ARV

CLIMATE POSITIVE CIRCULAR COMMUNITIES

ANNEX

9.2 Natural and mechanical ventilation in climate responsive and net-positive energy buildings

D4.5 DESIGN GUIDELINES OF CLIMATE POSITIVE CIRCULAR COMMUNITY IN TRENTO

WP4 SUSTAINABLE BUILDING (RE) DESIGN

Natural and mechanical ventilation in climate responsive and net-positive energy buildings

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1. Climate responsive and net-positive energy buildings: definitions

In the framework of research and practice within the field of building design, the aim of **responsive architecture** is to make the buildings able to adapt their shape, color, form or character (by means of actuators) using sensors' measurements of environmental conditions. In this way, responsive technologies such as control systems, sensors and actuators can be used to improve buildings' energy performance. This technique is distinguished from other forms of interactive building design, since smart and responsive technologies are embodied in building's fabric core elements, thus allowing, for instance, to connect the shape of the facility to the environment where it is located [1]–[6]. In practice, climatic responsive design uses weather data (e.g., wind, sun, humidity and rainfall) to create a building structure reflecting the weather conditions of the peculiar area where the building is located [7]. Some examples of applied climate responsive architecture are reported in Figures Figure 1 -Figure 2Figure 3.

Net-positive energy buildings (nPEBs) can be defined as ones that, on annual average, produce more renewable energy than they import from external sources. As Hu (2016) highlights "this is achieved using a combination of small power generators and low-energy building techniques, such as passive solar building design, insulation and careful site selection and placement" [8], [9]. In practice, many technologies and principles of net-zero energy buildings (nZEBs) are followed, with new district/network and alternative energy resources (instead than renewable) perspectives. Several techniques can be used to maximize the energy production and minimize the energy consumption in nPEB and nZEB, including: improved levels of building insulation, high performance glazing, daylight, efficient HVAC (Heating, Ventilation and Air Conditioning) systems (e.g. heat pumps and exhaust energy recovery), high efficiency lighting and control, natural ventilation and thermal regulation through thermal mass [8], [10], [11]. Examples of buildings exploiting these solutions are reported in Figure 4 and Figure 5.

Figure 1: "Ecobulevar de Vallecas" in Madrid (Spain). Built from recycled plants and materials, the building is able to lower the temperature by up to 10 °C by mimicking a greenhouse system [7], [12]

Figure 2: "Caixaforum Vertical Garden" in Madrid (Spain). 250 species of plants grow on a 460 square meters vertical garden, contributing in creating indoor and outdoor thermal comfort conditions [7], [13]

Figure 3: "Abu Dhabi Central Market" (United Arab Emirates, UAE). Resembling the traditional Islamic art of coffered roofs, the covering is able to adapt to different sunlight conditions, with natural cooling when allowed by outside conditions [7], [14]

Figure 4: "Sustainable Energy Fund Office Building" in Schnecksville (Pennsylvania, USA). The building orientation and windows' design allows to take advantage from shade, sun and daylight, minimizing the loss of energy. It also uses a roof photovoltaic array. It is planned to generate 130 % of the required energy [15]

Figure 5: "2226" in Lustenau (Austria). The office building does not use energy sources different than internal gains or solar gains, being able to always maintain a temperature comprised between 22 °C and 26 °C by means of construction techniques, night cooling by means of natural ventilation, proper use of thermal mass and sensors' support [10], [11], [16]

2. Natural ventilation principles in climate responsive and energy positive buildings

By definition, **natural ventilation** (**NV**) relies on natural forces. For this reason, it is considered one as one of the main techniques to lower buildings' energy consumption [17]. Moreover, NV was observed to significantly enlarge the acceptable range of indoor thermal comfort, with respect to mechanical ventilation (MV) systems [18]. This led to the modification of ASHRAE Standard 55 [19], which introduced adaptive model for naturally ventilated buildings, beside the steady state *PMV-PPD* model from Fanger [20]. This allowed the possibility to accept an increase of indoor temperature when outdoor temperature is higher. Moreover, it was observed that NV also led to benefits related with symptoms associated with Sick Building Syndrome, satisfaction with the environment, productivity and job satisfaction [17], [21].

For these reasons, it is clear that NV techniques are worth to be analyzed in the framework of climate responsive and net positive energy buildings For instance, eleven glass towers will be incorporated in Masdar Headquarters in Abu Dhabi, in order to achieve carbon neutrality firstly, and even energy generation later (Figure 6 -Figure 7Figure 8) [22], [23].

The natural forces used by NV are of two types: (1) wind coming from the outdoor environment and (2) buoyancy forces formed by gradients of temperature inside building [17]. Efficiency of NV depends on building's architectural and location characteristics, such as spacing and arrangements, building orientation, landscaping and size of openings [24].

Following subsections explore different techniques of NV, grouped according to the driving forces they exploit. Examples of real buildings using the techniques are also included. Main purposes NV can be used for and some guidelines to be consulted for developing NV in buildings are also listed.

It is important to highlight that more than one technique (and driving force) can be used in the same building.

Figure 6: Rendering of Masdar Headquarters in Abu Dhabi (UAE) [23]

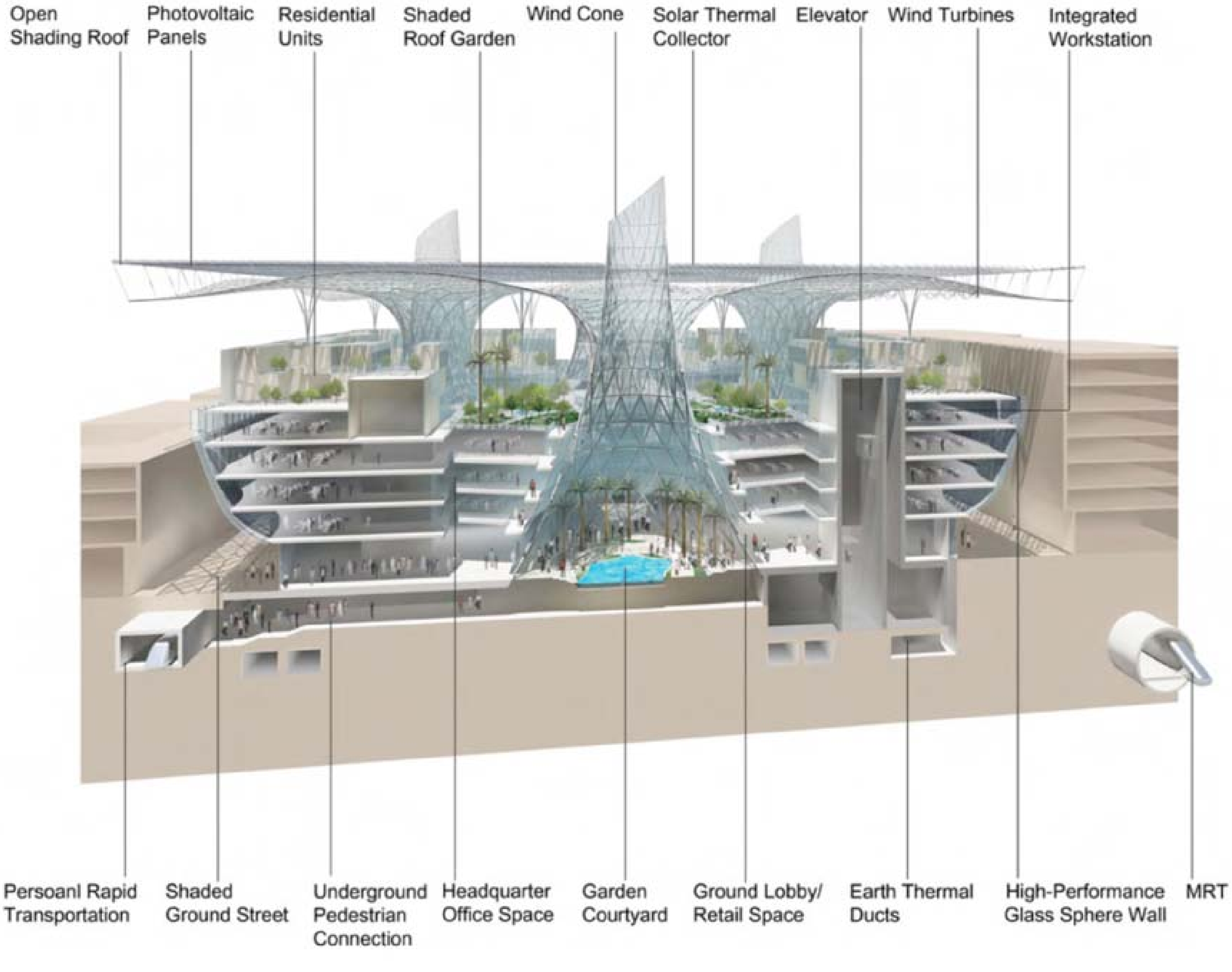


Figure 7: Section of Masdar Headquarter (Abu Dhabi, UAE) with different sustainability strategies, including wind towers [23]

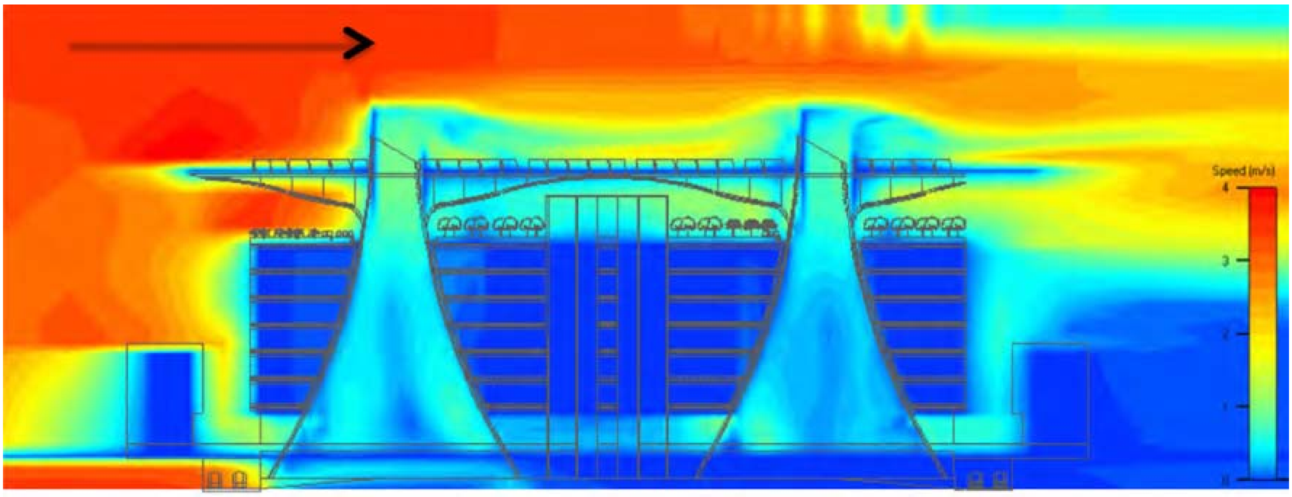


Figure 8: Section of Masdar Headquarters (Abu Dhabi, UAE) - natural ventilation through wind towers: Computational Fluid Dynamics [23]

2.1 Wind induced natural ventilation

This NV technique is driven by a difference of pressure between the windward and the leeward side of a building, resulting in an air movement due to the pressure gradient (Figure 9) [24]–[30]. It is important to remark that architectonic solutions for wind induced NV (listed below) can also be exploited for buoyancy driven NV, even if some further attentions might be needed (i.e. windows or openings at different heights to take advantage of convection).

