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Opportunities of Natural Resources Making Buildings more Resilient

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Summary

An overview is given of the state-of-the-art of natural and hybrid ventilation in buildings in general. The focus of this paper is on boundary conditions for openable windows. As a case study the Co Creation Centre at the TU-Delft is discussed. 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 for ventilation 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. Current examples of integration are discussed, in which BMS-systems play a key role.

Keywords: Natural Resources; Buildings; Natural Ventilation; Climate

Introduction

General

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 [1]. 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 [2]. 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 [44]. This discussion is embedded here in a large overview of the current stat-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 [22]. 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.

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 [3] and his research team P.J. Lute [4] 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 [5], 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 houses, schools and offices.

More recently Ben Bronsema [6,7] had developed a hybrid ventilation system based on the idea of termite hills like Mick Pierce and Alan Short had done [8,9]. The difference with termite hills is that termite hills have always upward (day) and top down (night) air flows [10], 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 till 24 °C 50 % RH when the temperature of the droplets is sufficient low (like in an air handling unit) (Figure 3).

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 [11,12].

What can be noticed that there are high tech solutions with central hybrid or natural ventilation via ducts and shafts [6,9] and low tech solutions with direct natural air supply via the façade [5] and openable windows [3,13]. 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 [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 [14]. This has been noticed earlier by comparing demand controlled domestic ventilation systems in TRNSYS with exergy analysis [15]. An important factor for more reduction of energy and improving comfort in bedrooms is the usage of warmer and colder zones within homes [16]. 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.

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.

Typologies of Natural or Hybrid Ventilation

Introduction

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, depending on the way of design [5,17,18]. 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 [9]. 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, making use of the adaptation of people to a colder climate in winter and warmer in summer. It depends on what you call comfortable [19].

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 [20]. 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 [21]. 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 maintain air quality, prevent draught or to save heating and cooling energy. This can be a natural, hybrid or a pure mechanical ventilation system.

In an "ideal" climate with a mean annual outdoor temperature of 20 °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 [22]. 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.

Discussions about Openable Windows

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.

All these points should carefully be evaluated during the early design-process. In very advanced ventilation buildings [22] 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 for efficient, successful and cost-effective monitoring and managing 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, combined with awareness raising campaigns. Preventing unnecessary heating and cooling is also increasingly necessary in workers own homes. Key lessons can be transferred from the work place to residences, and vice versa.

Discussion about Risks

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 °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, when heat transfer from the air to the mass is possible. Personal cooling is possible at higher temperatures with the aid of higher air velocities that accelerate evaporative cooling from the skin up to upper skin temperatures of around 35^{0}C. This "comfort cooling" is sometimes called "ventilative cooling" [23,24]. This system can also be used when the indoor temperature follows the outdoor temperature but this is 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.

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 [25]. Nevertheless, this reaction could be optimized.

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 [27]. 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.

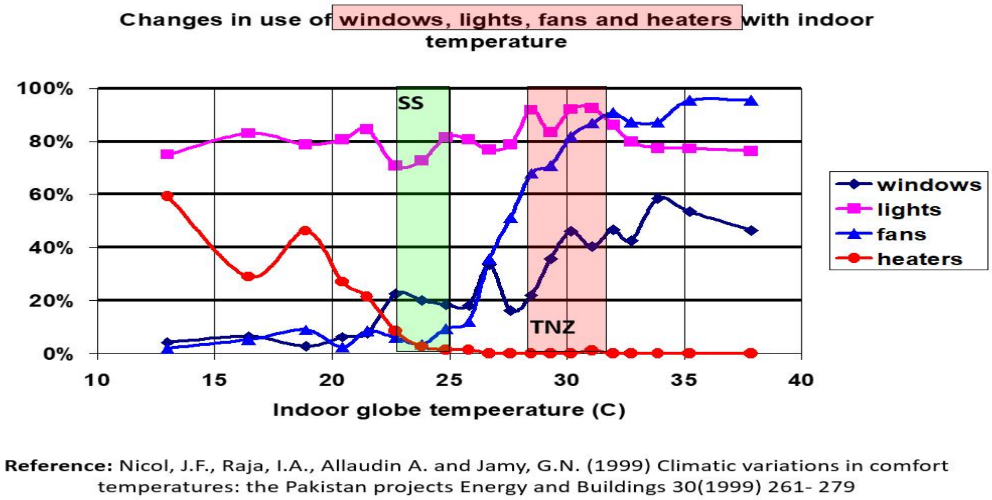


Figure 1: Adaptive control options in winter an summer [39]

