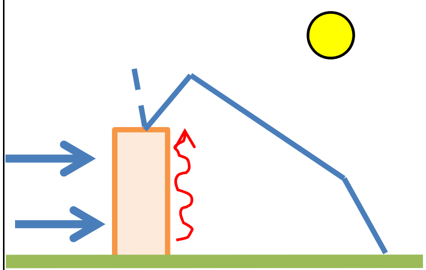
b Wind reduction by hedges, h = the distance from the hedge related to the height of the hedge.

Figure 2.3.1: Wind reduction by trees or fences, a wind-reduction up to 80 % is possible with fences (Sturrock 1972).

Figure 2.3.2: An aerodynamic shape, enough thermal mass, small windows and protecting trees are basic starting points for comfort in winter and summer. This was already known in the iron age.
Of course, nowadays requirements are more complex and demanding, but basic starting points have not been changed. Archeon.

The façade can be designed as a protection against the predominant wind:

Example of a grape greenhouse at the Streekmuseum Westland, Honselersdijk.



The green house is protected against the cold sea wind from the North-West by the brick wall. The brick wall accumulates solar energy as well.

a

b

Figure 2.3.3: In this kind of space cooling is only realized with a window at the top of the greenhouse.

d. The usage of the sun

In low energy buildings smart usage of the sun is essential. Especially in winter solar energy should be used as much as possible. The design of the façade can take into account the low angle of the sun in winter. Thermal mass in the building can accumulate the heat which can often be used for more than one day. In summer, spring and autumn there is a danger of too much sun, so a façade design should be optimized for both seasons. Preheating of air is possible in trombe walls or adjacent non-heated zones with much glazing (buffer zones).

e. Local wind-patterns

Buildings can protect against wind when buildings are close together or produce wind at street level, like skyscrapers in a surrounding with lower buildings do and thus create a cooling effect. Wind is a very relevant parameter related to outdoor comfort.

f. Local differences in temperature and air quality

If there is enough freedom of choice, and depending on the system, fresh air intake should be at the side where air quality is relatively high and where the air is cool. The best choice also depends on the overall design of the ventilation system.

Normally, the higher the air intake, the cleaner the air will be, but this is strongly dependent on the surroundings. Beside a busy road much pollution is possible at the top of a building, near the road. Parks and open water are often regions with less air pollution and a lower temperature. When the use of buoyancy is important a low location of the inlet will work better. However, there is always another risk with low placed inlets: more vulnerable for possible terrorist attacks.

A façade and roof design that reduces the temperature has also a very positive effect on the inlet temperature of the air.

2.4 Optimized façade design for summer and winter

- How to keep the building warm or cool

In order to keep heat inside in the heating season the building should be well insulated. Thermal mass in direct contact with the inside air works as a heat storage system. This will keep the heat inside much longer.

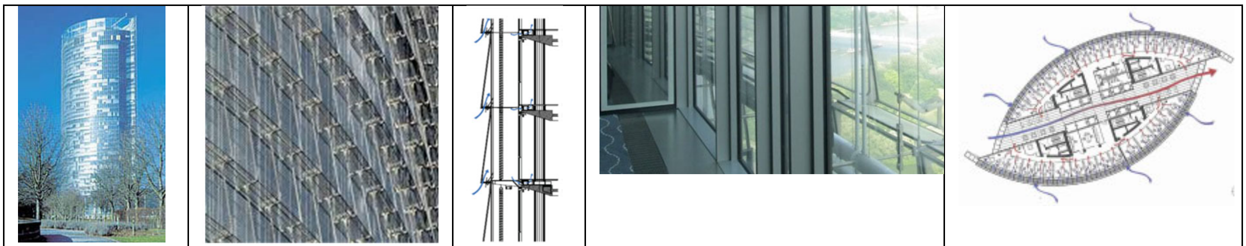
In summer reduction of the entry of sunlight is necessary to keep the building cool. With ventilation, when the outdoor temperature is lower than the indoor temperature, up to 35 W/m^2 cooling is possible. This means that the combination of internal and external heat load should be limited strongly in order to prevent cooling. When the internal heat load is 25 W/m^2, an external heat load of 10 W/m^2 is acceptable. In order to make the consequences clear, the following façade solution is an option: a window of 1 m high, a room of 6 m deep, a g-value of 0.1 (outside sunshade) and 600 W/m^2 solar radiation will lead to this value of 10 W/m^2. When the glass percentage (p) is 30 %, g * p = 0.03. In case of natural ventilation as climate control only very low values of this kind lead to acceptable highest temperatures in summer.

In the current design practice the disadvantage for energy and comfort of much glazing is often overlooked.

a. Façade of the old townhall. b. Façade of the new town-hall.

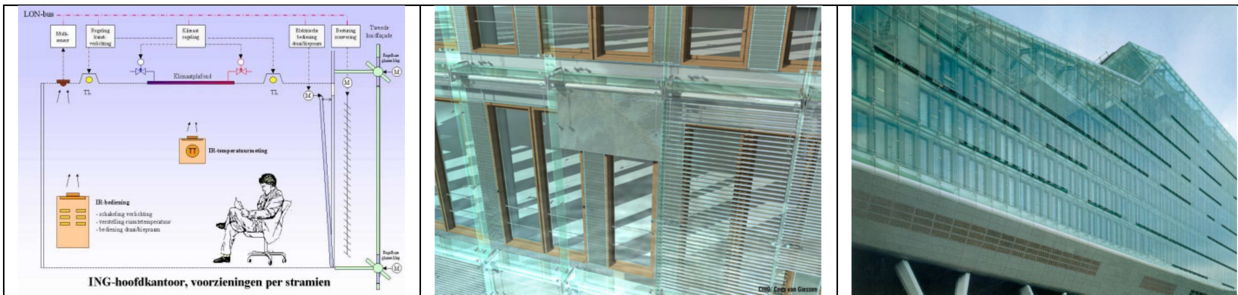
Figure 2.4.1: Comparison of the façade of the old and new town hall of the municipality Westland. The glass-percentage multiplied with the g-value of the old town hall maybe 30 % * 0.10 = 0.03 and of the new town hall 100 % * 0.30 = 0.30. With internal sunshade (66 % of the façade) this might be reduced to 0.20. However, the external cooling load of the new town hall will be 7 – 10 times more. Because of glare on pc-screens the inside-sunshade, developed for greenhouses, will be replaced.

Interesting examples of buildings in which a high transparency is combined with low g-values (around 0.07) are the Post Tower in Bonn and the ING headquarters in Amsterdam.



a b c d e

Figure 2.4.2: The Post Tower has a very well ventilated second skin façade and movable blinds. Although the glass percentage is almost 100 % the solar load is still low.



a b c

Figure 2.4.3: The ING head office in Amsterdam has a high glass percentage but due to combination of a well ventilated cavity, sun protecting glass and reflecting blinds the g-value is still low, around 0.07.

Especially in museums much glass is not favourable due to the high cooling load and risk of damage to paintings by solar radiation (UV). However there is an interesting example, the Nelson-Atkins museum in Kansas city where this problem has been overcome in some way. The façade is designed as a double façade with translucent materials, inside sunshade and natural ventilation of the cavity, where possible. The effective g-value is unknown.

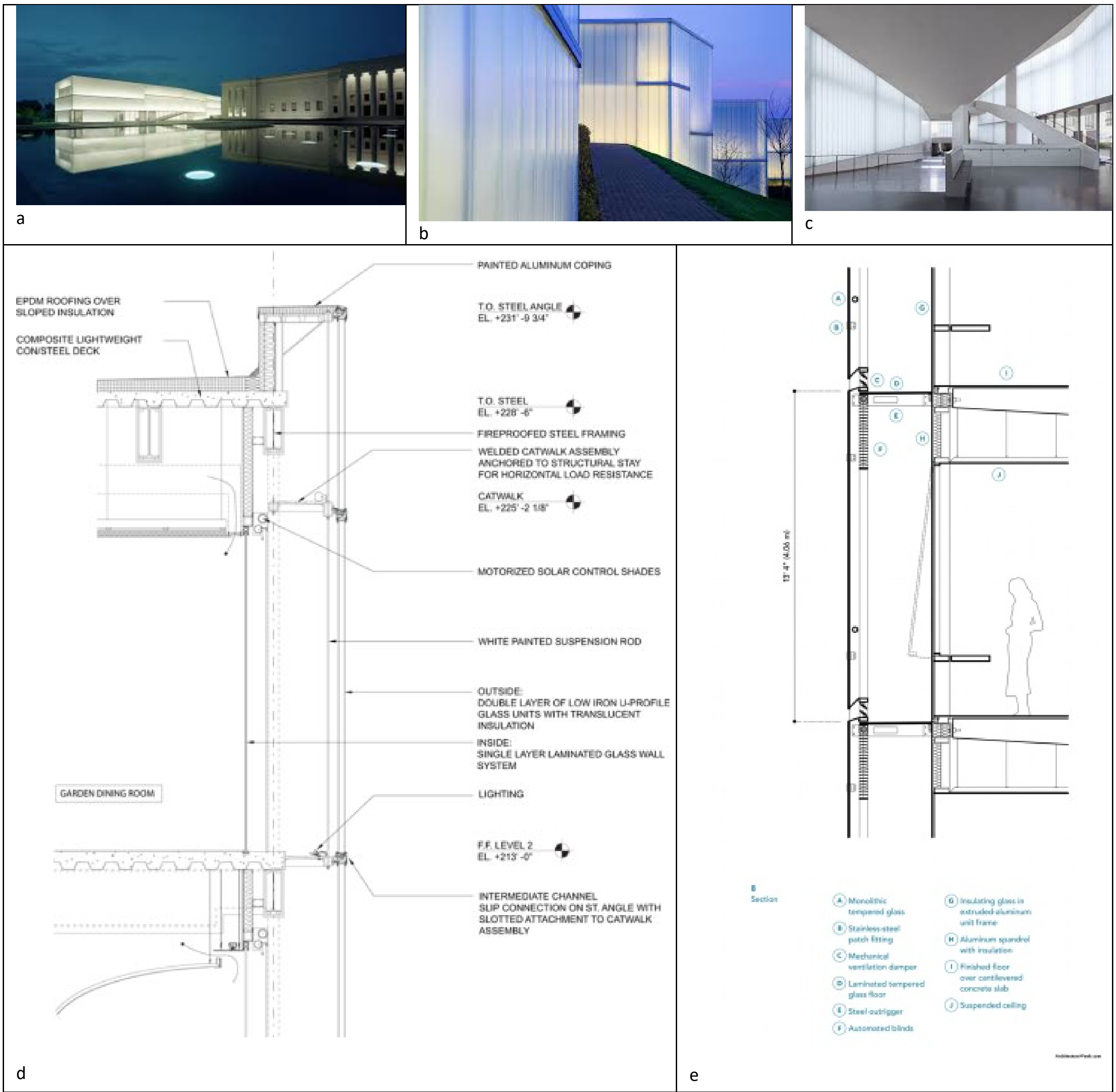


Figure 2.4.4: Nelson-Atkins museum, example of an extreme transparent façade for a museum.

- Optimal usage of daylight

The most optimal degree of transparency of the façade should be a starting point in the initial stage of the design for enough daylight-access, prevention of overheating and unnecessary heat loss. For winter as well as summer conditions the window design should be as adequate as practical possible. Making use of diffuse day- or sunlight for museums can be an interesting added value. It can save energy an create a more poetic atmosphere. An interesting example is the museum Voorlinden in Wassenaar (Kraaijvanger) where an abundance of daylight is available via a perforated roof. However, in most cases only very small amounts of daylight are used and possible (Kimbel Art Museum in Texas (Kahn), Gemeente Museum The Hague (Berlage) and Rijksmuseum Amsterdam (Kuijpers). The Kunzhaus in Bregenz designed by Peter Zumthor with ceilings illuminated by diffuse daylight near the façade is another kind of compromise. It is a building in which the effect of transparency is realized without being fully transparent.

For sculptures day- or sunlight is seldom a problem, for paintings and sketches it generally is.

- Optimal ventilation strategy

The amount of ventilation should be adapted to the outdoor and indoor climate. The effectiveness of the elements determines how and when these elements can be used. Usually rain and burglary protection is necessary, and the size of the openings should be made small or large. A control strategy as simple as possible is the best thing to do.

- Keeping the building between temperature limits

A diurnal swing in the temperature and differences in temperature within a building is acceptable and can give the building even more quality. However, people do not like large (and unexpected) temperature differences within a short time.

2.5 Making a choice

Making a choice for a certain kind of ventilation system is generally complicated. It has to do with the architectural design, functional requirements, the available budget and the risk of having to make a new design.

Conventional mechanical systems can be changed in a low pressure system with less fan noise. By adding operable windows there are many positive but sometimes also negative effects, these should be taken into account.

Comfort requirements are always an important basic starting point. Natural ventilation will not reduce the humidity/enthalpy level of the air when this is high in summer. When a maximum level is required dehumidification will be necessary, like Bronsema (2013) advices. However, it is also related to the idea about the effect of adaptive capacities of human and other living beings.

The importance of direct contact with outdoor air and nature is an important parameter and cannot be underestimated. It is difficult to measure its positive influence only in a physical way. By making long supply ducts and air paths natural ventilation may reduce fan energy but the air quality may become closer to the air quality of mechanical systems.

In chapter 3.4 very different buildings with “proved” hybrid ventilation systems are presented, which shows something of the great amount of possible options. The idea is that, like in evolution, only smart, robust and relatively simple and smart concepts will survive and develop.

3. Typologies of naturally or hybrid ventilated buildings

3.1 A short history of natural ventilation

In old times natural ventilation was the only option to supply fresh air, cool the space and remove smoke.

Figure 3.1.1: In The Netherlands - like in many other places in the world - the first inhabitants after the last ice age were hunter/gatherers. This kind of hut from the stone age was built 7000 BC. (Archeon)

In the stone age when farming started to develop, the walls became thicker and heavier usually made of loam, but the way of ventilation remained almost the same.

Figure 3.1.2: Example of a house of the early Middle Ages. The air exhaust can be controlled. The main original function of high openings was smoke removal, which has, without a chimney, a low effectiveness. When chimneys were being used air indoor quality and fire safety improved. (Archeon)

The focus in many buildings was on the improvement of efficiency of the removal of smoke from the fire for cooking and heating. In course of time it was required that chimneys were made of fire-resistant materials like brick.

Houses, schools and offices

In school buildings from the beginning of the 20th century there was often a window that opened near the ceiling and could reduce to a large extend draught. Combined with a large height of the space this was favourable to cool the classroom in summer as well.

Figure 3.1.3: Bottom-hung window of a school in Poeldijk from 1921.

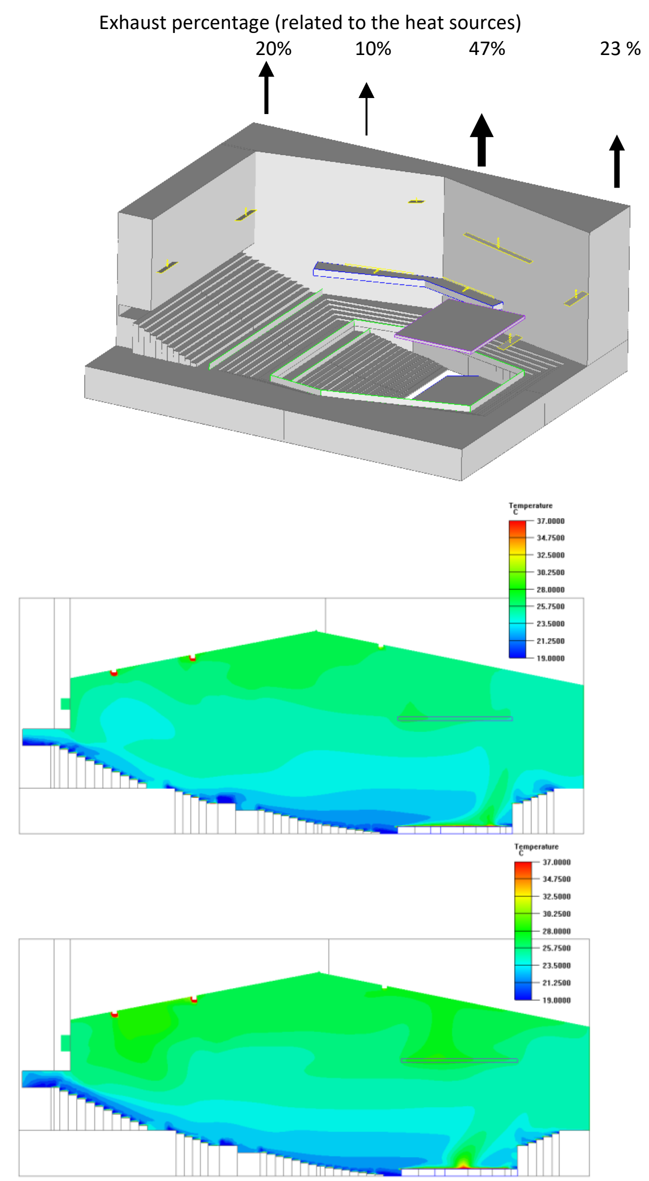
In the fifties and sixties many buildings in a temperate climate were still ventilated by operable windows: offices, schools and houses.