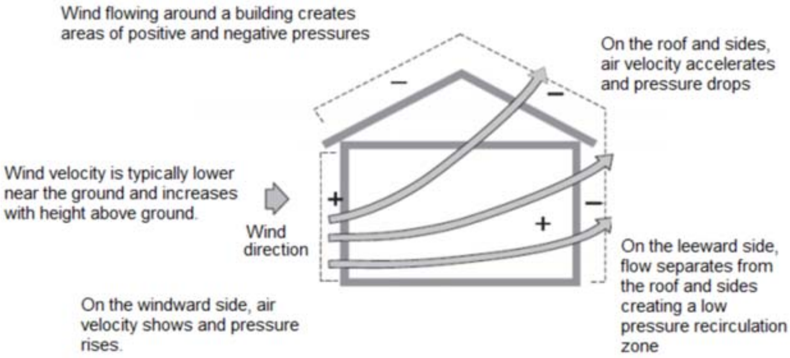


Figure 9: Mechanism of wind induced natural ventilation [24]

2.1.1 *Fenestration: single-sided ventilation*

This type of NV is produced through one or more openings on the same side (wall) of an enclosed indoor space. Ventilation is mainly driven by turbulence. It is the most simple technique, but low ventilation rates and airflow depth penetration are induced. The ventilation rate can be increased by stack effect if more than one opening at different heights are present [24]–[30].

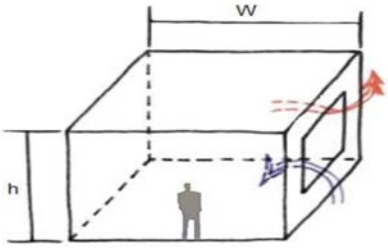


Figure 10: Single-sided ventilation [24]

Figure 11: Bauhaus (Dessau-Roßlau) – lined up windows operated by one unique joint actuator [25]

2.1.2 Fenestration: cross ventilation

This NV technique is driven by airflow entering an indoor space from an opening on one side (windward wall), and leaving from another side (leeward wall). Consistent airflow and deep air penetration can be achieved. An additional buoyancy effect can be produced if intake and outtake openings are located at different heights. Nevertheless, uncomfortable drafts might be produced by inappropriate windows' design [24]–[30].

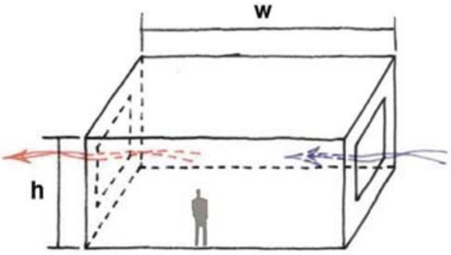


Figure 12: Cross ventilation [24]

2.1.3 Wind tower / Wind catcher

Being located next to the roof or as separate structures, they are designed to cool and circulate air by means of prevailing summer winds. Having several openings on different sides, they can work as inlets and outlets at the same time. They can be used together with wind scoops (see Paragraph 2.1.6), with the latter working as inlets. More air flow can be produced collecting and extracting air at higher levels [24]–[30].

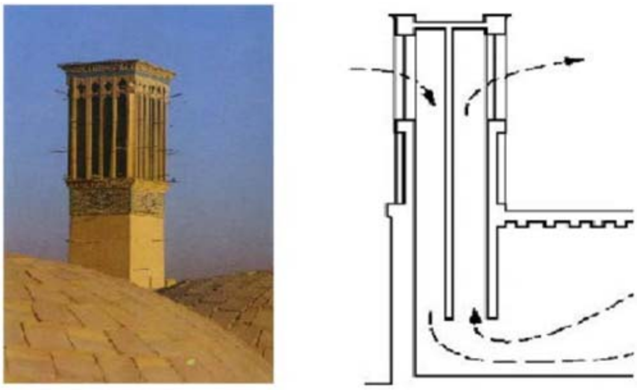


Figure 13: Wind tower [24]

Figure 14: Yazd (Iran) – traditional wind towers [25]

2.1.4 Wing walls

Wing walls are used to increase efficiency of NV, especially with single-sided NV and on sites with variable direction and/or low velocity of external wind. Constructive elements are used to increase the pressure gradient between inflow and outflow of air [24]–[30].

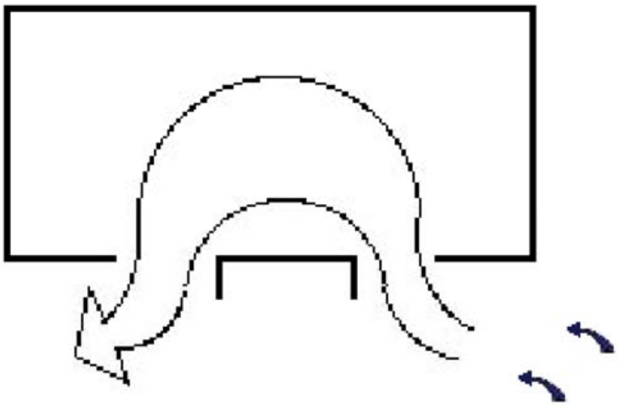


Figure 15: Wing walls [24]

2.1.5 Deflection by edges

This constructive technique is also used to improve the air-change, by means of deflection of the prevailing wind direction [24]–[30].

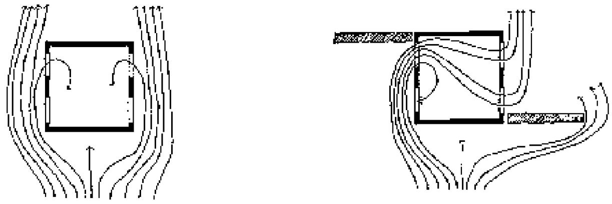


Figure 16: Example of a 90° deflection obtained by edges [24]

2.1.6 Wind cowls / Scoops

This architectural element is thought to catch a higher pressure air from roof top, carrying it below. This allows warm air to escape again from a higher opening. The effectiveness of the scoop depends on the opening angle (with an angle higher than 30° it starts to be ineffective). They can also be placed in the landscape outside of the building, with air being conducted via embedded ducts [24]–[30].

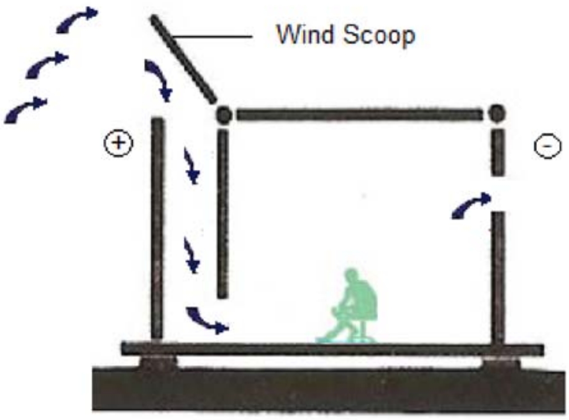


Figure 17: Wind scoop [24]

Figure 18: Wind cowls able to move with the wind changing direction in a beer brewing of Kent (England) [25]

Figure 19: Wind cowls enhancing NV in Nottingham Jubilee Campus (England) [25]

2.1.7 Rotating wind cowl, turbine ventilators, exhaust cowls, roof vents, roof cowls

These elements are used to enhance wind-driven ventilation. In order to improve the interaction with the external wind, they can be installed on the roof [24]–[30].

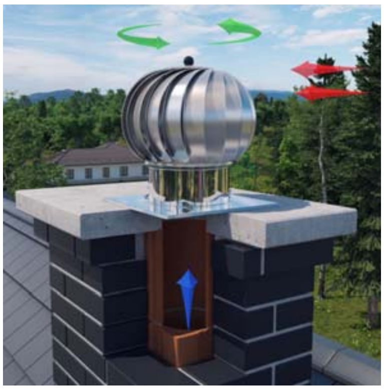


Figure 20: A roof chimney cowl, designed to increase and stabilize the draft of the chimney and the smoke ducts *[31]*

2.1.8 Ventilation openings in the façade

These elements are designed with the sole scope of being inlets and outlets for ventilation. In order to support a sufficient pressure drop, their size needs to be adequately designed. They can also be coupled with local suppliers or extractors [24]–[30].

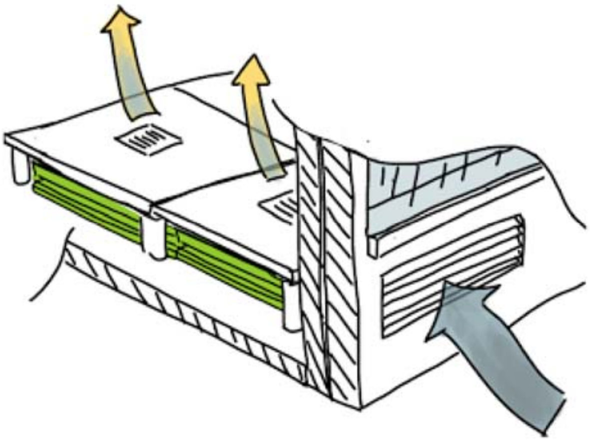


Figure 21: Ventilation openings in the façade [24]

Figure 22: Harm A. Weber Academic Center at Judson University in Elgin (Illinois, USA) – ventilation exhaust device on the roof [25]

2.1.9 Embedded ducts, ventilation chambers

These elements are defined as spaces within buildings, with the primary scope of collecting, transporting and distributing ventilation air [24]–[30].

2.2 Buoyancy driven natural ventilation

This technique of NV is driven by temperature gradient, which produces an upward airflow due to thermal buoyancy (Figure 23) [24]–[26], [28]–[30].

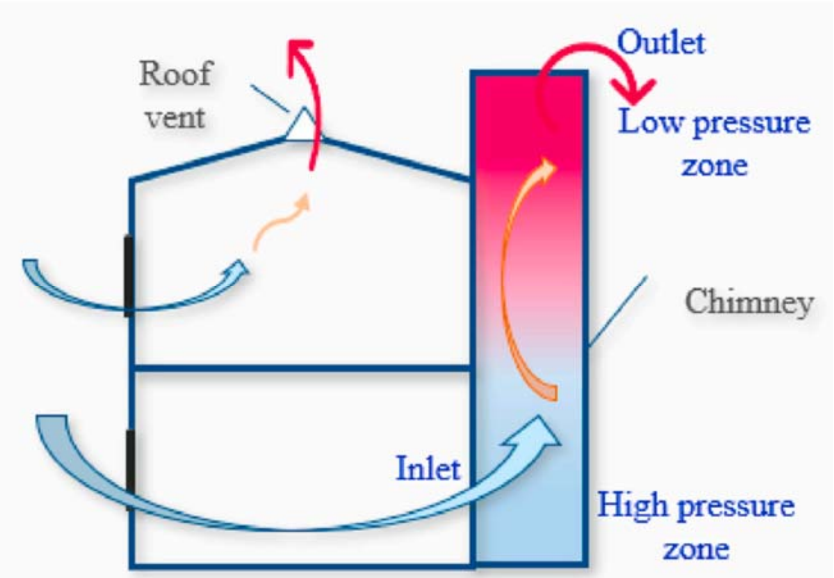


Figure 23: Stack ventilation [26]

2.2.1 Stack ventilation

With stack ventilation technique, cold air enters from lower openings in the envelope. Being heated inside the building, and thus becoming less dense, it leaves the building from openings high up in the envelope. With this technique, the heat removed from indoor environments is proportional to height difference between inlets and outlets [24]–[26], [28]–[30].

