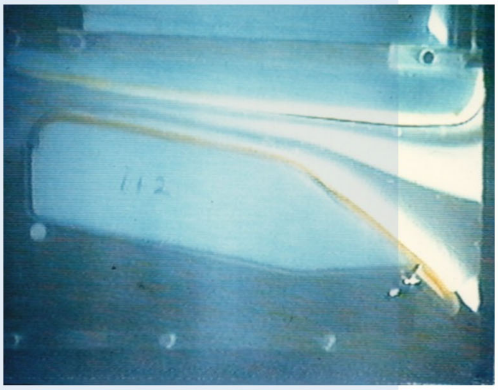
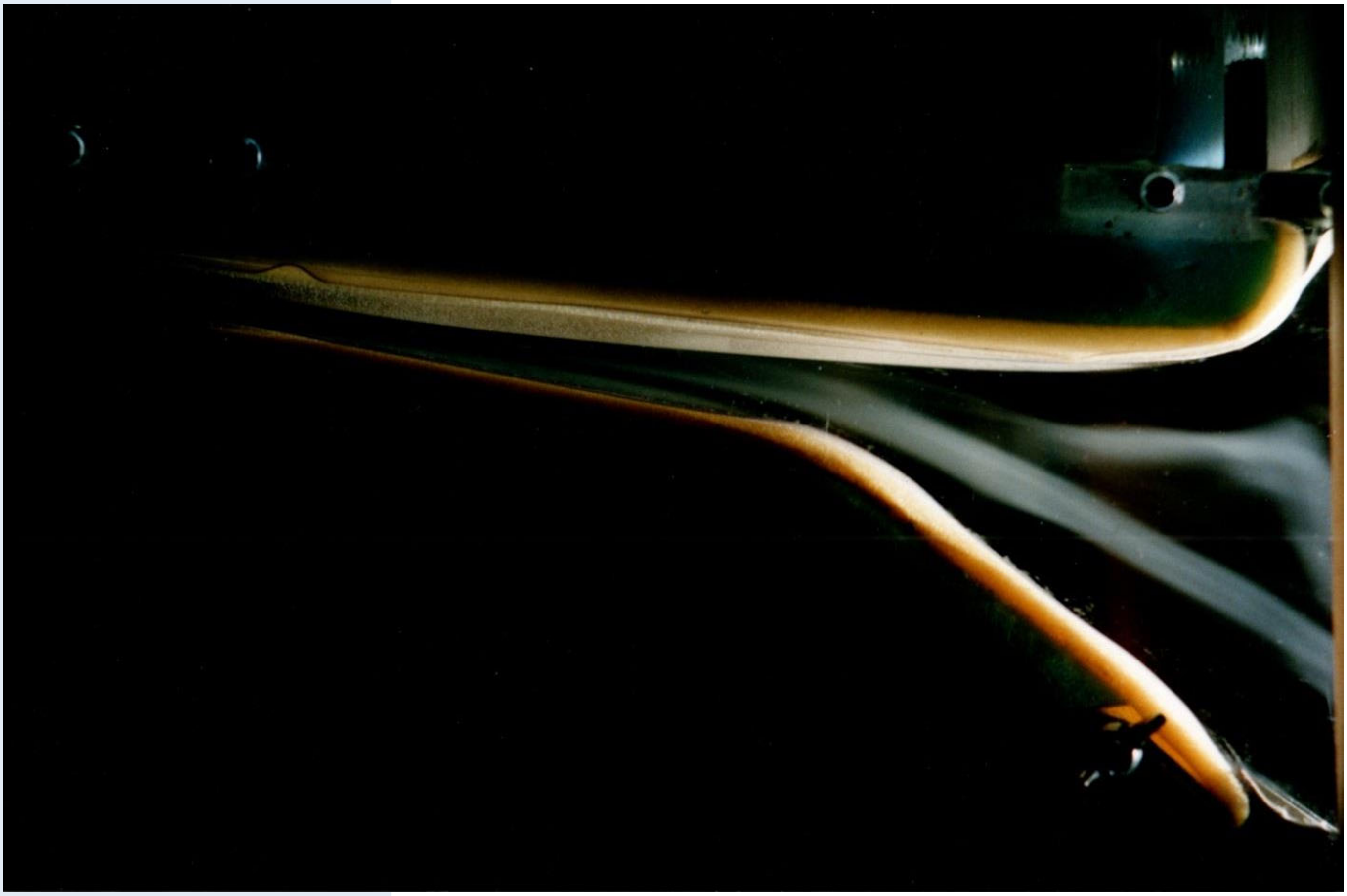
# HYBRID VENTILATION – A DESIGN GUIDE





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).

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# 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.

Smart hybrid ventilation is only one of the options to reduce the energy demand of a building and achieve the required comfort. The energy demand for heating, cooling and lighting can in principle be reduced even more by a smart and balanced design of the skin and usage of thermal mass. Sufficient isolation combined with a limited percentage and well oriented glass with effective sunshade are main parameters (Lechner 2015, Engel 2022). Although this is not the main focus of this book the discussions in the book take this into account as well. Most architects are still not sufficient aware of the necessity of this holistic approach, so there are still many additional lessons to be learned.

Since the start of the COVID epidemic there is much discussion about the role of natural ventilation to reduce infection risks. The discussion follows often an unscientific and emotional pattern which makes the design of future better ventilation-systems more difficult. The name “natural ventilation” in itself can already lead to confusion about the meaning and shape. There is a very long debate about the qualities of natural or mechanical ventilation, but it is often more based on belief than science or experience (MacFadden 2021). The background and quality of some different opinions will be evaluated here in more detail. Starting point of a discussion should be that the option of opening a window is in principle a human right for office workers and other people who are obligatory working or to staying at the same place for a long time. Only at very rare circumstances other solutions should be found. A very strong statement about the feeling about natural ventilation and openable windows is expressed by Mary Guzowski (2003). It is more than a feeling of thermal pleasure, it refers to enjoyment of all the senses.

*“This fine April afternoon, as garden bubs push their way out from under the winter months, a cool spring breeze blows through the room. I throw my house open to spring, knowing that these beautiful days are precious and few in Minnesota. Throughout the city we’re celebrating and relishing the return of the sun and the coming days of summer. On a day such as this, I wonder how it came to be that operable windows are the exception, rather than the norm, in commercial and institutional buildings throughout Minnesota.”*

Some answers can be found in the interviews in her paper. It is not only an attitude to choose for openable windows and a challenge for technology to overcome related problems for indoor climate. It is a solution as well. For a better comfort it is recommended to take into account personal preferences, also because of differences in thermal experience between people (Day 2022). This discussion is embedded here in a large overview of the current state-of-the-art of the opportunities of natural ventilation in general. There are many misunderstandings related to hybrid ventilation, because of the complexity of the relation between ventilation, energy and comfort. Even at the CLIMA 2022 congress in Rotterdam organized by the REHVA the two different opinions about natural ventilation could be noticed via the keynote speakers: Lydia Morawska, one of the most leading COVID-scientists, discourages the usage of natural ventilation because of draught risk, although it is the most dominant advice in The Netherlands and on most places elsewhere in the world. In contrary of this opinion Thomas Auer encourages natural ventilation via windows with an examples of hopper windows in a German school of more than 100 years old. Due to the large height and volume of the space and the position and shape of the windows there is a limited draught risk. Recent built apartments designed by his university team are even inspired on this school. He is also the climate designer of the hybrid ventilated Manitoba Hydro Place head-office in Canada (Wood 2013). This building could have been a prototype for any other skyscraper with a higher occupant satisfaction and low energy consumption for this type of climate in the world.

Important to note is that many comfort-problems are related to a too high solar load and have no direct relation with the kind of ventilation system, so an integrated approach is necessary. During and after the workshop “passive solutions” of CLIMA 2022 several buildings have been compared. These are discussed again in this paper.

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 and viruses.
  With ventilation it is possible to remove pollutants. Cross-ventilation is most effective (Bluyssen 2022). Anyway, the location of the inlet and outlet should be placed as far from each other as possible to increase the air change and contaminant removal efficiency (Cai 2022).
- 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 °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, this is strongly related to the way of using sun- and daylight via the façade. In this time, where many new buildings have efficient cooling and heating systems with heat pumps and aquifers and the availability of efficient LED-lighting is seems almost unnecessary to spend much design energy on this item. Our time could be again compared with the time when air-conditioning was introduced by Carrier (Short, 2017) and the availability of efficient LED-lighting it is less urgent to spend much attention to daylight-design.

However, reduction of the energy-demand, as far as possible, is always better. It will lead to more robust, easier to maintain, buildings that will be less dependent on the grid and more understandable for the users. The relation to the nature, and experience of time and season is very important for the feeling of well-being of the users (Guzowski, 1999).

The following energy-parameters are relevant:

- Reduction of fan energy and low air pressure ventilation systems

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.

Designing ventilation systems in which the average air velocity in ducts and appliances is between 0.5 to 3 m/s will reduce fan energy significantly (Schild 2009, Lignarolo 2023). These low velocities will reduce the noise level as well and can often be combined with natural ventilation principles. The lower the air velocity, the lower the pressure loss and the lower the required fan-power. This is expressed in the SFP-value (Specific Fan Power) in kW/(m$^3$/s). In Europe the requirements become more and more higher to reduce the energy-consumption of fans. In these requirements the efficiency of the fan itself and heat recovery is also included. When a fan is integrated in a low pressure or natural ventilation system, a low pressure loss over the fan, also when the fan is not in use, is essential. The main parameter is the free surface. This should be the same in the fan as well as in the connecting ducts: the smallest surface determines the highest pressure loss. The shape of the fins in or near the fan to conduct the air is also important to reduce resistance. For high pressure systems with large flows centrifugal fans are generally most efficient with an overall efficiency (electrical and aerodynamic) up to 70 %. For low pressure systems axial fans are more convenient having a highest overall efficiency up to 40 %.

Small aerodynamic improvements of air inlets can reduce the resistance significantly as is shown by the example of a crawl space ventilation inlet in the next figure. The resistance was reduced with 50 %:

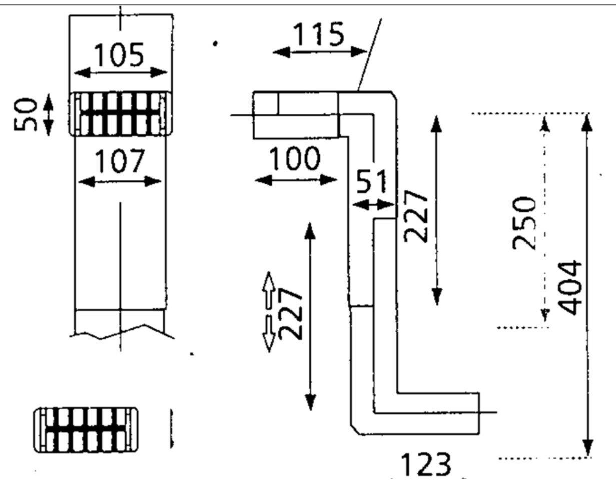
|  |  |
|---|---|
| Original crawl space ventilation air inlet 51 mm (@Ubbink) | Test phase of the improved crawl space ventilation air inlet 32 mm (Engel 1996) |



Figure 1.5.1: The outside vertical width of this crawls space ventilation air inlet was reduced from 51 to 32 mm in order to fit in a isolated brick wall cavity. However, the air flow is kept the same due to aerodynamic improvements.

- 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.

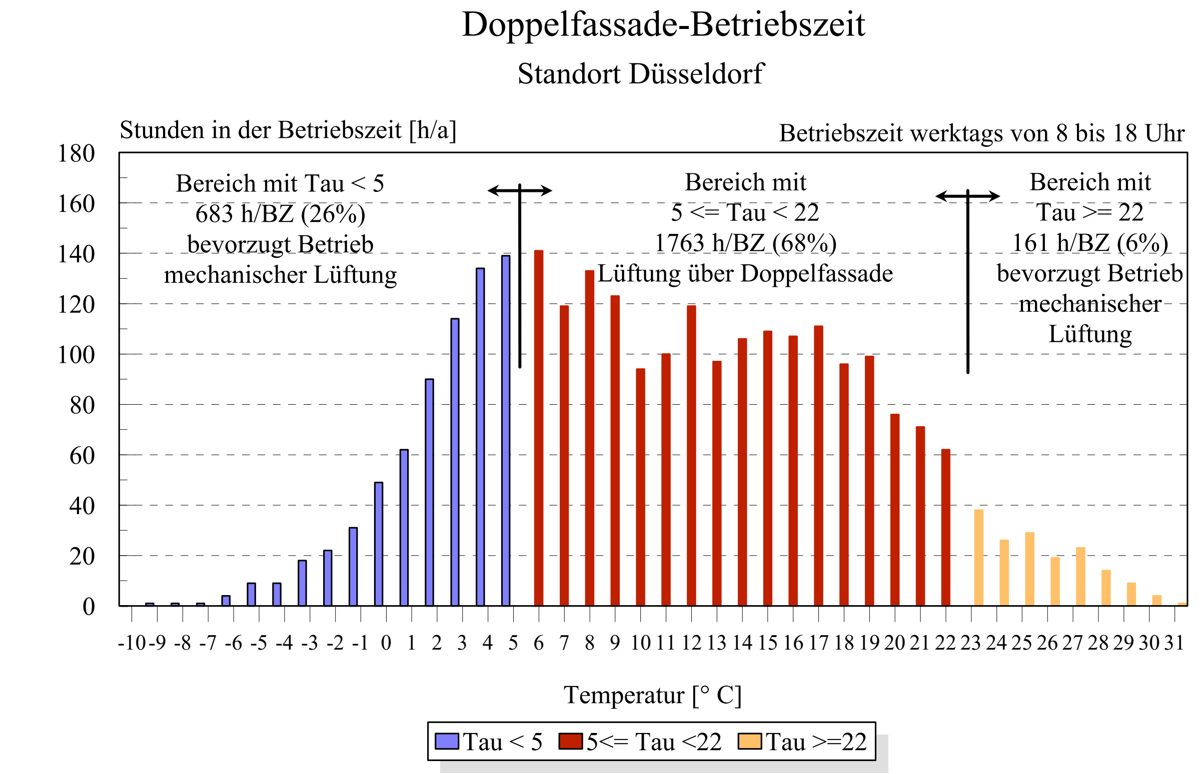



Figure 1.5.2: Proposed period in which natural ventilation can be used. This example is from the ARAG Tower (see also section 3.4.8) with a second skin façade. Natural ventilation can be used here between 5 and 22 °C (68 % of the time). This is to prevent unnecessary heating or cooling.

- Reduction of lighting energy
  A hybrid ventilated building can only be successful related to user-satisfaction, comfort and energy when much attention has been spend to the usage of daylight without unnecessary heat from the sun. In that way energy for lighting can be saved and unnecessary cooling prevented.

- Reduction of heating energy and harvesting of heat

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

When the fresh supplied air flow is relatively high heat-recovery of ventilation air becomes more and more relevant (Engel 2022 a and b). Low pressure heat recovery systems which are possible with a twin-coil (IEA 2000), a cross-flow heat exchanger (Engel 2022 a and b) or a heat recovery wheel are all options to save energy. In this case it remains relevant to make use of natural forces like the stack-effect and wind as much as possible. Integration of a PCM-battery in the ventilation system (Engel 2022 a ad b) is an extra option to store solar and internal heat. As long as the fan-energy is lower than the energy for heating, which is mostly the case at low pressure ventilation systems, these additions are relevant to consider.

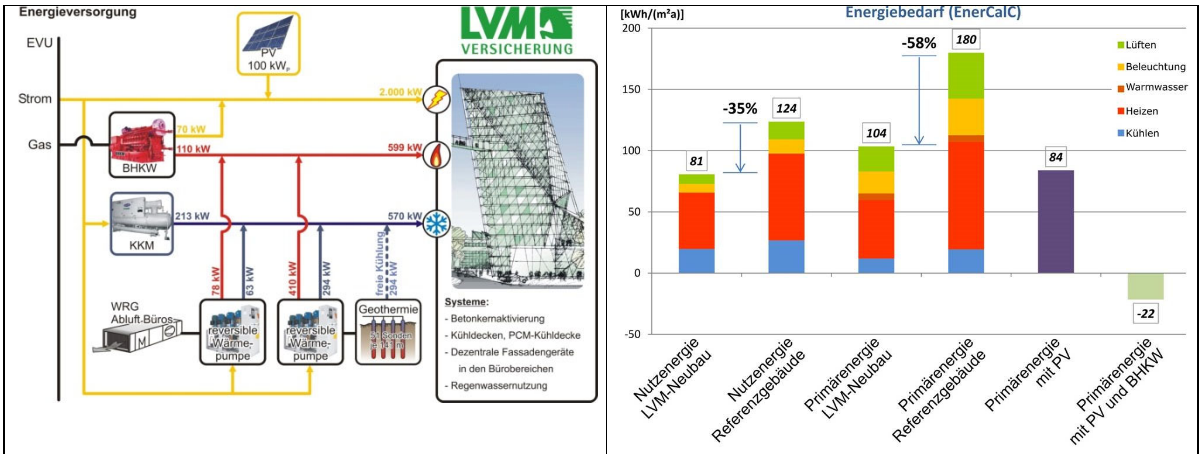
## 1.6 The effect of LCA-analysis

The environmental effect of the materials has an increasing impact on the final climate design. Although mechanical ventilation with heat-recovery often has a lower energy consumption than natural air supply, the environmental impact of materials is huge. A Flemish LCA-research (Seuntjes 2022) shows that for a school in which the energy consumption of natural air supply and decentral mechanical exhaust is more than twice higher than central mechanical ventilation with heat recovery. However, due the extra materials necessary for centralized mechanical ventilation the environmental impact over a period of 15 years of natural air supply is still lower.

## 1.7 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$^2$ (primary energy, Schuler 2005, Wood 2013) |
| 2 | LVM Münster | 70 kWh/m$^2$ (primary energy, 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$^2$ (electrical energy, COP heating 5.3, cooling 4.5, design study Transsolar 2018) |




| | |
|---|---|
| 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.

## 1.8 Well-being, health and risk-assessment

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.

An item that is often overlooked is  the risk of failure of the mechanical ventilation system, due to:

- a sudden failure of the electricity grid;

- a failure in the working of fans and/or cooling connected to an air handling-unit, without redundancy

In these cases natural ventilation-facilities, like operable windows, will reduce discomfort and possible health danger for vulnerable people.

## 1.9 Hybrid ventilation and Covid-19

When the Covid-19 pandemic started early 2020 a for many unexpected new role of natural ventilation became relevant. One of the most effective measures to reduce the infection risk reduction is by increasing the air change rate with outdoor air. With the existing HVAC-systems alone the options are very limited, but with operable windows it is relative easy to increase the air change rate. Of course, draught, thermal discomfort in general and unnecessary heat loss should be prevented as much as possible. Apart from natural ventilation measures like (local) air filtering and improving the contaminant removal effectiveness and local air quality index (REHVA, 2004) are very relevant and can also be combined with natural ventilation.