Figure 3.1.4: Example of a naturally ventilated school in Middelburg from around 1960. There are sufficient windows with different size and location and thermal mass that can be cooled down. Outside sunshade is available. The climate system was unchanged in 2006 when this picture was taken.

Gradually more and more buildings became mechanical ventilated, often in combination with operable windows. Nowadays, many offices even have no operable windows at all. These are often considered as harmful for the climate control (draught, air flow control via the ducts, condensation and cooling capacity) and working of the air handling units. However, there is little scientific evidence that this is really the case. On top of that, there are many options to overcome these problems.

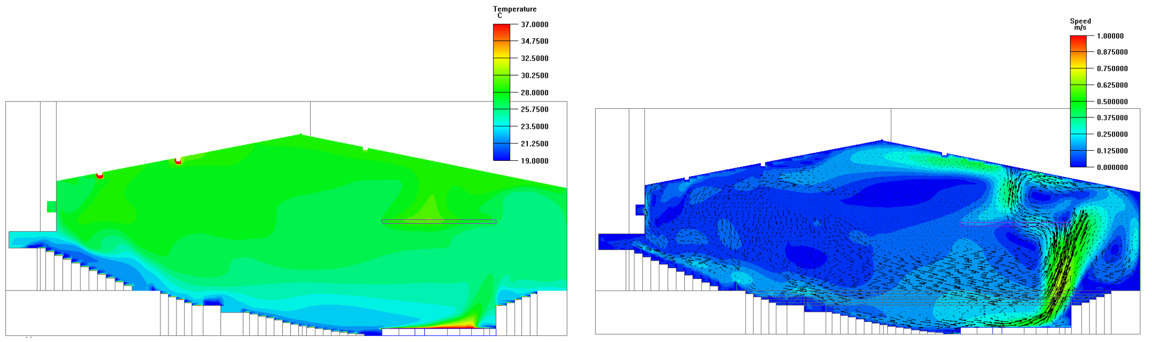
Theatres

Theatres in the 19th century were often ventilated via the ceiling. Other options are preheated air in plenums underneath the seats or via the corridors. At the moment there are several examples of relatively new and already partly renovated buildings, like De Doelen in Rotterdam, in which those principles are reused (Short 2005, Engel 2010). Ventilation with the inlets at the top could create draught, especially when the concert hall was half full (Awbi 2003). On top of that energy consumption for cooling and ventilation was high. In order to solve this problem the direction of the air flows has completely been reversed to displacement ventilation leading to a much better thermal comfort and lower energy consumption. His example shows that even in fully mechanical ventilated buildings it is wise to make use of the characteristics of natural air flows.



Spotlight power 25 kW

Spotlight power 50 kW



Spotlight power 75 kW

Figure 3.1.5 CFD-simulations with Fluent of De Doelen (Engel 2010). In order to reduce the risk of return flows the location and amount of exhaust should be proportional to the heat sources. The thermal stratification reduces draught, fan and cooling energy.

3.2 Natural ventilation in different climates

a. Moderate Climate

In a moderate climate a different ventilation strategy is necessary for summer, autumn, winter and spring. This means often different air supply systems for summer and winter.

In summer large air flows can be necessary to cool the building. The most efficient ventilation strategy is to ventilate the building only when the inside temperature is higher than the outside temperature. The size of the air flow may vary depending on the heat load and the temperature difference between inside and outside.

When the outside temperature is higher than the inside temperature the air change rate should be limited to that what is necessary to guarantee the air quality with an air change rate (ach) of 0.5 - 1. This is also the required strategy for winter in order to reduce energy consumption. On top of that, in winter it should be clear that the supplied air flow does not produce draught. At the moment there are enough examples for different functions like offices, schools and houses showing that this is possible. However, there are significant differences in the design strategy between The Netherlands, Scandinavia and England. The most relevant Scandinavian examples are presented and discussed by Heiselberg (Awby 2008). In England there are developments of fully natural ventilated buildings with air supply and exhaust shafts. Air supply via the façade is often integrated in the canopy combined with local preheating of the air. In The Netherlands most systems are based on natural air supply via the façade at a height of 1.8 m above the floor, which is also incorporated in the building code. For this system preheating of air is generally not necessary. This depends on the amount of outdoor air per m inlet.

b. Cold climate

In a cold climate a different ventilation strategy is necessary for winter, autumn/spring and summer. The Manitoba Hydro Place in Winnipeg, Canada (Wood 2013) shows that it is possible to develop a low energy building in which natural ventilation still plays an important role. This building is a mixed mode type. This is an option for a climate with extreme differences between summer and winter (+35 to -35 °C). For regions with smaller temperature differences ground ducts are also possible, such as applied in the Mediå primary school in Grong, Norway (Kleiven 2003). In arctic regions adjacent glass houses for natural ventilation are an option, making use of the heating capacity of the sun.

c. Hot and dry climate

In hot and dry climates cooling by shading and air flows are essential. When the temperature differences between day and night are large enough night cooling is also an effective strategy. Especially in arid climates the difference between day and night temperature can be huge. For ventilation via windows or large grilles there are many hand-calculations tools and evaluated examples of low rise buildings (Allard 1998) in order to assess the optimal size and positon of openings. In hot and dry climate cross ventilation and night cooling are effective options. An interesting example of cross ventilation is the Unite d'Habitation in Marseille designed by Le Corbusier (Passe and Bataglia 2015). Several passive strategies are possible to cool a building in this type of climate such as ventilative cooling, radiant cooling, evaporative cooling and earth cooling (Givoni 1996).

d. Hot and humid climate

There air large differences between hot and humid climate-types. In climates with much rain and forest, the temperature differences between day and night and between the seasons are usually small. This is partly due to the large cooling capacity of plants, more than 400 W/m^2 because of evaporation (Engel 2017b). In these climates enough shading and comfort cooling by ventilation is sufficient to create a comfortable environment for persons adapted to natural ventilation.

There are also regions where the humidity level is high, combined with a high temperature, for instance in the United Arabic Emirates where the enthalpy of the air can be more than 130 kJ/kg air, whereas 65 kg/kg air is already high in a temperate climate. This high enthalpy will double the amount of energy necessary to dehumidify the air in fully air-conditioned buildings.

In such a region especially in winter natural ventilation is easy to integrate. However, natural ventilation is also possible in other seasons, making use of wind tower principles.

An excellent example of a high rise apartment building with cross-ventilation and effective sunshade is the Kanchangjunga apartment building in Mumbai (Passe and Bataglia 2015).

A different design direction can be found in the work of Oscar Niemeyer in South America. His buildings have an "open" and monumental expression, closely related to the later work of Le Corbusier. With large canopies, brise soleil sunshade and effective use of natural ventilation he managed to keep the temperature in his buildings within acceptable limits.

3.3 Advanced naturally ventilated buildings

1. Low tech

Low-tech solutions are control-options and building elements that can be manually used, such as the operable window position and the opening and closing of a vent. Those actions do not require central and decentral control systems, or a complex interaction with a mechanical ventilation or a heating and cooling system. However, they can influence the temperature, which might lead to additional necessary actions of the user.

2. High tech

High tech solutions are generally incorporated in a building management system, in which electronic and mechanical control is important. Other examples are:

- Motorized valves of the air inlets to control the air flow.
- Mechanical ventilation that stops when the CO_2-level is low enough.
- Systems that can overrule manual control of windows in case of cold or hot and humid outside air conditions, high wind speed or rain.

3.4 Types of mixed mode systems

In the following chapter several hybrid ventilated buildings are discussed. There is a fundamental difference between buildings based on direct air supply via the façade with windows and grilles and buildings based on air supply with ducts.

- With air supply via the façade and rooms with a limited depth more fresh outdoor air supply is possible, there is more contact with the outdoor climate and comfort cooling by air movement is easier to realize.
- With air supply via ducts it is easy to apply preheating, filtering and heat recovery. Normally these are applied in more centralized systems with deep plans.

1. Air supply via high placed inlets in the façade and exhaust via a shaft or central roof (1)

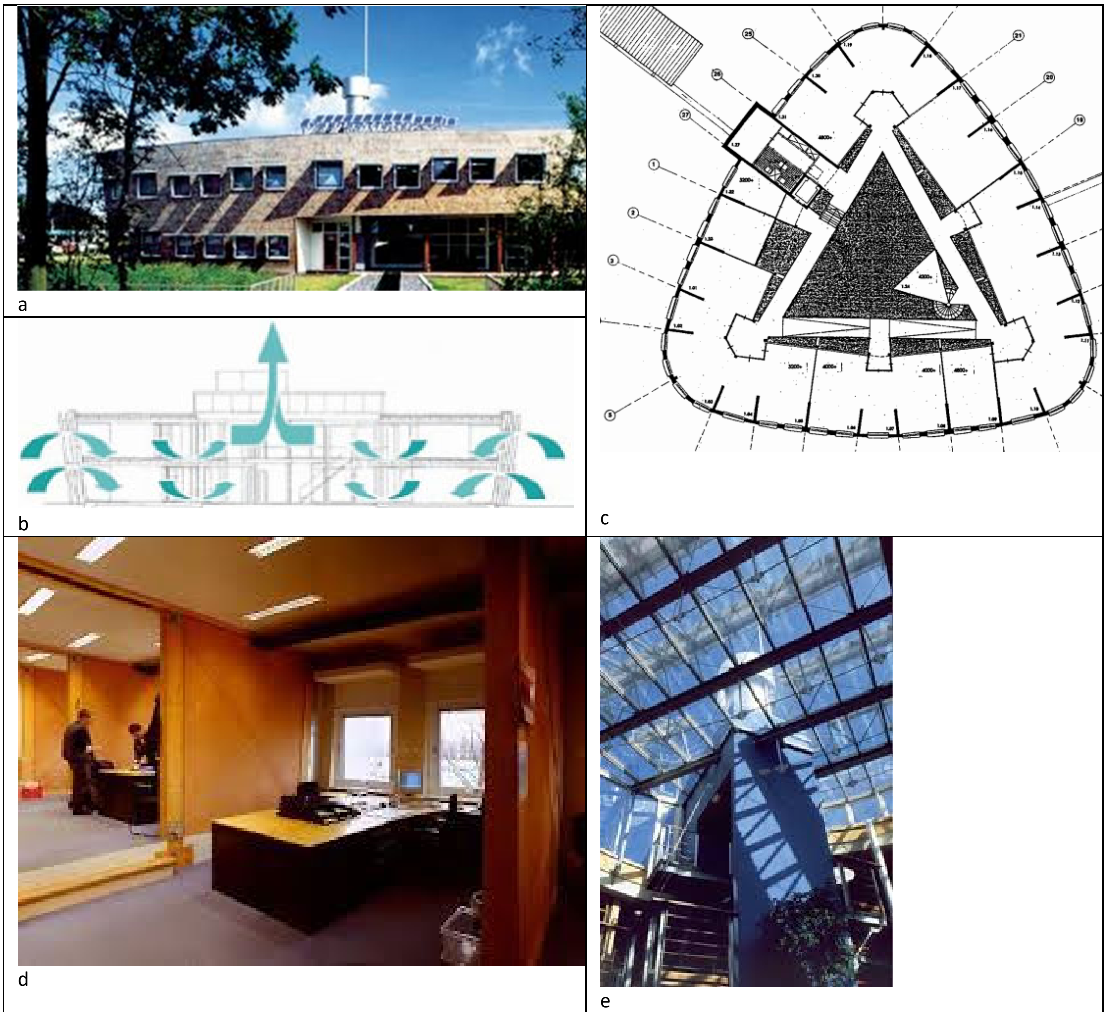
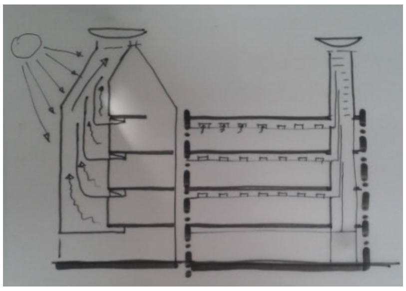


Figure 3.4.1: Office Rijkswaterstaat Terneuzen: high position of the inlet, low air velocity.

2. Air supply via high placed inlets in the façade and exhaust via a shaft or central roof (2)


a


b

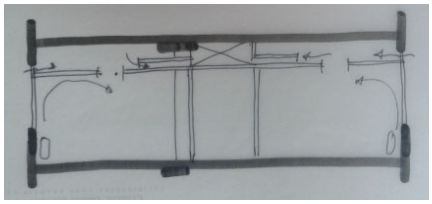
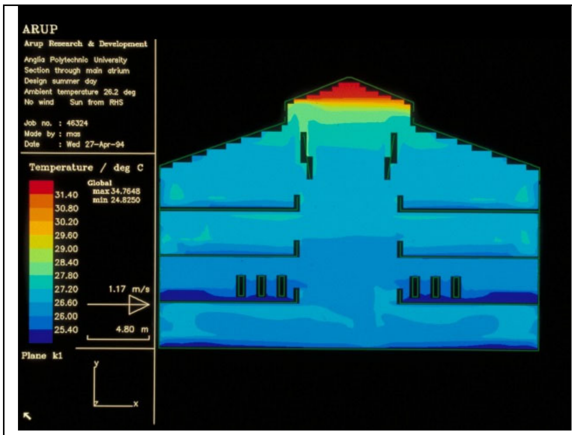
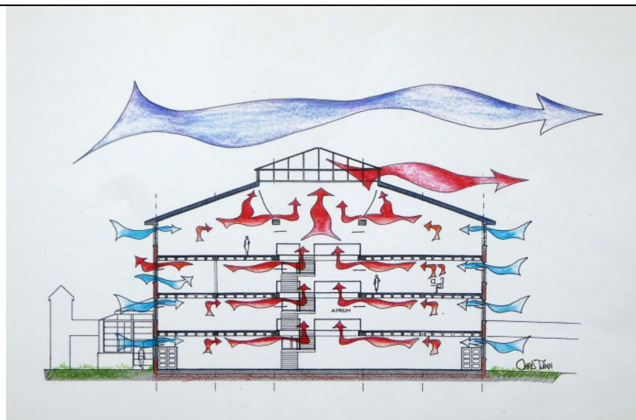

c

Figure 3.4.2: Rijksverzamelkantoor Maastricht, Ceramique site (architect Henket): high position of the inlet, low supply air velocity. Other principles are: a solar chimney, venturi roof and smart usage of the neutral zone.

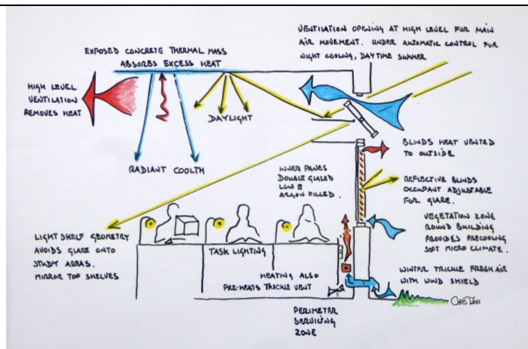
3. Air supply via low placed inlets in the façade and exhaust via a shaft or central roof



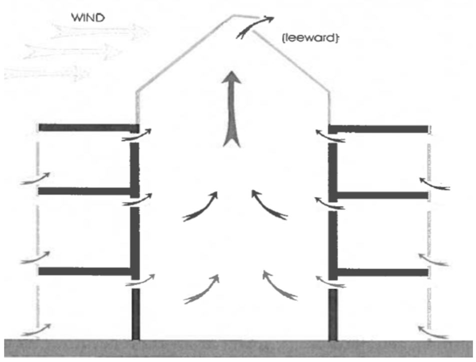
a CFD-analysis (Twinn and Arup).


b One of the ventilation strategies in summer.


c Overview of the Anglia Polytechnic University.



d Usage of natural elements.