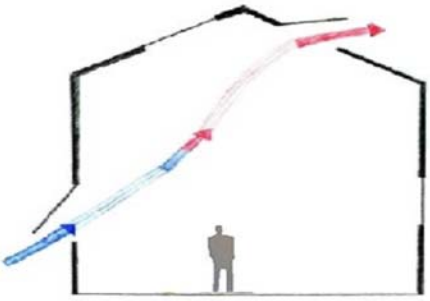


Figure 24: Mechanism of buoyancy driven natural ventilation [24]

Figure 25: Openings on opposite sides and at different heights of a space, allowing cross and stack ventilation [32]

2.2.2 Double skin façade (Vent-skin walls)

An additional second glazed envelope is added on the outside, creating a remarkable gradient of temperature, forcing the air to migrate upwards, being released by vents at the top. Automated vents in the inner skin allow indoor air to migrate from inside to the façade. Greenhouse effect can be used to pre-heat air during winter, but may constitute a drawback during summer. This design element can also be exploited for more advanced energy performance and daylight use [24]–[26], [28]–[30].

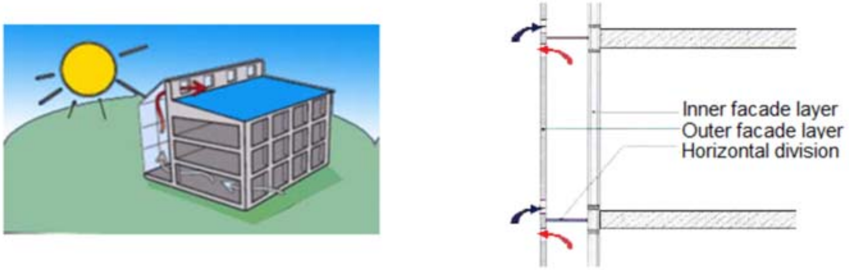


Figure 26: Mechanism of buoyancy driven natural ventilation in a double skin façade [24]

Figure 27: GSW building in Berlin (Germany) – cross ventilation is facilitated by the double glass façade providing a stack [25]

2.2.3 Trombe wall

Trombe wall is similar to a double-skin façade, but heat is also absorbed by the black-painted exterior surface of the more internal massive wall [33].

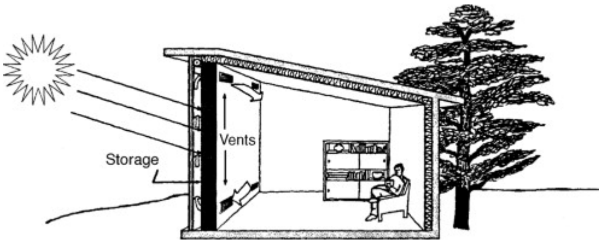


Figure 28: Trombe wall [33]

Figure 29: Trombe wall in Vivienda Trombe (Odeillo, France) [34]

2.2.4 Solar (thermal) chimney / Roof solar chimney

Chimneys are used to enhance the stack ventilation effect, used as a way out for air exhaust. The stack pressures can be increased by using incorporated glass elements (solar chimneys). Care needs to be taken in the design, e.g. chimney outlet needs to be located in a negative wind pressure zone (obtained by roof profile design). An extra fan can be incorporated for air extraction [24]–[26], [28]–[30].

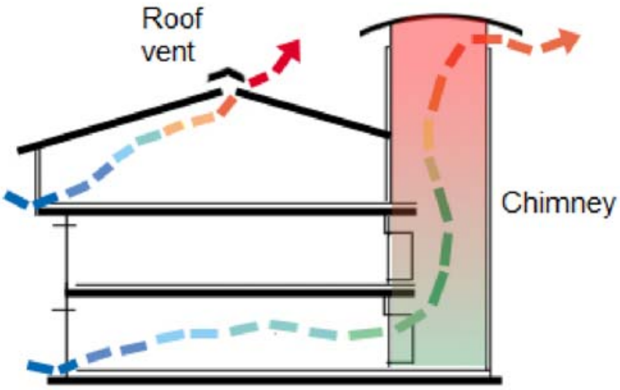


Figure 30: Chimney for NV [24]

Figure 31: McEwen Graduate Study & Research Building in York University (Toronto, Ontario, Canada) – a solar chimney for facilitating NV [35]

2.2.5 Solar façades (e.g. unglazed transpired solar façade and glazed transpired solar façade)

Solar façades are active façades designed in order to interact with solar radiation, exploiting it for heating, lighting or ventilation. Opaque façades absorb and reflect the incident solar radiation, without being able to directly transfer it inside the building. The scheme of a transpired solar collector is reported in Figure 32 [36].

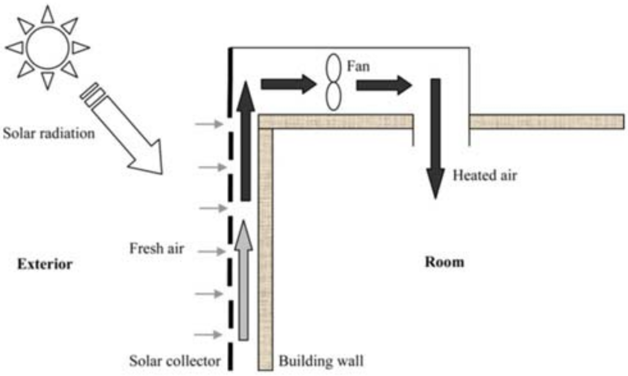


Figure 32: A scheme of a building integrated solar thermal system, such as the unglazed transpired solar collector [36]

2.2.6 *Atrium*

It is a variant of the chimney principles. In fact, air can be drawn out from both building sides to a central point for extraction. Also in this case, particular care needs to be taken with the positioning of outlet vents. This design element can also be used for more advanced daylight exploitation [24]–[26], [28]–[30].

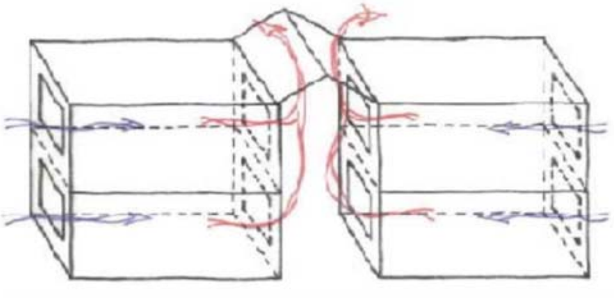


Figure 33: A NV strategy obtained by means of an internal atrium [24]

2.3 Main ways to exploit natural ventilation

NV can be used for different purposes, concerning the regulation of indoor environmental conditions. Main ways to exploit NV are listed here below.

2.3.1 *Air-change*

One first and intuitive purpose of NV is air-change. Thus, NV can be exploited for enhancing the Indoor Air Quality (IAQ) conditions, with CO_2, pollutants and pathogens removal. The effectiveness of removal depends on NV efficiency and, of course, on outdoor conditions [37], [38].

2.3.2 *Thermal regulation*

Thermal regulation is the process of variating internal thermal conditions by means heat removal (cooling). This process depends on external environmental conditions, and is therefore dependent on the climate area and the season. As previously introduced, it was observed that the use of NV enlarges the temperature range of satisfaction inside building, thus allowing to develop adaptive model [18], [37], [39].

2.3.3 *Night cooling*

It is a particular way of thermal regulation, which consists in using NV (e.g., opening windows) during colder hours of the day (during night) for cooling the indoor environment. This technique can be coupled with the use of massive materials for improving thermal inertia of buildings and shifting the indoor heating later during daytime. Home automation systems (i.e., automated windows opening, automated shadings) can also be exploited for properly regulating indoor conditions depending on daytime and/or outdoor conditions [40]–[43].

2.4 Standards and guidelines for NV

- Theory and measurement of NV, application to design, strength and weaknesses of techniques of NV, mathematical modeling and computational fluid dynamics (CFD): *D. Etheridge, Natural ventilation of buildings: theory, measurement and design. John Wiley & Sons.* [28]
- Potential, appropriate use dimensioning, barriers' overcome of NV: *S. Alvarez, E. Dascalaki, G. Guarracino, E. Maldonado, S. Sciuto, and L. Vandaele, Natural ventilation in buildings. A design handbook. James & James, 1998.* [29]
- Reference book for designing low carbon/low energy buildings using NV, with example case studies: *U. Passe and F. Battaglia, Designing spaces for natural ventilation - An architect's guide. Routledge.* [25]
- Guideline on hybrid and passive cooling techniques for building (Italian language): *M. Grosso, Il raffrescamento passivo degli edifici in zone a clima temperato, Second. Maggioli Editore.* [30]
- Environmental design guideline containing NV recommendations applicable worldwide: *CIBSE, 'TM40: Health and wellbeing in building services'. Chartered Institution of Building Services Engineers (CIBSE), 2019. [Online]. Available: https://www.cibse.org/Knowledge/CIBSETM/TM40-2019-Health-Issues-and-Wellbeing-in-Building-Services#Exec%20summary (https://www.cibse.org/Knowledge/CIBSE-TM/TM40-2019-Health-Issues-and-Wellbeing-in-BuildingServices#Exec%20summary)* [44]

3. Mechanical ventilation principles in climate responsive energy positive buildings

Mechanical ventilation (**MV**) uses a powered induced airflow by means of a mechanical external source of power. For this reason, MV has the clear advantage to have the possibility to be perfectly regulated (airflow, volume, velocity, temperature), regardless of outdoor conditions. Thus, the performance of MV system is constant and perfectly predictable, and units of air treatment can be incorporated, remarkably improving IAQ conditions [45]–[47]. Main disadvantages are dealing with the running cost of MV systems, as they require electric energy to function. Moreover, mechanical systems for ventilation can lead to noise due to the functioning of plants. Lack of control (fixed air flow, not self-regulating) is also a disadvantage, as the air flow is fixed and not self-regulated [45]. Moreover, disadvantages dealing with the loss of contact with the outside environment might be associated with the use of MV systems instead of windows, even if this is depends on the typology of view, area or landscape [48]–[54].

The disadvantage of the larger amount of consumed energy can be partially overcome by the use of heat recovery units, leading to passive houses applications of MV techniques [55]–[57]. An example of a heat recovery unit is reported in Figure 34.

A quick overview of the functioning of a heat recovery ventilation (HRV) plant, especially when coupled with a heat pump, is reported in following Subsection. Finally, a list of standards and guidelines for MV and heat recovery units is reported.

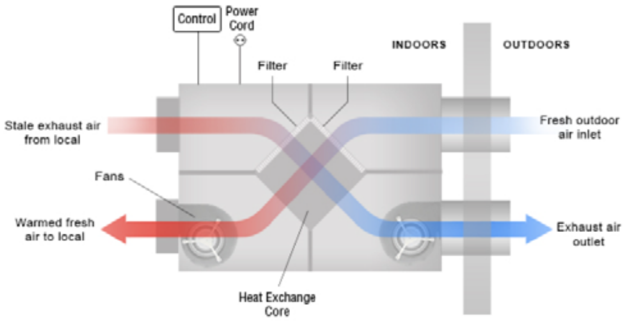


Figure 34: Scheme of a heat recovery unit [58]

3.1 Overview of Heat Recovery Ventilation (HRV) functioning

A HRV system is aimed at the exploitation of expelled exhausts to pre-heat or pre-cool the inlet air before it enters the room or air treatment units. It is normally composed of channels for exhaust and fresh air, a core unit and blower fans. It can generally improve the building energy efficiency by recovering between 60 and 95 % of heat in exhaust air. Several heat exchangers technologies are available for HRV, differentiating for the constructive point of view, as well as the air-flow inside them (parallel or counter-flow) [59]. Some examples of typical heat exchangers are [59]–[62]:

- **Fixed plate heat exchangers**, the most commonly used, with streams of cold and hot air passing through adjacent spaces between plates
- **Heat pipes**, transferring heat from between the two streams by means of a multi-phase process (evaporator-condenser)
- **Rotary thermal wheels**, mechanical exchangers with a porous metallic wheel alternatively in contact with cold or hot stream
- **Run-around**, hybrid systems using a mix of previous technologies to deliver heat between two distant air streams.