A general infection risk assessment is possible with the (adapted) Wells-Riley approach (Riley 1982) and the following two equations:

$$P(\inf\ ) = 1 - e^{-I*p*C_{gem}*t} \qquad (1.1)$$

where P = infection risk via aerosols ( - ), I = number of infected persons ( - ), p = pulmonary air volume ($m^3/h$), $C_{gem}$ = average virus concentration ($quanta/m^3$), t = exposure time (h)

$$C_{gemm} = \frac{1}{t}\int_0^t C(t)dt = \frac{q}{Q}\left[1 - \frac{1}{\frac{q}{V}*t}(1 - e^{-\frac{Q}{V}*t}\right] \qquad (2.2)$$

where q = the expected virus-emission of one person (quanta/h), Q = total fresh air supply in the room ($m^3/h$), V = volume of the space ($m^3$).

The virus emission for sitting people in rest is considered as 5, for speaking people 70 and for people in a meeting room 25 quanta per hour (Buannono 2020, Kulve 2020). However, the quanta per hour are also effected by the type of virus. The delta-variant is estimated around 60 % more infectious. A rather safe situation realized is when the infection risk ($P_{inf}$) is lower than 1 – 5 %. Via the Wells-Riley approach with a meeting room two hours in use and 25 quanta per hour, an air change rate of 6 would be necessary to realize a risk lower than 5 %.

Ventilation-efficiency plays a dominant role removing COVID-aerosols. For the reduction of COVID-infection risks the number of air change rates is the main parameter. The higher the air change rate, the lower the risk. This can also be realized via a high recirculation rate via effective filters, although there is still uncertainty about that (Roaf 2022). In both cases the efficiency is only high when there is a perfect mixing of all the air, which is also the assumption in the Wells-Riley equation that is used all over the world by climate consultants (Kulve et al 2020). Effective displacement or personal ventilation are other options with a potential high efficiency.

One of the most underestimated problems is short-circuiting of air flows. When there is not sufficient distance between the air supply and exhaust short-circuiting will occur. When the distance between the supply and exhaust of fresh air, or recirculated air with an effective filter is the same, the risk reduction of both systems is comparable (Cai 2022). Short-circuiting is one of the main problems of movable local air filters. Most of the local filters have a low ventilation efficiency because the in- and outlet are to near to each other. For this reason, cross-ventilation is also much more effective than single sided ventilation, apart from the increased air change rate (Engel 2022), but this has a higher draught risk and more difficult to control.

## 1.10 Developments at the TU-Delft

At the Delft University of Technology research about natural ventilation via automatic openable windows has been carried out by Dolf van Paassen (Paassen 1996) and his research team P.J. Lute (Lute 1992) and P.J.M van Galen. Thermal comfort achievements, investment and energy-costs of (1) natural ventilation, (2) natural ventilation with local cooling and (3) air-conditioning have been compared showing that option (1) and (2) have substantial lower total costs. Usually the maximum cooling load of only natural ventilation is around 20 W/m$^2$. When the cooling load is 50 W/m$^2$ and a local cool-unit is applied, the capacity of the cooler can be 50 % lower.

Parallel on his research a draught-free natural air supply-system has been evaluated (Engel 1995), based on the expectation that occupants close supply-grilles when there is a feeling of draught. With such a system, for instance, mould in insufficient isolated houses with a high moisture production could be prevented and it is an alternative for fully mechanical ventilation in schools and offices.

More recently Ben Bronsema (Bronsema 2013, 2022 and figure 3.1.11) had developed a hybrid ventilation system based on the idea of termite hills like Mick Pierce and Alan Short had done (Pierce 2022, Lomas 2007). The difference with termite hills is that termite hills have always upward (day) and top down (night) air flows (King 2015), making optimal use of the differences between day and night. The addition of Ben Bronsema to Mick Pierces and Alan Shorts designs is that not only buoyancy and pressure differences by the wind are the main driving forces. The additional driving force is a kind of "shower" producing small droplets at the top of a building that can create pressure differences above 100 Pa, also be able to humidify, dry, cool and clean the air. The air can be dehumidified  when the difference in absolute humidity between the outdoor and indoor air is sufficient large.

In the Netherlands, in a large university building, single-sided natural ventilation with awning windows as main ventilation system is recently upgraded in better isolated façades. With sufficient efficient control of window-openings and solar shading the energy consumption will remain low (Cai 2019, Wang 2015).

What can be noticed that there are high tech solutions with central hybrid or natural ventilation via ducts and shafts (Lomas 2007 and Bronsema 2013) and low tech solutions with direct natural air supply via the façade (Engel 1995) and openable windows (Van Paassen 1996 and Cai 2021). However, the control systems with natural air supply and openable windows have also the tendency to become high-tech. Due to reduction of heat loss and draught risk these systems have the potential to be economic and energy-efficient, compared to systems with central mechanical air supply and exhaust with heat-recovery (Cai 2021).

## 1.11 Ventilation of houses

For houses there is already a long discussion about the differences between energy consumption of natural air supply and mechanical exhaust and mechanical air supply and exhaust with heat recovery. Field research shows that there are no substantial differences (Derycke 2018). This has been noticed earlier by comparing demand controlled domestic ventilation systems in TRNSYS with exergy analysis (Sakulpipatsin 2007). An important factor for more reduction of energy and improving comfort in bedrooms is the usage of warmer and colder zones within homes (Janssens 2018). In this case the differences between the two systems are also smaller. Mechanical air supply and exhaust with heat recovery is often a single zone system, making it more difficult to make optimal use of two zones with different temperatures. Because the heating season in mild climates becomes shorter due to climate change the advantage of natural air supply will become more favourable.

## 1.12 The role of BMS

For BMS-controlled systems it is a challenge. Integration of user preferences, like openable windows, will lead to a more complex control system with an increased risk of system failure, maintenance costs and less robustness from the viewpoint of many mechanical engineers. More research is needed on how to overcome this problem. The aim of the BMS-system of the Co Creation Centre (see § 3.4.1) is to increase user comfort and reduce energy, making as much as possible use of natural sources. In fact, that is also the aim of buildings with second skin façades, but those buildings of have mostly a higher energy consumption than predicted, also compared to single skin façades (Leão 2016). The feedback systems within the BMS are often not capable to predict unnecessary energy loss and the costs of continuing monitoring the behaviour of the building are generally too high. Probably this will change due to the current very high energy prices. A digital twin-system simulating the performances of the building seems to be necessary for a building with a complex installation, but will also increase the dependence of expensive control-engineers. All these parameters are a challenge for architects and mechanical engineers to design smarter buildings that do not need much heat or cold and a very complex BMS-system. Only small additional amounts of energy should be necessary to fulfil personal preferences.

Building control operators should pay more attention to the prevention of simultaneously heating and cooling and the value of personal interventions of occupants, like the opening of windows. At the moment this is often seen as a risk for extra maintenance.

Homeowners, caretakers, operators and occupants should be informed of the effect of their behaviour on the everyday energy consumption of the building. More research is necessary to find good control-examples and effective ways of user-information in buildings.

## 1.13 User experience and behaviour

It is necessary to use the experience of the occupants as a starting point for control-actions.

For large buildings with openable windows experiments are recommended in order to know how occupants can be encouraged to use windows and sunshade in an effective way. This has especially sense when there are no sufficient financial means for an automatic control-system.

When occupants show a non-energy or comfort effective behaviour it is recommended to analyse its background. What will be the increase in energy consumption? Could the building or installation be adapted in such a way that the negative effect is small?

Attention must also be given to security fittings for windows to give occupants confidence in their own safety when opening windows.

# 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 sun has an efficacy of 93 lumen per Watt, and (white) LED lighting already more than 170 lumen per Watt. This shows that LED-lighting becomes extremely efficient (Wikipedia, Luminous efficacy, 2019). However, apart from the fact that light from the sun requires no electrical energy, the quality of daylight (level, glare, total visual spectrum) should always be compared with artificial light.

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

Natural ventilation usually refers to openable windows, but natural ventilation can also have a wider meaning. Windows and combinations of them have very different shapes, like a second skin (window) and hopper windows. One of the most used hybrid systems is natural air supply via the façade with a trickle vent and mechanical exhaust at the opposite side, which is common in new houses and many offices in the Netherlands and surrounding countries. This system has a low draught risk, also depending on the way of design (Engel 1995, Engel 2017, Bile 2018). It is also possible to use only natural ventilation during the whole year in a moderate climate like England like in the Lanchaster library and SSEES building of Alan Short (Lomas 2007). These are controlled air flows preventing draught by preheating cold supplied air and preventing unnecessary energy-loss making optimal use of the buoyancy effect of air and valves.

In Portugal most offices relied entirely on natural ventilation for comfort – despite making people colder in winter and possibly too hot in summer. It depends what you call comfortable?  (Nicol 2000).

The discussion becomes difficult due to a lack of understanding of air flows inside the building via connected spaces or surfaces with a different temperature and via cracks in the envelope. This cannot be ignored, even when there is mechanical ventilation (Jo 2007). Both systems should support each other. This requires sufficient physical understanding of what really happens inside a building.

Openable windows are widely used all over the world, especially in houses but also in older offices when there is no other option to ventilate, apart from cracks in the envelope. Especially for many poor people in the world the opening of windows is the only available option, so one should be reluctant to criticise this system for draught risks alone. Moreover, during a large part of the year there is no draught risk via windows and windows can be used to remove pollutants and pathogens in a short time when the space is in use or not in use (Bluyssen 2022). As extreme weather events become more common, often triggering grid failures and power outages the option to open windows enables buildings to remain occupied during such events.

In new or renovated buildings and houses it is important to have at least an additional minimum ventilation system, apart from openable windows, in order to prevent draught or to save heating and cooling energy. This can be a natural, hybrid or pure mechanical ventilation system.

In an "ideal" climate with a mean annual outdoor temperature of 20 $^{o}$C it is possible to use only openable windows and natural exhaust without heating or cooling, like in the Torre Cube in Guadalajaro in Mexico (Wood et al 2013). This is also possible in climate zones with a warm climate with high of low humidity's where people are already adapted to this climate.

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

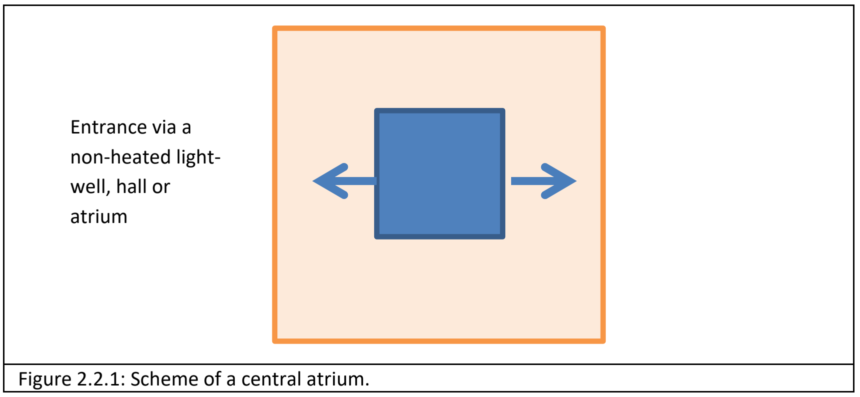



Figure 2.2.1: Scheme of a central atrium.

b. Adjacent glass-houses and entrances

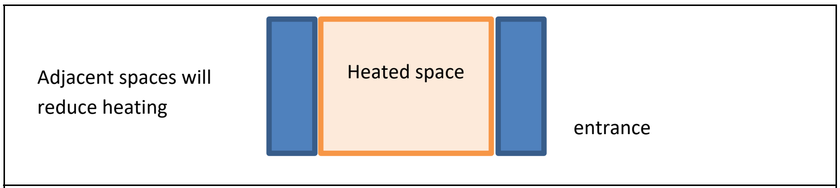


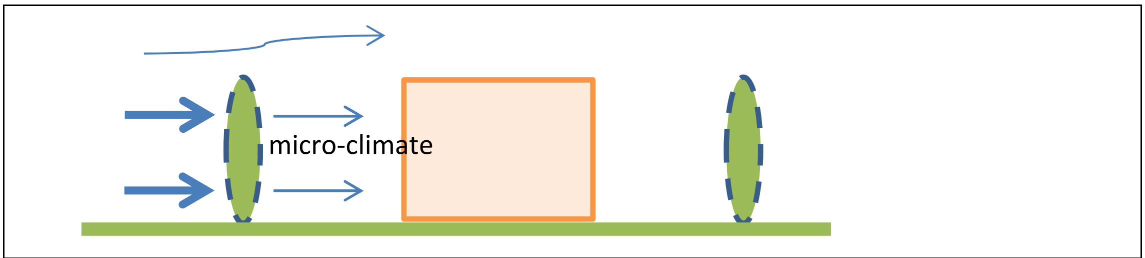

Figure 2.2.2: Scheme of an adjacent glass house.

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.

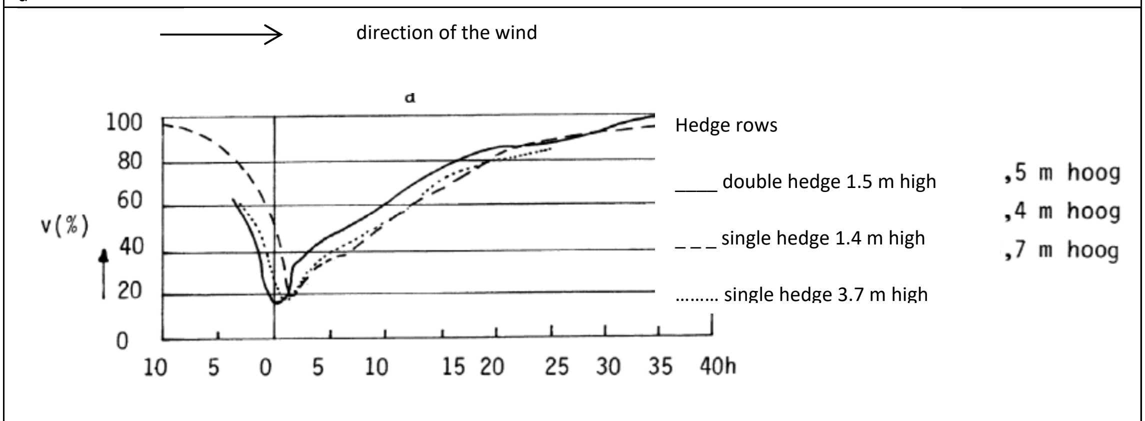
## 2.3 Microclimate, influence of the surroundings

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



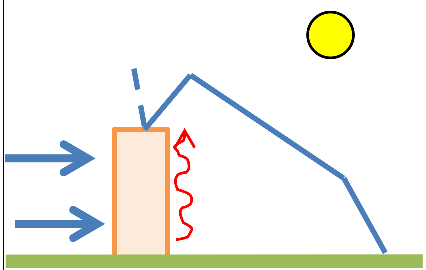

b Wind reduction by hedges, h = the distance from the hedge related to the height of the hedge.

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, a well isolating roof, 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, which can leave the space in an efficient way to prevent overheating of grapes.

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

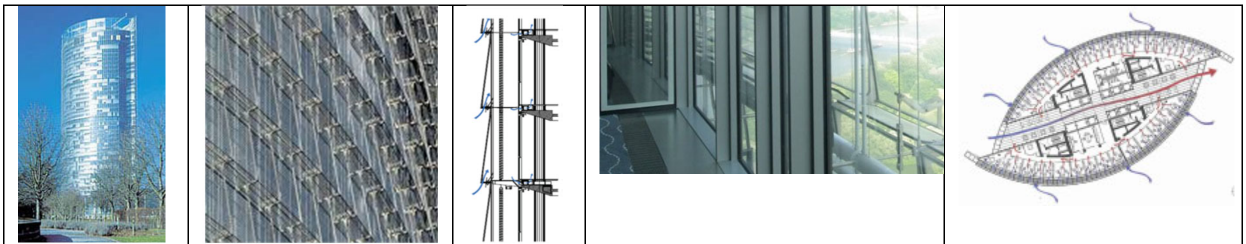
In order to keep heat inside in the heating season the building should be well insulated. Thermal mass in direct contact with the inside air works as a heat storage system. This will keep the heat inside much longer.

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.

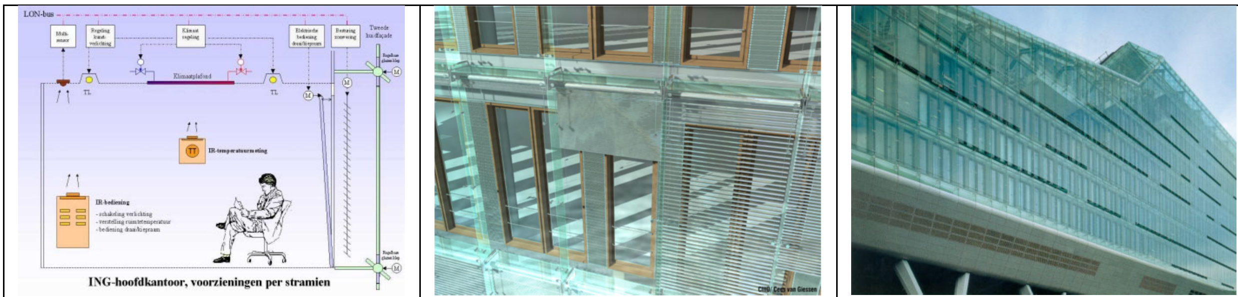
Figure 2.4.1: Comparison of the façade of the old and new town hall of the municipality Westland. The glass-percentage multiplied with the g-value of the old town hall maybe 30 % * 0.10 = 0.03 and of the new town hall 100 % * 0.30 = 0.30. With internal sunshade (66 % of the façade) this might be reduced 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, has been 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.