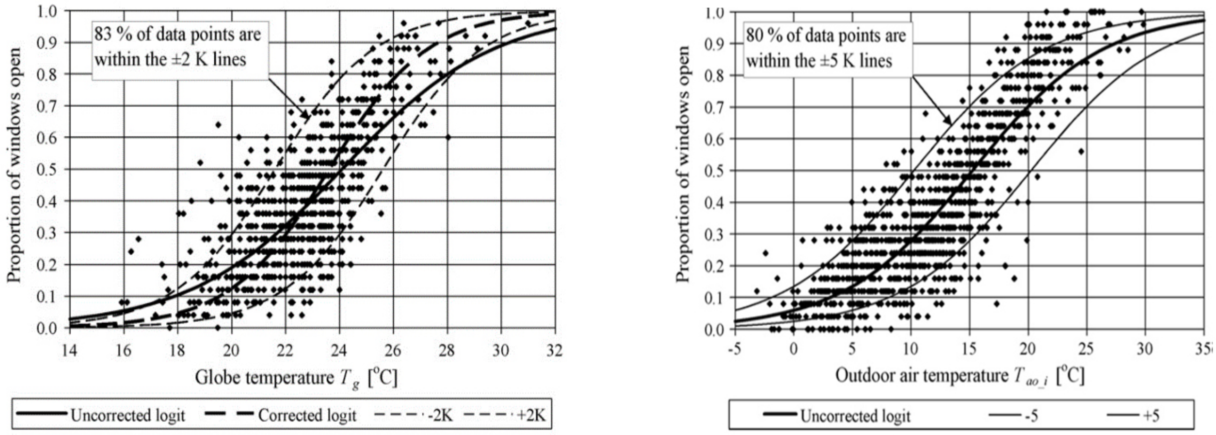


Figure 2: Relation between the operative indoor (left) and outdoor (right) temperature and the frequency and size of opening of windows [25].

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. 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 [28]. In the heating season unnecessary ventilation during non-occupancy time is one of the main reasons of to much energy consumption.

Shortage of Cooling Capacity of the Chiller, Heat pump or Cold storage

When there is much extra outdoor air with a high enthalpy 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.

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 shops and restaurants 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 [40].

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 [5,17], which is completely ignored in current Dutch standards [41]. 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.

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.

Outdoor Pollution

In general, outdoor air is almost always cleaner than indoor air [29]. 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.

Disturbance of Mechanical Ventilation

Due to pressure differences the air distribution within the building might become disturbed. At the moment there is not much scientific information how large this problem is. It probably occurs only 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.

Figure 3: In the Langeveld building, a multipurpose study centre, at the Erasmus university in Rotterdam, a very low pressure hybrid ventilated building with solar/wind towers still has openable windows. The air can be cooled and humidified via a droplet shower in the central shafts, creating significant air pressure to induce the air flow [6,7].

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°C at unfavourable outdoor circumstances. To remain 18 °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 °C and 50 % or 28 °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 °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.

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 [30]. 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.

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. 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.

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 [2]. Energy-consumption of fans and cooling can 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, but might increase maintenance. A quality and cost-benefit analysis is necessary.

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 [26]. 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.

Ventilation-efficiency and COVID

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 [31]. 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 [32]. Effective displacement or personal ventilation are other options with a potential high efficiency.

The Wells-Riley equation [33,34] leads to substantial higher ventilation rates when a low infection risk is required: for instance 1, 5 or 10 %. The Wells-Riley equation assumes fully mixed air. When the ventilation effectiveness is better the risk will become lower. Normally a volume of fresh air of minimal 25 m^3/h (fully mixed air) per person would be just enough to keep the CO_2-level of the air below 1200 ppm. This is often considered as the maximum for health reasons, but event that is a point of discussion [35]. When the infection risk should be below 10 % and a small room is 70 m^3 used for 2 hours by an infected person producing 25 "quanta" per hour (a quanta is a unit of virus-emissions that can lead to infection), 2 x 100 m^3/h of uninfected air will be necessary for two persons. More efficient ventilation, natural ventilation and filtering of air are all options to reduce this infection risk [13]. New insights [36] show that distance between people in a room is also an important parameter to consider.