As heat pumps can be particularly efficiency and need electrical energy instead of fossil fuel to work, they are particularly interesting to be used in HVAC plants, when related with climate responsive energy positive buildings. In fact, they could cover most of global heating needs, remarkably reducing the CO_2 emissions [63]–[65]. Moreover, they can be inverted acting both for heating and cooling the environment. Performance of heat pumps is normally measured using the Coefficient of Performance (COP), defined as the heat transferred from low temperature to high temperature source divided by the work required [66]. A brief summary of heat pumps types of working technologies is here provided [67]–[69]:

- **Air source**, using outside air as heat source, being relatively easy to install, but being more performant in mild weathers than in cold ones; modern air source heat pumps are more performant, allowing to achieve COPs comparable to ones of ground source heat pumps
- **Ground source** (**geothermal**), drawing heat from soil or groundwater, which (at a certain depth) maintains a relatively constant temperature for all the year (Figure 36)
- **Water source**, taking heat from a water source, which needs to be large enough not to freeze and not to affect wildlife
- **Exhaust air**, transferring heat from exhausts of a MV system to intake air or a water circuit
- **Solar assisted**, with a solar panel used as low-temperature heat source feeding the evaporator
- **Absorption**, which uses thermal energy (natural gas, steam solar-heated water or air, geothermal-heated water, …); this system is more complex than compression heat pumps, requiring larger units
- **Hybrid**, drawing heat from different sources depending on temperature present outside.

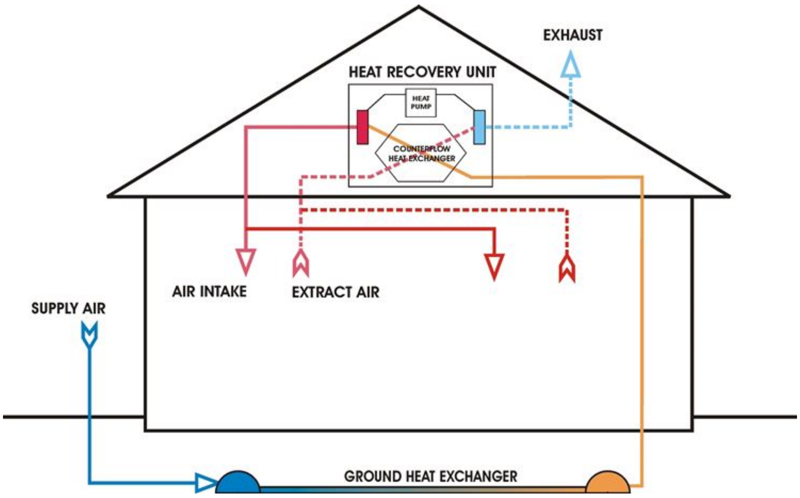


Figure 35: Scheme of a HRV system [70]

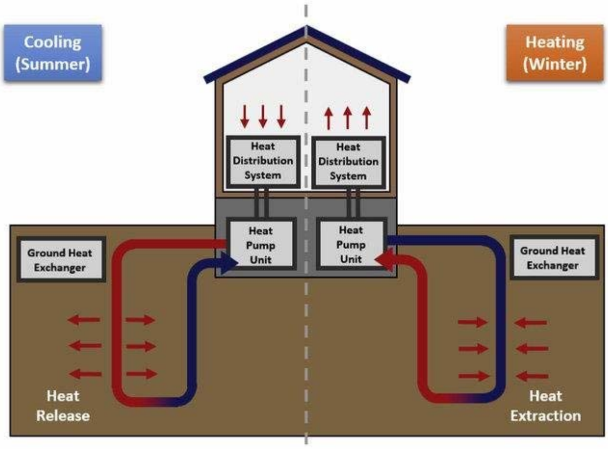


Figure 36: Scheme of a ground source heat pump in cooling and heating mode [71]

3.2 Standards and guidelines for MV

- Basic principles and data used in the HVAC industry: *ASHRAE, ASHRAE Handbook - Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2021.* [72]
- Standard for plants' classification, minimal requirements of plants and indoor environments: *UNI 10339 - Air-conditioning systems for thermal comfort in buildings - General, classification and requirements - Offer, order and supply specifications*. [46]
- Handbooks and manuals on domestic ventilation:
  HRAI, *Residential Mechanical Ventilation - National (SAR-R4)*. The Heating, Refrigeration and Air Conditioning Institute of Canada (HRAI), 2010. Available: https://www.hrai.ca/technical-manual/residential-mechanical-ventilation---national--sar-r4- [73]
  R. Edwards, Handbook of Domestic Ventilation. London: Taylor & Francis, 2005. Available: https://doi.org/10.4324/9780080454580 [74]
  P. H. Raymer, Residential Ventilation Handbook, 2nd ed. Home Ventilation Management, 2017. [75]
- Overview on main building heat recovery technologies: A. Mardiana-Idayu and S. B. Riffat, 'Review on heat recovery technologies for building applications', *Renewable and Sustainable Energy Reviews*, vol. 16, no. 2, pp. 1241–1255, Feb. 2012, doi: 10.1016/j.rser.2011.09.026. [59]

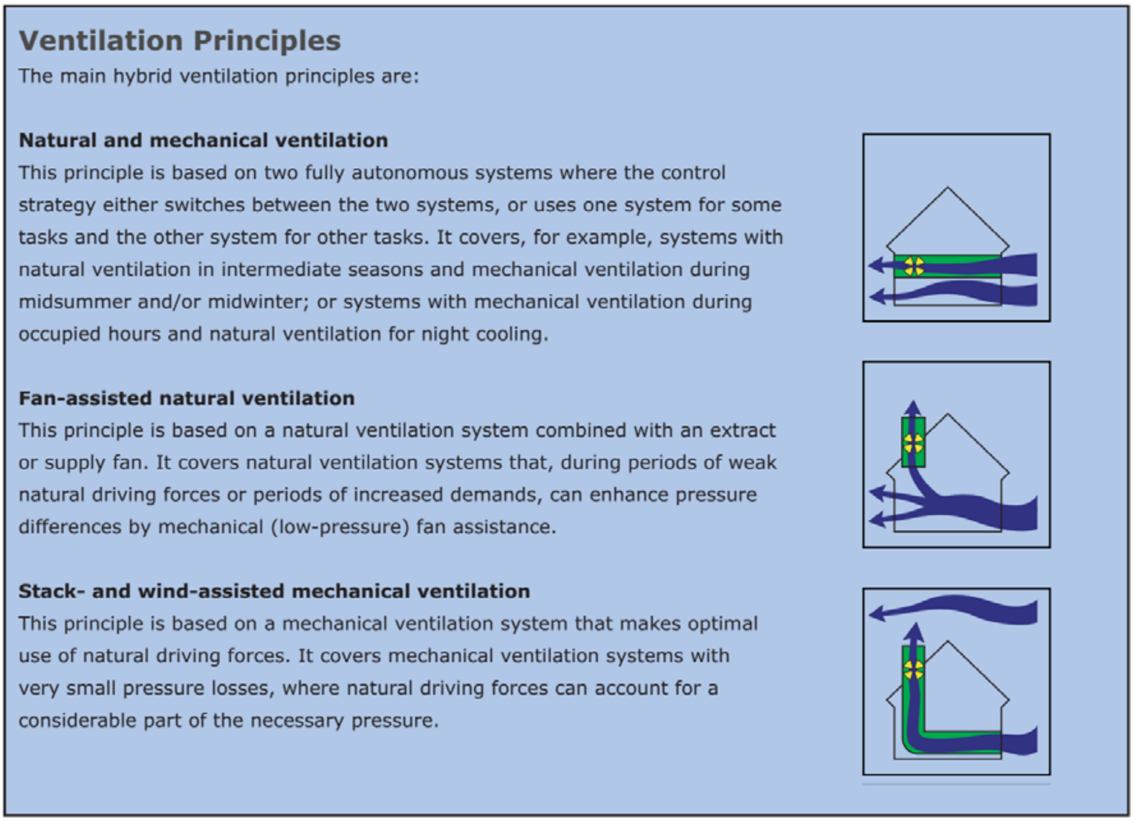
- Guidelines on heat pumps:
  ASHRAE, 'Applied Heat Pump and Heat Recovery System', ASHRAE. https://www.ashrae.org/advertising/handbook-advertising/systems/applied-heat-pump-and-heat-recovery-systems [76]
  'Domestic Heat Pumps - A best Practice Guide'. Available: https://mcscertified.com/wp-content/uploads/2020/07/Heat-Pump-Guide.pdf [69]

4. Hybrid ventilation principles in climate responsive energy positive buildings

As introduced in Section 2, NV has the advantages of reducing the carbon footprint of buildings, while also improving some comfort elements, such as ones dealing with users' willingness of control and access to the outside/nature. On the other hand, MV (Section 3) is a "safer" technique, as it permits to have more controllable IAQ and thermo-hygrometric conditions, also allowing for filtering pollutants and better removing pathogens. A compromise between the two methodologies is **hybrid ventilation** (**HV**), or **mixed-mode ventilation** (**MMV**) [77]–[82]. In fact, the primary purpose of HV can be defined as "to provide acceptable indoor environment and thermal comfort […] using different features of these systems at different times of the day or season of the year". Therefore "Hybrid ventilation buildings, or mixed mode buildings, represent the buildings that have the capability of running the natural ventilation and mechanical ventilation concurrently or switching between these two modes during the building operation" [83]. In this way, the greatest advantages of ambient conditions can be exploited at any time. Moreover, an automatic intelligent control can allow to switch from one mode to the other when needed [84], [85]. The main principles of HV are reported in Figure 37.
Thus, the alternation of MV and NV could save up to 75 % of the energy use [80], while guaranteeing proper IAQ conditions. For this reason, this solution is particularly interesting for climate responsive and energy positive buildings.

Further information on HV technique can be found, for instance, on:

- *Principles of Hybrid Ventilation. Aalborg (Denmark): Aalborg University, Hybrid Ventilation Centre. Available: https://iea-ebc.org/Data/publications/EBC_Annex_35_Principles_of_H_V.pdf* [84]
- *Annex 35 - Hybrid Ventilation in New and Retrofitted Office Buildings. Hybrid Ventilation in New and Retrofitted Office Buildings. Available: https://www.iea-ebc.org/Data/publications/EBC_Annex_35_tsr.pdf* [81]



Ventilation Principles

The main hybrid ventilation principles are:

Natural and mechanical ventilation

This principle is based on two fully autonomous systems where the control strategy either switches between the two systems, or uses one system for some tasks and the other system for other tasks. It covers, for example, systems with natural ventilation in intermediate seasons and mechanical ventilation during midsummer and/or midwinter; or systems with mechanical ventilation during occupied hours and natural ventilation for night cooling.

Fan-assisted natural ventilation

This principle is based on a natural ventilation system combined with an extract or supply fan. It covers natural ventilation systems that, during periods of weak natural driving forces or periods of increased demands, can enhance pressure differences by mechanical (low-pressure) fan assistance.

Stack- and wind-assisted mechanical ventilation

This principle is based on a mechanical ventilation system that makes optimal use of natural driving forces. It covers mechanical ventilation systems with very small pressure losses, where natural driving forces can account for a considerable part of the necessary pressure.