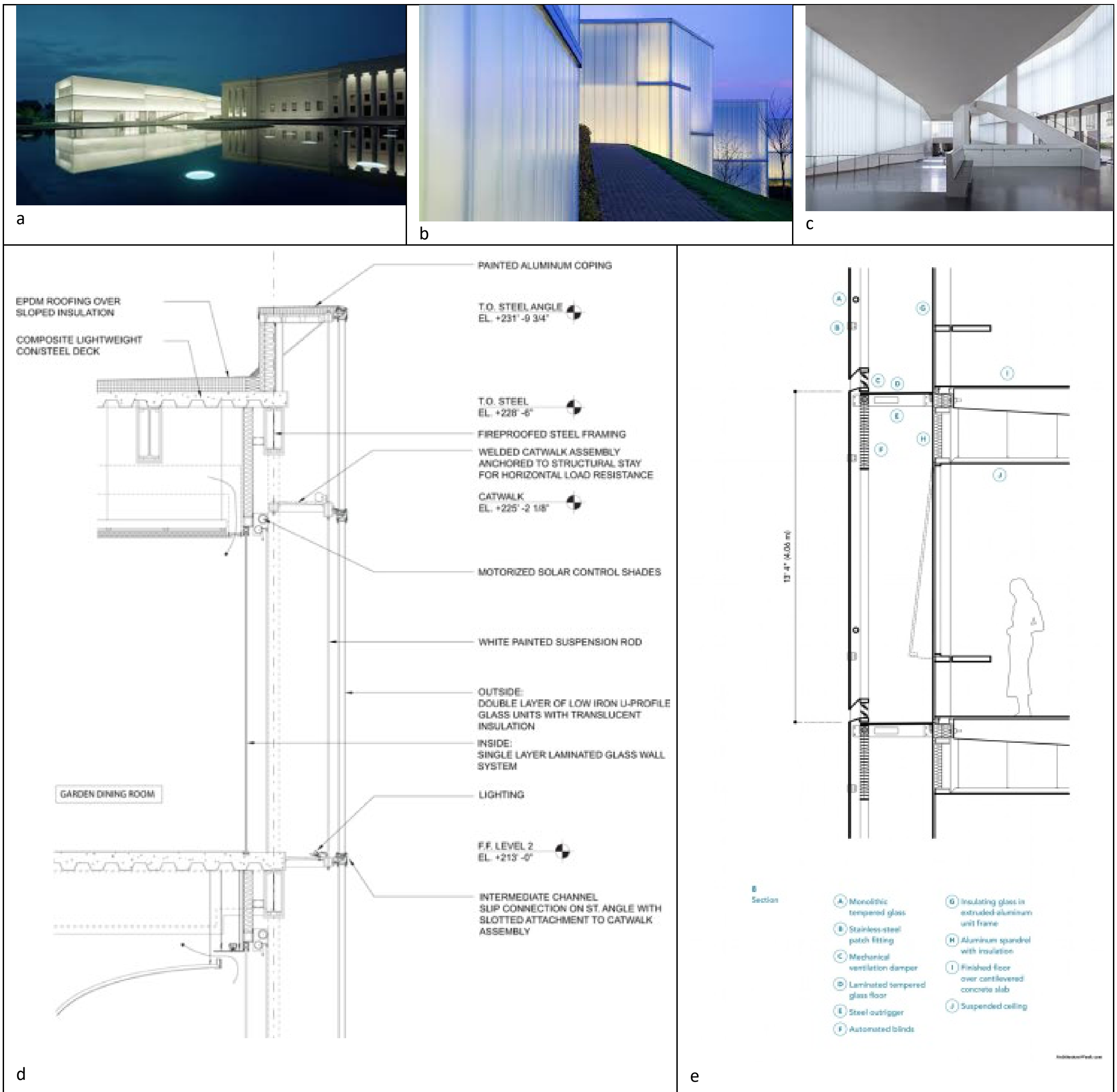


Figure 2.4.4: Nelson-Atkins museum, example of an extreme transparent façade for a museum.

- 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. However, usage of daylight is more than just numbers about the amount of lux. Maybe most important is the poetry of light supporting our joy of living. Just a few architects are able to integrate this in their designs (Guzowski 1999). For instance, it is one of the strong elements of Alvar Aalto in his designs like the townhall Säynätsalo and the library in Seinäjoki (Fleig 1991).

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.

- Reduction of overheating in houses

Openable windows or natural ventilation is often associated with draught, energy loss and little control. These problems are often exaggerated as discussed in this paper. The positive experiences do not get sufficient attention.

However, for some situations natural ventilation is also essential for another reason, like resilience in case of heat waves. The most striking incidents are fugitives hidden in containers on trucks without ventilation. Many of them have died because of lack of fresh air and overheating. This seems an extreme example, but recently in June 2022 there was a big problem with a Thalys train where the electrical system and air-conditioning failed. The train could not move for three hours and the doors could not be opened for safety-reasons. The windows could not be opened in this high tech train and many people suffered seriously from heat stress. This shows that solutions considered as “low-tech” are still essential.

In many Dutch houses with much glass a comparable problem can been noticed in summer. Since 1950 many row-houses have large glass-surfaces at the front- and backside of the house. With a colder climate, single glass, no isolation combined, overheating was not a big issue. The lack of insulation was possibly due to rather cheap energy and only heating the living room. However, at the moment many of these houses have double, often high efficiency glazing and more insulation, especially of the roof. The solar heat, once captured, stays very long in the house leading to temperatures of 32 - 36 $^{o}$C or sometimes up to 40 $^{o}$C. One of the solutions could be outside sunshade and windows with netting against insects and, as far as possible, protection against raining in or burglary. A very large number of Dutch people rent their houses from a housing company. These sunshades are not delivered by the housing companies and sometimes even forbidden because of architectural of monumental reasons. The costs of sunshade are often too high for the tenants, but there is often a lack of awareness as well, both by the tenants and housing companies, of the source and solution of the problem. An effective openable window-system that can also be used during the night does not get sufficient attention as well. At the moment many tenants buy cheap movable air-conditioners that have not sufficient capacity to compensate the incoming solar energy. A strategy should be developed to find solutions for combined design challenge and economic problems. This could start with outside sunshade, but also with a window-system in which netting can be added and protection against rain or burglary is an option. The housing company could take the lead for that.

Many overheating problems are related to the roof. Especially in many apartment buildings the top floor gets too much solar heat via the roof. This leads to indoor temperatures that are a few degrees higher than the houses below. Often the top-layer has a dark colour and has a high absorption-coefficient. This problem could, for instance, be reduced by the addition of solar panels that can be cooled down by the wind. A recent discussion with a housing company manager showed that there are different ideas about building physics in this field: his belief was that the heat came from below. This example shows the necessity of wide knowledge development.

## 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.

- It is necessary to have a scientific and evidence based approach during discussions about natural, hybrid or mechanical ventilation, with the connected options and (dis)advantages.

- There is still a general lack of knowledge, even by professionals, of the physical causes and effects of overheating of houses and buildings in general, like the impacts of solar radiation via roofs and façades.

- Much research about hybrid ventilation exists, but there is a real need to make the developed knowledge more easily understandable for climatic designers, bot least to reinforce the fact that natural air supply to spaces can have a low draught risk and a low energy consumption. For instance, there is little difference between domestic demand controlled air supply compared to mechanical ventilation with heat recovery.

- It is necessary to educate HVAC-engineers, façade engineers and architects to be able to design low energy and hybrid ventilated buildings.

- More systematic cost-benefit analyses should be undertaken to see when there is a break-even point to apply automatic controlled systems. Examples are mechanical openable windows, opening sensors, warning sensors in case of unnecessary heat loss, $CO_2$-sensors and valves for return ducts connected with flow-controlled fans.

- Effective outside sunshade combined with effective night-ventilation options are essential elements for many existing houses, especially with much glass. This is a relative low-cost and low-energy solution to prevent overheating. Housing companies should play a more active role to assist tenants to find affordable solutions.

# 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.

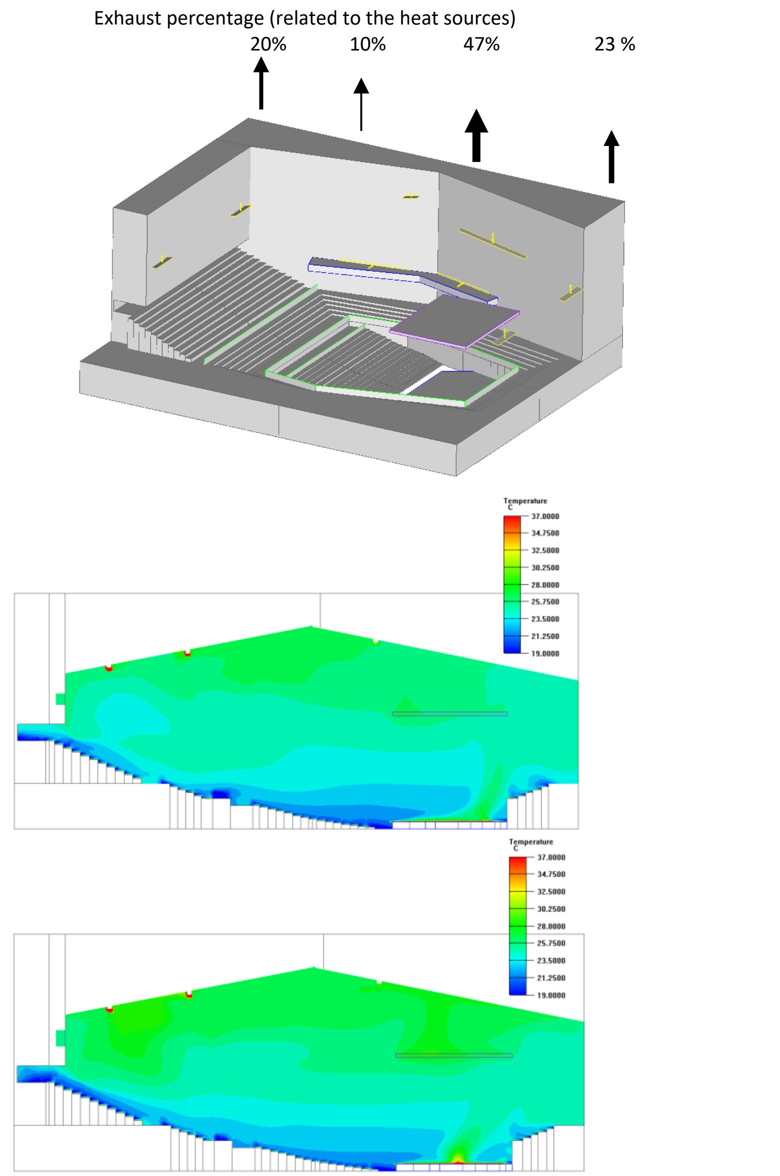
In the fifties and sixties many buildings in a temperate climate were still ventilated by operable windows: offices, schools and houses.

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.

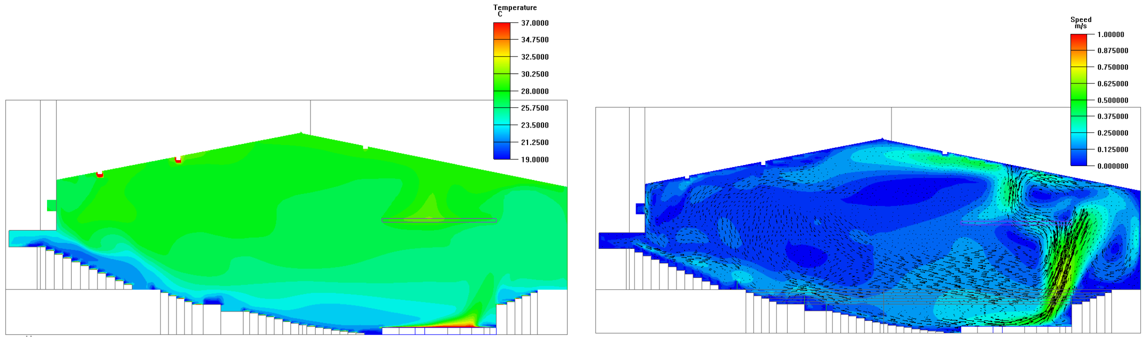
Gradually more and more buildings became mechanical ventilated, often in combination with operable windows. Nowadays, many offices even have no operable windows at all. These are often considered as harmful for the climate control (draught, air flow control via the ducts, condensation and cooling capacity) 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 $^{o}$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. One problem that needs more attention is that due to the large differences illumination (lux) and brightness of the surrounding surfaces (candela/m$^2$) between outside and inside, users tend to turn the lighting always "on" (Naves et al, 2006) leading to high electricity and cooling loads. This can only be solved by reducing the light level with, for instance, an extra semi-transparent layer, which should be open for natural ventilation as well. This is almost the same problem that occurs with fully glazed facades with integrated venetian blinds. Because of the large differences in daylight near the façade and the corridor-zone users have the feeling that it is dark in the middle-zone, which is in reality often not the case.

## 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)

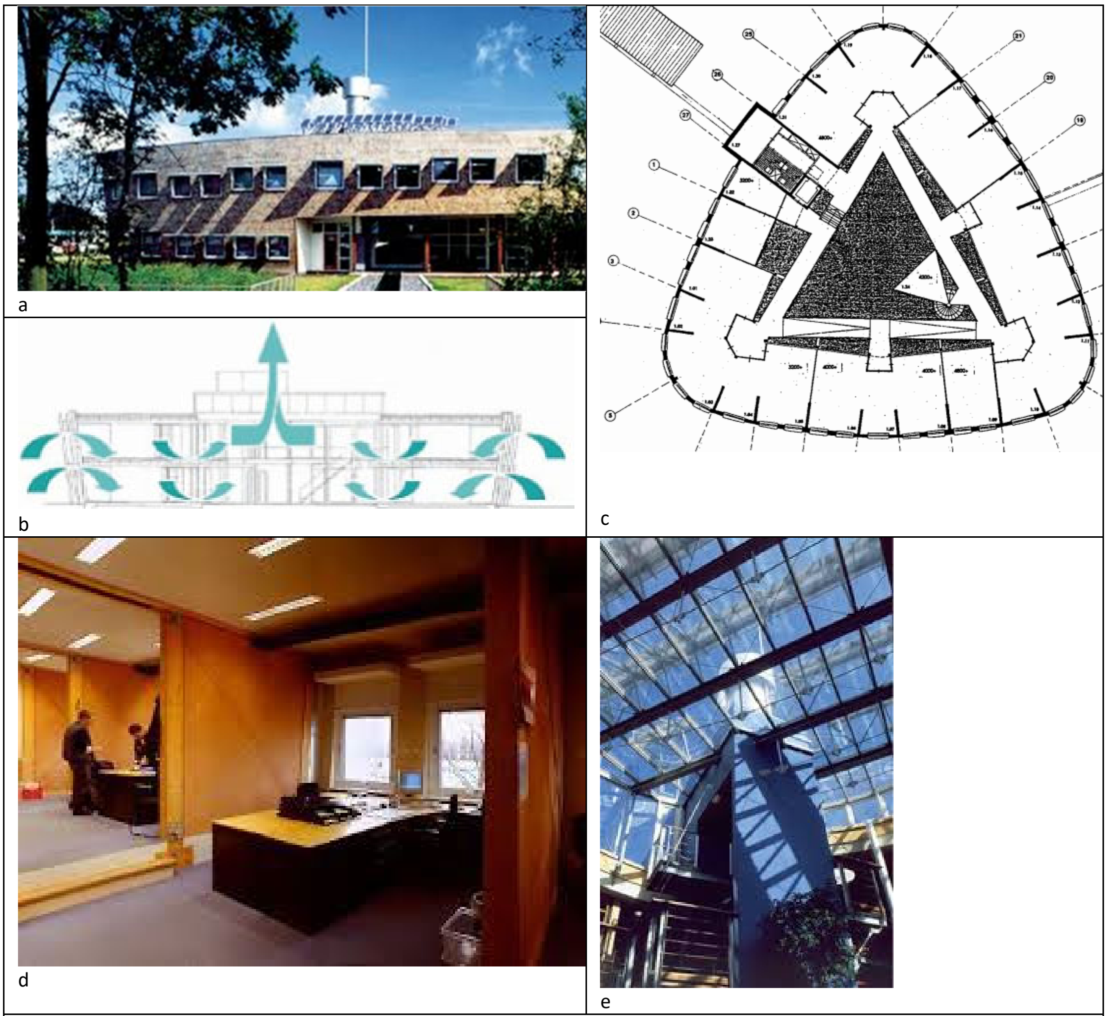
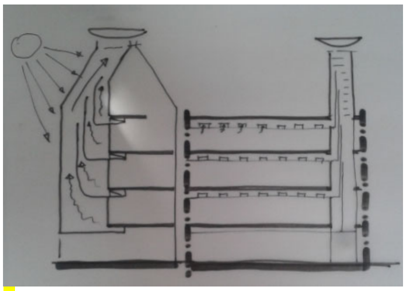


Figure 3.4.1: Office Rijkswaterstaat Terneuzen: high position of the inlet, low air velocity.

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


a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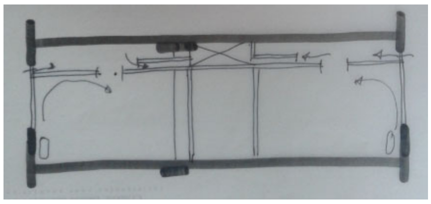
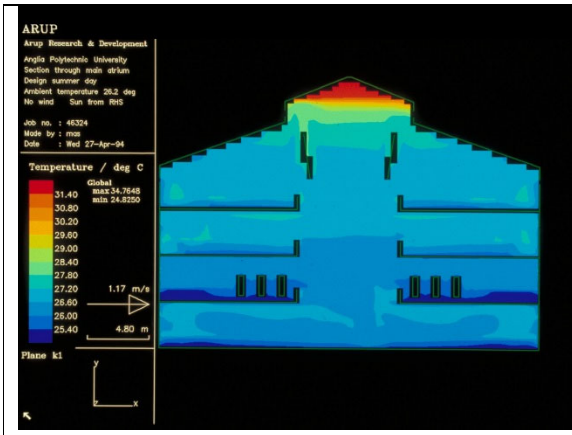
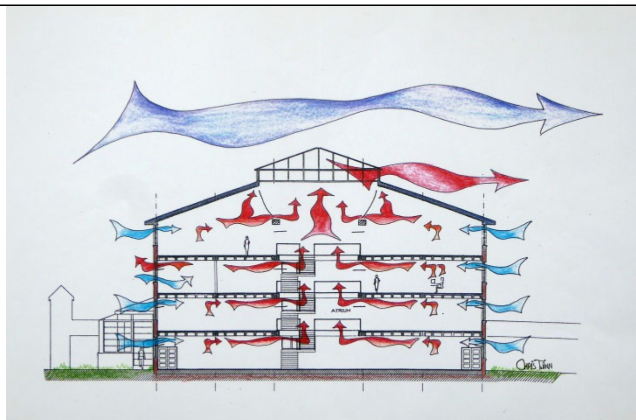

c

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.

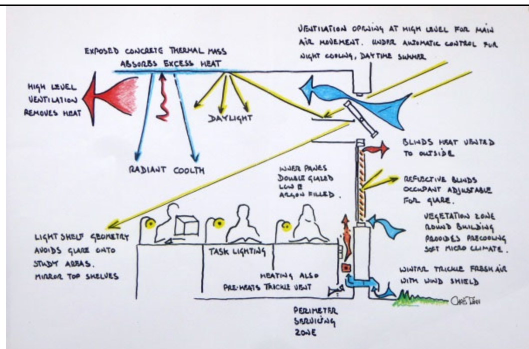
3. Air supply via low placed inlets in the façade and exhaust via a shaft or central roof



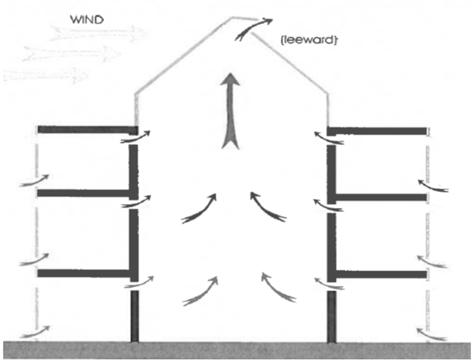
a CFD-analysis (Twinn and Arup).


b One of the ventilation strategies in summer.


c Overview of the Anglia Polytechnic University



d Usage of natural elements.