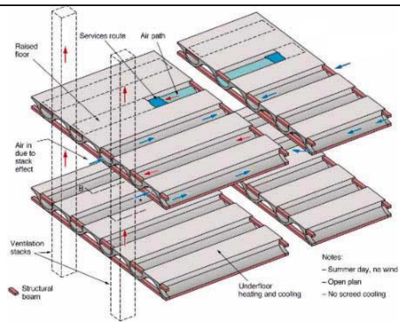
d Principle scheme ventilation, smart usage of the position of the neutral zone.

Figure 3.4.3: Anglia Polytechnic University: low position of the inlet, low inlet air velocity. The lowest possible position of the neutral zone has been an important issue in the design (Twinn 1997, Allard 1998).

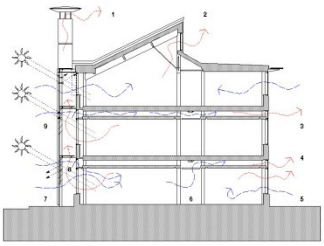
4. Air supply via windows in the façade and exhaust via a shaft or central roof (1)

a

b Abundant and creative presence of thermal mass in the ceiling.



c

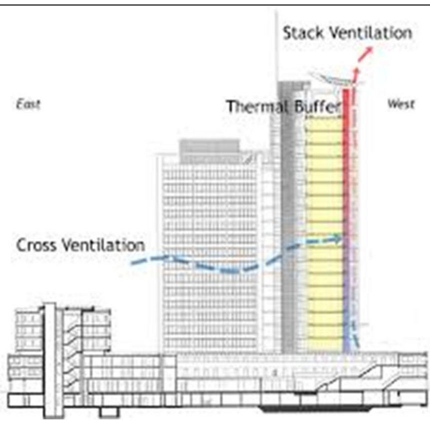


d

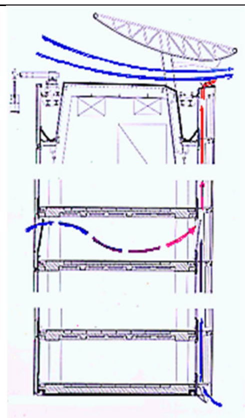
e

Figure 3.4.4: BRE Experimental building, optimal usage of the thermal mass, due to the chimneys the position of the neutral zone has a higher level.

5. Air supply via windows in the façade and exhaust via a shaft in the facade (2)

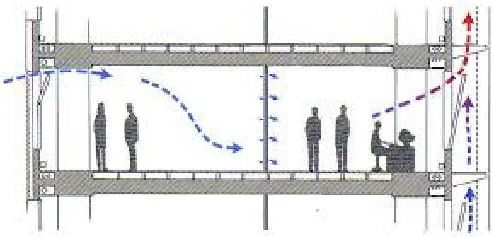


a



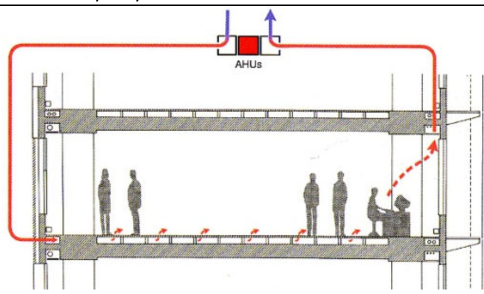
b

The position of the neutral level is increased by the top-buffer, the solar increased buoyancy forces and the wind via the venturi roof.



c

Natural ventilation mode.



d

Mechanical ventilation with heat recovery mode.

Figure 3.4.5: GSW-headquarters.

This building is a mixed mode building, in winter and summer a mechanical system can take over the climate control. The top of the façade chimney is increased to prevent reverse flows.

6. Air supply via windows in the façade, exhaust via central shafts

a

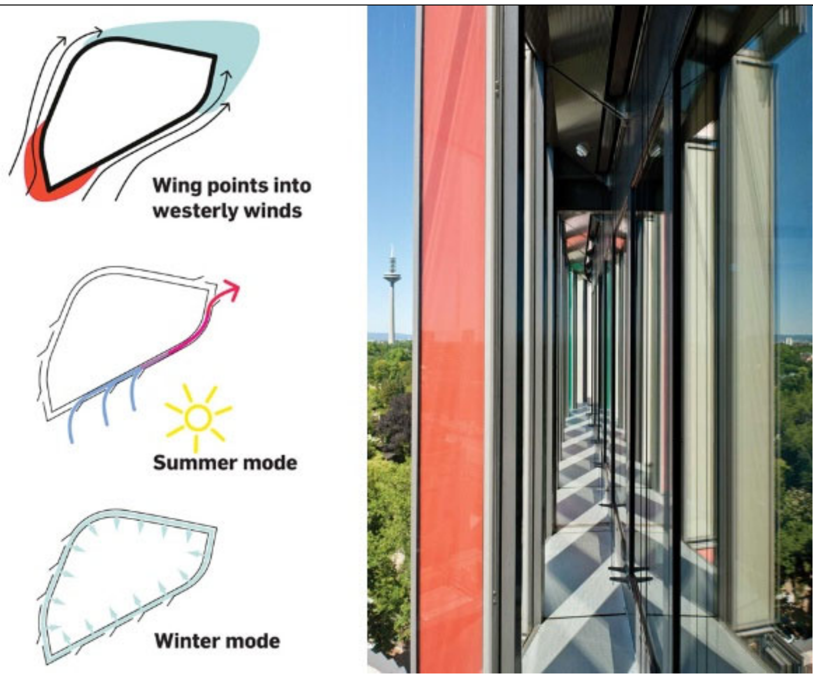
b

The air is transported from the rooms to the chimneys via duct in the corridors. The building has a height of 30 m , like most of the centre of Paris. The additional "chimneys" on the top of the building, integrated in the shape of the roof, are 15 high. The minimum calculated pressure difference in summer is 10 Pa.

Figure 3.4.6: Ministry of Defence Paris, natural air supply via windows, only when the outdoor climate is favourable enough (mixed mode type).

This building is a mixed mode building, in winter and summer a mechanical system can take over the climate control.

7. Air supply via a second skin façade to a central shaft

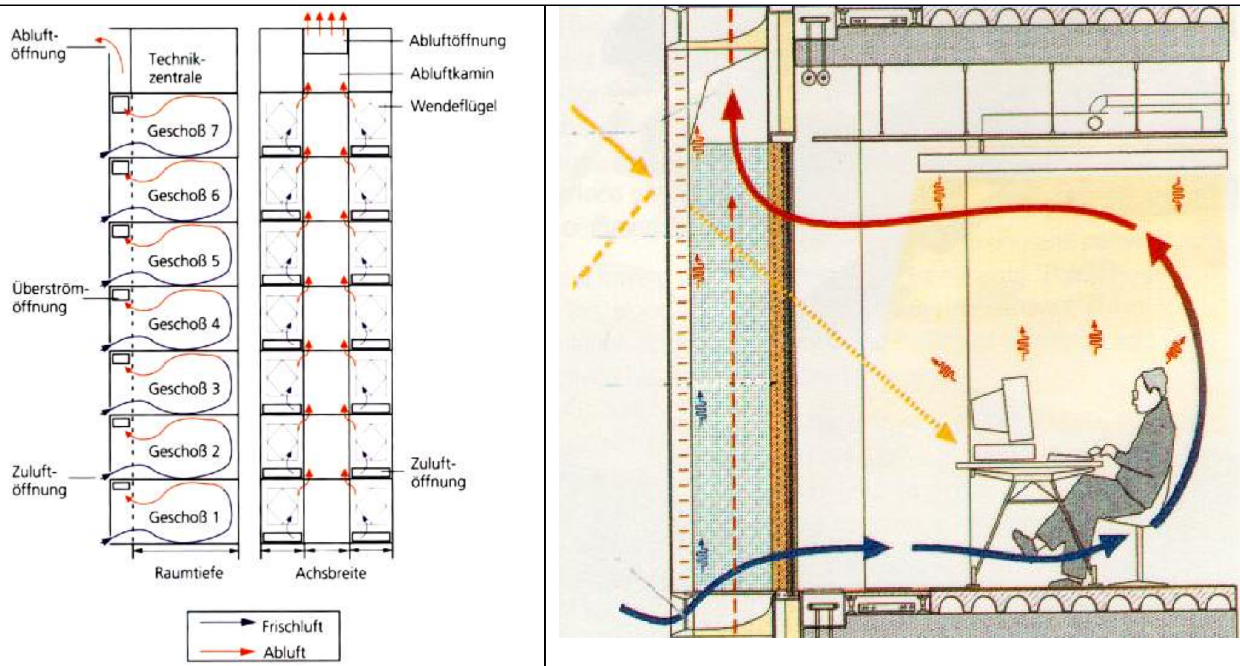


Overpressure system, mixed mode.

Figure 3.4.7: Kfw Westarkade, Frankfurt .

This building is a mixed mode building, in winter and summer a mechanical system can take over the climate control.

8. Air supply and exhaust via a shaftbox façade



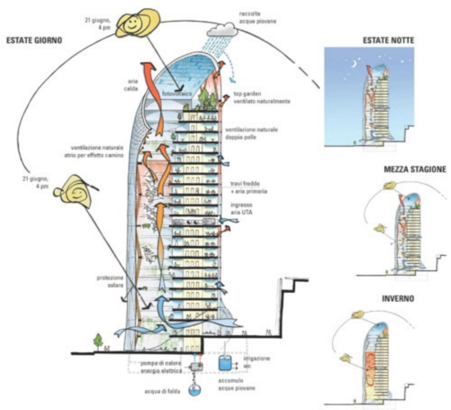
a b

Figure 3.4.8: ARAG Tower: Combination of natural with mechanical ventilation, if necessary. Cooled ceilings.

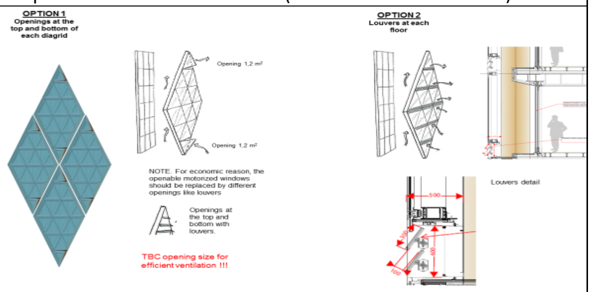
9. Air supply and exhaust via a double skin façade and atrium

a Unipol Tower Milan with the Bosco Verticale building nearby.

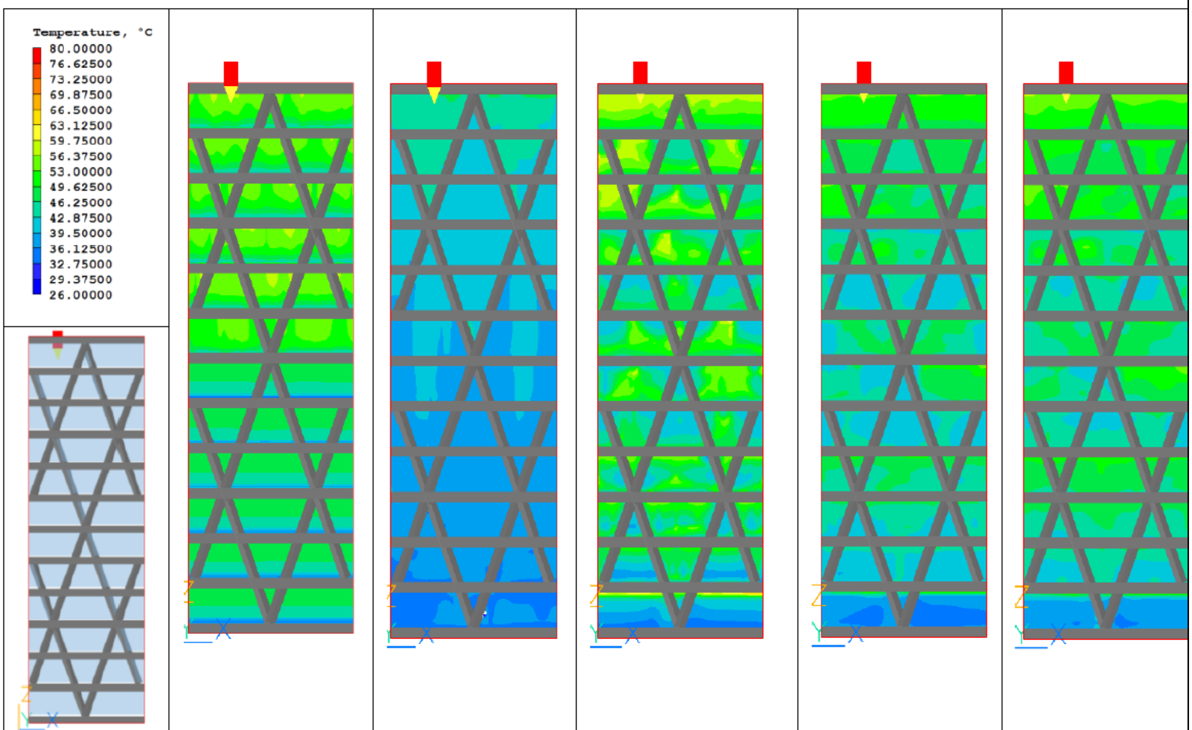
b Unipol Tower Milan and atrium (achitect Mario Cucinella.)



c Climate principle of the atrium and second skin. Openings of 20 m^2 low and high in the atrium will keep the temperature in summer close to outside temperature.



d Design sketches of the ventilation of the second skin. Reflective blinds in the cavity and high efficiency glass with a low g-value (0.30) will keep the indoor solar load low (g = 0.06).



temperatures	outside glass	cavity	screen	behind screen	inside glass, cavity side

e CFD-analysis overheating risk second skin façade at the hottest day. At each floor there is an opening of 25 cm (7.5 % of the facade).

Figure 3.4.9: Overview natural ventilation principle Unipol Tower. A combination of hourly simulations with IES of the second skin together with CFD of the whole façade can give a good prediction of the maximum temperature in the cavity of the façade.

10. Air supply via a shaft and/or exhaust via a shaft

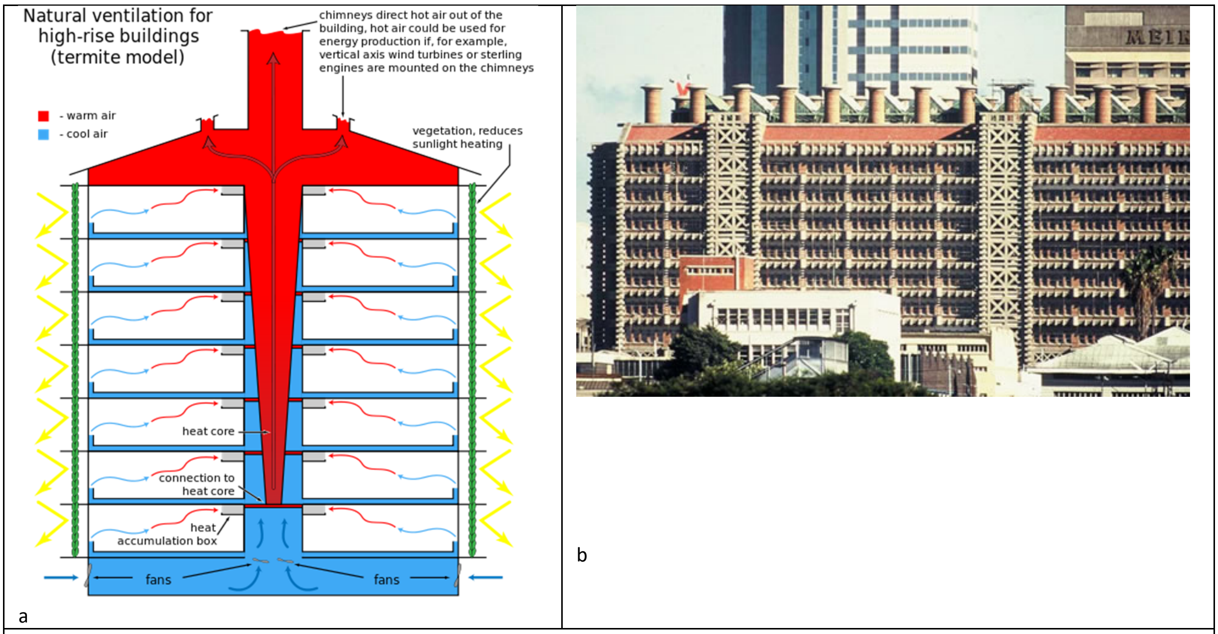


Figure 3.4.10: Eastgate Centre Harare, Mick Pierce (1996) in a hot and humid climate, air flow model inspired on the flow in a termite hill during the night, generally buoyancy. In reality the direction of air flows in termite hills reverses between day and night (King, 2015).