Figure 37: Examples of HV principles [84]

5. Natural, mechanical and hybrid ventilation with a double perspective, focusing on both energy consumption and indoor well-being

Given these premises, it is clear that the concept of ventilation is fundamental, when dealing with both climate responsive and nPEBs. In fact, NV can remarkably reduce the carbon footprint, which is a clear requisite of both these forms of energy-efficient architecture [86], [87]. Climate responsive principles can be observed in traditional buildings such as vernacular architecture in Nepal, which have been using natural ventilation for years, in order to adapt to climate conditions and improve comfort of occupants [88]. Nevertheless, as previously stated, MV allows for a better regulation of IAQ and thermal conditions. In fact, building design cannot overlook indoor comfort. Good environmental quality is also fundamental for work and performance, as well as for energy consumption. In fact, energy implications may derive from actions taken from occupants to improve their uncomfortable conditions [89], [90]. As Chenari et al. [91] points out, it is not possible to choose one ventilation solution relying on energy savings criteria, if indoor comfort cannot be met. In fact, ventilation is fundamental to provide a health and comfortable indoor condition, avoiding illnesses and complaints present in 40 % of cases [92]. Also, COVID-19 pandemic highlighted the importance of ventilation in buildings, with controversial opinions about the preferred use of MV [10], [93]–[97]. In fact, NV re-gained interest because of its utility to manage infection control in buildings [37], [98] and because of the preference of nature-connected environments by people [50]–[54]. For instance, window presence and window opening were found to possibly positively cross-influence the mental well-being of occupants during COVID-19 lockdown in London, as positive perceived soundscapes were found associated with psychological well-being, as well as with natural sounds and view of vegetation [48], [49]. On one hand, in the field of building resilience to climate change, within the next decade indoor spaces might terminate to fulfil adaptive comfort model [99]. Moreover, global warming will probably provoke an higher number overheating hours in warm areas, but the shifting of climate conditions might cause a higher use of NV in cold or mild climates [79]. On the other hand, even though open windows cannot be a proper solution when poor outdoor air quality, too warm conditions or too low wind are present, other future Indoor Environmental Quality (IEQ) issues might be created by totally avoiding NV. This solution would also create a situation relying on a totally dependence on HVAC systems, with large emissions and energy demand. For this reason, new regulatory criteria on overall IEQ in buildings are necessary, not to worsen the global climate emergency and future health problems [10].

For all these reasons, the careful study of ventilation with both an energy saving and IEQ perspective is fundamental. Both the two criteria need to be considered when designing climate responsive and net-positive energy buildings. In this section, a systematic literature review on studies analyzing an indoor comfort and/or well-being comparison between NV and MV is presented. The aim is to offer an overview aiming as a guideline for choice of best solution of NV, MV or HV in the design of nPEB or climate responsive buildings.

5.1. Methodology

A process of systematic review was used [100] on the Web of Science database [101]. A search using AND/OR Boolean operators [102] (Figure 38) was performed in order to identify all the studies concerning a comparison of NV and MV in terms of indoor comfort and well-being. A total number of 94 papers was found. A first screening process was applied considering only English-written studies and limiting the research areas to the following: 1. *Construction Building Technology*; 2. *Engineering Civil*; 3. *Engineering Environmental*; 4. *Green Sustainable Science Technology*; 5. *Environmental Sciences*; 6. *Public Environmental Occupational Health*; 7. *Environmental Studies*; 8. *Architecture*; 9. *Thermodynamics*; 10. *Engineering Mechanical*; 11. *Infectious Diseases*; 12. *Regional Urban Planning*; 13. *Urban Studies*. All types of documents (articles, proceedings papers, review articles and book chapters) were considered, obtaining a total number of 80 papers. A second screening process consisted in titles and abstracts reading, with the rejection of all the papers which topic was not in compliance with a comparison of natural and mechanical ventilation related with occupants' comfort and/or well-being. This screening allowed to obtain 69 papers for full reading. After the reading process, five additional papers were discarded, with a final number of 63 studies considered. Figure 39 reports the details about the screening process, and the number of studies obtained after each phase.

Resulting studies were categorized according to the comfort field considered (thermo-hygrometric, visual, IAQ, acoustic and multi-domain approach), as well as the type of ventilation recommended ("NV", "MV", "HV or both HV and NV", "no clear preference between MV and NV/HV"). Papers are presented here below grouped according to this last categorization. The type of paper (journal paper, journal review, conference proceedings), the type of indoor environment (residential, educational, working, …) and the climate or geographical area considered were also highlighted. When specified, the type of NV ("thermal regulation", "air-change" or "night cooling") was also highlighted.

Finally, statistical data about papers are presented, highlighting the number of studies per publication year, geographical area, research field and other types of categorization.

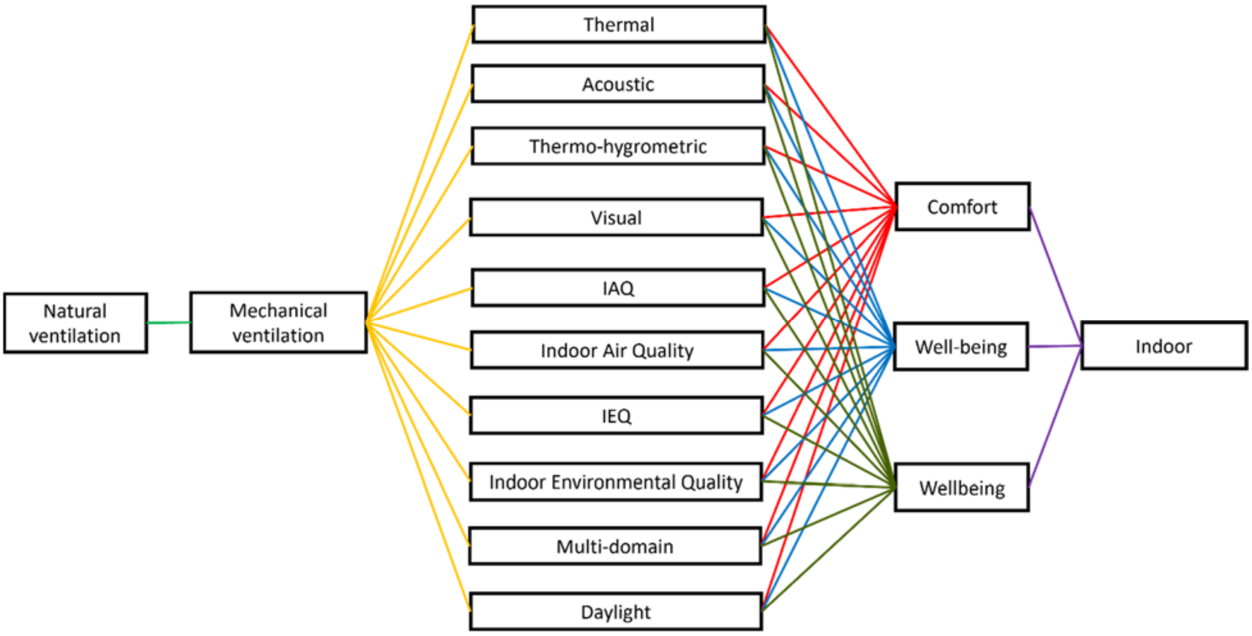


Figure 38: Boolean research string used for a first search of papers on the Web of Science database. Linking lines represent "AND" operator, while "OR" operator was used for keywords on the same column in the scheme

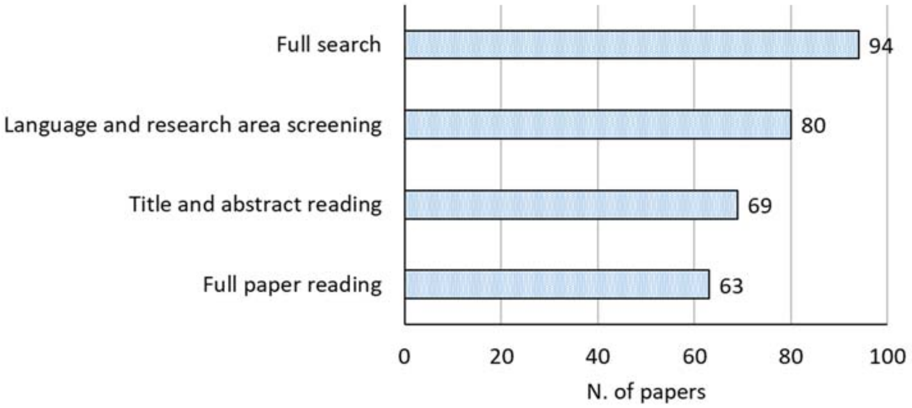


Figure 39: Details about the screening process applied and number of results after each phase

5.2. Results

5.2.1. Studies suggesting the use of NV

A Slovenian study of 2007 [103] analyzed comfort in three working buildings (two with MV and one with NV). It used surveys performed during normal activities of work, in the cold season. Thermal measurements of the environments were taken simultaneously. Health problems and health status of occupants were also surveyed. Deviations between predicted and subjective evaluations were noticed, with possible influence of psychological factors. Moreover, in mechanically ventilated buildings, a higher dissatisfaction with thermal and air quality environment was present. On the other hand, neutral condition was expressed by a higher percentage of occupants in the naturally ventilated building than in the two other buildings.

In a review by Omer (2008) [104], a description of several low-energy buildings design solutions was performed, also highlighting implications of dense urban building nature on consumption of energy and climate change. It was highlighted how maintaining thermal comfort in buildings by means of low-energy and passive techniques is one effective way to save energy, and therefore maximum share of natural energy should be used. For these reasons, new technologies like louvers for distribution of light, insulation, MV operations and simple passive cooling can help in fulfilling this target, with a combination of well-known technologies like shading, glazing, NV and insulation and other advanced solutions such as dynamic insulation, roof pond and evaporative water jacket. Moreover, the need of mechanical cooling and heating could be reduced designing buildings taking into account the climate of the area (climatic design). Using the proper building and urban design, the deterioration of environmental quality after urban densification could be minimized. For instance, thermal comfort could be maintained in arid regions by means of wind towers. Moreover, CO_2 emissions are also increased by poor design or control of passive ventilation systems (i.e., too high inflow), besides than too strong use of MV. Discomfort and draught are caused by too high outdoor air, while poor IAQ is caused by little inflow. For these reasons, proper design of NV solutions (single-sided ventilation, cross-flow ventilation, mixed-flow ventilation or other solutions like solar-induced ventilation) need to take into account the following buildings' factors and characteristics: ceiling height, space exposed thermal mass and building materials (e.g. for night cooling), depth of space in relation with ventilation openings, heat gain, building location in relation with sources of pollution (such as traffic noise and air pollution). Also, geographic location, exposure to sun, wind and rain (including effect of buildings themselves on them), building height and form, need to be taken into account. In this framework, CFD can help with problems in the design of air movement in rooms and airflow control.

In 2008, Stavrakakis et al. [105] performed a test-chamber and numerical (CFD) examination of natural cross-ventilation with non-symmetrical openings. In a test-chamber in rural Greece, velocity and temperature measurements were recorded during noon and afternoon in the hot season, while a weather station provided data about external weather conditions. Thermal comfort (thermal regulation perspective) was studied by means of both PMV and adaptive models. The study started from the idea that NV can help in saving energy, but needs to be properly designed based on airflow detailed understandings (pressure differences due to wind and buoyancy). It was highlighted that experimental measurements agreed quite well with all turbulence models, pointing out that well-mixed conditions can be provided by openings' locations which are not symmetrical. This can minimize local air draughts and temperature differences, avoiding unsatisfactory thermal environment even close to obstacles like pieces of furniture.

A CFD modeling to investigate the comfort performance of stack effect (buoyancy) and two driving forces-wind ventilation in a double-skin-façade university building (Figure 40) in Mediterranean climate (Eugene, Oregon), was studied by Azarbayjani (2013) [106]. The study highlighted that heat can be effectively drawn out by means of cool night air through top openings and that acceptable thermal comfort conditions can be provided by NV in the building with double-skin-façade. Moreover, air extraction can be obtained using the convective forces in the cavity, but air movement within the room should be promoted in order to release heat in excess. Finally, the climate analysis showed that, in summer or shoulder seasons, NV was made possible by orientation of building, which considered the prevailing winds. Therefore, comfort was studied with a thermo-hygrometric perspective and NV for night cooling and thermal regulation was considered.