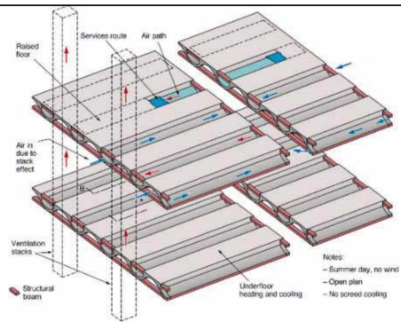
d Principle scheme ventilation, smart usage of the position of the neutral zone.

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).

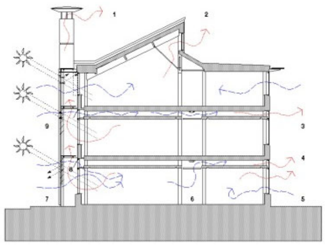
4. Air supply via windows in the façade and exhaust via a shaft or central roof (1)

a

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




c

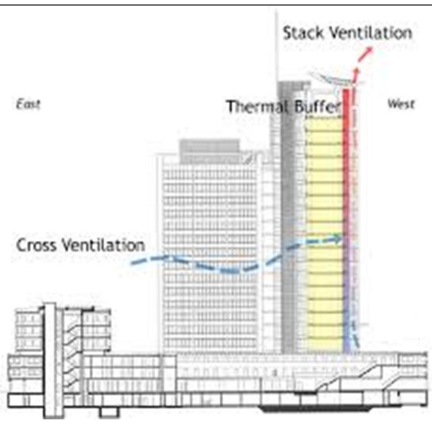


d

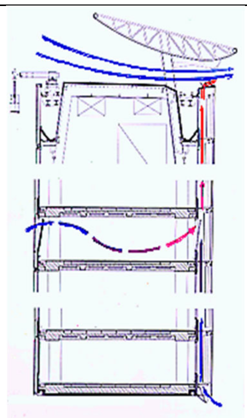
e

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)

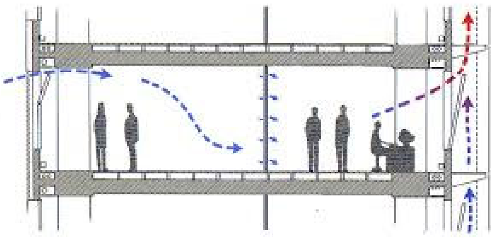



a



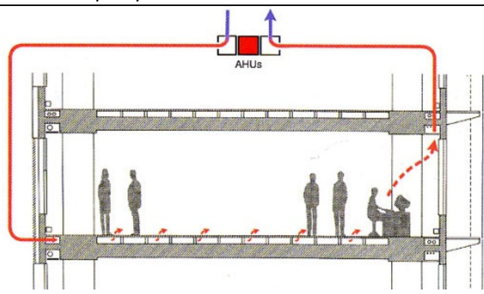
b

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

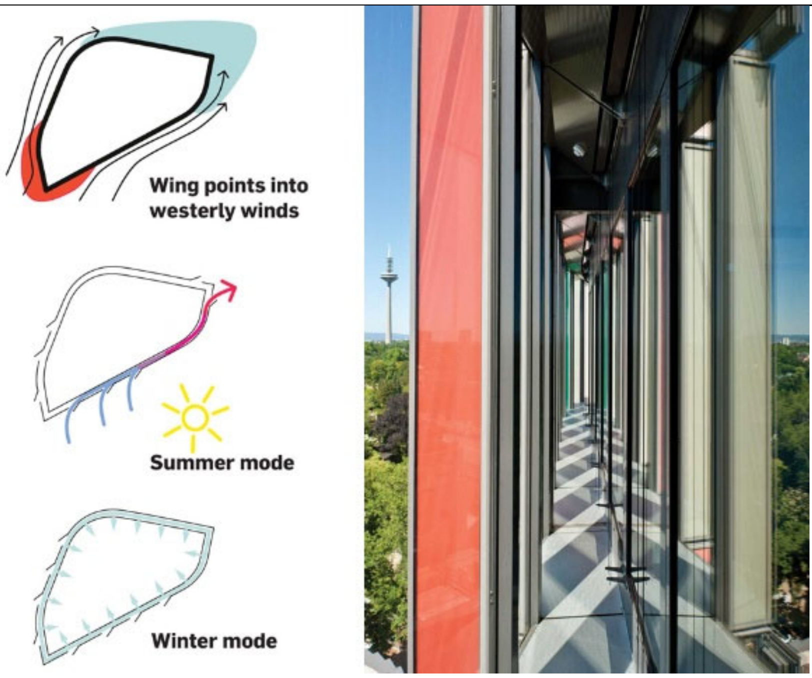

b

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

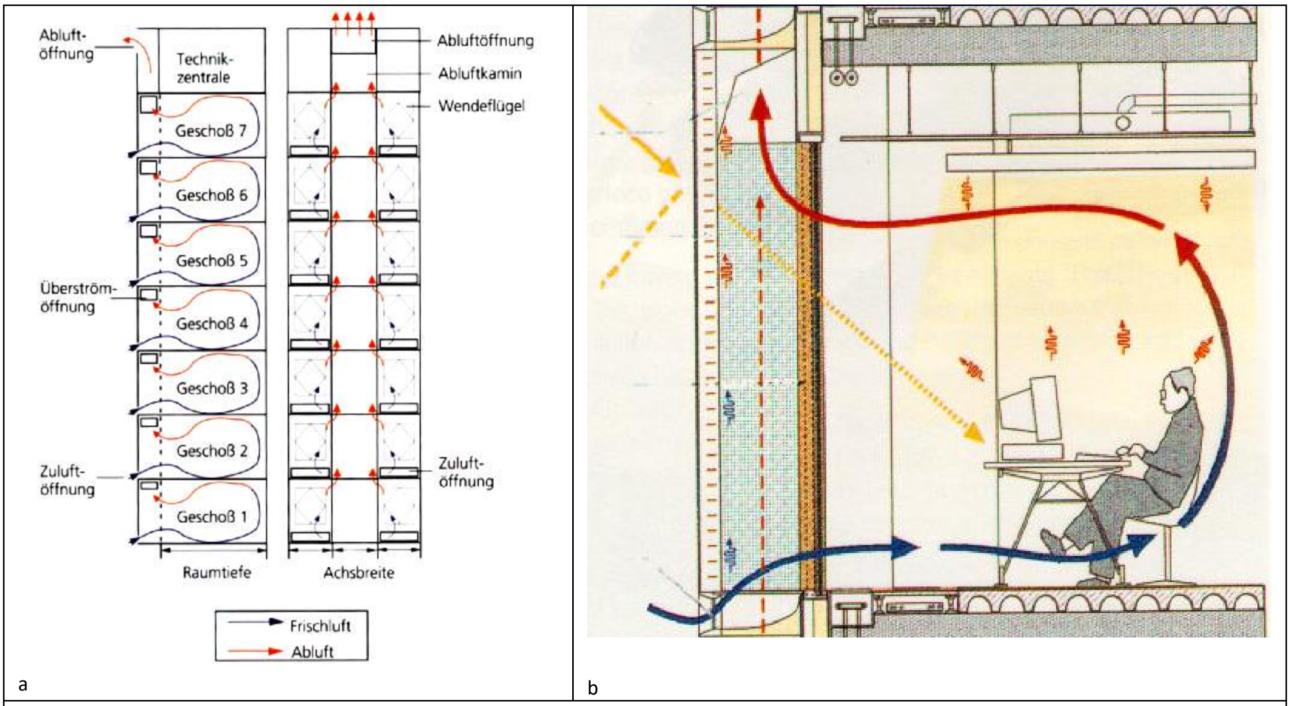
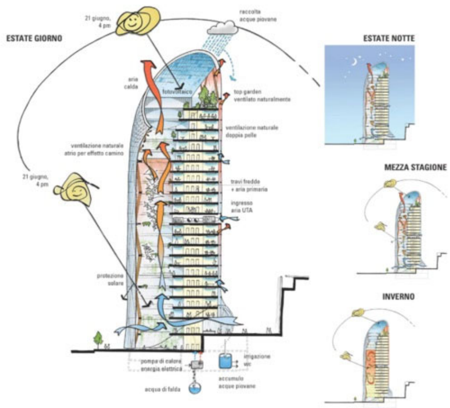



Figure 3.4.8: ARAG Tower: Combination of natural with mechanical ventilation, if necessary. Cooled ceilings.

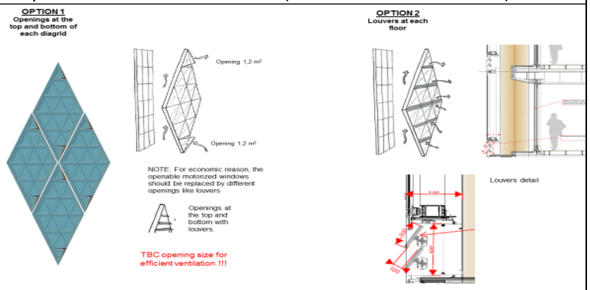
## 9. Air supply and exhaust via a double skin façade and atrium

a Unipol Tower Milan with the Bosco Verticale building nearby.

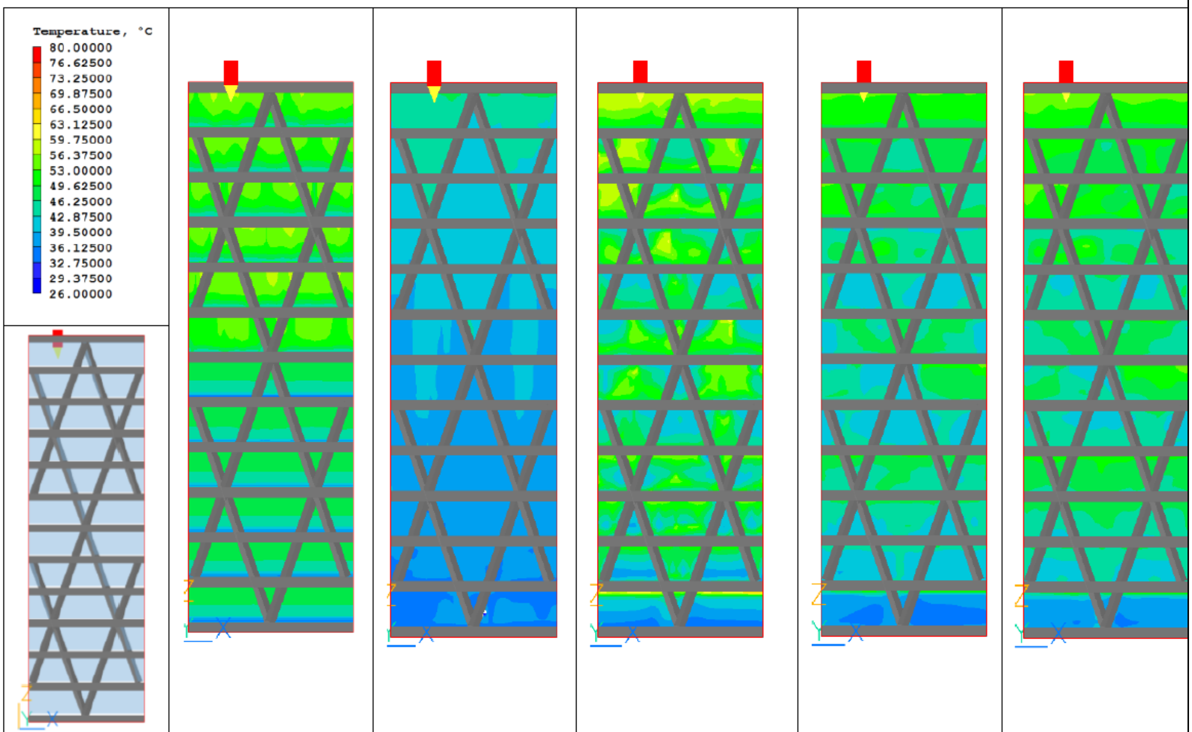
b Unipol Tower Milan and atrium (achitect Mario Cucinella.)




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.



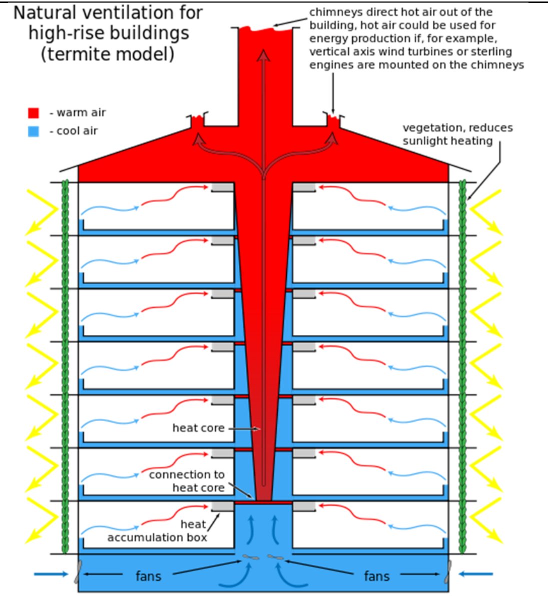

d Design sketches of the ventilation of the second skin. Reflective blinds in the cavity and high efficiency glass with a low g-value (0.30) will keep the indoor solar load low (g = 0.06).




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

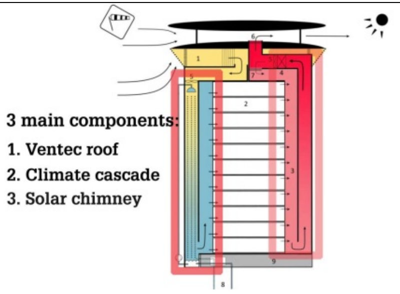
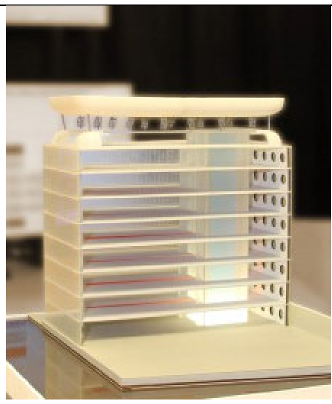
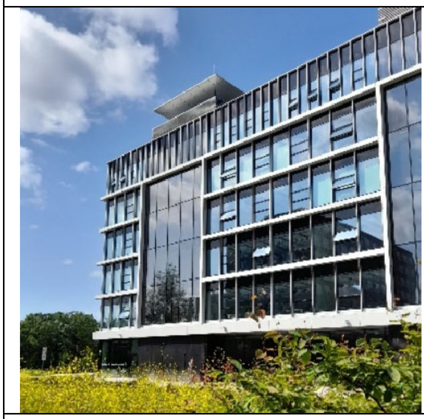
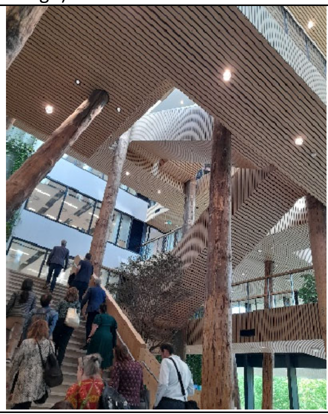
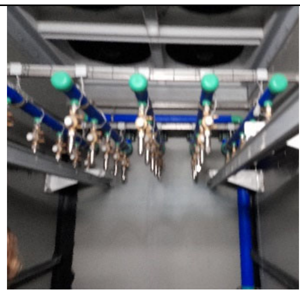



a

b

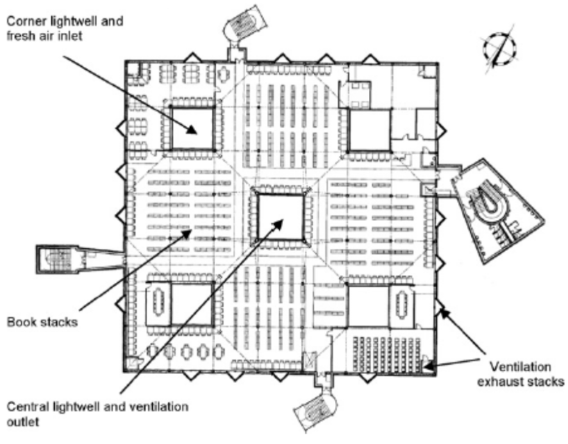
Figure 3.4.10: Eastgate Centre Harare, Mick Pierce (1996) in a hot and humid climate, air flow model inspired on the flow in a termite hill during the night, generally buoyancy. In reality the direction of air flows in termite hills reverses between day and night (King, 2015).

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

| | | |
|---|---|---|
|  |  |  |
| a. PhD-research | b Breeze hotel Amsterdam (early design) | c Breeze hotel, as built |
|  |  |  |
| d. Langeveld building (educational building of the Erasmus university). The ventec roof is visible. | e. Atrium of the Langeveld building | f. Sprinklers at the top of the climate cascade |
| Figure 3.1.11: Earth, wind & fire research (Bronsema 2013), moderate climate, buoyancy/sun/wind/cold droplets/vapour (12 °C) to induce a vertical air flow (extra air pressure), 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.<br>The Langeveld building shows that openable windows can even be combined with a low pressure ventilation system. When a window is opened and the $CO_2$-level becomes lower, the central air supply in a room is reduced or shut off. | | |

Because of the complexity and large amount of components in the ventilation system the total air resistance may be different from the calculations and assumptions, leading to a higher regular usage of the low-pressure fans. For the optimal development of the EW&F-system it is relevant to check this, like has been done in the Mediå School (Wachenfeld 2003). Alans Short already presented many buildings in which buoyancy alone was already mostly sufficient as a ventilation driving force. This development already started around 1860 (Short 2017 and 2020).