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 is the same between the supply and exhaust of fresh air, or recirculated air with an effective filter, the risk reduction of both systems is comparable [13]. Short-circuiting is one of the main problems of movable local air filters as well. 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 much more effective than single sided ventilation, apart from the increased air change rate [21,37], but this has a higher draught risk and is more difficult to control.

After increasing infection risks of new variants of Covid, the risk is now much lower and the discussion will come back during a new pandemic. However, a smart integrated and flexible ventilation design, able to reduce the infection risk and prepared for a new virus outbreak remains important. Natural ventilation and substantial more ventilation in general, which is the current trend already, can play an important role to reduce the risks.

Reduction of Overheating

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 possible 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 °C or sometimes up to 40 °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 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.

Building Examples

During and after the workshop "passive solutions" of CLIMA 2022 several buildings have been compared. These are discussed again in this paper.

Energy Academy Europe

The Energy Academy Europe has been discussed in a workshop "Innovative Passive Solutions" at Clima 2022. The building is hybrid ventilated and has a glass façade.

Figure 4: Energy Academy Europe, inside and outside

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.

Co Creation Centre

The Co Creation Centre at the Green Village of the TU-Delft has different control strategies.

Figure 5: Automatic openable roof-windows in the Co Creation Centre of the TU-Delft. This building has different climate strategies [37].

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

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.

Rooftop-windows can be opened from circa 10 °C, without a serious draught problem giving already sufficient fresh air for 15 persons. 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. Only controlling the air flow by the CO_2-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 stay below a preferred 800 ppm for a situation without ventilation. To prevent the stuffy air experience, probably exacerbated by the synthetic carpets, some minimum ventilation still will be necessary.

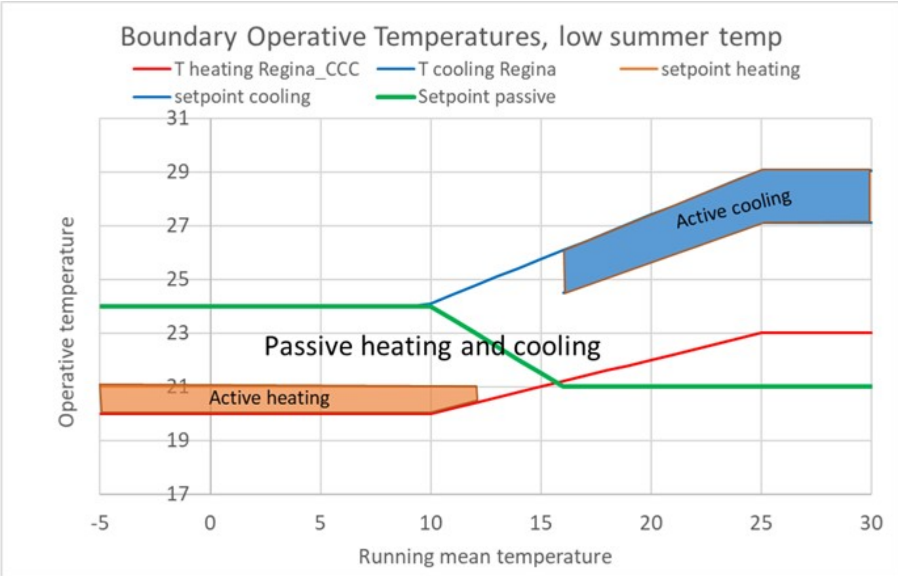
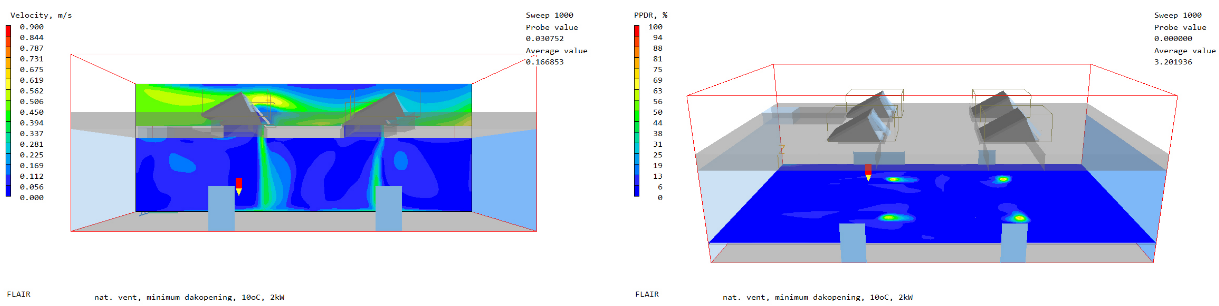