Figure 40: Double-skin façade of the university building considered by Azarbayjani study [106]

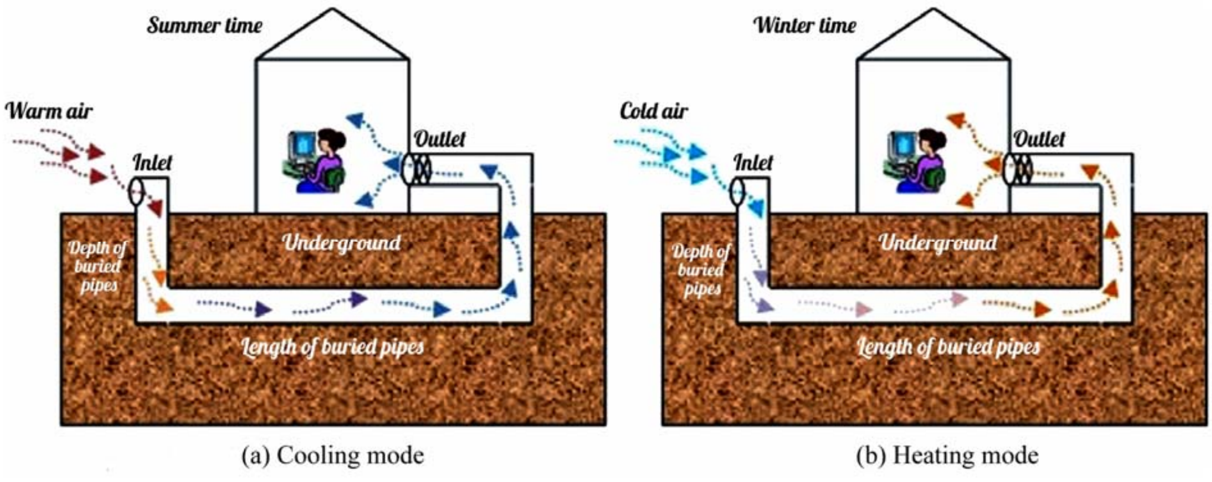
A review on existing studies supporting NV efficiency and architectural designs and solutions to maximize the efficacy of NV in buildings in tropical (hot and humid) climates was performed by Aflaki et al. (2015) [107]. The paper points out how high humidity and temperature might provoke occupants to use MV in tropical climates. Nevertheless, the authors state that, with passive techniques such as NV, smaller operational cost and better IAQ and thermal comfort have been shown by many researches. Review results showed that future constructions should exploit design strategies such as window-to-wall ratio, orientation of buildings, position and size of openings, façade elements, balconies' form and ventilation shafts in order to optimize NV. Moreover, further studies on louvered windows' shape (for night ventilation), vernacular elements and apertures' forms could be needed.

The importance of design elements such as façades, orientation and structure in non-residential buildings in warm climates was pointed out by Annan & Nehme in 2016 [108], assessing the effect of cross and single-sided ventilation by windows and skylights openings that can be used for cooling the building with a thermal regulation perspective.

Da Graça & Linden (2016) [79] developed a list of 10 open questions about design of NV in non-domestic environments, from building, neighborhood and urban point of view. The authors linked the answers to the proposed questions with current literature, in order to identify the scientific gaps and provide designers with proper suggestions. It was pointed out how NV benefits of the preference of most people, who are also characterized by a higher thermal tolerance when rooms are naturally ventilated and openings can be controlled by users. Nevertheless, NV is still rare in non-domestic and modern buildings, but its usage could make the energy consumption decrease. Recent design solutions with the massive use large glazed walls have driven to the misunderstanding that NV and natural light compete. Nevertheless, the two systems can benefit from similar constructive techniques (i.e., high widows, high floor to ceiling height, operable skylights, both have a small penetration depth when windows are located on the same side, ...). Moreover, direct sunlight on large glazed façades can lead to both overheating and glare. Thus, both systems could benefit of a return to smaller window to wall ratios, climate adaptive building shells and use of external shadings. NV can possibly be applied with an outside temperature range from 10 °C to 25 °C. For this reason, climate change will rise the number of hours of overheating in non-commercial buildings, but, in cold and mild climates, will also lead to an expansion of hours of open windows. Innovative approaches (e.g., night cooling with thermal massive or phase-change materials equipped buildings, controls avoiding overheating during the warmest hours) may be useful for a NV use expansion. Moreover, coupling with external shadings, responsive glazing and ceiling fans to move air could be necessary. Modern mobility solutions (i.e., electric cars and bikes) will improve the urban environment in terms of particles and noise pollution. Thus, NV will further benefit.

Reasons of unpopularity of NV (with respect to air-conditioning or HV) in Green-rated offices of New Zealand were investigated by Rasheed et al. (2017) [109] by means of: (1) revision of criteria of thermal comfort in NZ Green Star [110], [111] rating tool; (2) online questionnaires of workers' perception of thermal comfort in the city of Auckland (most populated and with high number of modern office buildings; oceanic subtropical climate); (3) building experts' interviews. The following conclusions were listed: (1) NV was not encouraged by NZ Green Star IEQ thermal comfort criteria. (2) No preference of NV over MV and HV was observed among workers. (3) Among thermal comfort factors, the highest impact on workers' performance was noticed to be by temperature control and temperature extremity. (4) NV could be promoted by a better support to adaptive criteria from NZ Green Star IEQ thermal comfort criteria. This would possibly imply a preference change of accustomed workers. In this way, thermally comfortable Green offices would be achievable. (5) NV negative implications on productivity are still under debate. Therefore, energy inefficient buildings should not be built on those basis. (6) Other IEQ aspects connected to NV (i.e., lighting and noise) should be deepened by further studies.

In 2019, Mukhtar et al. [112] performed a review on strategies of passive design and building optimization potential in underground buildings. It was stated that incorporating passive systems in underground buildings is fundamental to mitigate the carbon impact. In this sense, IEQ level could be improved by including passive design strategies and optimization approach in building performance simulations. Moreover, the energy consumption could be decreased by adopting natural and soil ventilation (Figure 41: Earth to air heat exchanger (EATHE). Nevertheless, factors like geological features, physiological and psychological issues, construction typologies and ventilation system should be taken into account for the proper design of underground buildings. In this framework, thermal comfort improvement and reduction of the energy consumption could be fostered by passive design technologies specifically associated with underground buildings.



(a) Cooling mode (b) Heating mode

Figure 41: Earth to air heat exchanger (EATHE), reproduced from [112], [113]

Maas et al. (2019) [114] studied a 60 seats capacity seminar room of University of Luxembourg (a Seventies building with no major retrofitting). The MV system was switched on and off for periods of some weeks each. After each period, measurements of final energy consumption and of indoor climate (by both physical measurements and questionnaires) were performed. The building was not air-tight and manually operable windows were present. The research led to the following conclusions: (1) When the system was “on”, light measurable benefits in the CO_2 concentrations were present, and it was not perceived by the occupants. (2) Primary energy consumption of the building was clearly higher when the system was “on”, due to fans' electric demand. (3) There was no relationship between the climate perceived and the perceived percentage of dissatisfied. (4) Advantages can be achieved in older buildings' seminar rooms, by shutting down or semi-automatic user-controlled modus by low-cost retrofitting.

A literature study on the influence of openings of façades and geometry of balconies on perception of occupants and NV performance, comparing design characteristics and geometries, was performed by Izadyar et al. in 2020 [115]. The paper started from the idea that NV could be used on its full potential, in particular in medium- and high- rise buildings. In this framework, airflow could be guided by balconies into the indoor environment, reducing the need of MV and improving the comfort conditions. Not enough studies were performed on the exploitation of balconies for NV. More studies, comprising both experiments (like Post-occupancy Evaluation) and simulations, should be made. Most of the studies present in the literature, have been performed in cooling dominant warm/hot climates. Nevertheless, climate change should drive the research expand also to heating-dominant areas. Design process impact of passive elements was not sufficiently explored, with indoor comfort and health factors being mainly considered in previous studies. More post-occupancy evaluation studies should be made, in order to link NV design and perception of occupants: this would allow to better investigate the façade openings' design effect on occupants.

In 2020, two other studies from Izadyar et al. [116], [117] analysed the performance of single-sided NV and related thermal comfort of a living room depending on depth (fixed length over depth size, L/D) and opening scale of a balcony, in a high-rise residential building in Brisbane (Australia). CFD simulations were performed after measurements’ validation, assessing the mean Indoor Air Velocity (IAV), the Indoor Air Distribution (IAD), and the PMV. Nine depth scenarios and five openings were considered. The following aspects were highlighted in [116]: (1) NV could decrease energy consumption and GHG emissions with respect to MV. (2) Depth and openings of balconies have an impact on IAD and IAV and indoor temperature. (3) Shallowest balconies give a weak IAD, and small openings give acceptable IAV indoor. (4) Further research to study the influence of geometry on indoor comfort and indoor temperature and air velocity distribution are necessary. Moreover, these additional points were pointed out in [117]: (1) Balconies could enhance NV, reducing dependence on MV in climates with cooling dominance. (2) The opening size and the depth scale influence IAD, IAV and thermal comfort. In fact, a small opening could reduce exterior air acting like a nozzle in transferring the recirculation farther in the room. Larger openings were seen to create extended cold areas close to the opening. (3) Smaller depth (less than 2 m) gave not stable and not uniform IAD, with deeper balconies being more performant on the point of view of thermal condition and IAV. In terms of thermal conditions, it was noticed that the best solution had a L/D of 35 % and opening size of 1.1 m. (4) Orientation of buildings influence the balcony's depth impact on mean IAV. Further studies are necessary to assess the proper depth with other orientations.

Yadeta et al. (2022) [118] performed a field survey (questionnaires, indoor and outdoor air temperature, humidity and air speed) in 104 naturally ventilated residential buildings in Jimma (South-West Ethiopia, warm-temperate climate), during the dry season (from 1st of February to 31st of May 2020). A neutral temperature of 20.4 °C and a wide comfort range (14.6 - 26.3 °C) were found. This suggested that, in developing countries like Ethiopia, thermal comfort can be achieved by NV, with occupants using natural adaptive means, allowing to save energy for MV, if compared with areas with narrower ranges. Moreover, it was highlighted how further studies on energy consumption from heating and cooling in the households would be necessary is these countries.

Mba et al. (2022) [119] investigated the NV effect of orientation of 60 primary schools buildings in the city of Enugu (Nigeria, hot-humid tropical climate). The paper firstly stated the fact that, in developing countries, educational buildings rely on NV in order to save energy. It was found out that the efficiency of ventilation depends on the orientation: inlet window planes perpendicular to the wind direction are recommended.

Moreover, inlet and outlet dimensions and positioning have an impact. Additionally, the authors stated that shading devices and corridors to promote the use of NV also during rainy and windy days should be used, and encouraged architectural solutions to couple wind and stack effect ventilation.

5.2.2. Studies suggesting the use of MV

A review by Braham (2000) [120] focused on independently published information on low-energy office buildings performance data about the ventilation and fabric energy storage strategies available, in the temperate maritime climate of the UK. The work started from the idea that not many studies about annual energy associated with NV and MV coupled with fabric thermal storage were published. The review concluded that, when including effective fabric energy storage with the integration of efficient heat recovery (using hollow-core slabs), low-energy MV systems can provide better comfort all over the year (with summer cooling included) and lower energy consumption than NV. Moreover, less maintenance is necessary. In temperate marine climates, it was shown that minimal supplementary demand and consumption of heating and cooling are needed.