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




a

b

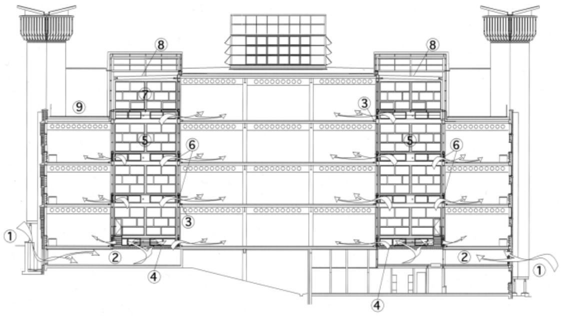


**Figure 5** Lanchester Library: air supply strategy. 1 = Fresh air inlet, 2 = fresh air supply plenum, 3 = trench heating, 4 = heater batteries, 5 = light wells providing ventilation and daylight, 6 = building energy management system-controlled louvers, 7 = ventilated void, 8 = retractable translucent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

c

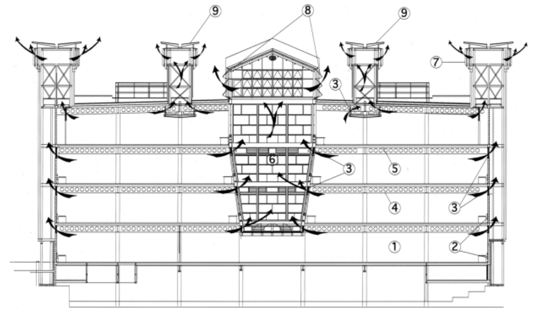
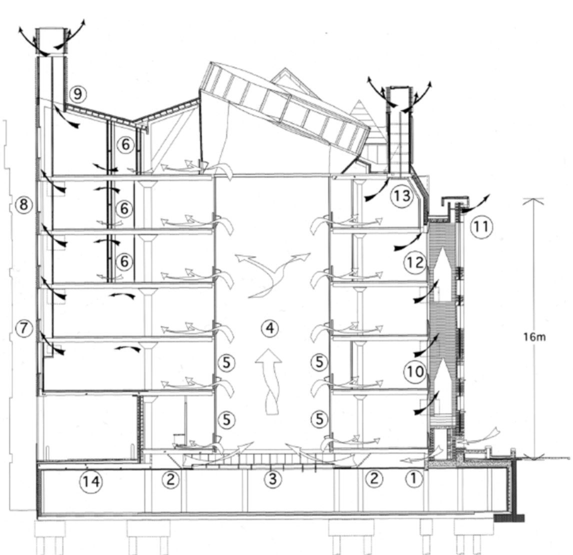


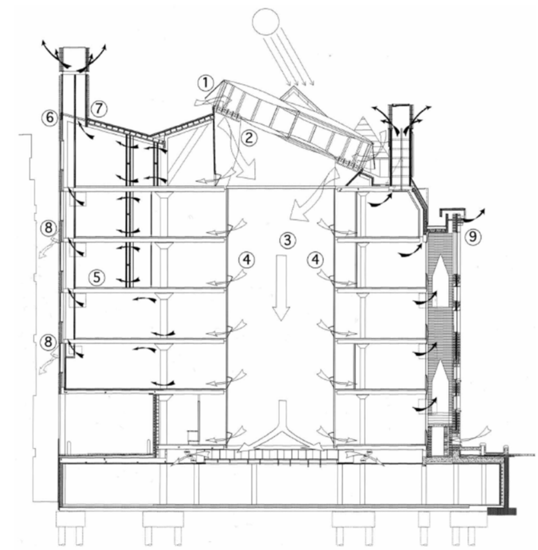
**Figure 6** Lanchester Library: air exhaust strategy. 1 = Carbon dioxide and temperature sensors providing input to the building energy management system, 2 = perimeter radiators with thermostats, 3 = exhaust dampers at a high level on each floor, 4 = castellated beams, 5 = thermally massive (concrete) 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.

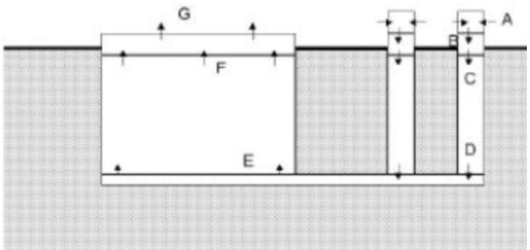


f. summer ventilation.

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

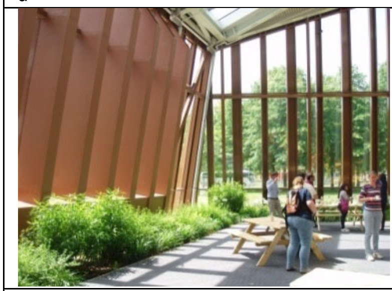

c


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.

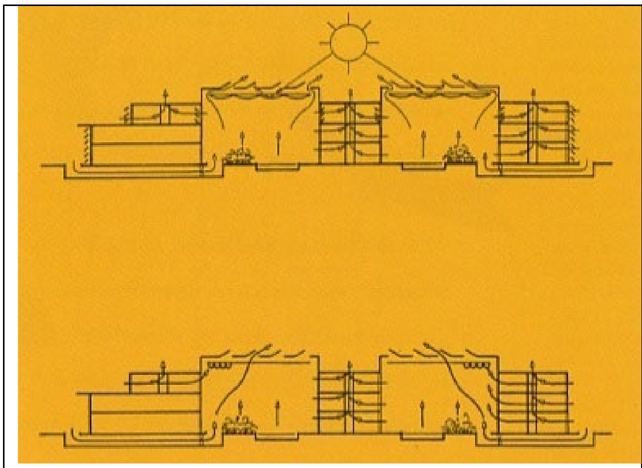

c atrium.


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.

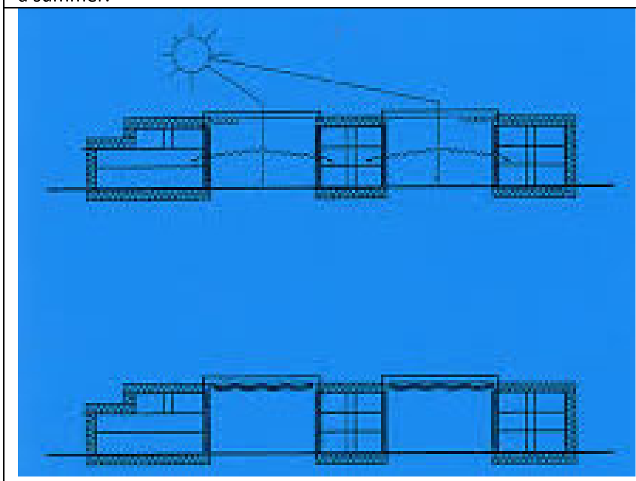
Energy Academy Europe as discussed in a workshop Innovative Passive Solutions at Clima 2022. The building is hybrid ventilated and has a glass façade.  Although designed as a very low energy building the energy consumption is twice as high as predicted: 100 kW/m$^2$ instead of 50 kWh/m$^2$. The building has used in 2019 circa 48,000 kWh of thermal heating and 12,000 kWh of cooling energy per month all over the year. There is no difference between winter and summer. The impression is that operators who fill in the set-points and operation times of the installation first react on comfort complaints, having less attention for the energy consumption. When a building is cooled off to much during the night, most of that energy has to be used again to heat up the building. This is not only an issue for the strategy of openable windows but for mechanical ventilation as well.

15. Air supply and exhaust via an atrium


a summer.


b


c


d winter.

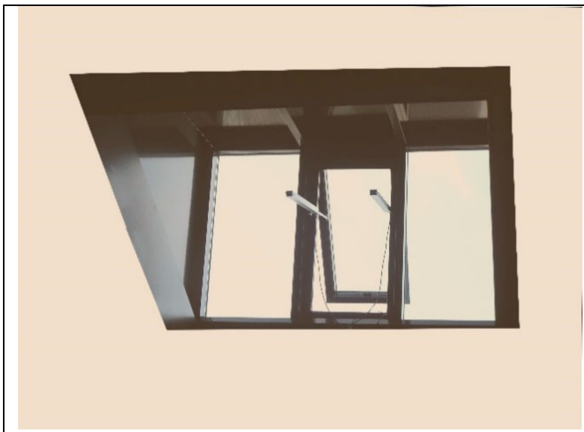

e


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.

16. Air supply and exhaust via windows, otherwise mechanical ventilation

In the Co Creation Centre at the Green Village of the TU-Delft, a building with a fully transparent façade, there are different control strategies.


a


b

Figure 3.4.16a and b: Automatic openable roof-windows in the transparent Co Creation Centre of the TU-Delft. This building has different climate strategies (Engel 2022).

Passive control is the preferred control-mode. The following control-modes are availab

1. Passive, when mechanical ventilation is not necessary, where the central set-point follows the most optimal line between the upper and lower band of the minimum and maximum adaptive temperature. Passive options are openable roof windows and external sunshade, making access of sun possible when necessary and acceptable related to visual comfort.
2. Passive/active making use of the thermal mass of the building and a PCM-battery.
3. Active mechanical ventilation with heating and cooling when necessary following an adaptive control strategy and set-points.

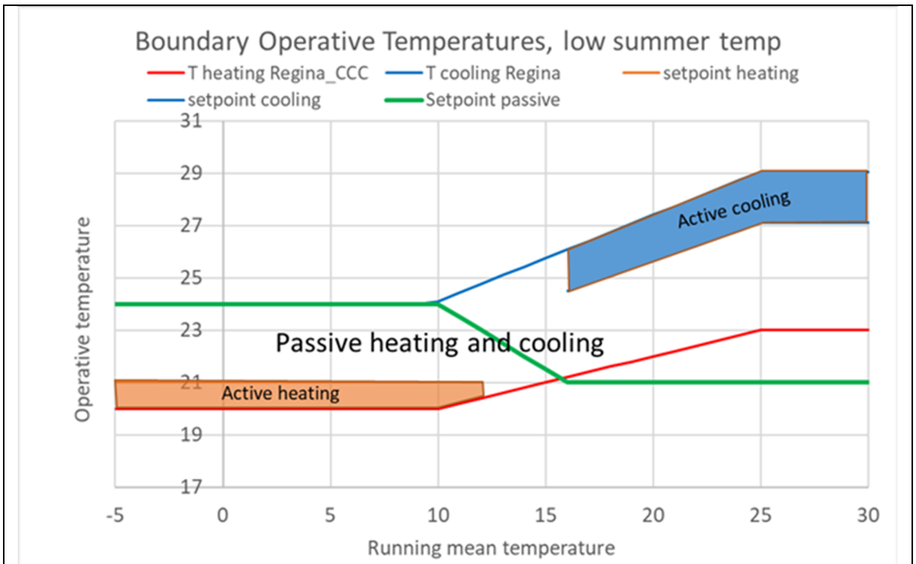
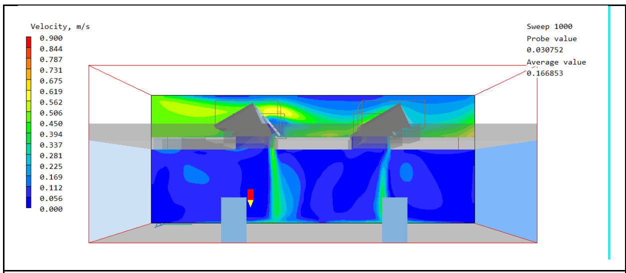
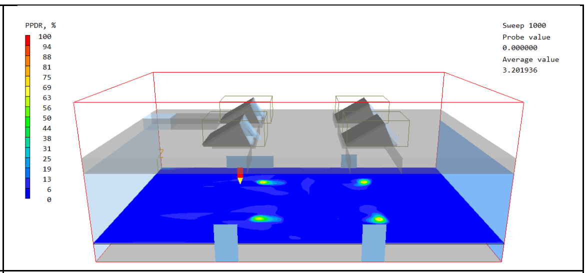



Figure 3.4.16c: Temperature control strategy of the Co Creation Centre, making use as much as possible from passive energy. For instance, a higher indoor temperature in winter due to the sun is accepted, as a buffer for a colder day.

Window-control strategies

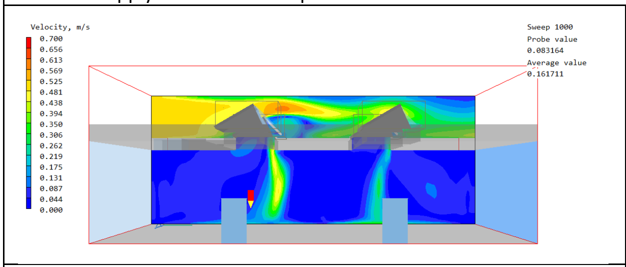
Windows are only opened when there is no active heating or cooling demand, so with indoor temperatures above 20 and 24 - 27 °C, depending on the clothing isolation of the occupants and the required comfort level.

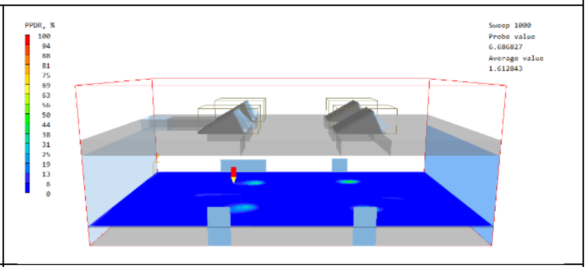



d. Air velocities | e. Draught Rate values at 1.1 m

CFD-Draught risk analysis of natural ventilation with rooftop windows at an outside temperature of 10 °C. Window-opening 20 cm. Fresh air supply sufficient for 15 persons.



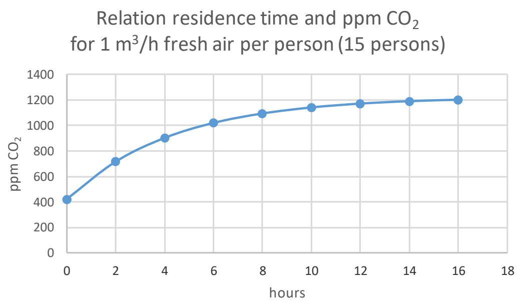




f. Air velocities | g. Draught Rate values at 1.1 m

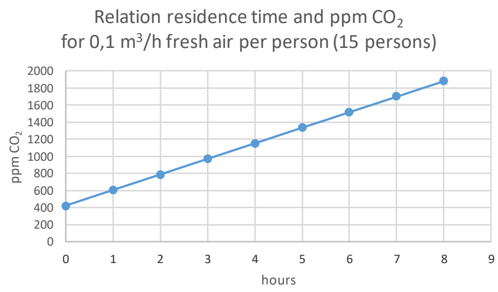
CFD-Draught risk analysis of natural ventilation with rooftop windows at an outside temperature of 15 °C. Window-opening 40 cm. Fresh air supply sufficient for 24 persons.

Figure 3.4.16 d - g: Draught risk analysis to support the window-control-strategy

Rooftop-windows can be opened from circa 10 °C, without a serious draught problem giving already sufficient fresh air for 15 persons, see figure 6. The height of the space makes opening at a wide range of outdoor temperatures possible. However, because the volume of the space is so large, without any ventilation it takes more than 8 hours before the $CO_2$-concentration reaches the 1200 ppm level. However, only controlling the air flow by the PCM-level in the exhaust is not sufficient. In that case still a sense of stuffy air can occur. The sensors show different $CO_2$-levels in the space. At the moment the highest registration in the space is used as control-parameter and the $CO_2$-setpoint is reduced to 800 ppm. When 25 $m^3/h$ per person is supplied and there is an average meeting time of 2 hours with 15 persons the $CO_2$-level will stays below a preferred 800 ppm for a situation without ventilation (see figure 3.4.16d). To prevent the stuffy air experience, probably exacerbated by the synthetic carpets, some minimum ventilation still will be necessary.




h. $CO_2$-concentration for 15 persons with 25m³/h pp air supply in relation to time




i. $CO_2$-concentration for 15 persons with 0.1 m³/h pp air (almost no ventilation) supply in relation to time

Figure 3.4.16 h and i: Rise of the $CO_2$-concentration when there are 15 persons in the space

The higher the outdoor temperature, the more outdoor air can be supplied. Rooftop-windows can be opened from circa 10 °C, without a serious draught problem giving already sufficient fresh air for 15 persons, see figure 8. Above 15 °C some cross-ventilation is possible via other windows in the façade. This leads to the following relation between the number of occupants and outdoor temperature:

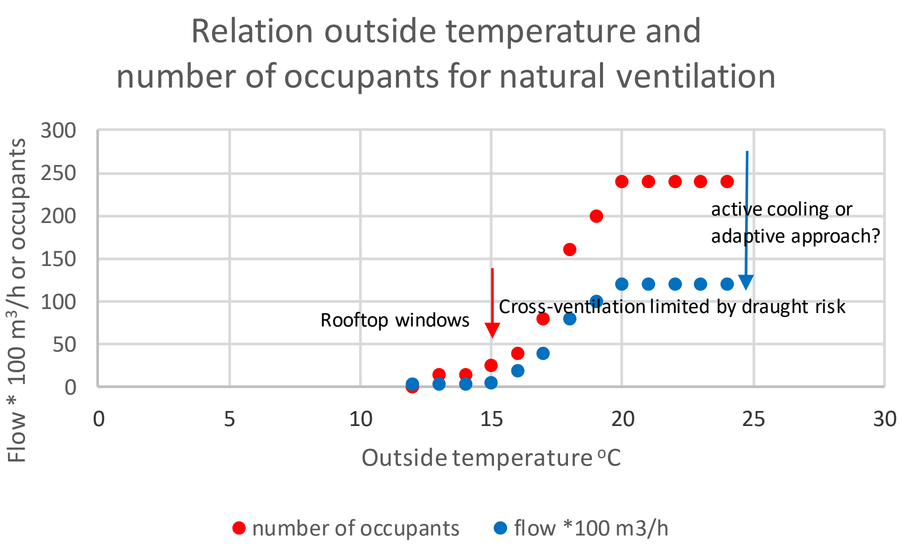
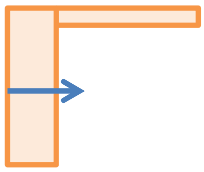



Figure 3.4.16j: Relation outdoor temperature and natural ventilation in the Co Creation Centre

In this building natural ventilation is the preferred passive control-mode, when there is no active cooling or heating demand, which is estimated for 30 % of the time. When the local $CO_2$-level becomes too high, the mechanical ventilation will gradually supply more fresh air.

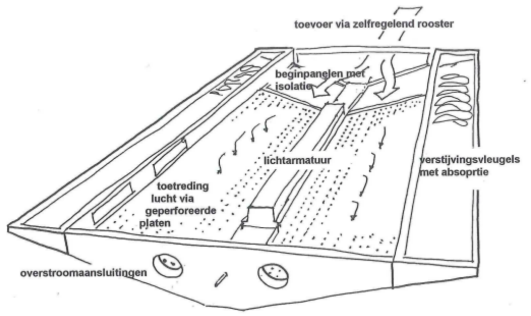
# 4. Ventilation elements

## 4.1 Natural supply systems



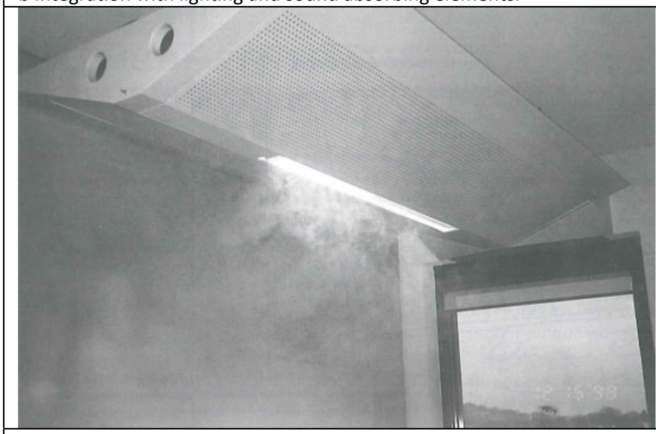
As long as the air flow is smaller than 10 - 15 l/sm façade there is little draught risk. A convector or radiator will reduce draught risk even more.