11. Air supply and exhaust via shafts with different thermal characteristics

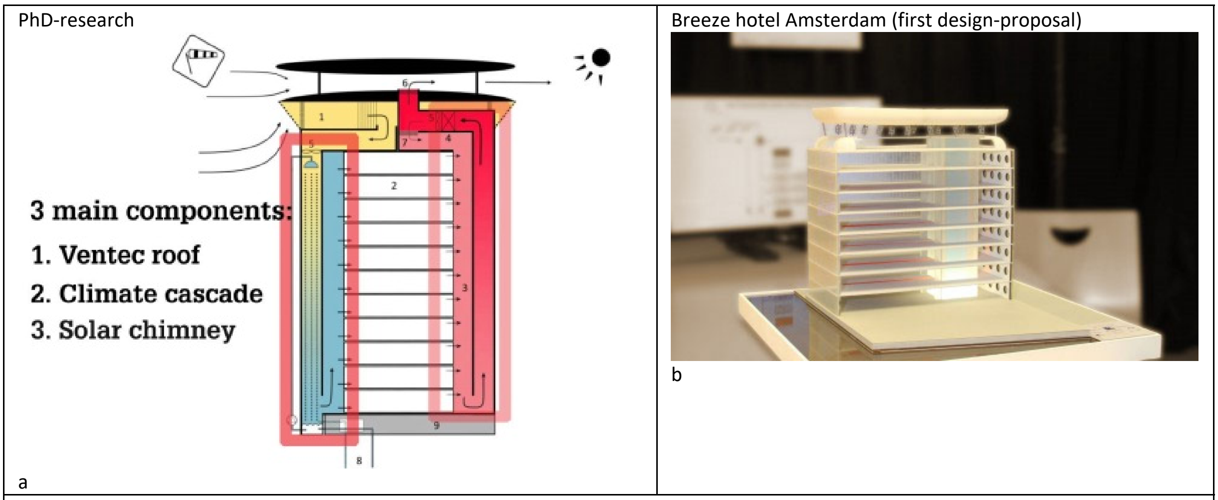
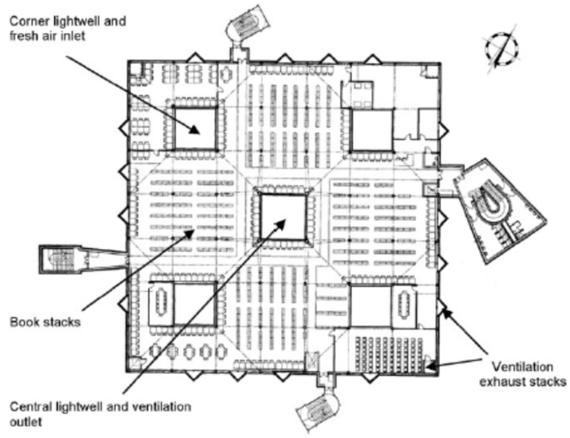


Figure 3.1.11: Earth, wind & fire research (Bronsema 2013), moderate climate, buoyancy/sun/wind/cold vapour (12 °C) to induce a vertical air flow, clean the air and provide cooling without producing a high humidity level. Mixed-mode, low air pressure building with a very high degree of natural ventilation.

12. Air supply via central shafts or atria and exhaust via decentral shafts or atria



a

b

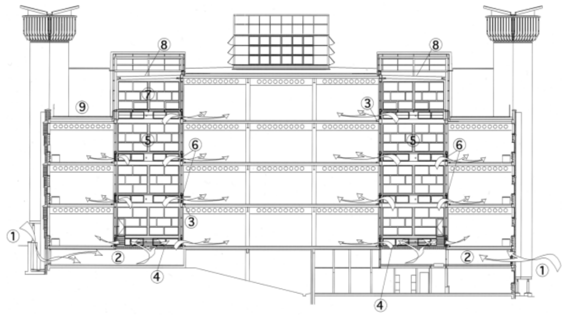


Figure 5 Lanchester Library: air supply strategy. 1 = Fresh air inlet, 2 = fresh air supply plenum, 3 = trench heating, 4 = heater batteries, 5 = light wells providing ventilation and daylight, 6 = building energy management system-controlled louvers, 7 = ventilated void, 8 = retractable translucent blinds, 9 = well-insulated roof

c

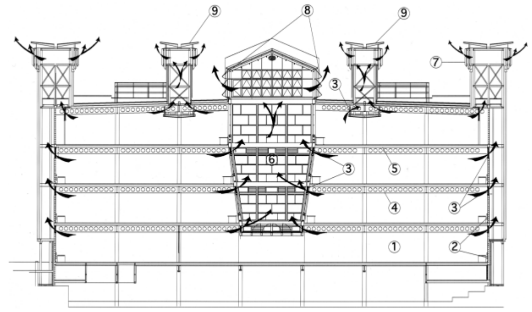
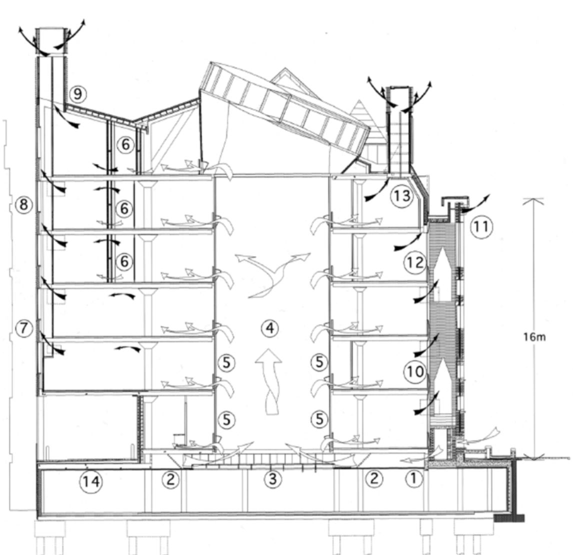


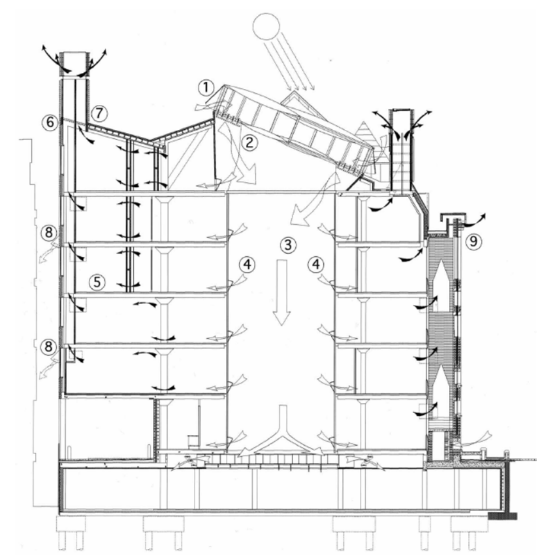
Figure 6 Lanchester Library: air exhaust strategy. 1 = Carbon dioxide and temperature sensors providing input to the building energy management system, 2 = perimeter radiators with thermostats, 3 = exhaust dampers at a high level on each floor, 4 = castellated beams, 5 = thermally massive (concrete) ceilings, painted white to assist daylight penetration, 6 = light well providing ventilation and daylight with solar shading, 7 = stack termination with wind protection, 8 = building energy management system-controlled windows, 9 = dedicated stacks to the third floor

d

Lanchester Library, Coventry, moderate climate, generally buoyancy. The top floor has an own air inlet and outlet system in order to increase the level of the neutral zone at the lower levels. The air inlet is in the basement level of the building. The building is carefully protected against overheating due to the façade design with small shaded windows and the usage of thermal mass with night ventilation.



e. winter ventilation.

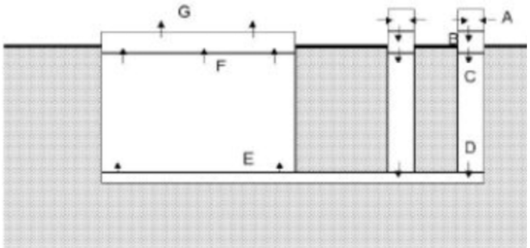


f. summer ventilation.

School of Slavonic and East European Studies (SSEES). Because of the location in the centre of London, an urban heat island, air can be precooled by elements in the top of a central atrium which is the fresh air supply zone of the building. Windows are still operable.

Figure 3.4.12: A library and school by Alan Short, outside and in an urban heat island.

13. Air supply via a shaft in the ground, supply via the ground and exhaust via the atrium-top



a

b

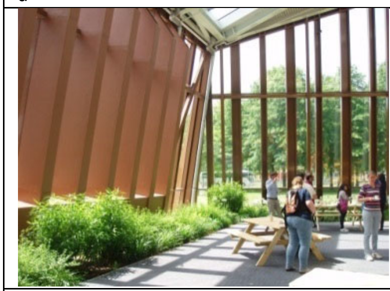
c

d

Figure 3.4.13: Theatre and Dance Academy Arnhem. The atrium is generally natural ventilated. The adjacent dance studios are mechanical ventilated.

14. Air supply via a ground-duct, ducts in the façade and exhaust via an atrium with chimney

a



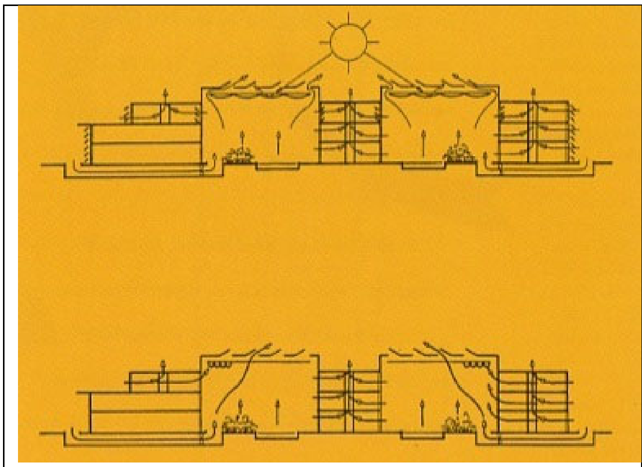
b winter garden.

c atrium.

d ground duct.

Figure 3.4.14: Energy Academy Europe in Groningen (BroekBakema). At the right side air is supplied via a ground duct, at the left side via a winter garden. The air is exhausted at the top the atrium and flows to a solar/wind-induced chimney at the top of the building. It is a mixed mode concept. Laboratories and offices in the building can also be ventilated and cooled in a mechanical way. The central inlet and outlet of the mechanical systems follows the same path as the natural system. Windows can be opened as well.

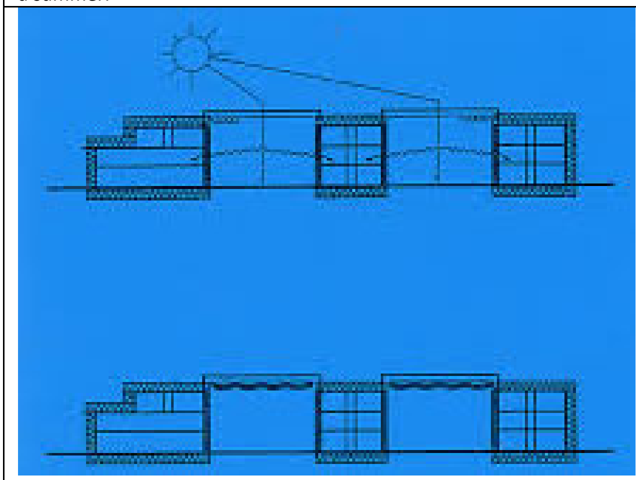
15. Air supply and exhaust via an atrium



a summer.

b

c



d winter.

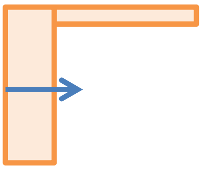
e

f

Figure 3.4.15: IBN-DLO (Lumen) Wageningen The ventilation of the offices is generally via the atria. Additionally there is mechanical exhaust in the offices and there is ground duct air supply in the atrium. Adaptation of the occupants to the climate is the starting point of the design.

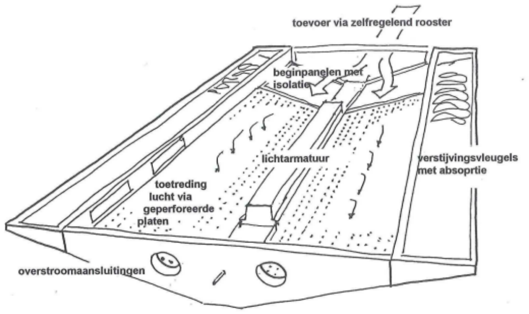
4. Ventilation elements

4.1 Natural supply systems



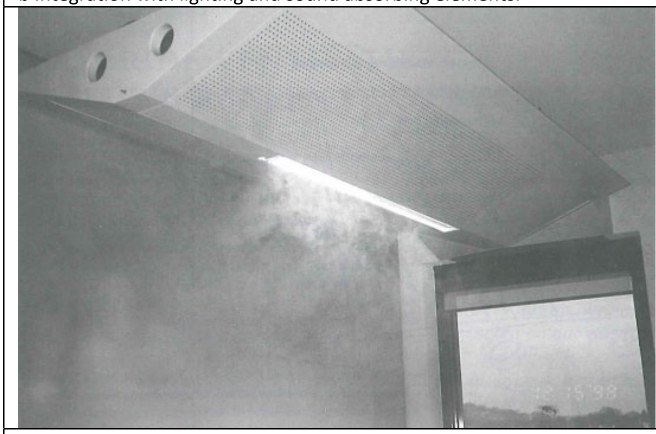
As long as the air flow is smaller than 10 - 15 l/sm façade there is little draught risk. A convector or radiator will reduce draught risk even more.

a More than 1.8 m above the floor (requirement Dutch building code to prevent draught).

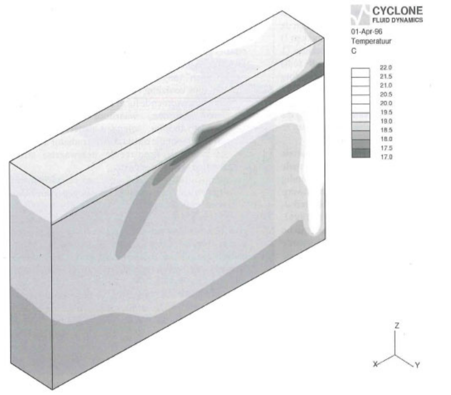


b Integration with lighting and sound absorbing elements.

c Optimal usage of the thermal mass.



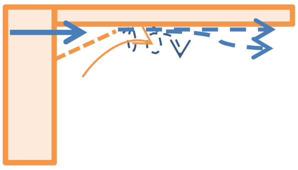
d smoke visualisation test of air flows.



e CFD-simulation to assess draught risk.

Inlet near the ceiling, Rijksverzamelkantoor Ceramique site Maastricht.

Figure 4.1.1: Options of natural supply systems with a low inlet air velocity and a high position of the inlet.