A paper by Sultan (2007) [121] estimated the effects of outdoor PM (particulate matter) mortality and morbidity effects on the Singapore population under various buildings and conditions of ventilation and filtration. The study concluded that nationwide adoption of NV in residential buildings was associated with higher morbidity cases and mortality. Moreover, MV and filtration from current NV in schools was associated with less asthma cases. Additionally, better filtration in workplaces was associated with lower morbidity cases and mortality.

A study by Khaleghi et al. (2011) [122] provided a direct monitoring of IAQ (volatile organic compounds - VOCs and ultrafine particles, respirable-fibre concentrations), ventilation rates (air changes per hour) and acoustical conditions (times of reverberation and levels of noise) in study rooms located in selected "non-green" and "green" university campus buildings (Vancouver, Canada). Then, the two aspects of IAQ and acoustic comfort were considered, with an air-change point of view. The goal was to quantify these IEQ aspects, determining their relationship with design of building and windows' status and assessing the effects for systems of ventilation, especially in buildings considered as "green". The measurements were taken both in buildings with MV (mixed-flow and/or displacement) and NV. NV produced lower total sound-pressure and low-frequency noise, as well as lower fibre concentrations, but also lower rates of ventilation and higher ultrafine-particulates. Direct association between noise level and IAQ was observed with MV. It was concluded that a generally better IAQ can be provided by MV, even if poorly designed systems can produce noise issues. Higher noise levels was produced with higher ventilation rate by windows' openings. Finally, the use of MV with careful attention to noise, was suggested for optimum building design.

Guo et al. (2018) [123] used reduced-scale model, full-scale numerical simulation and similarity analysis to evaluate performance of buoyancy-driven ventilation in a large space building (ocean park) with a large glass ceiling. An investigation of conditions of thermal comfort was performed numerically. It was concluded that in a similar type of building (with a large glass ceiling), buoyancy-driven ventilation alone is not enough to ensure thermal comfort conditions, when high ambient temperature is present. Therefore, MV is needed in similar environments.

Measurements of indoor and outdoor particle number, as well as concentration of CO_2, were performed by Stabile et al. (2019) [124] in a school of Cassino (Central Italy). Pre-retrofit (different procedures of manual airing) and post-retrofit (CO_2-based controlled ventilation, with a set-point of 1000 ppm) solutions were considered. It was highlighted that, for highly crowded buildings like schools, MV is necessary. Moreover, evaluating the air quality just by means of CO_2 concentration constitutes an over-simplified approach, since other pollutants are present. The study concluded that: (1) With longer airing period, significantly lower CO_2

was present, but more sub-micron particles infiltrated from outside and no reduction of PM_{10} generated indoor were observed. (2) MV produced improvements on all the measured pollutants and on energy savings. The reduction of PM_{10} particles was caused by the higher rates of air exchange, giving better dilution effects. Moreover, the lower energy consumption was due to the presence of a heat recovery unit after retrofit. (3) Further analysis dealing with other pollutants (e.g., NOx), as well as thermal comfort and performance of children are necessary.

Zender-Świercz (2020) [125] performed an analysis of indoor air parameters of a Polish (moderate climate zone, low temperatures in winter and high temperatures in summer) office equipped with a façade ventilation device. Measurements of indoor and outdoor temperature, indoor and outdoor humidity, indoor CO_2 concentration were performed. The monitoring lasted twenty-six weeks during the fall-winter-spring period. Three different periods with different unit settings for the supply/exhaust cycle (2 min, 4 min and 10 min) were analyzed. In was pointed out how, with thermal insulation and new sealed windows, buildings only exploiting NV can undergo to lack of infiltration and insufficient air exchange. Moreover, due to a lack of place and architectural requirements, MV cannot be always installed. Temperature was observed to be in the range of 20 - 22 °C despite the absence of a heater in the device. PMV calculations showed that building categories B or C (PN EN 7730 [126] categorization) were maintained. Local draught risks with long air supply/exhaust cycle, when users stands in the air stream axis, were also noticed. Exhaust heat recovery and electric heater were recommended to decrease the possibility of local discomfort. Finally, low RH values (27 - 43 %) suggested to recommend air humidification.

A numerical energy efficiency assessment and an IAQ assessment were performed by Mareș et al. (2021) [127] in a single-family thermally insulated house in Cluj (Romania). The house was also equipped with low-transmittance windows and an efficient boiler. Since the substitution of old wooden framed windows with double glazed PVC windows, even if giving better thermal performances, might create air sealing issues, an evaluation of a controlled MV remedial system mitigating IAQ problems was performed. The mitigation solution considered was a decentralized MV with heat recovery coupled with a sub-slab depressurization system to reduce the radon concentration. This system gave a reduction in the radon average concentration from 425 to 70 Bq/m^3, also guaranteeing a CO_2 concentration around 760 ppm and thermal comfort (temperature around 21 °C). Compared to NV solution, this system gave an energy reduction of 86 %. It was therefore concluded that, when thermally retrofitting a building, there is the need to perform a balance between IAQ and energy consumption, allowing to find a remediation solution for poor IAQ.

Liao et al. (2021) [128] used an online questionnaire survey on the type of ventilation and the associated subjective sleep quality among 517 people in Danish dwellings, during winter 2020 (before COVID). The following information was asked: type of ventilation of bedroom, respondents' behavior on bedroom airing, information on bedroom environment, building location and surroundings, information on sleep disturbance by noise, stuffy air and thermal environment. Pittsburgh Sleep Quality Index (PSQI) was used to assess the sleep quality. An average reduced sleep quality was reported (median PSQI > 5). Noise, thermal discomfort and stuffy air were found to be related with less subjective quality of sleep. The presence of MV reduced the disturbance by “too cool” conditions and stuffy air while sleeping (Figure 42). The presence of carpets and the absence of MV seemed to cause sleep disturbance due to stuffy air. A more frequent opening of windows was detected among people who reported disturbed sleep by "too warm" or stuffy air conditions. On the other hand, no association between airing behaviors and PSQI was observed. Finally, it was specified that this study presented qualitative results and associations during the heating season: therefore, they need to be validated with field measurements and repeated during non-heating season to be generalized.

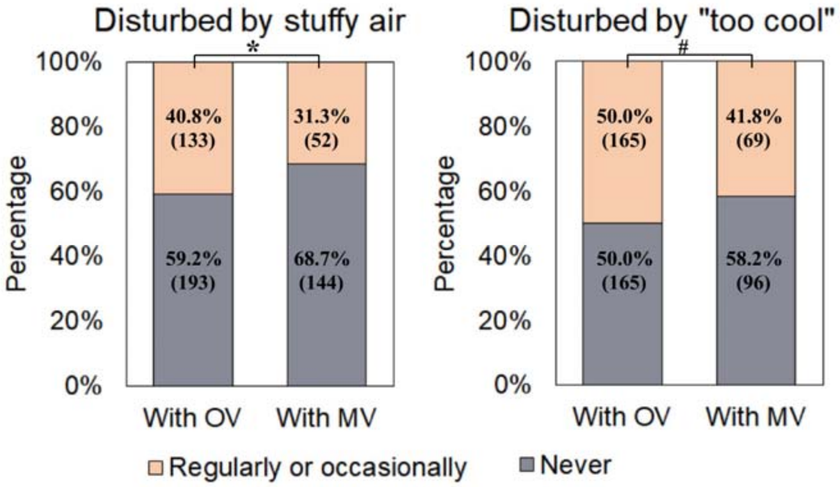


Figure 42: Percentage of people disturbed (“regularly or occasionally” and “never”) by stuffy air or “too cool” conditions during sleep. Results for mechanical ventilation (MV) and other ventilation (OV) are differentiated. Reproduced from Liao et al. (2021) [128]

A review by Ding et al. (2022) [129] analyzed the ventilation strategies and IAQ conditions of classrooms, in order to study the capacity and further improvements in minimizing the presence of infectious aerosols. The following aspects were highlighted: (1) NV and mixing mechanical ventilation are mainly used in schools, but these systems are not fully effective in dealing with short-range and long-range airborne transmissions. (2) Current literature and standards lack of knowledge dealing with design and rates to ensure safety from airborne transmittable pathogens. There is still uncertainty about patterns of air distribution and rates of ventilation. There is still a main focus on perceived air quality, CO_2 concentration and energy savings on standards, and many schools even fail to meet the current air-change requirements. Therefore, there are several reports of problems dealing with comfort, IAQ, performance or health. (3) New ways of ventilation are needed in classrooms, moving the design from comfort- to health-based. Personalized ventilation can potentially protect from short-range generated aerosols, with a simultaneous IAQ improvement, compensating existing ventilation regimes. (4) Before applying these new methods in classrooms, there is the need of more studies, also considering the types and activities of occupants. (5) IAQ changes have the potential to influence the other IEQ factors, which interact together into giving occupants' comfort and health. This aspect needs to be considered when updating ventilation systems, with a holistic approach both ensuring health and IAQ in schools.

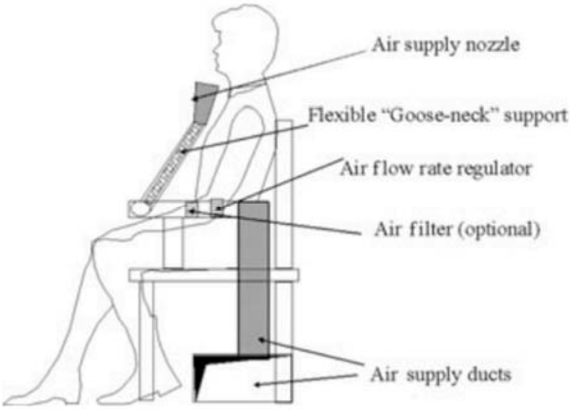


Figure 43: A chair-based system of personalized ventilation, reproduced from [129], [130].

5.2.3. Studies suggesting the use of HV or both NV and HV

The first paper recommending the exploitation of HV was written by Mathews et al. in 1994 [77]. The study validated and proposed a procedure to verify efficiency of load predictions of programs for thermal analysis to be used at the design stage to assess comfort regulating methods. The research involved 36 buildings in various climate conditions for 46 case studies. The article highlights how the study of NV, MV, passive performance and building's structural and evaporative cooling are necessary in the thermal and energy efficient design of buildings. Mechanical cooling techniques should be used only when these systems cannot provide with the desired thermal comfort. Moreover, by combining passive and mechanical cooling and various strategies of control, energy use and system size can be reduced by more of the 60 %.

Brager & Baker (2009) [78] performed a web-based survey in 12 buildings with mixed mode ventilation (with operable windows), compared with a database of over 43000 responses provided in 370 buildings, available at Center for the Built Environment (CBE). Thermal comfort, acoustics, air quality, cleanliness, lighting, office furnishing, spatial layout, maintenance and overall satisfaction were investigated. The following aspects were highlighted: (1) Hybrid approach consists in the use of some types of MV and/or cooling, combined with NV. (2) Most buildings in the CBE database (89 %) did not respect thermal comfort standards, with thermal environment satisfaction expressed by only 59 % of occupants on average. Too low air movement and lack of control were seen to be the main drivers of dissatisfaction. (3) Especially in terms of air quality and thermal comfort, HV buildings were found to perform extremely better than the benchmark buildings. On a scale from “-3” (very dissatisfied) to “+3” (very satisfied), mixed-mode buildings' thermal satisfaction was 0.94 points higher than in benchmark buildings. Additionally, air quality satisfaction was even larger (1.43 points higher). (4) In MMV buildings, a relationship was observed between air quality and thermal satisfaction and age of buildings (higher in most recent buildings) and climate (higher in moderate climates). (5) Causal mechanisms explaining trends in satisfaction would require more studies. Nevertheless, comments and previous research suggest people preferring operable windows because of a better personal control or the environment, fresh air perceived, major air movement and outdoor connection. The advantage of MMV buildings is that they offer these benefits and also high thermal control by mechanical devices. (6) Best performance buildings were observed to be the ones with MV only (no air-cooled systems) and radiant cooling. On the other hand, problems with the window interlock in changeover systems were associated with the lowest performance. The co-existence of NV and MV being able to work well together, with occupants able to ignore automated controls if desired or needed, was therefore pointed out. Moreover, occupants' comments indicated that MV - NV relationship does not always work as it was expected, having windows shut more than necessary.