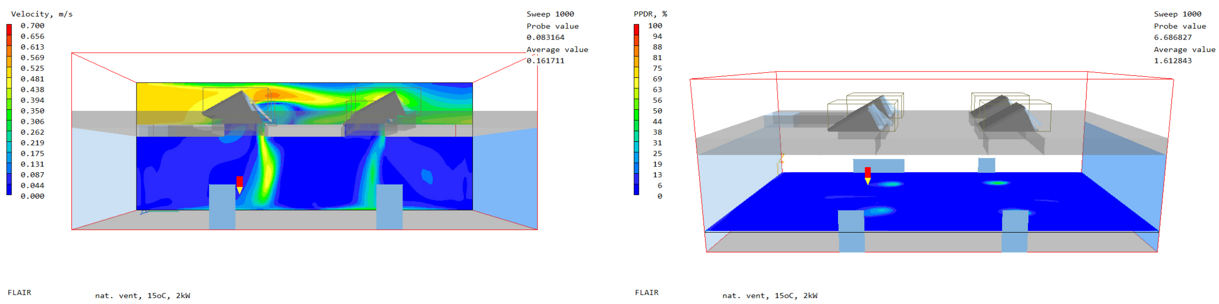
Figure 6: Temperature control strategy of the Co Creation Centre, making use as much as possible of passive energy. For instance, a higher indoor temperature in winter due to the sun is accepted, as a buffer for a colder day.

Window-Control Strategy

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



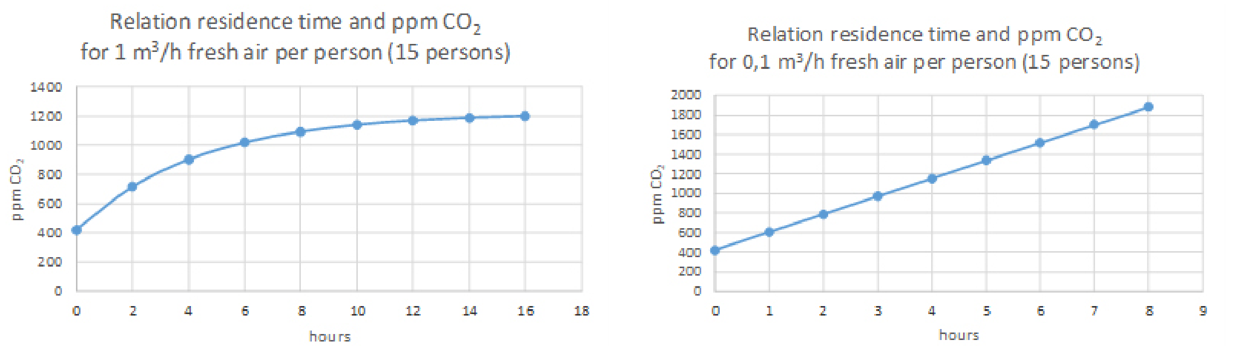
a. Air velocities	b. Draught Rate Values at 1.1 m
CFD-Draught risk analysis of natural ventilation with rooftop windows at an outside temparature of 10 °c. Window-opening 10 cm. Fresh air supply sufficient for 15 persons.	



c. Air velocities	d. Draught Rate Values at 1.1 m
CFD-Draught risk analysis of natural ventilation with rooftop windows at an outside temparature of 15 °c. Window-opening 40 cm. Fresh air supply sufficient for 24 persons.	