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

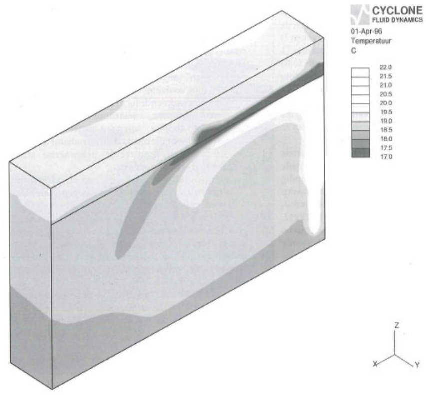



b Integration with lighting and sound absorbing elements.

c Optimal usage of the thermal mass.



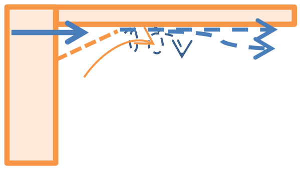
d smoke visualisation test of air flows.




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.



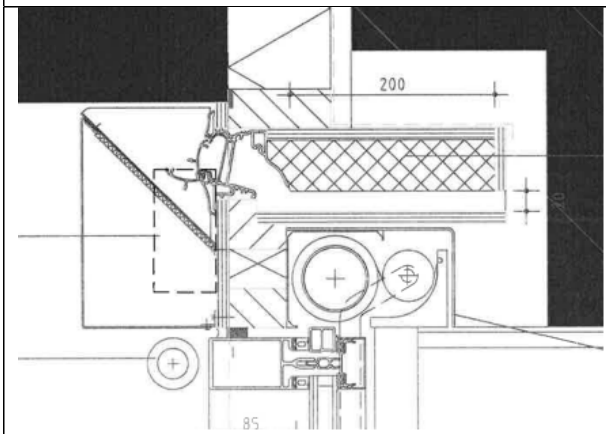
Air inlet 5 – 20 mm direct beneath the ceiling, > 2 m/s if possible, as long as the air temperature is higher than 0 °C there will be no draught (DR < 20%). Three physical principals are used:

- 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

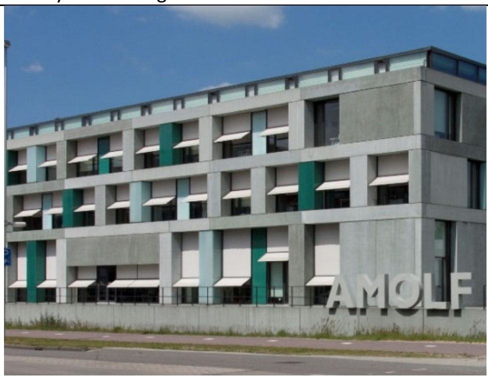
Option for offices in order to prevent draught.

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

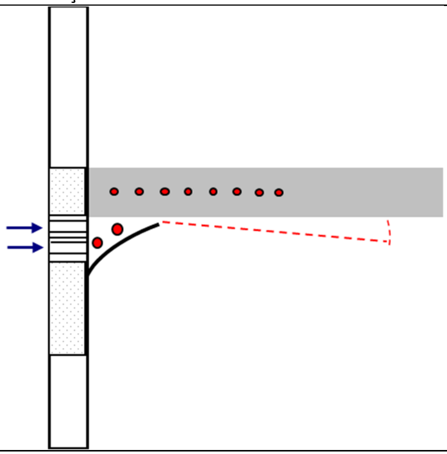
Air inlet for an office (Amolf research centre).



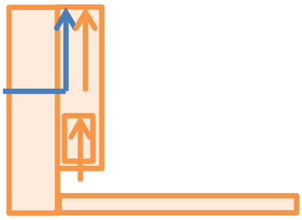

c

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).

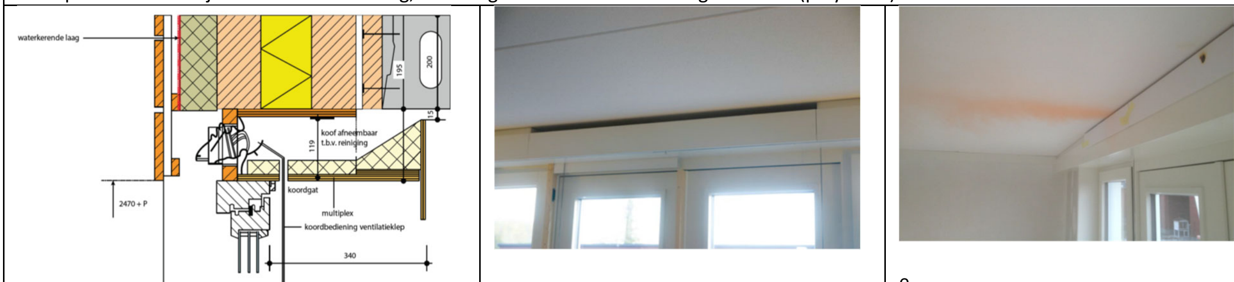
Grilles (trickle vents) are small elements that can control air flows much better than windows can do. This is especially important for the heating season. In the Netherlands grilles are usually almost invisible from outside, upon the frame or wall above the window or underneath the ceiling.

a b

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).

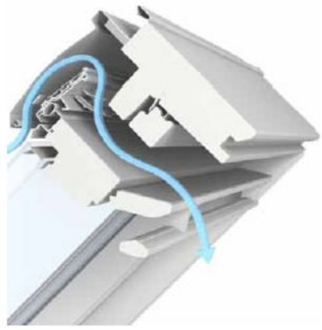



c d e

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. In figure 4.1.4e the coanda-effect is made visible by coloured smoke.

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

Sometimes architects or manufacturers look for very simple solutions:

| | |
|---|---|
|  |  |
| a Air grille of which the size of opening can be easy controlled and closed (Tilmar) | b Ventilation opening for Velux skylights for minimum ventilation. The way of integration prevents rain coming in and the opening can be closed. However, the size of the opening is more difficult to control. |
|  |  |
| c Air grille completely integrated in the frame, closed and open (Velfac) | |
| Figure 4.1.5: Options of air inlets that can be combined with or integrated in a window-frame | |

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, limitations and opportunities

The focus of this paragraph is on boundary conditions for openable windows. Occupants live in their own houses and often in an office or other working environments as well. Due to the development of working on a distance, accelerated by the COVID-pandemics, they generally have more choice which environment is the best. That is why a holistic approach is necessary for buildings in general and houses. Natural ventilation offers a wide range of low-cost opportunities to realize the required thermal comfort and need of fresh air. Boundary conditions are the limitation of cooling and heating by intelligent building physical design of the façade or roof, with better balancing heat loss due to transmission and heat gain by solar access. In this field there is still a lack of knowledge at many professionals. In most cases natural ventilation has to be supported by robust mechanical systems. Effective integration is a rather new field of research, learning from the past. BMS-systems play more and more  a key role. There is no good reason *not* to apply openable windows as addition to another permanent ventilation system. It will increase the user comfort and the building will become more resilient (not unacceptable hot) during heat-waves, cold storms and grid failures. However, there are often arguments by mechanical engineers or investors against openings in the façade. These are summarized in the following paragraph. It should carefully be evaluated during the early design-process. In very advanced ventilation buildings (Wood 2013, Engel 2019) these problems have already been solved due to high degree of control of windows, cooled ceilings and valves in ducts. In general, these are very expensive buildings for the top of the market. However, instead of more control-systems the knowledge of the user can also be used to efficiently, successfully and cost-effectively monitoring and manage energy consumption. Elevating the role of the operator, facilities manager and/or caretaker of the building in conjunction with user feedback systems are other important improvements to be considered, couple with awareness raising campaigns. Preventing unnecessary heating and cooling is increasingly necessary in workers own homes and key lessons can be transferred from the workplace to residences, and vice versa.

Discussion about limitations

Regular discussions about the effect of openable windows are summarized in this parafgraph;

a. unnecessary loss of heating and cooling energy

Cooling with outdoor air is most effective when the outdoor air is cooler than the indoor air. However, anywhere around the Thermo-Neutral zone, say 26 -35 $^{o}$C. additional air movement cools bodies. This is even the case when the moving air is warmer – as it accelerated evaporative cooling from the skin. In that case the total amount of cooling energy will be highly reduced. Additionally, the thermal mass of a building can work as a thermal battery of the building given the boundary conditions exist to permit heat transfer from the air to the mass. Personal cooling is possible at higher temperatures with the aid of higher air velocities that accelerate evaporative cooling form the skin up to upper skin temperatures of around 35$^{0}$C. This “comfort cooling” is sometimes called “ventilative cooling” (Chiesa 2021, Nicol 2012). This system can also be used when the indoor temperature follows the outdoor temperature but this a different type of indoor climate, often used in warm and humid climates. It is, for instance, also used in many houses and other buildings when night-ventilation is not possible.

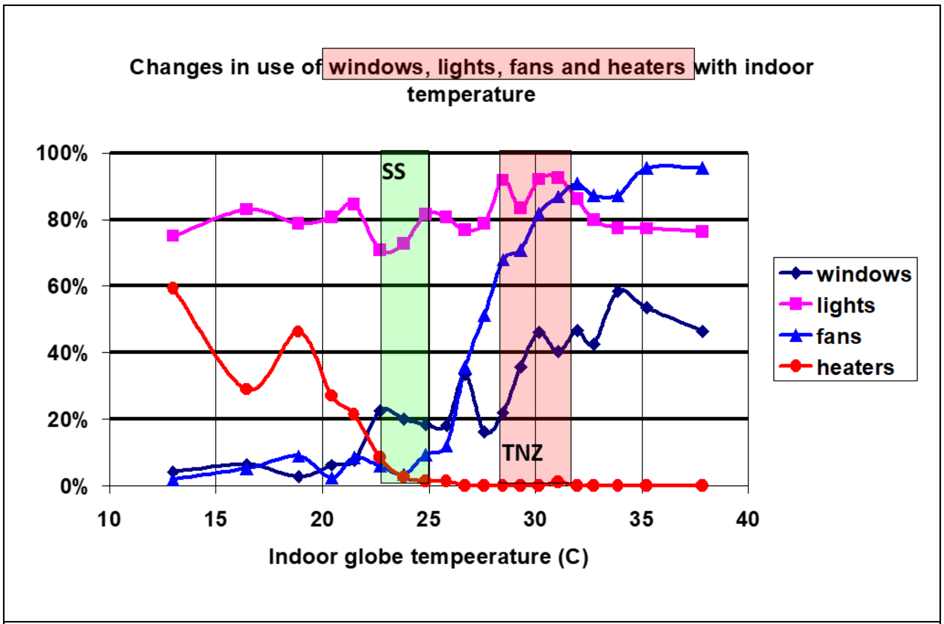



Figure 4.2.1: Adaptive control options in winter an summer (Nicol 1999)

Unnecessary heating can be prevented when a window is only opened when the indoor temperature is higher than a certain set-point, for example 20 or 21 °C. In practise occupants open a window when they feel it too warm and close it when they feel it too cold. When it is too cold or too warm indoor or outdoor there is already an automatic reaction by the users to close or open windows (Rijal 2007). Nevertheless, this reaction could be optimized.

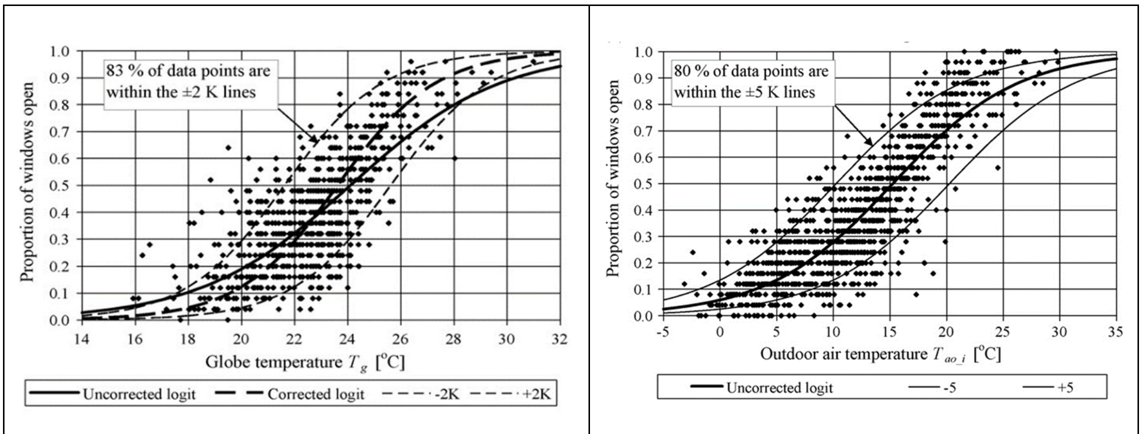



Figure 4.2.2: Relation between the operative indoor (left) and outdoor temperature (right) and the frequency and size of opening of windows (Rijal 2007)

When a hybrid ventilated building is controlled in a non-smart way, energy consumption will increase instead of decrease, so the critics have a point here (Leão 2016, Shahzad 2022). The most efficient control strategies require sufficient information for and awareness of the user, both of which can be learnt, when there is no automatic control system available. Information could be given for instance via a weather-station. When there are many different users in a building more research is needed for this design challenge on how to limit the risk of discomfort for the many, and to understand and enhance the awareness of the necessary actions involved. In 'broken plan' buildings with many separate rooms, their energy loss is mainly limited to the room itself.

The simplest solution for automatic control is to shut the mechanical ventilation off when a windows is opened. This does not require high-tech smart controls and such systems have been used for decades in buildings like hotels. Because of the danger of getting insufficient fresh air in the space, especially with large spaces and single-sided window ventilation, a $CO_2$-controlled mechanical air supply is a viable option. Natural and mechanical air supply can easily and effectively support each-other.

A real problem for many buildings is that heating and cooling takes often place at the same time due to miss-set controls, leading to high energy consumption over the whole year, but especially in the cooling season. This does not relate specifically to buildings with openable windows, but occurs in almost all buildings. It very often happens that occupants want very different comfort temperatures to those supplied by the mechanical systems, for instance in over-cooled buildings during hot weather, so they open the window for fresh air and a warmer breeze, leading to higher energy use to compensate. The real problem here is the use of inappropriate set points. The over-cooling of fixed envelope buildings in the USA in 2012 resulted in US $10 billion alone (Alnuaimi 2022).

b. shortage of cooling capacity of the chiller, heat pump or cold storage

When there is much extra outdoor air with a high enthalpy is supplied, the chiller can reach earlier its maximum. It is necessary to close windows when it is outside warmer than inside, like occupants in houses normally do.

c. draught risk

The experience of draught risk via windows is very dependant of the user. The decision of the position of the window-opening should be made by the user or combination of users. Draught risk is a very personal experience, because people react very differently on air flows, temperatures and turbulence levels. Draught is also produced by mechanical systems, for instance, in many stores the temperature is set too low. Natural air flows have a lower draught risk than mechanical at the same temperature, because of the different turbulence spectra between mechanical and natural flows (Quyang 2006).

Usually draught can be prevented by reducing the size, shape and place of an opening. This should be made possible by the designer. It is already known that hopper windows have a lower draught risk and second skin windows as well. As to air inlets (trickle vents) the location of the inlet and size of the air flow has influence. In houses with a low-temperature heating special solutions are available (Engel 1994 and 2017), which is completely ignored in current Dutch standards (SKNNI 2022). On the other hand, air flows can also produce thermal pleasure at higher temperatures.

However, many elements related to draught are still unclear. Is draught a physical or psychological feeling or both? Quite number of occupants close trickle vents completely due to a feeling or idea of draught even when the supplied air flow is very small.

d. outdoor noise

Windows can be closed when the outdoor noise is too high. But it is also a personal choice of the user how much background noise is accepted. “White noise” can even be pleasant to mask the sound of voices. The Unilever head office at the Weena in Rotterdam has sound absorbing materials in the cavity of second skin windows to increase the time that users can open the window.

e. outdoor pollution

In general, outdoor air is almost always cleaner than indoor air (Ragas 2011). However, there are exceptions and air quality can vary during the day. Occupants should have the right to choose what they prefer. An information system about the outdoor air quality could support them.

f. disturbance of mechanical ventilation

Due to pressure differences the air distribution within the building might become insufficient. At the moment there is not much scientific information how large this problem is. It probably only occurs for a limited number of hours per year at high wind speeds when users close the windows anyway and when there is often already a larger air change rate via infiltration.

g. condensation risk

When the temperature of a surface is lower than the condensation temperature of outdoor air and moisture is being produced by occupants, surfaces can become wet. When surfaces have a sufficient high temperature this problem can be evaded. In the Netherlands condensation can usually be prevented when surface-temperatures are above of 18 $^{o}$C at unfavourable outdoor circumstances. To remain 18 $^{o}$C the enthalpy of the air should be lower than 45,000 kJ/kg (water content of the air 11.5 g/kg). However, at very rare outdoor conditions of 30 $^{o}$C and 50 % or 28 $^{o}$C 60 % of relative humidity with an enthalpy of 65,000 kJ/kg (water-content 16,9 g/kg), a surface-temperature of 21 - 22 $^{o}$C will be necessary. This problem can be evaded with enthalpy-control of cooled water. This kind of control is for instance used in the town-hall of Amsterdam with cooled ceilings and in the high rise of the Ministry of Justice in The Hague with concrete core activation. In these buildings all the users still have openable windows.

h. Relative humidity too low or too high

There is still an ongoing discussion about the effect of the relative humidity on adaptive thermal comfort. The effect of the level of humidity on overheating seems to be overestimated by 30% compared to the current adaptive model (Vellei 2017). Nevertheless, dryer air allows higher temperatures at which people feel still sufficient comfortable. It is not clear how much effect dry air has on health and wellbeing and which level is really critical. The feeling of dry air seems often be produced by small dust particles. On top of that, people react in a different way on dry air. A dry throat and skin can be disturbing, but there are also people with asthma who have an allergic reaction on house dust mites and prefer dry air. On top of that, infection risks are different for bacteria and viruses leading to different preferred ideal humidity's. Most of the current mechanical ventilated buildings are not humidified, generally without loss of comfort. However, the main reason seems to be to save investment and maintenance costs.

i. other limitations and boundary conditions

Prevention of the ingress of rain, burglars and insects or birds is important. There are many solutions for these problems such as sheltered windows, limitation of the opening width, security grilles and insect and bird netting. Solutions depend on the design and surrounding of the building and location, and type of windows to what optimal prevention options are. Solar shading like screens can also limit the amount of ventilation and will influence the temperature of incoming air. There are special design solutions to prevent this, like keeping some free space between the screen and the façade.

Many automatic openable windows have systems that make much noise during opening or closing. Solving this problem needs more attention.

j. higher investment and maintenance costs of the façade

The costs of façades with openable windows are indeed higher, but it should be compared with the losses related to reduced user satisfaction, productivity loss, future value of the building, reduced resilience in times with a failure of the installation, or increased infection risk. On top of that the costs of the installation is usually higher because all the required cooling should be realized with the installation. The experience of the outdoor environment and seasons inside, like the odour of air and daylight is most relevant (Guzowski 2003). Energy-consumption of fans and cooling will be lower than with only a mechanical system or a single skin façade.