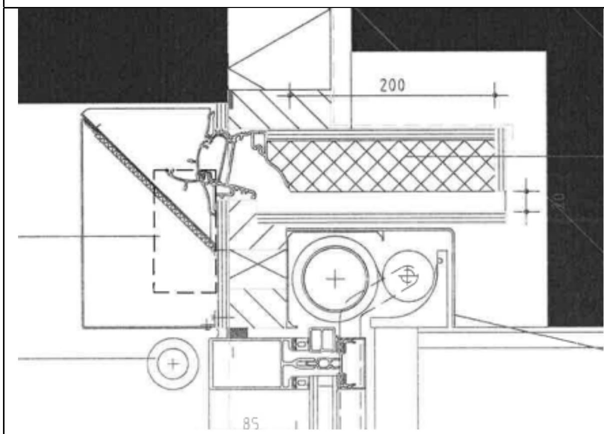


Air inlet 5 – 20 mm direct beneath the ceiling, > 2 m/s if possible, as long as the air temperature is higher than 0 °C there will be no draught (DR < 20%). Three physical principals are used:

- Coanda effect. Due to Bernouilli's law the air flow is pushed upwards when the velocity decreases.
- High turbulence at the inlet (fast mixing).
- Small deflection of the air flow (low Archimedes number, Ar < 0.001).

a

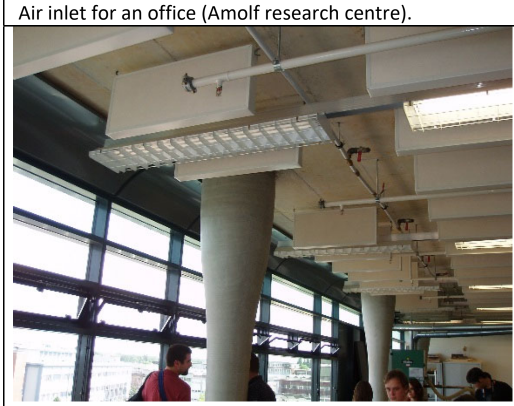
Option for offices in order to prevent draught.	For schools preheating of the air to 0 °C is necessary. For large air flows, such as for schools, higher pressure differences are necessary: > 3 Pa, depending on the aerodynamic design of the air inlet.

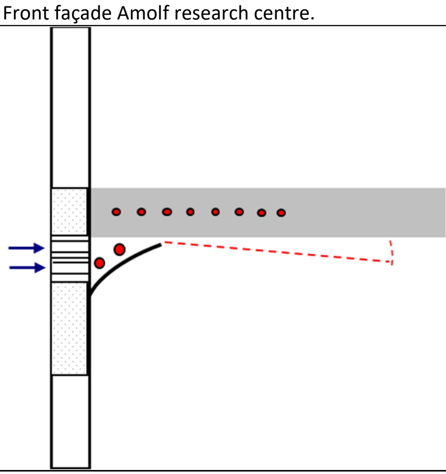


b

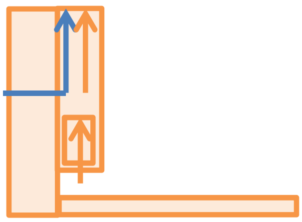
c

Air inlet for an office (Amolf research centre).	Front façade Amolf research centre.





d Air inlet for a school (ROC van Twente, air is preheated by two pipes).	e



f Jaga/Oxygen system (mechanical air supply), low position of the inlet, high velocity.

A disadvantage of a low position of an inlet is that there is more risk of simultaneously heating and cooling, because the temperature of the supplied air cannot be too low. This also depends on the inlet air velocity.

Figure 4.1.2: Options of air supply systems via the façade.

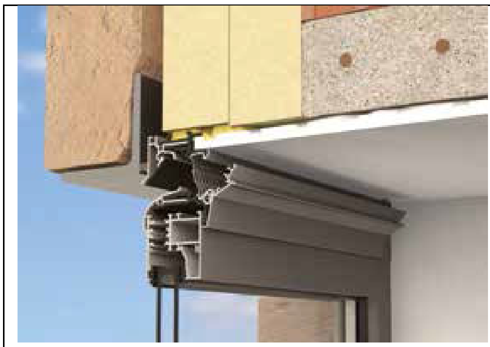
Inlets just underneath the ceiling with air colder than the room temperature and a high velocity should not deflect too early to the occupancy zone. In order to prevent this the Archimedes number should be lower than 0.001 (Engel 1995). The Archimedes number is defined in the following way:

$$Ar = \frac{g * h_{inlet} * (T_{room} - T_{inlet})}{U^2 * T_{room}} \qquad (4.1.1.)$$

The value of 0.001 is usually low enough for outside temperatures till 0 °C. For lower temperatures or Draught Rates below 20 % this value should even be lower (Engel 2017).

Grilles (trickle vents) are small elements that can control air flows much better than windows can do. This is especially important for the heating season. In the Netherlands grilles are usually placed as invisible as possible, direct above the window frame, in the wall above the window or underneath the ceiling.

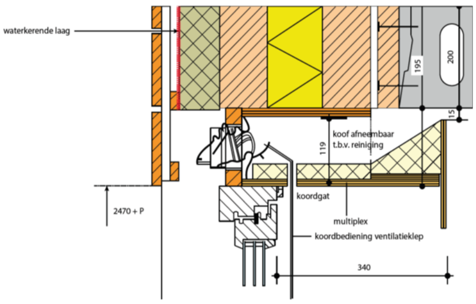
Figure 4.1.3: Example of an air inlet hidden from outside, one of the most common ways of integration of grilles in new houses in the Netherlands.



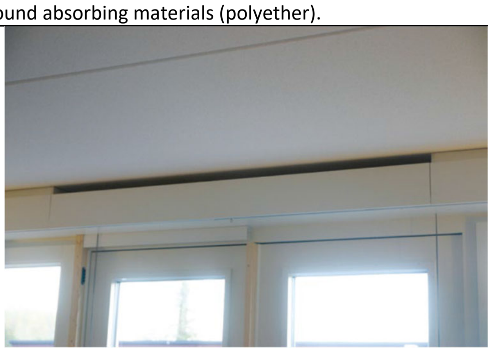
a

b

Examples of air inlets just beneath the ceiling, at the right with sound absorbing materials (polyether).



c



d

Example of an air inlet near the ceiling with an excellent option to integrate curtains without disturbing the air flows (architect: Renz Pijnenborgh, Archi Service). This social housing-type (Brabantwoning) is an example of zero energy design with natural air supply and mechanical exhaust connected to a heat pump. Night ventilation via a window in the roof (with a rain-sensor) supports free cooling.

Figure 4.1.4: Options of integration of air inlets near the ceiling.

At the moment in the Netherlands natural air inlets are placed in low and in high rise buildings up to 73 m (Buma 2016). It is not clear yet what the maximum allowable height is.

Dynamic insulation

Air supply is also possible over the full height of the façade, with the application of dynamic insulation. In this case air flows via a porous insulation layer in the façade. The air flow should be controlled in case of high pressure differences.

4.2 Windows

Windows

Windows are often used to ventilate a building and cool spaces. The larger the window, the larger the ventilation capacity. In order to increase thermal comfort options and to prevent draught it is necessary to make a window that can create large as well as very small openings and can be fixed on different positions.

Windows consisting of small and large elements are preferable. Small elements are also better for night ventilation. Protection against rain and burglary is easier to realize. Rain protection is also effected by the location in the façade.

Tilt and turn windows are very popular at the moment, because they can deliver very different sizes of openings. It is necessary to make it possible to open the window only a few mm as well in case of low outside temperatures or much wind.

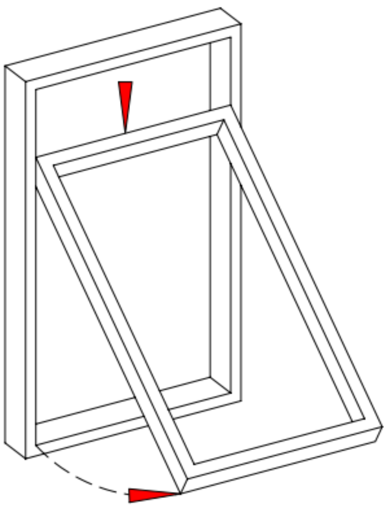
 a	 b
Example of a window type that can realize many different sizes and positions of ventilation openings for cooling and draught prevention.	Tilt and turn window, relative small and large openings are possible. A maximum of draught reduction is possible when the turn-opening can be reduced to a few mm or cm.

Figure 4.2.1: Large windows with several opening options.

Points of attention are:

- Prevention against burglary
- Privacy protection
- Protection against rain
- Option of night ventilation and comfort cooling
- Ventilation capacity
- Reduction of draught
- Control-options of the size of the opening
- Effect of operable windows on air flows

To calculate single sided ventilation via a window in which temperature difference, wind velocity and turbulence is incorporated the following equation is available (Phaff 1980):

$$Q = 0.5 * A_{eff} * \sqrt{0.0035 * h * \Delta T + 0.001 * U^2 + 0.01} \qquad (4.3.1)$$

With an opening of 1 m^2, a wind velocity U of 5 m/s on the window and a temperature difference ΔT of 3 K the air flow will only be 0.107 m^3/s. A low and high opening of 0.5 m^2 with a distance of 1 m is around 2 times more effective (Paassen 1995).

For a single large opening with only buoyancy forces Awbi derived the following equation (Awbi 1996):

$$Q = \frac{C_d}{3}\sqrt{\frac{g * h * \Delta T}{T}} \qquad (4.3.2)$$

An opening of 1 m^2 with a height of 2 m (0.5 m wide) and a temperature difference of 3 K and C_d = 0,6 will lead to an air flow of only 0.045 m^3/s, so the effect of only buoyancy in windows is very low.

Cross ventilation is 15 times more effective with an opening of 2 x 0.5 m^2, a wind velocity of 5 m/s, modest C_p-values of +0.2 and -0.2 for a shielded location and Cd-values of 0.6. This will give an air flow of 0.67 m^3/s. Air flows between two openings only due to wind pressures can be calculated as following (Aynsley 1977):

$$Q = \sqrt{\frac{C_{p1} - C_{p2}}{\frac{1}{A_1^2 C_{d1}^2} + \frac{1}{A_2^2 C_{d2}^2}}} \bullet U_z \qquad (4.3.3)$$

C_{p1} and C_{p2} are the wind pressure coefficients on the façades, A and C_d are the opening size with its discharge coefficient and U_z is the reference air velocity.

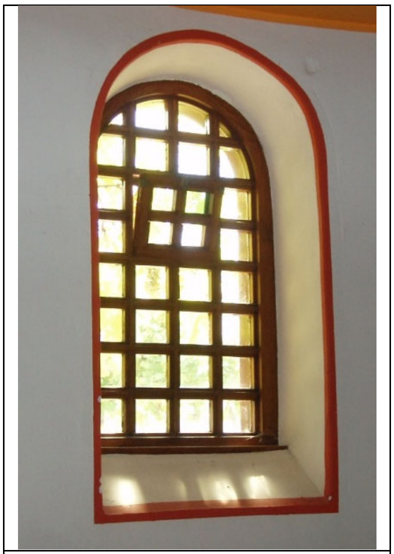
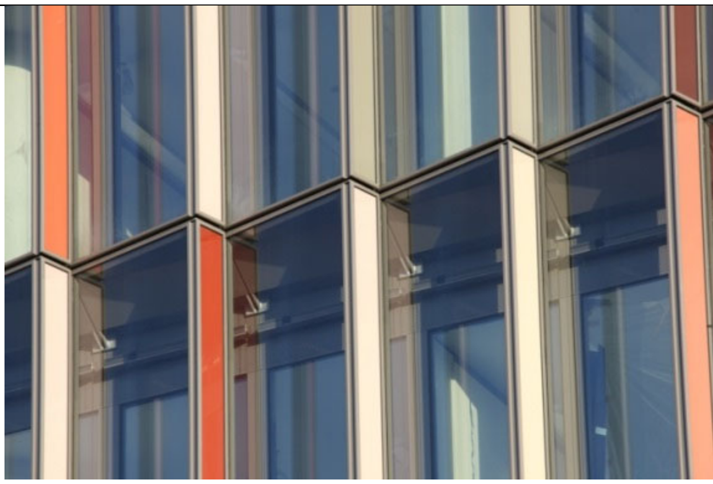


Figure 4.2.2: In Roman bath houses small ventilation elements were necessary to keep the heat inside (Archeon).

Operable windows do not have to be ugly elements that badly effect the architecture. Just like outside sunshade, when thoughtfully designed it can increase the expression of a building.

a

St Mary Axe in London (Foster).



b

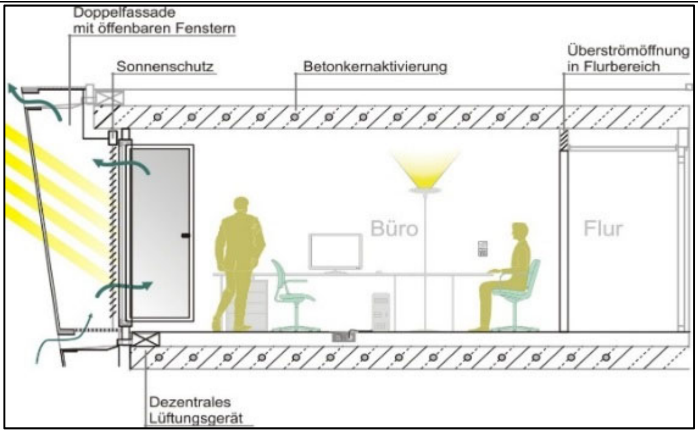
Kfw Westarkade in Frankfurt (Sauerbruch Hutton). The panels can be opened.

Figure 4.2.3: Operable windows can have a strong architectural expression.

4.3 Second skin façades

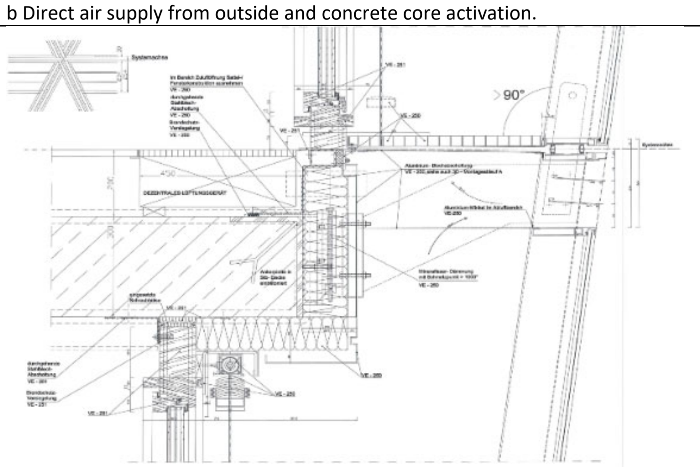
Second skin façade and natural or local mechanical air supply via the façade

a Overview facade.



b Direct air supply from outside and concrete core activation.

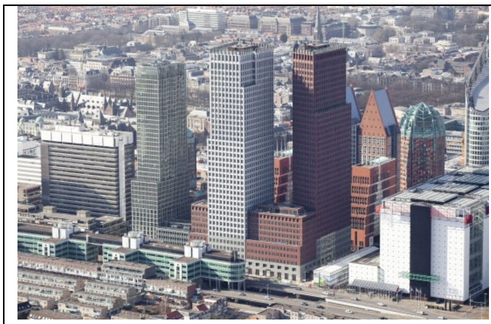
c Air supply in the floor, air can be cooled or heated.



d Detail façade near floor.

Figure 4.3.1: Second skin and separate air supply LVM Münster.