Figure 7: Draught risk analysis to support the window-control-strategy

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. 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:



a. CO2-concentration for 15 persons with 25m³/h pp air supply in relation to time

b. CO2-concentration for 15 persons with 0.1 m³/h pp air (almost no ventilation) supply in relation to time

Figure 8: Rise of the CO_2-concentration when there are 15 persons in the space

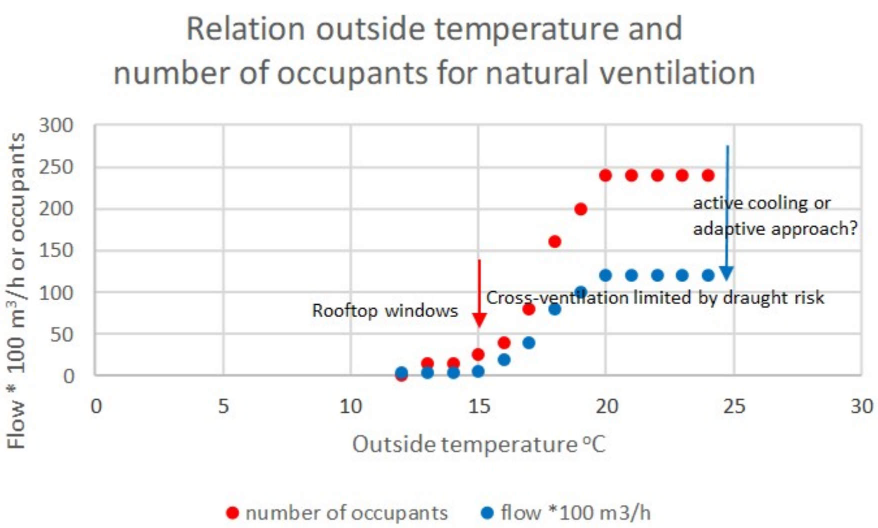


Figure 9: Relation outdoor temperature and natural ventilation in the Co Creation Centre

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.

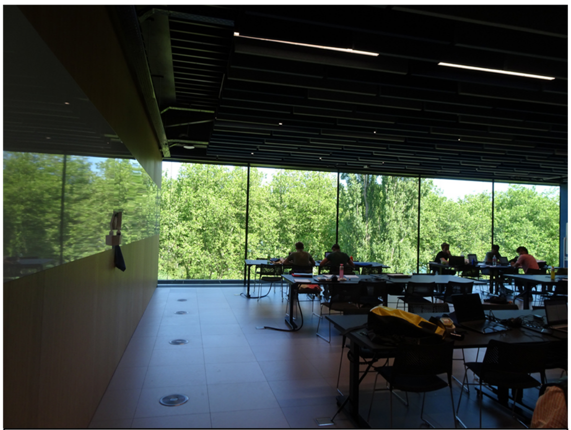
Echo-Building

A typical example of the return of closed façades is the Echo-building at the TU-Delft campus. 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.

In the connected old building 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, on a sunny 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, due to the high glass percentage there is much cooling energy necessary to compensate the outside solar load and the heat loss 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.

a. Echo a full glaze multipurpose study centre (left) connected to the informatics building (right). The informatics building still has openable windows.



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 10: pictures of the new study centre of the TU-Delft

The Development of BMS-Systems that Allow Personal Comfort and Save Energy

The aim of the BMS-system of the Co Creation Centre is to increase user comfort and reduce energy by making use of natural sources. In fact, that is also the aim of buildings with second skin façades, but those buildings of have mostly a much higher energy consumption than predicted, also compared to single skin façades [26]. Feedback systems within the BMS are often unable 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 high energy prices. A digital twin-system simulating the performances of the building seems to be necessary for a building with a complex installation in order to reduce energy with the same level of comfort, but will also increase the dependence of expensive control-engineers. On top of that human common sense remains always required, especially during the first year of usage, to react on installation-failures and unnecessary energy loss. This is the experience with the Co Creation Centre.

In the Co Creation Centre thermal comfort and energy management is controlled and optimized via a digital twin computer program. There are two options to optimize climate control, a Matlab-model via which all the relevant components of the building are simulated [38] or a model called "PrivaEco" developed by Priva, the company that designed the BMS-system. This is, in principle, a one-zone self-learning computer-model like the Matlab model, which can learn from the combined control-settings and resulting climate from the past and weather forecast. This program is, for instance, also applied in other buildings like the Lely Campus in Maassluis, of a developer of agricultural robots (Lely Nederland - Lely). This building is fully glazed without outside sunshade, making it more difficult to control the climate and save energy at the same time.