This discussion can be compared with the application of outside sunshade which reduces the cooling demand and increases visual comfort. A cost-benefit analysis is necessary.

k. Ineffective behaviour and insufficient awareness of the user

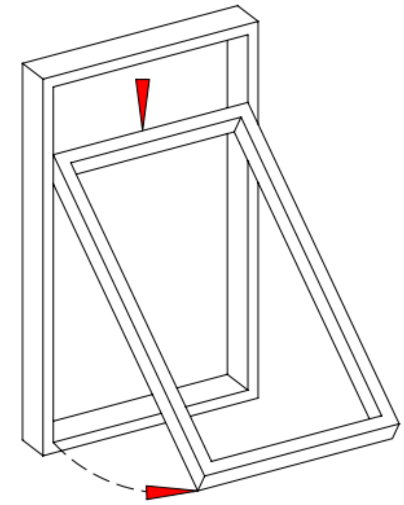
One of the main questions about window-control related to energy consumption, or protection against rain or burglary is user behaviour. What is reasonable to expect from a user? This question is not easy to answer. In the users own house, it is usually rather well understood when to open or close a window. In winter it will influence the energy bill when windows are open too long, but not all users are aware of this because there is no direct feedback-system. When a user leaves the house mostly the window will be closed because of the risk of burglary and raining in. Not all users know that leaving window open on a very hot day the house will become warmer as well. In offices occupant behaviour is even more difficult to predict because usually it is not the property of the occupant which generally leads to a feeling of being less responsible. Double skin facades in principle can save energy compared to single skin façades, but at the moment the opposite is often the case in Germany (Leão 2016). In many buildings there is someone who has to close all the windows after office time, such as a caretaker or someone who cleans the rooms. For large offices this is a time-consuming and rather costly activity. On top of that some office-rooms maybe forbidden to enter without permission. A completely different approach could be making buildings and spaces - to a certain extent - “fool-proof” against user behaviour that is not energy- of comfort-efficient. This is, for instance, an approach that can also be seen in houses where is too much moisture production leading to mould. In many modern apartments this is not a problem anymore. Locally a user might open windows on unfavourable moments, but it could have little effect on the building as a whole. There is always a limit to inefficient behaviour. When it becomes too hot in a space, occupants will tend to close sunshades or open a window by themselves. In winter openable windows will be closed when it becomes too cold. It is a logical human response. Most problems occur when there are no occupants during the night, weekends or holidays.

Some types of 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.

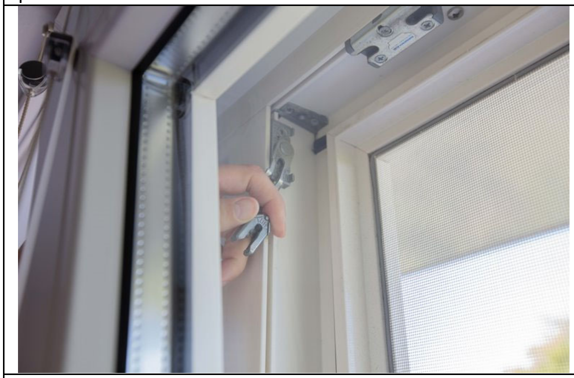


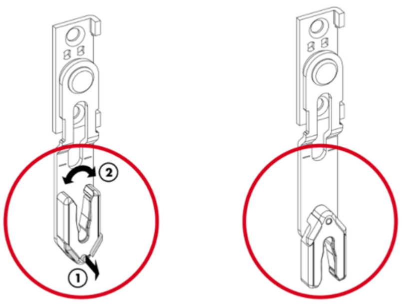
a

Example of a window type that can realize many different sizes and positions of ventilation openings for cooling and draught prevention.

b

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.





| Winter position | Summer position |
| --- | --- |

c option to create a winter or summer position of a window (Schipper kozijnen)

Figure 4.2.3: Large windows with several opening options.

Points of attention are (summarized):

- 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):

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

An opening A 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.

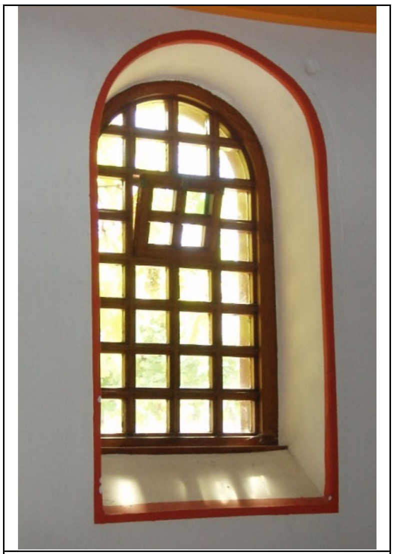
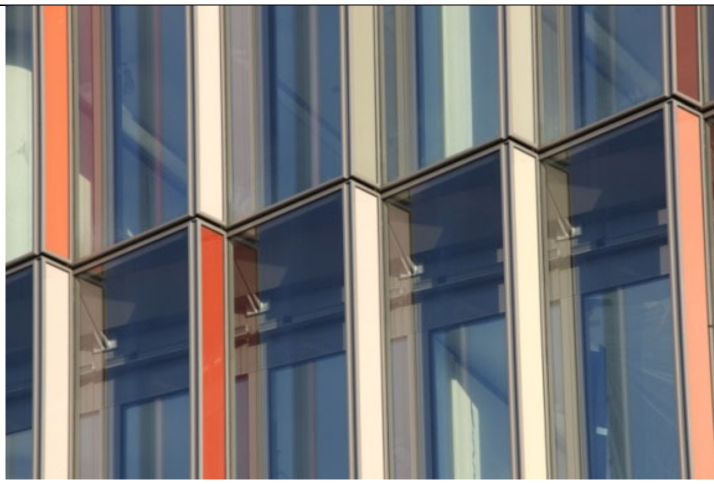


Figure 4.2.4: In Roman bath houses small ventilation elements were necessary to keep the heat inside (Archeon). Glass was already invented by the Romans

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



b

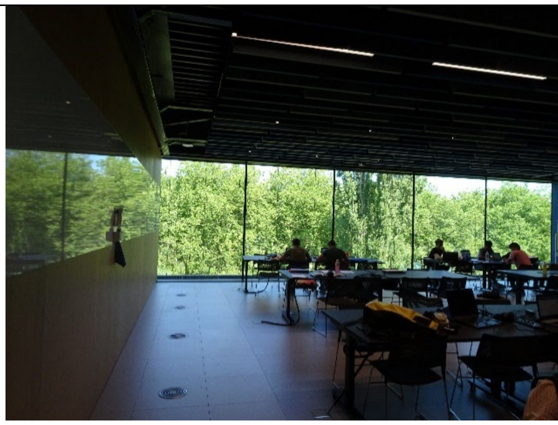
| | |
|---|---|
| St Mary Axe in London (Foster). | Kfw Westarkade in Frankfurt (Sauerbruch Hutton). The panels can be opened. |

Figure 4.2.5: Openable windows can have a strong architectural expression.

## 4.3 Second skin façades

### 4.3.1 Closed, partly or fully openable facades?

This paragraph starts with the discussion about the new Echo building at the TU-Delft that aims to be a transparent zero energy building with a fully closed facade. It is connected to the Informatics building with openable windows. It is a building where students follow lectures of all faculties, where working in project teams is possible and where students can study alone or meet each other.



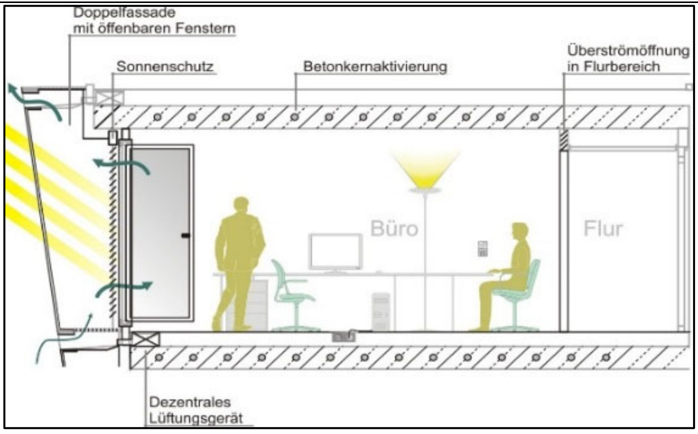
| | |
|---|---|
| a. Echo a full glaze multipurpose study centre (left) connected to the informatics building (right). The informatics building still has openable windows and robust outside sunshade. | b. Vison from a space for teamwork and workshops. Via the window there is a strong connection with outdoor nature at this side of the building. |

Figure 4.3: pictures of the new study centre of the TU-Delft

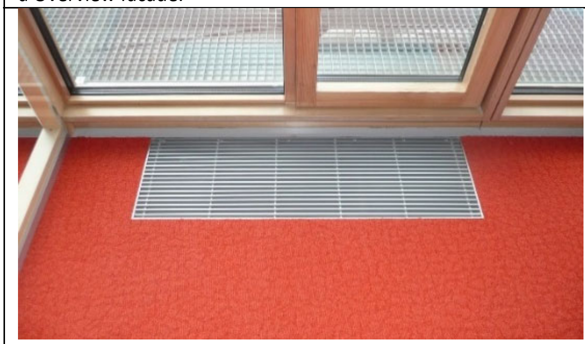
In the connected old building at figure 4.3a at the right windows can be opened and there is robust sliding outside sunshade making it possible to have an optimal daylight experience, without the effect of unnecessary solar heat from outside. In the new Echo-building this is not the case, the glass at the outside is dark (g = 0.28, with inside sunshade 0.18), making the building less transparent from outside and to some extent also from inside, what was one of the design-goals. A positive point is the strong relation with the outdoor climate via the windows (figure 4.3b), on a bright day the sun-protection on the glass can hardly be noticed. Although the building aims to be energy positive due to the many PV-panels on the roof, there is more cooling energy necessary to compensate the outside solar load and the heat loss via the façade will be significant as well. The Echo-building could be equipped with windows on strategic locations that can be opened by the BMS-system when outdoor circumstances are favourable enough, with an override function for the occupants (between limits). This should also have saved ventilation and cooling energy and would also have reduced the "chemical odour", probably VOC's, at the start of the usage of the building, for instance, via ventilation before the period of usage.

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

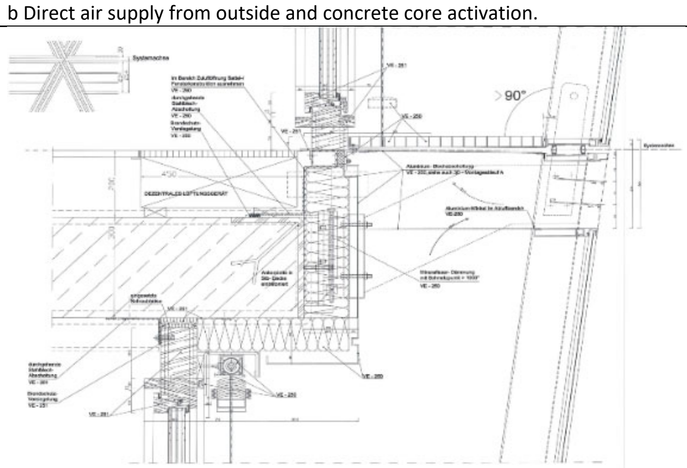
a Overview facade.




b Direct air supply from outside and concrete core activation.



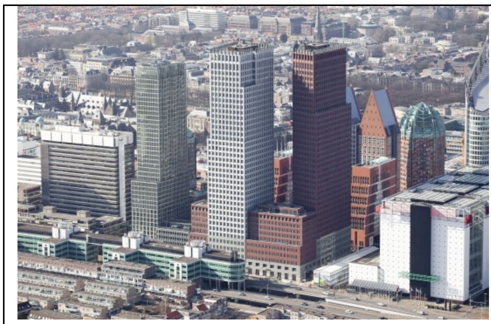
c Air supply in the floor, air can be cooled or heated.




d Detail façade near floor.

Figure 4.3.2: Second skin and separate air supply LVM Münster.

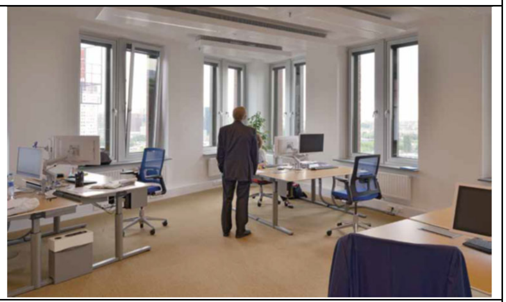
### 4.3.3 Second skin window in a high rise building, combined with mechanical air supply and exhaust



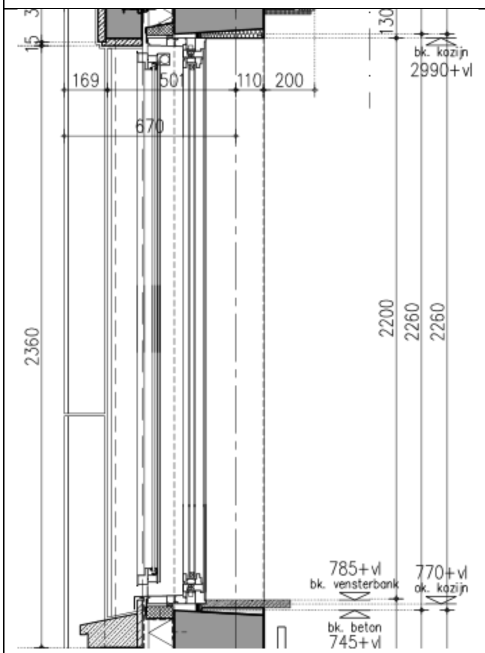
a

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.

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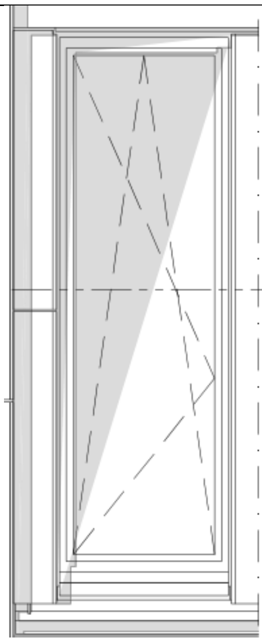

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Figure 4.3.3: Ministry of Justice and Internal Affairs, the Hague, second skin windows (“Kastenfenster”), Hans Kolhoff.

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 $\rho_1$ and $\rho_2$ of the inside and outside air is different. In equation 5.4 this difference is represented by ΔT/T.

The pressure differences due to buoyancy can also be calculated in a different, more fundamental way, by calculating the differences in volumic mass of the air:

$$\rho = \frac{P}{RT} \qquad (5.4)$$

where ρ = the density of air in kg/m$^3$, P = the atmospheric air pressure in Pa (circa 100.000 Pa), R = the gas constant for air = 287 J/kgK and T is the absolute temperature.

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:

$$\Delta P = \frac{\rho g h \Delta T}{T} \qquad (5.5)$$

or

$$\Delta P = (\rho_{cold} - \rho_{hot}) g h \qquad (5.6)$$

The air flow Q via an opening is:

$$\Delta P = \zeta \frac{\rho U^2}{2} \qquad (5.7)$$

And

$$Q = \frac{U}{A} \qquad (5.8)$$

Combining of equations leads to:

$$Q = \sqrt{\frac{2\Delta P}{\zeta \rho}} = C_d A \sqrt{\frac{2\Delta P}{\rho}} \qquad (5.9 \text{ and } 5.10)$$

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

$$\frac{1}{A_e^2} = \left[\frac{1}{A_1^2} + \frac{1}{A_2^2}\right] \qquad (5.11)$$

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:

$$\frac{\rho g h \Delta T}{T} = \frac{Q^2 \rho}{2 C_d^2}\left[\frac{1}{A_1^2} + \frac{1}{A_2^2}\right] \qquad (5.12)$$

Or:

$$Q = C_d A_e \sqrt{\frac{2 g h \Delta T}{T}} \qquad (5.13)$$

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

$$H = Q \rho c \Delta T \qquad (5.14)$$

$$H = \rho c C_d A_e \sqrt{\frac{2gh\Delta T}{T}} \Delta T = \rho c C_d A_e \sqrt{\frac{2gh\Delta T^3}{T}} \qquad \text{(5.15 and 5.16)}$$

$$\Delta T = \frac{H^{\frac{2}{3}} T^{\frac{1}{3}}}{(2gh)^{\frac{1}{3}} \left( pcC_d A_e \right)^{\frac{2}{3}}} \qquad \text{(5.17)}$$

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:

$$h_0 = \frac{A_1^2 h_1 + A_2^2 h_2}{A_1^2 + A_2^2} \qquad \text{(5.18)}$$

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.