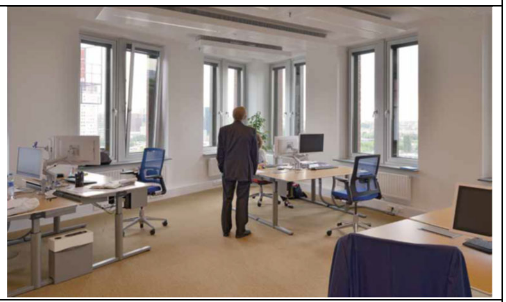
Second skin window in a high rise building, combined with mechanical air supply and exhaust



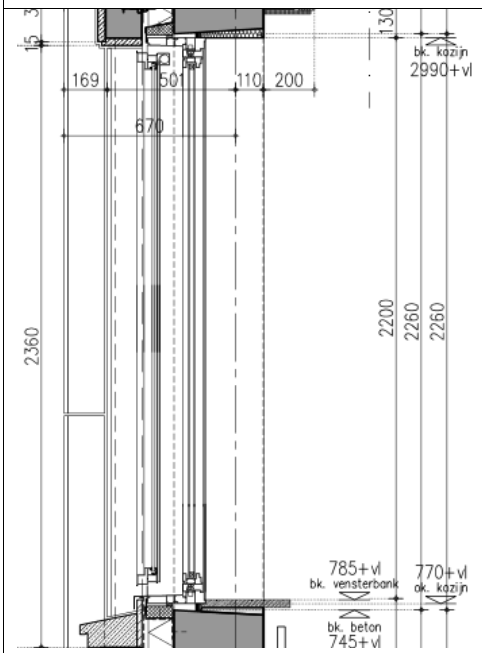
a

b

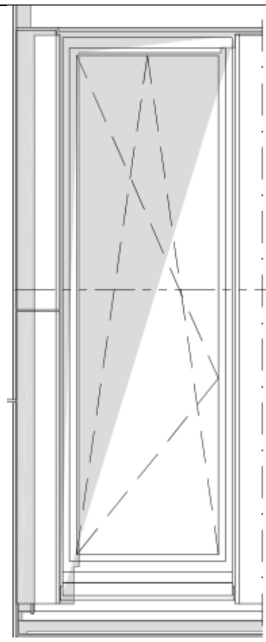
c Floors and ceilings with concrete core activation and radiators under the window. Air of 18 °C is supplied via inlets integrated in ceiling islands with acoustical properties in which the lighting is integrated as well.



d The operable windows create a better user comfort.



e



f

Figure 4.3.2: Ministry of Justice and Internal Affairs, the Hague, second skin windows (“Kastenfenster”), Hans Kolhoff.

The tilt and turn windows are appreciated by the users and the fresh air supply proved to have a high cooling effect (there is always much wind around high rise buildings) as well. In fact it is a low tech option, with a minimum of control.

However, more attention is required to prevent pressure differences via central shafts for staircases and elevators. Options are a buffer zone between offices and shaft or improved air tightness of the shafts (Jo 2007).

5. Appendix

5.1 Physical forces, principles and background

a. Stack and buoyancy

Cold air is heavier than warm air and dry air heavier than humid air. Density differences of air will create a buoyancy or stack effect. Cold air will enter at the bottom of a space and will leave at the top. The air flow is effected by:

- The height of the space.
- The temperature differences.
- The size and resistance of the openings

In termite hills during the night the buoyancy forces are dominant. During the day the inside is usually colder than outside and the flow will reverse. This principle is not very known yet and normally not used in buildings in this way.

First let's go back to the roots:
The following equation (adaptation of equation 5.1 is essential to understand because it shows the maximum air flow via an opening without resistance (Engel, 1995):

$$\Delta P = \frac{\rho U^2}{2} \qquad (5.1)$$

In fact this is derived from the law of conservation of energy of Bernouilli:

$$P_1 + \frac{\rho_1 U_1^2}{2} = P_2 + \frac{\rho_2 U_2^2}{2} \qquad (5.2)$$

P_1 and P_2 are the absolute surrounding atmospheric pressures (around 100,000 Pa).

Bernouilli's equation is important to understand many flow characteristics.

In the complete equation of Bernouilli also the height is included:

$$P_1 + \frac{\rho_1 U_1^2}{2} + \rho_1 g h_1 = P_2 + \frac{\rho_2 U_2^2}{2} + \rho_2 g h_2 \qquad (5.3)$$

In this way it is also possible to calculate buoyancy forces when the density ρ_1 and ρ_2 of the inside and outside air is different. In equation 4 this difference is represented by $\Delta T/T$.

Calculation example buoyancy

The following combination of equations shows how for a very basic situation the air flow due to buoyancy can be calculated:

The pressure difference due to buoyancy Is:

$$\Delta P = \frac{\rho g h \Delta T}{T} \qquad (5.4)$$

The air flow Q via an opening is:

$$\Delta P = \zeta \frac{\rho U^2}{2} \qquad (5.5)$$

And

$$Q = \frac{U}{A} \qquad (5.6)$$

Combining of equations leads to:

$$Q = \sqrt{\frac{2\Delta P}{\zeta \rho}} = C_d A \sqrt{\frac{2\Delta P}{\rho}} \qquad (5.7 \text{ and } 5.8)$$

The equivalent surface A_e can be calculated when two openings are known of which the resistance (C_d-value) is the same:

$$\frac{1}{A_e^2} = \left[\frac{1}{A_1^2} + \frac{1}{A_2^2} \right] \qquad (5.9)$$

With an air inlet A_1 and outlet A_2 of an equal size the opening A_e should be √2 more in order to create the same air flow.

Combining these equations leads to:

$$\frac{\rho g h \Delta T}{T} = \frac{Q^2 \rho}{2C_d^2} \left[\frac{1}{A_1^2} + \frac{1}{A_2^2} \right] \qquad (5.10)$$

Or:

$$Q = C_d A_e \sqrt{\frac{2gh\Delta T}{T}} \qquad (5.11)$$

When the internal and external heat production H is known the maximum ΔT can be calculated:

$$H = Q \rho c \Delta T \qquad (5.12)$$

$$H = \rho c C_d A_e \sqrt{\frac{2gh\Delta T}{T}} \Delta T = \rho c C_d A_e \sqrt{\frac{2gh\Delta T^3}{T}} \qquad (5.13 \text{ and } 5.14)$$

$$\Delta T = \frac{H^{\frac{2}{3}} T^{\frac{1}{3}}}{(2gh)^{\frac{1}{3}} (pcC_d A_e)^{\frac{2}{3}}} \tag{5.15}$$

b. General dimensions of chimneys

In order to find the rough dimensions of chimneys for natural ventilation air velocity of 1 m/s or 0.5 m/s in case of valves or heat recovery units is a good starting point (Lomas 2007). In The Netherlands (1950 – 1970) 1 m/s has been a common starting point for exhaust ducts for houses and flats. In 1975 this was incorporated in a Dutch standard. This rule of thumb can still be used. However, the location of the neutral zone and prevention of return flows need attention. In naturally ventilated apartments with shunt ducts as an exhaust return flows can create nuisance of cooking odours from neighbours.

Another point of attention is the solution for cooking when a much higher air flow is required, around 360 m^3/h for kitchens in houses. This could be solved with a short time mechanical supported higher air flow to outside or by filtering recirculated air, although filtering of fine dust is still difficult. In order to make a natural exhaust effective a round duct size of around 0.3 m and 5 m length above the occupancy zone for a house is recommended (Axley 2008). In summer without wind, natural exhaust is still very limited, but due to the more frequent usage of windows this can be compensated (Engel 1990).

c. Position of the neutral zone on flow control

For buoyancy controlled and dominated air flows, where the direction of the air flow should be controlled as well, knowledge of the position of the neutral zone is essential. The position of this zone is effected by the size of inlets and outlets. A calculation only of the buoyancy forces gives basic information of the position of the neutral zone:

$$h_0 = \frac{A_1^2 h_1 + A_2^2 h_2}{A_1^2 + A_2^2} \tag{5.16}$$

For example: For a building with an opening A_1 of 1 m^2 at 3 m above the ground (h_1) and an opening A^2 of 3 m^2 at 100 m above the ground (h_2) the position of the neutral zone will be at circa 90 m above the ground.

The position of the neutral zone is largely effected by wind and large openings. A single window can change the direction of the air flows, depending on the outdoor conditions, so other control measures are necessary.

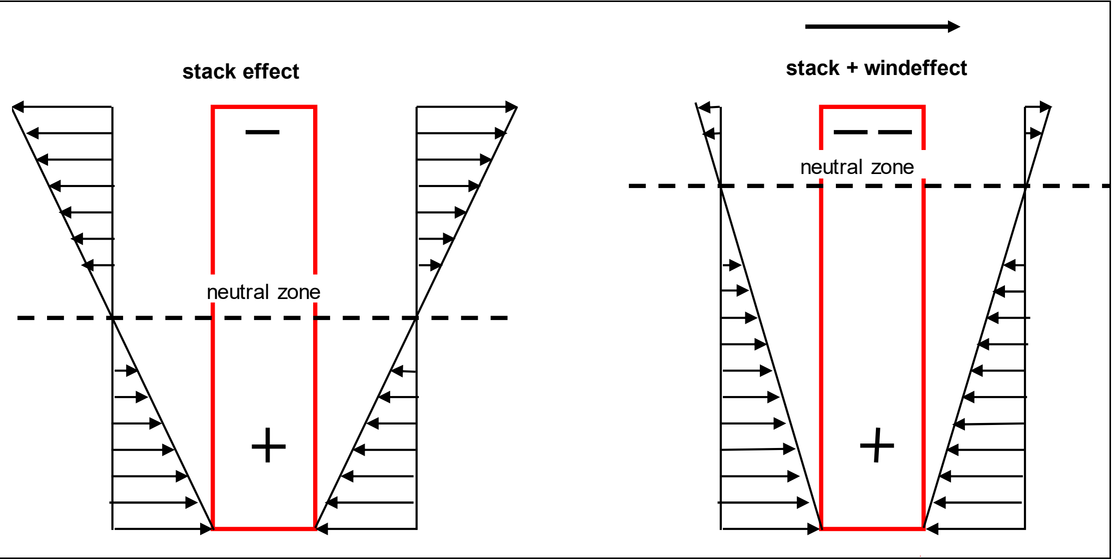


Figure 5.1.1.a: Position of the neutral zone in a high rise building. When leakages are evenly distributed over the façade the air will flow out above the neutral zone. The level of the neutral zone can increase due to more under pressure by the wind or by buoyancy forces. In the GSW-headquarters the position of the neutral zone is similar with the figure at the right side.

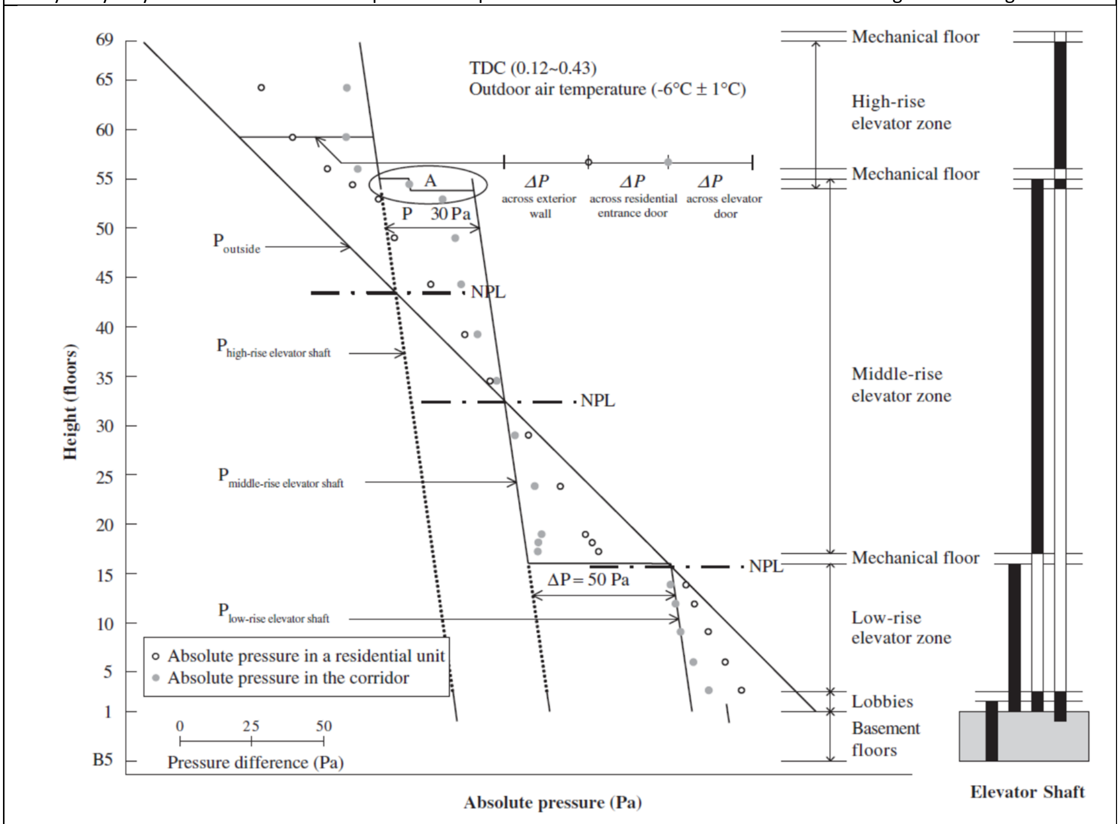


Figure 5.1.1.b: Example of real (measured) pressure distributions in a high rise residential building in Korea in winter (Jo et al 2007). Due to the presence of pressure correcting zones there are several neutral planes. The total pressure difference is around 150 Pa.

The high pressure differences in high rise buildings with operable windows can lead to high pressure differences in elevator- and staircase-shafts. For these type of buildings extra depressurisation zones around the shafts and near entrances are necessary to prevent high air velocities and noise due to strong air flows and that doors of fire safety staircases cannot be closed near the top of the buildings.

d. Wind (low pressure zone, venturi, cowls)

At the roof level the pressure is usually lowest and lower than the leeward side of the building. In this way chimneys can work during almost the whole year. Cross ventilation is very effective, but difficult to control. In case of single side ventilation the air velocity via a window can be 10 times higher when the wind is perpendicular on the façade compared with wind on the leeward side.

Wind cowls or wind towers are effective to supply or exhaust air. Both principles can also be combined. Chimneys on roofs can be effective as well. Chimneys are architectural important elements of which the expression does not always gets enough attention. Wind pressure on a façade is presented as following:

$$\Delta P = \frac{C_p \rho U^2}{2} \qquad (5.17)$$

The dimensionless wind pressure coefficient C_p represents a reduction or acceleration of the air velocity, depending on the building geometry and the wind direction. It can have a positive or negative sign.

Roof angles up to 15 ^{o} have always a negative pressure and pitched roofs have always a negative pressure up to 25 ^{o} (Allard 1998, Grosso 1994).

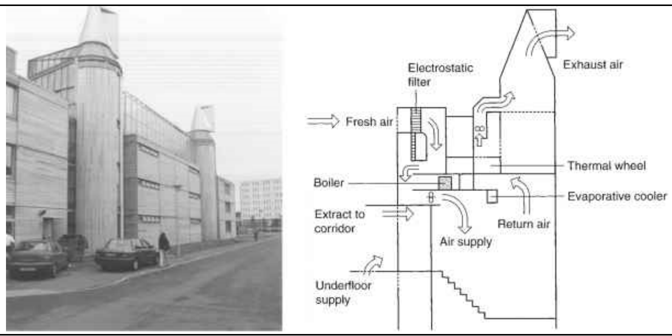
Wind towers doe not only make use of wind but also from buoyancy and downdraught. The thermal mass plays an important role. During the night the thermal mass is warmer than the surroundings, so buoyancy is available. During the day downdraught will be stimulated. In this way there is a parallel with the working principle of termite hills. Additional cooling is possible with fountains, floating water or cold ducts deep in the ground. Prevention of dust is necessary, for instance via the height above the ground and direction of the windcatcher, reduction of the air velocity in the tower and screens (Allard 1998).

Wind towers, wind catchers and wind cowls.

a Wind can be catched and air be exhausted by the same tower. The picture is of the Borujerdi House in Kashan, central Iran. Elements of the same principle can be used in modern systems.

b The exhaust is improved by windcowls on these oast houses in Kent. There are modern types of this system as well.

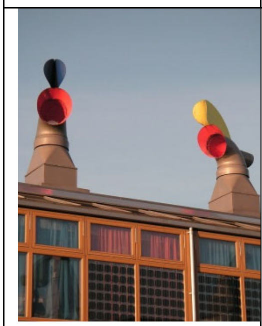
c Example of new designed windcatchers, Aga Khan Maternity.



d Modern version of an old principle. Jubilee campus Nottingham. Heat recovery, an electrostatic filter and heating of cooling is integrated.

Air supply and exhaust combined in one system.
Heat recovery is included.

Bedzed factory (Arup).