All these parameters are a challenge for architects and mechanical engineers to design smarter building physical optimized buildings with robust and understandable installations. Buildings that do not need much heat or cold, maintenance and a very complex BMS-system. Only small additional amounts of energy should be sufficient to fulfil personal preferences.

However, the current requirements for more sustainable solutions combined with the tendency of buildings with much glass will result in even more complex installations. These contradictory developments should be evaluated again in the next future.

Figure 11: general overview of the BMS-system of the Co Creation Centre. A heat pump, plate exchanger and PCM-battery are visible. Temperatures, CO_2-levels, relative humidity, air pressure and air flows are measured and presented. Apart from this there is also an energy management module under development.

Conclusion and Recommendations

General

The focus of this paper is on the advantages of openable windows. These can increase user satisfaction and connected productivity, reduce energy and infection risks. However, the way of design and integration of windows in the building and installation as a whole, determines if it is really successful or not. The state-of-the-art of current technologies and indoor climate science is presented, but not in much detail. More can be found in current design guides (for instance: [22,42]) and needs additional research.

Design

- 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. Natural air supply to spaces can have a low draught risk and result in 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. High glass

percentages should be evaded as much as reasonable possible.

- 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.

Control

- 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 out good control-examples and effective ways of user-information in buildings.

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.

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References

1. MacFadden J (2021) Life is simple: how Occams's razor set science free and unlocked the universe. Basic Books.

2. Guzowski M (2003) The "costs" of operable windows: on the question of operable windows in cold climate design. Proceedings of the Environmental Design Research Association (EDRA) Conference.

3. Paassen HAC van (1996) Cooling and ventilation with adjustable window openings. From symposium: Ventilation via the facade, a delicate balance between air quality and energy use.TU-Delft.

4. Lute PJ (1992) The use of predictions in temperature control in buildings. A passive climate system application. TU-Delft Master-report.

5. Engel PJW van den (1994) "Inducing vents and their effect on air flow patterns, thermal comfort and air quality." Indoor Air, an integrated approach.

6. Bronsema B (2013) Earth, Wind & Fire – Natuurlijke Air--conditioning. Thesis TU-Delft.

7. Bronsema B (2022) https://bronconsult.org/language/en/research/the-earth-wind-fire-concept/

8. Pierce M (2022) Eastgate Building Harare (mickpearce.-com).

9. Lomas KJ (2007) Architectural design of an advanced naturally ventilated building form. Energy and Buildings 39: 166-81.

10. King H, Ocko S, Mahadevan L (2015) Termite mounds harness diurnal temperature oscillations for ventilation. PNAS 112: 37.

11. Cai J (2019) Microgrid Integration of Smart facades: Integrated control of shading & operable window for CEG building. TU-Delft Master-report.

12. Wang H, Karavab P, Chen Q (2015) Development of simple semiempirical models for calculating airflow through hopper, awning, and casement windows for single-sidednatural ventilation. Energy and Buildings 96: 373-84.

13. Cai W (2022) Efficient local air recirculation at ceiling level promote the performance of purifiers and anti-epidemic efficiency of mixing ventilation in small shared rooms. Master-report TU-Delft.

14. Derycke E, Bracke W, Laverge J, Janssens A (2018) Energy performance of demand controlled mechanical extract ventilation system vs mechanical ventilation systems with heat recovery in operational conditions: Results of 12 months in situ-measurements at Kortrijk ECO-Life community. AIVC conference.

15. Sakulpipatsin P, Boelman EC, Cauberg JJM (2007) Exergy analysis as an assessment tool of heat recovery of dwelling ventilation systems. International Journal of Ventilation 6: 1.

16. Janssens A, Bracke W, Delghust M, Himpe E, Verbruggen S, Laverge J (2018) Utilization of heat recovery ventilation: steady-state two-zone heat loss analysis and field studies. 7th International Building Physics Conference, IBPC.

17. Engel PJW van den, Kurvers SR (2017) The scope of inducing natural air supply via the façade. Architectural Science Review.

18. Biler A, Tavil AU, Su Y, Khan N (2018) A review of performance specifications and studies of trickle vents. Buildings 8: 152.