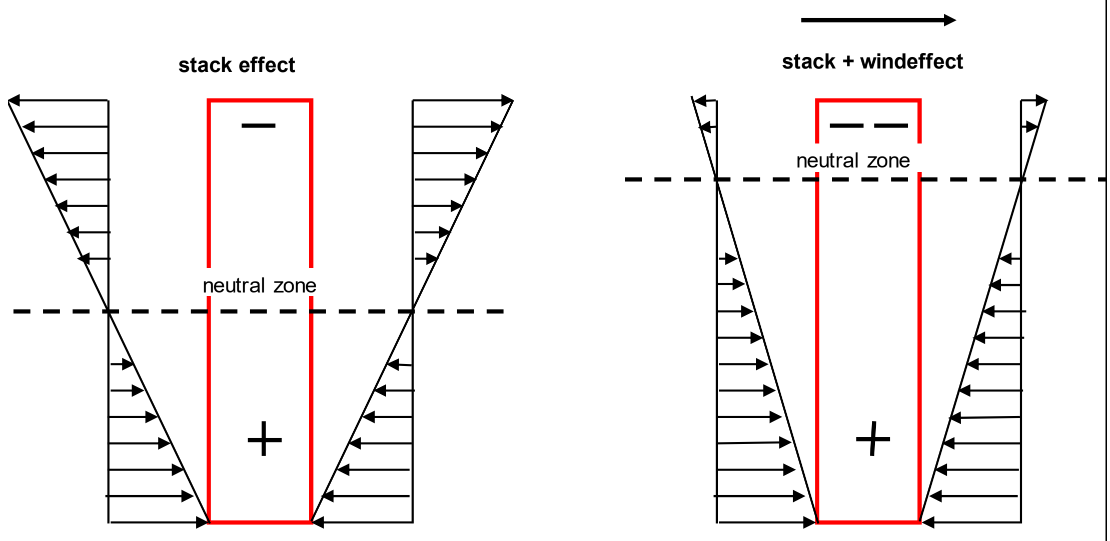



Figure 5.1.1.a: Position of the neutral zone in a high rise building. When leakages are evenly distributed over the façade the air will flow out above the neutral zone. The level of the neutral zone can increase due to more under pressure by the wind or by buoyancy forces. In the GSW-headquarters the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

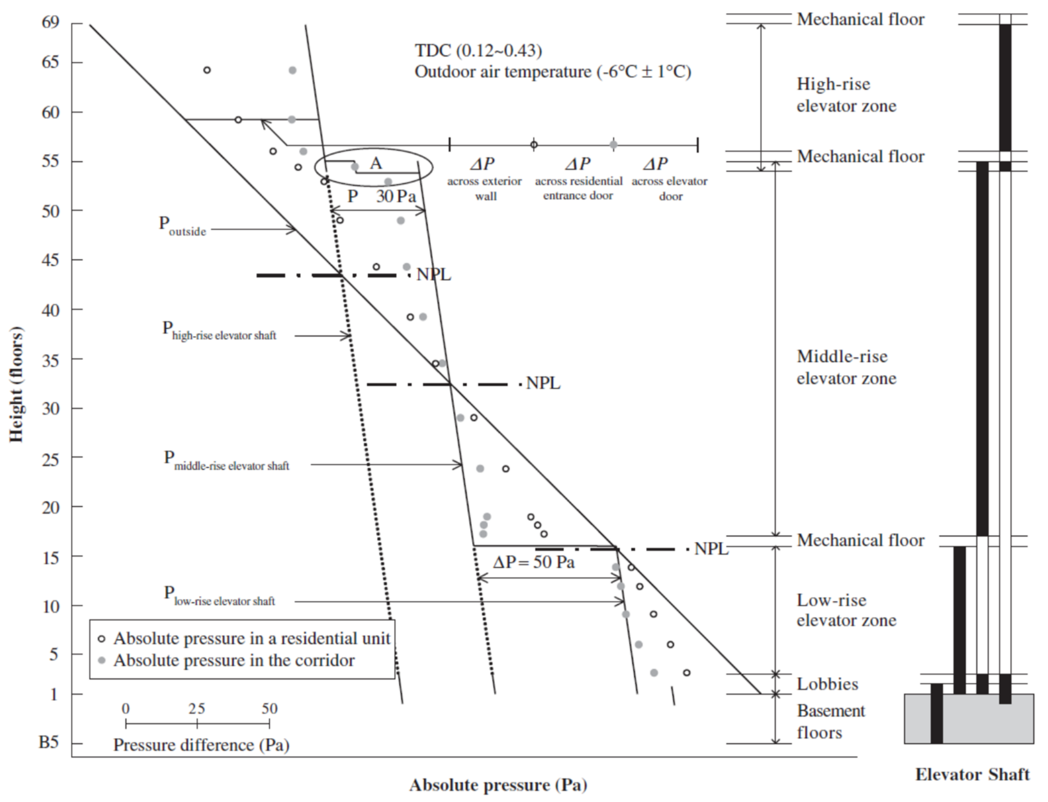



Figure 5.1.1.b: Example of real (measured) pressure distributions in a high rise residential building in Korea in winter (Jo et al 2007). Due to the presence of pressure correcting zones there are several neutral planes. The total pressure difference is around 150 Pa.

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:

$$\Delta P = \frac{C_p \rho U^2}{2} \qquad (5.19)$$

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 ° have always a negative pressure and pitched roofs have always a negative pressure up to 25 ° (Allard 1998, Grosso 1994).

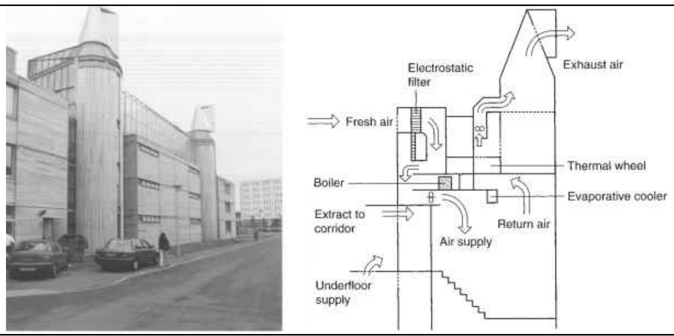
Wind towers doe not only make use of wind but also from buoyancy and downdraught. The thermal mass plays an important role. During the night the thermal mass is warmer than the surroundings, so buoyancy is available. During the day downdraught will be stimulated. In this way there is a parallel with 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.

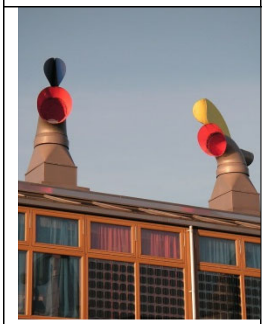
c Example of new designed windcatchers, Aga Khan Maternity.




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).



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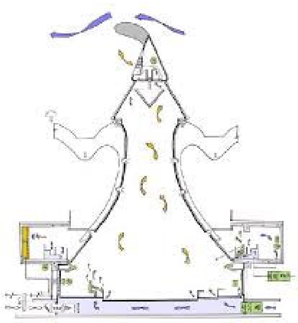
Prototype Tarmac for Bedzed.

f

Only exhaust.

National Assembly of Wales (Rogers).



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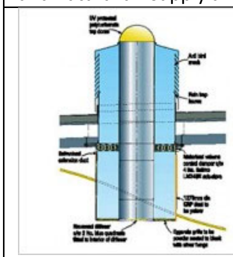
h

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



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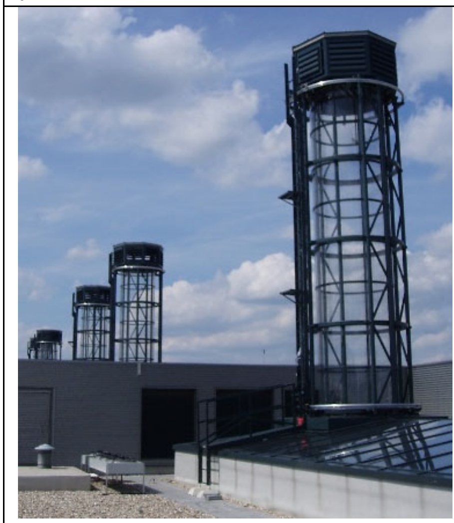
City-office Ypenburg (Halmos) This building has a stork-shaped outlet on the building. The direction of the stork depends on the windangle.

k

l

Figure 5.1.2: Examples of windcatchers/cowls.

a



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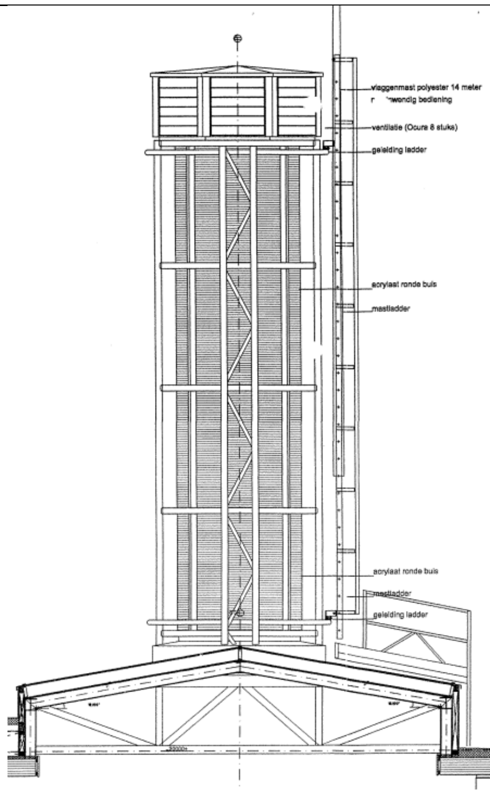
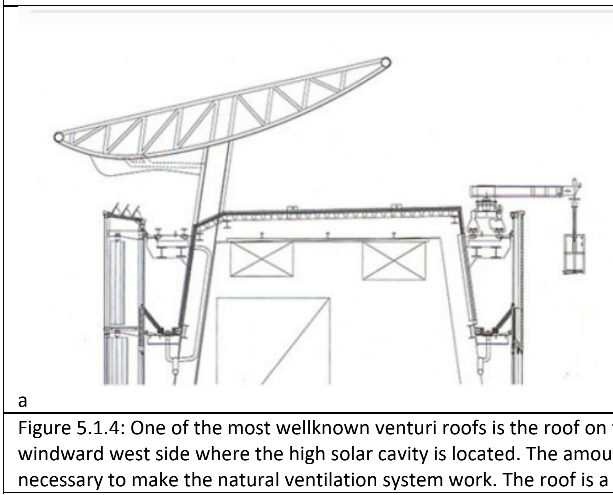


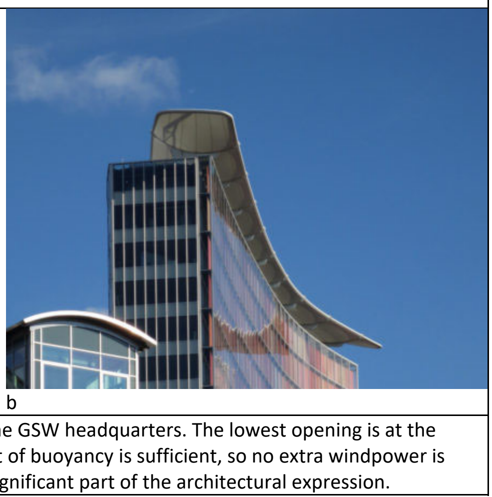

c

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.

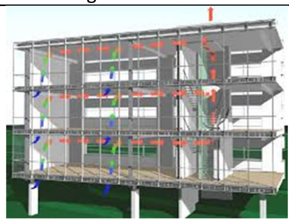
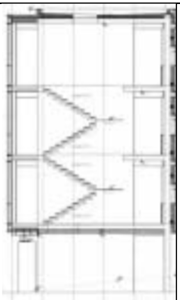
| Low and hidden chimneys, Bang & Olufsen building. | | | |
|---|---|---|---|
|  a |  b |  c |  d |
| There is no exhaust on the roof visible from outside the building. | Pattern air flows. | Crosssection staircase. | Exhaust on the roof, with integrated fan. |

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)

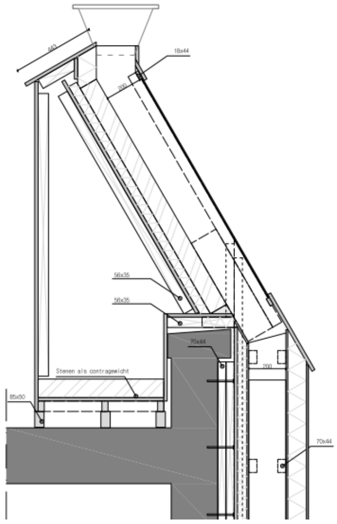
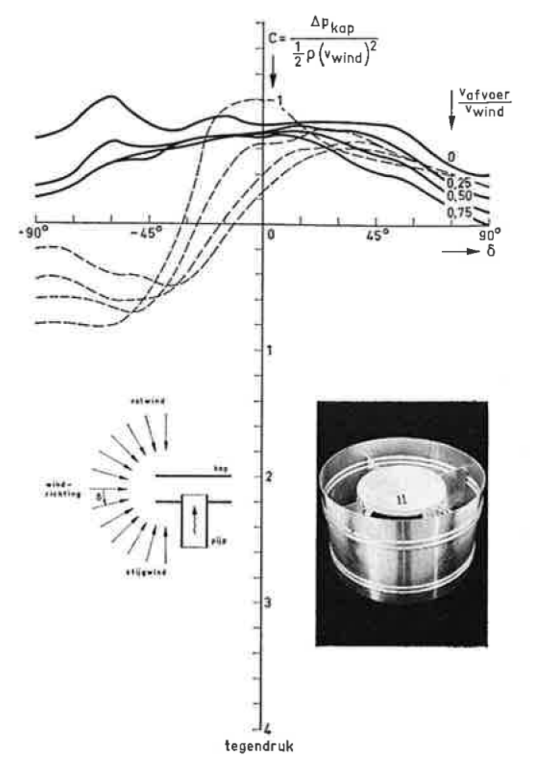
|  |  |
|---|---|
| a Prototype solar chimney for a house (research at the Hogeschool Rotterdam). | b Cross-section prototype solar chimney, the optimum slope was around 60°. |

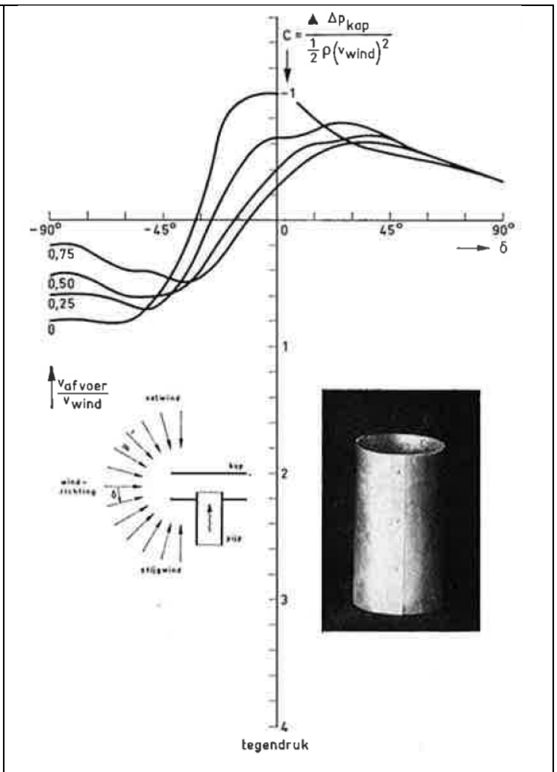
Figure 5.1.6: Example of a solar chimney for a house. The most optimal slope of the chimney is chosen with regard to solar gain and air flow. In the chimney a black surface with thermal mass and insulation behind the thermal mass is incorporated. With this shape the chimney can easily be integrated in 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 clean, 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 $^{o}$C, via filtering by reversed osmoses or via ozone radiation. A water-treatment procedure is necessary to prevent pollution or calcium in the water.

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.

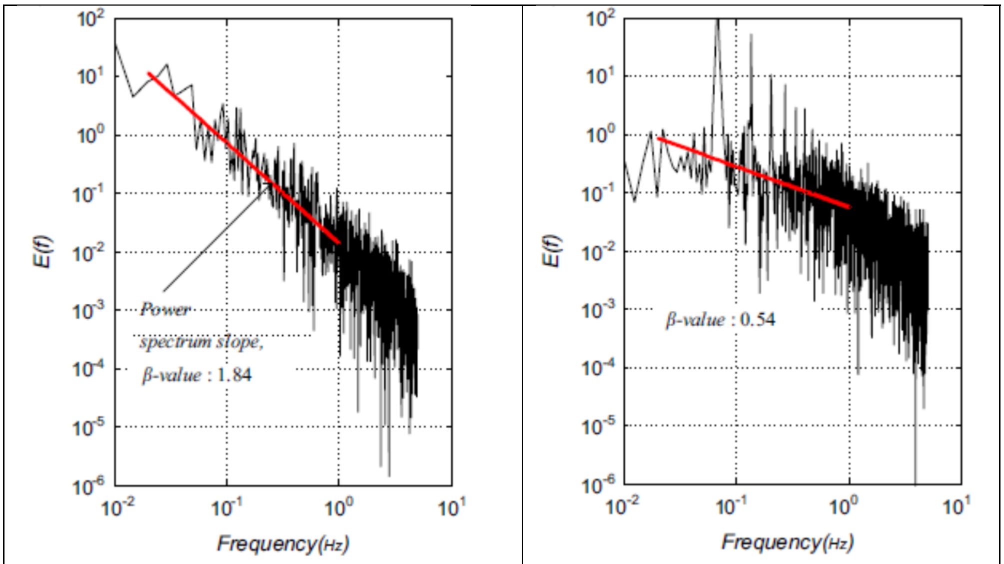
i. Effect of noise

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):

$$E_f \propto 1/f^B \qquad (5.20)$$

## 5.2 Computer calculations

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

a. Hand-calculations and Excel-models

In order to get a first-order insight to control design parameters it is often handy to make use of a hand- or Excel-calculation model. Excel-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.

For a relative simple model, a one storey house with a chimney, developed by Axley and Nielsen, show still the option of a hand-calculation of pressure and air flows (Axley 2008). This makes also clear that a computer-model is almost inevitable for more complex and realistic situations. Nevertheless hand-calculations always give essential insight and are often necessary to check the result of computer-calculations.

User-friendly and practical Excel-programs for single sided ventilation, cross ventilation and stack ventilation with a realistic physical background are, for instance, developed by Michiel van Bruggen for the TVVL (2017) and by CIBSE (2014). The weblinks are:

Single sided ventilation: http://mijnenergiemanager.nl//tools//Hyb//Isolated//Isolated.html

Ventilation via two sides of a building combined with a central chimney/atrium:

http://mijnenergiemanager.nl/hybvent/

This model can also be used to check if active cooling could be prevented or limited, because the external and internal heat load and thermal mass is included in the model. By variation of the internal pressure the position of the neutral zone can be chosen, which is essential to find a solution of the calculation with only one iteration. In this model a minimum and maximum chosen internal pressure gives an acceptable solution, which depends on the size of the exhaust.

The same procedure with a chosen internal pressure is followed in the excel-model (AM10CalcTool) of a natural ventilated building with a chimney of the CIBSE AM10 handbook (CIBSE 2014), but in this model the chosen flows are fixed. The AM10-model can be used for different ventilation situations related to under- and overpressure which is practical for an early evaluation of a design.

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). Relevant information of Cp-values can be found in the database of the Air Infiltration and Ventilation Centre (e.g. Liddament 1986).

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.

- LoopDA. In order to calculate the pressure balance in a building in detail LoopDA of the National Institute of Sandards and Technology (USA) can be used. https://www.nist.gov/el/energy-and-environment-division-73200/nist-multizone-modeling/software-tools/loopda. This software tool can be utilized to determine the size of natural ventilation openings necessary to provide airflow rates that satisfy design objectives based on minimum ventilation and cooling load requirements.

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)

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## 5.4 List of symbols

| | | | |
|---|---|---|---|
| A | = | opening | $m^2$ |
| $A_{eff}$ | = | effective opening | $m^2$ |
| Ar | = | Archimedes number | - |
| $C_d$ | = | drag or flow coefficient | - |
| $C_{gem}$ | = | average virus concentration | quanta/$m^3$ |
| $C_p$ | = | 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 | = | air pressure or atmospheric pressure | Pa |
| p | = | pulmonary air volume | $m^3/h$ |
| P(inf) | = | infection risk via aerosols | % |
| q | = | expected virus-emission of one person | quanta/h |
| R | | gas constant | J/kgK |
| T | = | absolute temperature | K |
| $T_{inlet}$ | = | air temperature in the inlet | K |
| $T_{room}$ | = | air temperature in a room | K |
| t | = | exposure time | s |
| U | = | air velocity | m/s |
| V | = | volume of a space | $m^3$ |
| Q | = | air flow | $m^3/s$ |

Greek symbols

| | | | |
|---|---|---|---|
| $\Delta P$ | = | pressure difference | Pa (or $N/m^2$) |
| $\rho$ | = | volumetric mass density | $kg/m^3$ |
| $\zeta$ | = | resistance coefficient | - |

## 5.5 List of figures and references

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## 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 working at Deerns and 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. Additional knowledge is based on literature research and discussions with other professionals in the field.

### 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 has been teaching at the faculty of Architecture of the TU Delft. At the moment he is consultant and guest-researcher at the TU-Delft.