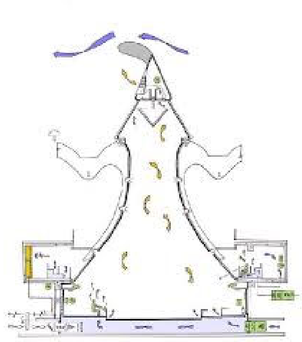
e

Prototype Tarmac for Bedzed.

f

Only exhaust.

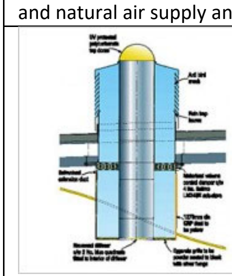
National Assembly of Wales (Rogers).



g

h

Air supply and exhaust combined in one system.
No heat recovery. Combination of natural daylight access and natural air supply and exhaust (Monodraught).



i

j

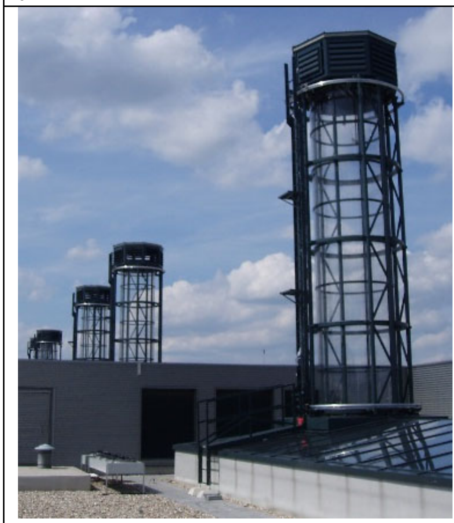
City-office Ypenburg (Halmos) This building has a stork-shaped outlet on the building. The direction of the stork depends on the windangle.

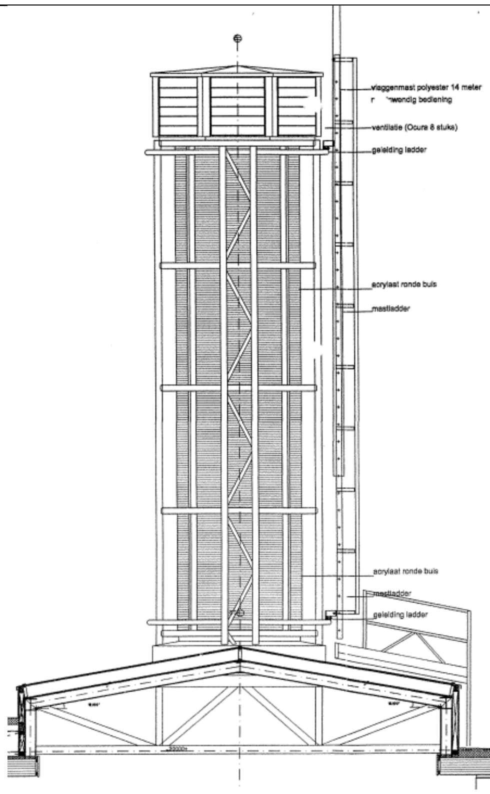
k

l

Figure 5.1.2: Examples of windcatchers/cowls.


a

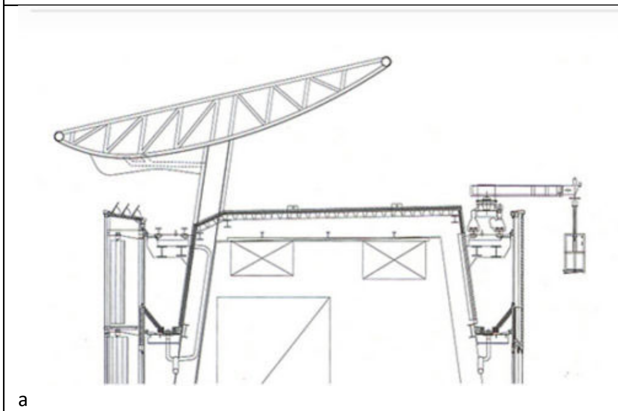

b



c

Figure 5.1.3: Pictures and construction drawing of the chimneys on the roof of the ROC of Twente. The chimneys are protected against too much air flow or rain by valves at the top. A velocity sensor determines the position of the valves. The driving forces of the air flow are buoyancy, wind, sun and overpressure due to small fans inside the building.

Venturi roofs.


a

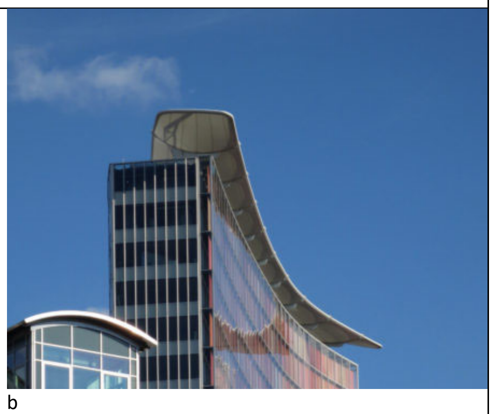

b

Figure 5.1.4: One of the most wellknown venturi roofs is the roof on the GSW headquarters. The lowest opening is at the windward west side where the high solar cavity is located. The amount of buoyancy is sufficient, so no extra windpower is necessary to make the natural ventilation system work. The roof is a significant part of the architectural expression.

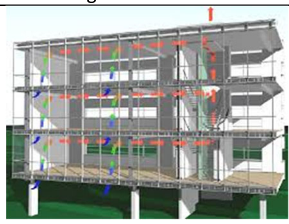
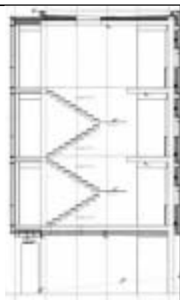
Low and hidden chimneys, Bang & Olufsen building.			
 a	 b	 c	 d
There is no exhaust on the roof visible from outside the building.	Pattern air flows.	Crosssection staircase.	Exhaust on the roof, with integrated fan.

Figure 5.1.5: Sometimes a chimney doesn't fit in the architecture. It is also possible to find a solution for that. A flat roof has always a negative pressure. In the Bang & Olufsen building the natural air inlets are integrated in the floor zone which increases the stack effect. Air flows from the offices via the staircases to the roof. The low location of the air inlet doesn't give draught problems, because air is preheated and there is enough distance from the workplace: there is a corridor first (Kleiven 2003). A second option for cold weather is ventilation via high located hopper windows at the south side. The fully glass façade is at the north side. The south side is massive with smaller windows.

e. Sun (solar chimneys, roofs)

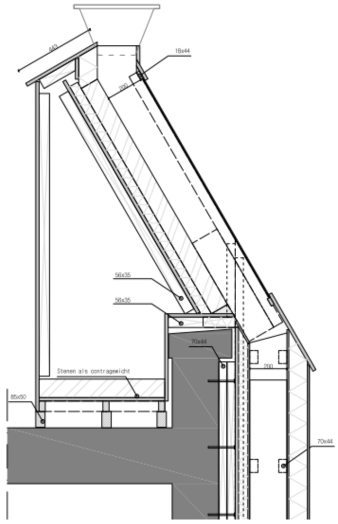
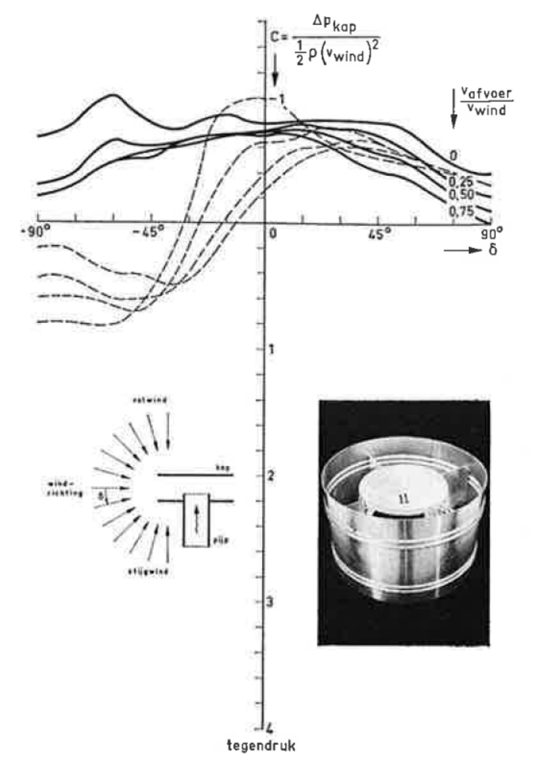
	
a Prototype solar chimney for a house (research at the Hogeschool Rotterdam).	b Cross-section prototype solar chimney, the optimum slope was around 60°.

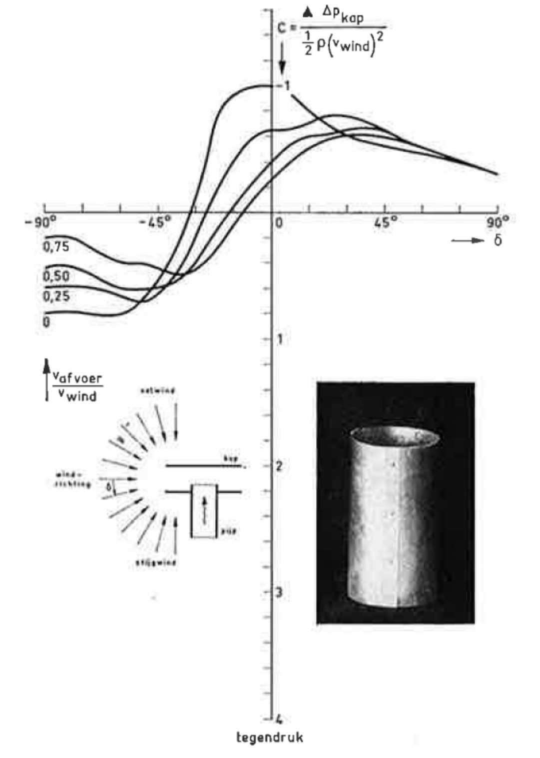
Figure 5.1.6: Example of a solar chimney for a house. The most optimal slope of the chimney is chosen with regard to solar gain and air flow. In the chimney a black surface with thermal mass and insulation behind the thermal mass is incorporated. With this shape the chimney can easily be integrated in a tilted roof. The air velocity in the chimney proved to be around 1 m/s.

In case of solar and buoyancy driven chimneys it is important that wind supports the flow.

f. Reduction of negative effects of the wind

In the past in many countries research has been executed to prevent that combustion gasses of the heating system returns to the living zone. This knowledge can also be used for natural air exhaust systems.





a With this shape there is always a positive flow, even with wind from the top side.	b A simple round outlet is more vulnerable for a return flow.

Figure 5.1.7: The effect of the shape of an outlet on the direction of the air flow.

g. Vapour/water (cooling in desert zones)

In the cooling season vapour can cool down a building. In greenhouses plants can even reduce the inside temperature below the outside temperature due to evaporation. A location with green and water will reduce the temperature of surroundings of a building and limit the risk of a heat island effect.

In the Earth, Wind and Fire-project (Bronsema 2013) cold water is used in an active way to dry and cool down or humidify the air. On top of that extra air pressure is generated. When water is used in an active way attention for the prevention of legionella bacteria is necessary. This is, for instance, possible by temperature control of the water below the 20 °C or via filtering by reversed osmoses.

h. Effect of flow control, usage of thermal mass, insulation, internal and external heat sources on comfort and energy consumption.

Effective flow control is necessary. This has to do with the preservation of heat, cold and moisture in a building. Interesting examples are the Oxford house of Susan Roaf (Roaf 2001) or the Brabantwoning of Renz Pijnenborgh (Buma 2016), both zero-energy houses with natural air supply. A strong limitation of the flow is only possible when there are no other pollutants in the building. Materials that can accumulate moisture as well are important to reduce a low humidity level in winter. In order to prevent mould the ventilation should be in balance with the moisture production.

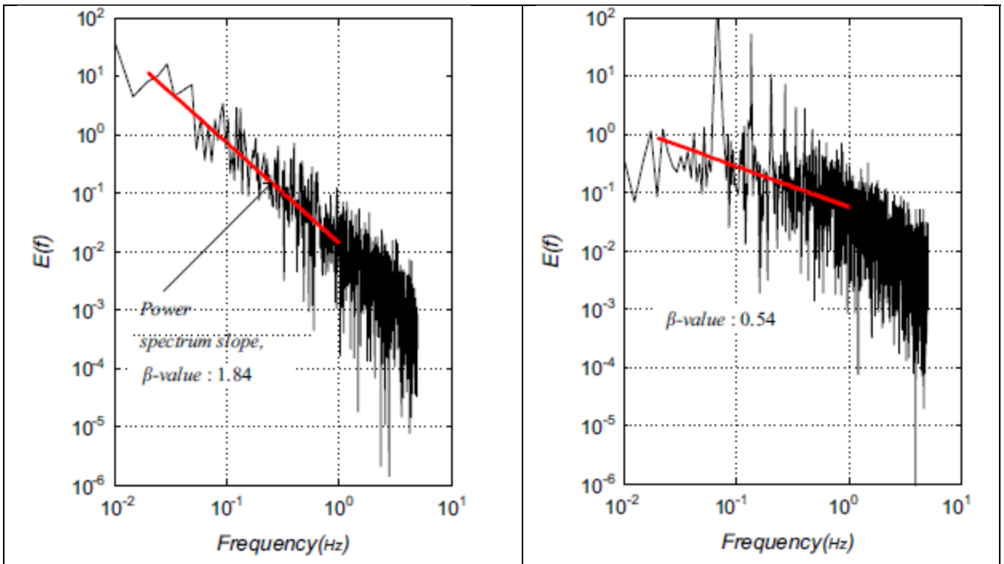
i. Effect of noise

The low noise level of ventilation systems with low air velocities is a very positive factor of natural ventilation. Very often sound attenuators inside the ducts because of fan-noise can be skipped. A point of attention is - for instance - the risk of noise from traffic. Especially with operable windows this can be a limiting factor.

j. Comfort and draught evaluation

Normally draught due to air flows can be evaluated with the Draught Rate equation from the NEN-EN-ISO 7730 (2006). However, this equation is based on air flows from mechanical air supply systems with much turbulent energy in high frequencies.

Natural air flows have more energy stored in low frequencies, which is experienced as more pleasant (Kang 2013). The Power Spectral Density (PSD-value) expresses the kind of turbulent character of the air flow. The *B*-value is the power spectrum slope. A *B*-value of circa 1.6 is a sign that the air flow has a comfortable character. Mechanical supply systems have usually a *B*-value of circa 0.5.



a Power Spectral Density of a natural wind.

b. Power Spectral Density of mechanical air supply, there is more turbulent energy in high frequencies.

Figure 5.1.8: Power Spectral Densities.

The power spectral density E(f) is defined as following (Quyang 2006):

$$E_f \propto 1/f^B \tag{5.18}$$

5.2 Computer calculations

There are many options to make use of computer calculations for air flow studies and design:

a. Excel-models

In order to get a first-order insight to control design parameters it is often handy to make use of an excel-calculation model. These models often make use of hourly climatic data. The advantage of such models, like the equations from § 5.1, that it gives direct and quick insight in the main parameters of air flows.

b. C_p-generator

For low rise buildings and simple geometries it is possible to make use of a computer program that can calculate roughly the Cp-values on a façade of a building (Grosso 1995). This program is based on statistical information derived from wind tunnel tests. Examples of the way such a model is developed, with a description of the equations, is presented in the handbook of Allard (1998).

c. Building simulation programs

For circa 30 years there are building simulation programs available that simulate the hourly thermal behaviour of buildings during a year. Often these simulation programs have integrated air flow simulation programs (zonal methods). The mass flow of the air between zones is calculated. Examples are:

- TRNSYS with TRNFlow, based on the air flow simulation program COMIS. COMIS is the product of an international research team. The simulation of horizontal openings is still difficult.

- DesignBuilder. In DesignBuilder an air flow simulation program is integrated and basic CFD-calculations are possible as well.