19. Nicol F, McCartney K (2000) Smart controls and thermal comfort project. Final report. Oxford Brooks university school of architecture. Joule III.

20. Jo JH, Lim JH, Song SY, Yeo MS, Kim KW (2007) Characteristics of pressure distribution and solution to the problems caused by stack effect in high-rise residential buildings. Building and Environment 42: 263-77.

21. Bluyssen PM (2022) How airborne transmission of SARS--COV2 confirmed the need for new ways of proper ventilation. Routledge handbook of resilient thermal comfort.

22. Wood A, Salib R (2013) CTBUH. Natural ventilation in high rise office buildings. Routledge.

23. Chiesa C, Kolotroni M, Heiselberg P (2021) Innovations in Ventilative Cooling. PoliTo Springer Series.

24. Nicol F, Humphreys M, Roaf S (2012) Adaptive Thermal Comfort: Principals and Practice, vol. 1 of a Trilogy. London: Earthscan/Routledge.

25. Rijal HB, Tuohy P, Humphreys MA, Nicol JF, Samuel A, Clark J (2007) Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. Energy and Buildings 39: 823-36.

26. Leão M, Leão EFTB, Sanches JCM, Straub KW (2016) Energy efficiency evaluation of single and double skin facade buildings: a survey in Germany. Espaço Energia, issue 25.

27. Shahsad S, Rijal HB (2022) Mixed mode is better than air--conditioned offices for resilient comfort. Adaptive behaviour and Visual Thermal Landscaping. Routledge handbook of resilient thermal comfort.

28. Alnuaimi A, Natarajan S, Kershaw T (2022) The comfort and energy impact of overcooled buildings in warm climates. Energy and Buildings, 260: 111938.

29. Ragas AMJ, Oldenkamp R, Preeker NL, Wernicke J, Schlinck U (2011) Cumulative risk assessment of chemical exposures in urban environments. Environment International 37: 872-81.

30. Vellei M, Herrera M, Fosas D, Natarajan S (2017) The influence of relative humidity on adaptive thermal comfort. Building and Environment 124: 171-85.

31. Roaf S (2022) Covid-19. Trust, windows and the psychology of resilience. Routledge handbook of resilient thermal comfort.

32. Kulve M te. Verlinde M, Boerstra A (2020) Risk assessment of COVID-19 transmission via aerosols. Church Reformed Community of Moerkapelle, consultancy report BBA.

33. Riley RL (1982) Indoor airborne infection. Environmental International 8: 317-20.

34. Buonanno B, Morawska L, Stabile L (2020) Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications. Environment International 145: 106112.

35. Zee T van der (2022) New era of comfort has arrived. Interview with Susan Roaf where she discusses the role of CO_2. TVVL magazine.

36. Marin-García D, Espino U, Bienvenido-Huertas D, Fernández-Valderrama P (2024) Risk of bioaerosols in small and poorly ventilated indoor places with low concurrent use. DYNA 99: 71-7.

37. Engel P van den, Bokel R, Brembilla E, Araujo Passos L de, Luscuere P (2022) Converge: low energy with active passiveness in a highly occupied building. Clima 2022.

38. Araujo Passos LA de, Engel PJW van den, Baldi S, de Schutter BHK (2023) Dynamic optimization for minimal HVAC demand with latent heat storage, heat recovery, natural ventilation, and solar shadings. Energy Conversion and Management 276.

39. Nicol JF, Raja IA, Allaudin IA and Jamy GN (1999) Climatic variations in comfortable temperatures: the Pakistan projects.

40. Quyang Q, Dai W, Li H, Zhu Y (2006) Study on dynamic characteristics of natural and mechanical wind in built environment using spectral analysis. Building and Environment 41: 418-26.

41. SKNNI (2022) NEN Guidance “Good and proper work”. For equal communication between resident and builder.

42. Engel PJW van den (2023) Hybrid ventilation – a design guide. Klimapedia.

43. Vellei M, Herrera M, Fosad D, Natarajan S (2017) The influence of relative humidity on adaptive thermal comfort. Building and Environment 124: 171-85.

44. Day JK (2022) Tools and rules for behavioural agency in building: minimizing energy whle maintaining comfort. Routledge handbook of resilient thermal comfort.