- ESP, normally used in an academic context.

d. CFD-programs

For circa 30 years there are CFD-programs (= Computational Fluid Dynamics) available that can be used on a personal computer. These programs can evaluate air flows in buildings in a large degree of detail. There is a big difference in easy-to-use level for the non-experienced CFD-user. On top of that open-source options are available with which users can develop their own CFD-models. Some well known CFD-programs for ventilation analysis are:

- ANSYS Fluent
- Phoenics (Flair)

5.3 Literature

1. Allard F. Natural ventilation in buildings. A design handbook. 1998.
2. Arnold D. Natural ventilation in a large mixed mode building. In: Naturally ventilated buildings. Buildings for the senses, the economy and society. Edited by Derek Clements-Croome. E & FN spon. 1997.
3. Awby HB. Air movement in naturally ventilated buildings. Renewable Energy. May 1996.
4. Awby HB. Ventilation of buildings. 2003.
5. Awby HB. Ventilation systems: design and performance. 2008.
6. Aynsley RM, Melbourn W, Vickery BJ. Architectural aerodynamics. Applied Science Publishers, London. 1977.
7. Axley J, Nielsen PV. Modeling of ventilation airflow. In: Awby HB. Ventilation systems: design and performance. 2008.
8. Beerkens G, Schoneveld G. Zonneschoorsteen als onderdeel van een passief ventilatiesysteem. Hogeschool Rotterdam 2013.
9. Bronsema B. Earth, Wind & Fire – Natuurlijke Airconditioning. 2013 (Thesis).
10. Buma W. Duurzaam, comfortabel en betaalbaar. De Brabantwoning. TVVL-magazine 04 2014
11. Buma W. Energieneutrale woontoren A’dam. TVVL-magazine 07/08 2016.
12. CIBSE AM10. Natural ventilation in non-domestic buildings. April 2014.
13. Engel PJW van den. Ventilatie in het woningontwerp. TU-Delft/TU-Eindhoven. 1990.
14. Engel PJW van den. Thermal comfort and ventilation efficiency by inducing ventilation via the façade. Thesis 1995.
15. Engel PJW van den. Theatre climate: design and control strategies. Clima 2010, Antalya.
16. Engel PJW van den, Kurvers SR. The scope of inducing natural air supply via the façade. Architectural Science Review. 2017. (a)
17. Engel PJW van den, Riera Sayol, Spoel WH van der. Opportunities of Ground Duct Ventilation in Greenhouses. Plea 2017, Edinburgh. (b)
18. Etheridge D, Natural ventilation of buildings. Theory, measurements and design. 2012.
19. Ghiaus C, Allard F. Natural ventilation in the urban environment. 2012.
20. Gids WF de, Ouden HPL den. Drie onderzoeken naar de werking van kanalen voor natuurlijke ventilatie waarbij nagegaan is de invloed van plaats en hoogte van de uitmonding, van de bebouwing in de omgeving en van de vorm van de uitmonding. Klimaat ventilatie verwarming in woningen en woongebouwen. IG-TNO 1974.
21. Givoni B. Passive and low energy cooling of buildings. Van Nostrand Reinhold. 1994.
22. Gonçalves H, Aelenei L, Rodrigues C. Solar XX1: A Portuguese office building towards net energy building. Rehva journal March 2012.
23. Grosso M, Marino D, Parisi E. Wind pressure distributions on flat and tilted roofs: a parametric model. Proceedings of the European conference on energy performance and indoor climate in buildings. Lyon, 1994.
24. Grosso. CPCALC+. Calculation of wind pressure coefficients on buildings. Software of the Polytechnic University of Turin. 1995.
25. Guzowski M. The “costs” of operable windows: on the question of operable windows in cold climate design. Proceedings of the Environmental Design Research Association (EDRA) Conference. June 2003.

26. Haartsen TJ, Ham ER van den. Geavanceerde natuurlijke ventilatie bij kantoorgebouw Rijkswaterstaat Maastricht. Bouwfysica (1) 2001.
27. Humphreys M, Nicol F, Roaf S. Adaptive thermal comfort. Foundations and analysis. 2016.
28. Jo JH, Lim JH, Song SY, Yeo MS, Kim KW. Characteristics of pressure distribution and solution to the problems caused by stack effect in high-rise residential buildings. Building and Environment 42 (2007) 263–277.
29. Kang K, Song D and Shiavon S. Correlations in thermal comfort and natural wind. Journal of Thermal Biology 38 (2013), 419-426.
30. King H, Ocko S, Mahadevan L. Termite mounds harness diurnal temperature oscillations for ventilation. PNAS volume 112, number 37 (2015).
31. Kleiven T. Natural ventilation in buildings. Architectural concepts, consequences and possibilities. Thesis. March 2003.
32. Krausse B, Cook M, Lomas K. Environmental performance of a naturally ventilated city centre library. Energy and Buildings 39 (2007), 792-801.
33. Lomas KJ. Architectural design of an advanced naturally ventilated building form. Energy and Buildings 39 (2007), 166-181.
34. NEN-EN 15251. Indoor environment input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. June 2007.
35. NEN-EN-ISO 7730. 2006. Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.
36. Nicol F, Humphreys M, Roaf S. Adaptive thermal comfort. Principles and practice. 2012.
37. Nieuwstadt FTM, Boersma BJ, Westerweel J. Turbulence. Introduction to theory and application of turbulent flows. Springer International Publishing 2016.
38. NNI. NEN 1087. Ventilatie van woongebouwen. 1975.
39. Nobel KJC, Haartsen TJ. ArtEZ. Faculteit Dans & Theater Arnhem. Bouwfysische uitdagingen bij ondergronds bouwen. Climatic Design Consult. 25 juni 2004.
40. Passe U and Bataglia F. Designing spaces for natural ventilation: an architects guide. 2015.
41. Leao M, Leao EFTB, Sanches JCM, Strab KW. Energy efficiency of single and double skin façade buildings: a survey in Germany. Espaço Energia, 25, October 2016.
42. Paassen AHC van, Liem SH, Galen PJM van. Veldtest passief klimaatsysteem, rapport k-207. TU-Delft 1995.
43. Pettenkofer MJ. Über den Luftwechsel in Wohngebäuden. 1858.
44. Phaff JC, Gids WF de, Toan JA, Ree D van der, Schijndel LLM van. Onderzoek naar de gevolgen van het openen van één raam op het binnenklimaat van een kamer. IMG-TNO 1980.
45. Ouyang Q, Dai W, Li H, Zhu Y. Study on dynamic characteristics of natural and mechanical wind in built environment using spectral analysis. Building and Environment 41 (2006), 418-426.
46. Roaf S, Fuentes M, Thomas S. Ecohouse: a design guide. 2001.
47. Sassi P. Evaluation of indoor environment in super-insulated naturally ventilated housing in the south of the United Kingdom. Proceedings of the 9th Windsor Conference. 7-10 April 2016.
48. Scholten R, Engel PJW van den, Klein T. Warmteterugwinning met een hybride ventilatiesysteem in kantoorgebouwen. Bouwfysica (1) 2016.
49. Schuler M, Reuss S. Comfort and energy concept Post Tower, Bonn. The 2005 World Sustainable Building Conference, Tokyo. 2005.

50. Short CA, Lomas KJ, Woods A. Design strategy for low-energy ventilation and cooling within an urban heat island. Building Research & Information 2004, 32(3), 187-206.
51. Short CA. The recovery of natural environments in architecture. Air, comfort and climate. 2017.
52. Short CA, Cook MJ. Design guidance for naturally ventilated theatres. Building Serv. Eng. Res. Technol. 26.3 (2005) pp. 259 -270.
53. Sturrock JW. Aerodynamic studies of shelterbelts in New Zealand. New Zealand Journal of Science. December 1969 and June 1972.
54. Twinn C. Environmental conditions for naturally ventilated buildings. In: Naturally ventilated buildings. Building for the senses, the economy and society. Edited by Derek Clements-Croome. E & FN Spon. 1997.
55. Vroon PA. Psychologische aspecten van ziekmakende gebouwen. July 1990.
56. Vongsingha P. Adaptive façade. For windload reduction in high rise. TU-Delft, June 2015.
57. Wood A and Salib R. CTBUH. Natural ventilation in high rise office buildings. Routledge. 2013.

5.4 List of symbols

A_{eff}	=	effective opening	m^2
Ar	=	Archimedes number	-
C_d	=	drag or flow coefficient	-
C_p	=	wind-reduction coefficient	-
c	=	specific energy content of material	J/kgK
E_f	=	power spectral energy	J/Hz
f^B	=	frequency	Hz
g	=	acceleration of gravity	m/s^2
H	=	heat source	W
h	=	height	m
h_{inlet}	=	height of the air inlet	m
P	=	pressure	Pa
T	=	temperature	K
T_{inlet}	=	air temperature in the inlet	K
T_{room}	=	air temperature in a room	K
U	=	air velocity	m/s
Q	=	air flow	m^3/s

Greek symbols

ΔP	=	pressure difference	Pa (or N/m^2)
ρ	=	volumetric mass density	kg/m^3
ζ	=	resistance coefficient	-

5.5 List of figures and references

Front-page	Laboratory research inducing air inlets 1993 Peter van den Engel, picture Hans Krüse TUD
1.6.1	@ Deerns Germany
2.2.1, 2.2.2	@Peter van den Engel
2.3.1	a @Peter van den Engel, b Sturrock 1972 (literature list)
2.3.2, 2.3.3	@Peter van den Engel
2.4.1	@Peter van den Engel
2.4.2	a Trox, b, c Wood 2013 (literature list) @Murphy/JahnArchitects, d, e
2.4.3	@Peter Luscuere, DUT-lecture, @MVSA Architects
2.4.4.	a, b, c https://resnicow.com/client-news/nelson-atkins-presents-gates-paradise; https://www.bnim.com/project/bloch-building; d, e https://www.archdaily.com/4369/the-nelson-atkins-museum-of-art-steven-holl-architects/500ef2d128ba0d0cc7000f2c-the-nelson-atkins-museum-of-art-steven-holl-architects-image; https://www.archdaily.com/content/terms-of-use/
3.1.1, 3.1.2, 3.1.3, 3.1.4	@Peter van den Engel
3.1.5	@Peter van den Engel, CFD-simulations by Pieter-Jan Hoes at Deerns
3.4.1	a, b, c https://www.ateliergroenblauw.nl/ontwerp/rijkswaterstaat-terneuzen/ d. http://www.tierrafino.nl/ (leembouw nederland) e. https://www.mimoa.eu/projects/Netherlands/Terneuzen/Rijkswaterstaat%20Terneuzen/
3.4.2	a https://architectenweb.nl/projecten/project.aspx?ID=263, b, c Information from Climatic Design Consult
3.4.3	a Twinn and Arup, b, c, d Twinn 1997 (literature list), e Allard 1998 (literature list)
3.4.4	a, b, c http://projects.bre.co.uk/envbuild/index.html d, e https://fcbstudios.com/work/view/new-environmental-office-bre
3.4.5	a http://venicebiennale2010.blogspot.com/2011/08/berlin.html, b http://space-modulator.jp/sm81~90/sm87_contents/sm87_e_gsw2.html, c https://arw5zn.wordpress.com/2012/11/14/office-space/, d Wood 2013 (literature list) @ Sauerbruch Hutton
3.4.6	a, b https://www.deerns.com/projects/real-estate/ministry-of-defence-paris-france
3.4.7	https://www.pinterest.com
3.4.8	a, b Presentation Dieter Thiel, Deerns Germany
3.4.9	a, b, c, https://www.mcarchitects.it/project/unipol-group-headquarters @ Mario Cucinelli d @ Deerns Italy, e @ Peter van den Engel at Deerns (CFD-simulations)
3.4.10	a. https://en.wikipedia.org/wiki/Eastgate_Centre,_Harare; b. https://biomimetisme.wordpress.com/le-biomimetisme-dans-lhabitat/
3.4.11	a, b http://bronconsult.org/
3.4.12	a Krausse 2007 (literature list), c, d, e, f Short 2004 (literature list), b https://www.geograph.org.uk/reuse.php?id=4440679 copyright Keith Williams
3.4.13	a Nobel 2004), b, d https://www.biermanhenket.nl/nl/projecten/architectuur/onderwijs/artez-ondergronds/ c https://www.climaticdesign.nl/nl/projecten/nieuwbouw-1039/43-hogeschool-voor-de-kunsten-artez-arnhem
3.4.14	a https://www.energyacademy.org/energy-academy-europe-building/, b, c, d @Peter van den Engel
3.4.15	a, b, c, d, e, f https://behnisch.com/work/projects/0022
4.1.1	a @Peter van den Engel , b, c, d, e Haartsen 2001 (literature list).
4.1.2	e, d, e, f @Peter van den Engel, b design Dick van Gameren. c https://nl.wikipedia.org/wiki/AMOLF
4.1.3	https://www.buva.nl/uploads/knowledge/topstream-onzichtbaar-ventileren-2009-07.pdf
4.1.4	a, b https://www.renson.eu/nl-nl/producten?s=ventilatie,raamverluchtingen, c https://klimapedia.nl/wp-content/uploads/2014/07/H6-Energievademecum-2017-5.10.pdf (@Renz Pijnenborgh), d. https://www.nieman.nl/wp-content/uploads/2018/07/BENG-scheidt-gebouw-en-installaties.pdf (Bouwspecial Beng juni 2018)
4.2.1	a www.pn-beslag.dk PN-combi 500 uitzetzakraam, b www.marvin.com
4.2.2	@ Peter van den Engel
4.2.3	a https://www.pinterest.com/pin/315533517627546257/, b https://www.wicona.com/
4.3.1	a, b, c Lecture Dieter Thiel Deerns Germany, d detail architect @ HPP Hentrich Petschnigg & Partner
4.3.2	a, https://www.denhaagcentraal.net, b www.architectuur.org, c, d, e, f, g @ Hans Kolhoff (architect) and Deerns
5.1.1	a @ Peter van den Engel, b Jo et al 2007 (literature list)
5.1.2	a https://en.wikipedia.org/wiki/Windcatcher#/media/File:Borujerdiha.jpg, b http://www.rgbstock.com/bigphoto/n5xD9Z0,

c https://www.pinterest.com/pin/518125132114327375/,
d https://www.briangwilliams.us/climage-change-2/mechanically-assisted-ventilation.html,
e https://en.wikipedia.org/wiki/BedZED#/media/File:BedZED.jpg,, f,
g https://www.assembly.wales/en/visiting/about_us-assembly_history_buildings/senedd_history/sen-environmental-features/sen-environmental-features-key-environmental-features/Pages/senedd-key-env-feat-ventilation-large.aspx
h https://www.rsh-p.com/projects/national-assembly-for-wales/,
i, j, https://www.monodraught.com,
k https://www.egm.nl/projecten/stadsdeelcomplex/79, l

5.1.3 a, b @ Peter van den Engel, c Deerns
5.1.4 a, b https://en.wikiarquitectura.com/building/gsw-headquarters/
5.1.5 a, b, c, d Lecture Per Heiselberg Workshop "What so great about natural ventilation?", 2007. Kleiven 2003 (literature list)
5.1.6 a @ Peter van den Engel, b Kimberly Beerkens en Gertjan Schoneveld, Hogeschool Rotterdam, 2013
5.1.7 a, b Gids 1974 (literature list)
5.1.8 a, b Kang 2013 (literature list)

5.6 Postface and author biography

Postface

The development of this book started already in 2010 after discussions with my colleagues Jules Huyghe (Deerns) and Stanley Kurvers (TU Delft). A few years later, in 2012, I met professor Susan Roaf at the ISIAQ-symposium in Eindhoven. I visited Susan two times in Edinburgh discussing with her the outline of the book. We both have a strong mutual interest in natural ventilation, inspire each other, but have a different audience. The content is strongly connected to the design practice at the TU Delft at Bachelors and Masters level. Much of the content is derived from the questions rising after individual consults and preparing lectures.

Author biography

Peter van den Engel (1952) is associate professor building services at the TU Delft, Climate Design Group. He has a Master degree in Architecture and worked several years as an architect. He developed interest in natural ventilation during a second Master study at the TU Eindhoven (till 1990). He got his PhD in draught-free natural air supply at the TU Delft in 1995. After that he worked as a consultant/expert at two consultancy offices for climate design, Valstar Simonis (till 2001) and Deerns (till 2018). He has been involved in the climate design of many public buildings, laboratories and datacentres. His main interests are integration of disciplines to create healthy, challenging low-energy buildings, usage of natural air flows and computational fluid dynamics, which he also teaches at the faculty of Architecture of the TU Delft.