Perino (2009) [131] performed an investigation about performance of buoyancy driven single-sided NV for IAQ management. This was done by means of measurements' series in a test lab (controlled environment) at the Aalborg University. Moreover, numerical models were used to assess different control strategies’ effects, as well as thermal and IAQ conditions. The following aspects were pointed out: (1) Innovative NV systems, integrating NV devices like motorized louvers and windows with MV, seem to be more welcomed by occupants. (2) Single-sided ventilation driven by buoyancy is effective, being able to guarantee good air-change rates, allowing to control IAQ and temperature; (3) Models can be used for control strategies optimization, to obtain adequate IAQ and indoor comfort. Thus, NV with thermal regulation and air-change perspectives was considered.

In a University building in mild oceanic climate (La Rochelle, France) a comparison of NV and MV strategies was performed by Dhalluin & Limam (2014) [132]. In particular, in two adjacent classrooms, a comparison of four ventilation modes was performed: (1) NV on a single room side; (2) NV with a systems of control of air-temperature and presence-based window control ("Self Opening and Shading System" = SOS), with 22 °C and 500 lx as summer setpoints and 21 °C and 500 lx as winter setpoints. (3) HV of 250 m^3h^{-1} associated with NV (manual windows only); (4) HV of 250 m^3h^{-1} associated with NV (SOS). A 40 % efficiency heat exchanger and a hot water battery made to supply a minimum of 20 °C air temperature in winter were present. Ambient parameters were measured and comfort questionnaires administered to teachers and students during hot and cold season in 2010. The following aspects were highlighted: (1) In many classrooms, poor ventilation leading to poor discomfort, learning performance and health risks is often present. (2) NV provided satisfactory IEQ, comfort and consumption of energy when well controlled. In this sense, the best compromise between energy demand and satisfactory learning was provided by SOS-NV. (3) When extreme conditions were present (i.e., very humid, cold or hot climate, or noisy outdoor conditions), no adequate energy savings and thermal comfort conditions could be provided. Therefore, HV might be necessary. Still, in environments where occupation density is lower (e.g., family houses), this would probably provide too many heat losses due to the too high amount of fresh air. Nevertheless, it would be easier to install than a MV system and would be associated with a good perception of occupants. (4) Good IEQ, comfort conditions and energy savings were guaranteed in summer by SOS system. During the whole year, this system provided good air-change rate and CO_2 conditions, even if particulate was slightly higher than with MV (because of the absence of filters). By means of windows, shadings control and night cooling action, SOS ensured a refreshment of 2 °C in summer, as well as meeting the setpoints in terms of lighting and air temperature levels. Best IAQ and thermal sensation were also met with this system. The drawback was a higher heat loss and necessity of backup electric heating in winter. Moreover, during the cold season, occupants often switched to manual modes in order to contrast colder draughts. (5) NV only (the most common in educational French buildings), despite being the most energy efficient, provides the lowest IEQ due to low air-change rate. Besides, this strategy provides the best acoustic and thermal sensation conditions, also saving the 85 % of electric energy. (6) Mixed modes, even if providing the most satisfactory IEQ due to lowest CO_2 concentration, provoked lowest comfort conditions and energy savings. Therefore, the lowest IAQ perception was given despite the best IAQ conditions in terms of CO_2 and particle concentration. (7) Overall IEQ conditions were generally "satisfactory" and "quite satisfactory", meeting French standards in both subjective and objective approach. (8) Consistency between sensation scores and the parameters measured was observed ("slightly cold" in cold season and "slightly warm" in hot season), as well as in the odor perception ("low odor in winter and "quite good" in summer). Therefore, World Health Organization (WHO) recommendations were fulfilled. (9) Acoustic perception was also "quite good" for all modes. Nevertheless, warm sensations seemed to be better tolerated with SOS system. The intermittent noise generated by this system was also better tolerated than the continuous one by MV. (10) Indoor environment was seen to provide a higher satisfaction in winter, despite a better footprint classification in summer. (11) Air velocity, lighting level and relative humidity (RH) subjective evaluations were observed to be homogeneous for all the ventilation types in both seasons, due to low sensitivity by occupants concerning these parameters' variations, which generally met standards' requirements. (12) Subjective approach did not suggest to use MV, despite the higher air-change rate. A multi-criteria approach is then justified.

In 2015, Montgomery et al. [133] investigated the IAQ of an office space in Vancouver (Canada), designed to be operated with both the ventilation types. TVOCs (total volatile organic compounds), CO_2 and PM in the space, with both NV and MV, were measured. It was observed that pollutants' concentration was more variable when using NV. Nevertheless, the concentration was still below thresholds from standards. On the other hand, higher control of pollutants' level was ensured by MV. NV air exchange rate was correlated with the TVOC concentration, while MV was not. $PM_{2.5}$ indoor-outdoor ratios were noticed to be 0.87 and 0.5 for NV and MV, respectively. Efficacy of NV also depends on indoor materials (VOC emission), outdoor pollution, period of the year (occupancy) and outdoor air velocity. In general, use of HV instead of NV would allow to save energy, while ensuring to meet IAQ needs. Moreover, these systems would benefit from occupancy control, sensors to detect differences of pressure on the envelope, PM and regional meteorological data, better occupants-building control interaction to optimize strategies of control. It was finally highlighted that investigations on sites with other systems of ventilation, outdoor air quality and types of building would be worth of interest.

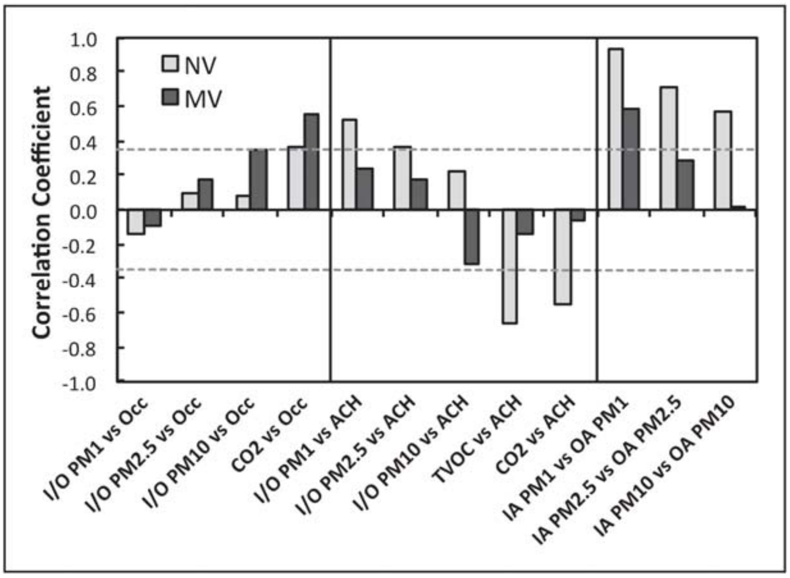


Figure 44: The correlation coefficient of Pearson between pairs of variables, 95 % confidence level indicated by dashed lines. Reproduced from Montgomery et al. (2015) [133].

In 2015, Daghigh [134] published a review about ventilation and thermal comfort in classrooms, residential and office buildings of Malaysia and the area nearby. It was firstly mentioned how, in order to obtain good IAQ levels, adequate ventilation system is necessary. On the other hand, too large amount of energy can be wasted by unnecessary ventilation. Moreover, energy efficiency can also enhance occupants' thermal comfort. On the other hand, NV could increase humidity levels and affect comfort in hot and humid climates. For this reason, MV and air conditioning use is broad in tropical climates. In this framework, the review concluded that, in hot-humid climates, the range of thermal comfort is wider than what is indicated in international standards, and that healthy IAQ and adequate ventilation strongly influence indoor thermal comfort sensation. In tropical climates, IAQ and thermal comfort could be improved (and energy consumption decreased) if more studies in the field would be performed. Findings could be exploited to modify building energy audits in order to obtain more energy efficiency. In the future, ventilation technologies and thermal comfort could be coupled with active and passive strategies and renewable energies. This would help overcoming building energy issues in hot-humid areas.

In 2016, a review by Salcido et al. (2016) [80] analyzed literature of 1996-2006 in order to understand the HV usage in offices, in terms of objectives, progresses fulfilled and challenges for the future. It was firstly stated that HV has been efficiently used to guarantee good indoor environment, since the alternation of MV and NV could save 75 % of the energy use, while 40 % of the energy could be saved by the optimization of windows' schedules. The following conclusions were listed: (1) Air quality, thermal comfort and consumption of energy are significantly influenced by occupancy and people behavior. (2) The design of HV systems by simulations is over-simplified in terms of occupants' behavior, and more advanced algorithms are needed. (3) In the future, HV should be optimized by proper design of layout of the building (internal and external), taking into account the direction and speed of the wind, and using the proper insulation, glazing, façade design and shadings. This would allow to minimize the use of MV cooling energy. (4) In order to improve the cooling systems' efficiency, better understanding of proper HV strategies depending on the climatic areas are necessary in the future. (5) Potentially higher energy savings can be obtained by users' education about thermal conditions and behaviors expected.

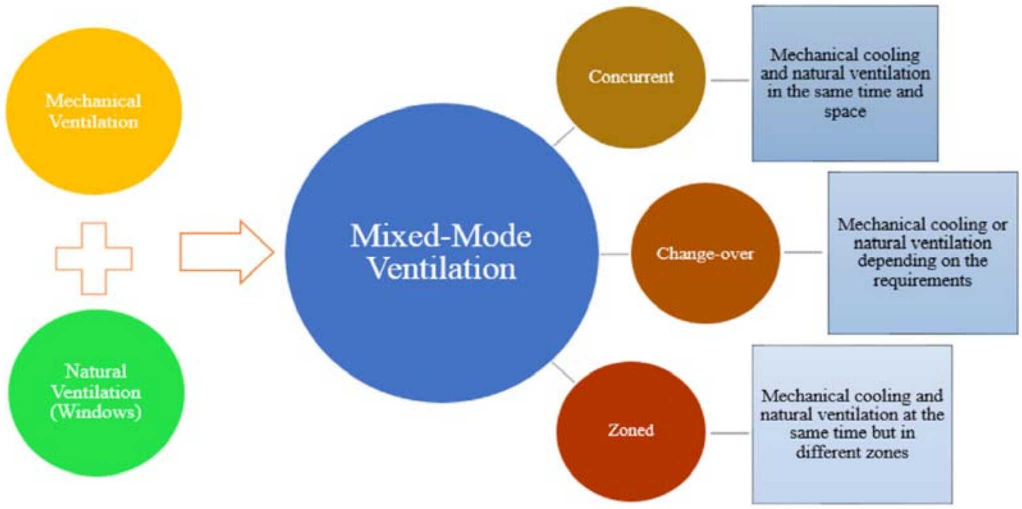


Figure 45: Types of HV systems, reproduced from Salcido et al. (2016) [80]

A review of standards, regulation, reports and scientific studies on energy efficient methodologies for ventilation, considering also occupants' behavior influence on energy use and correlation of ventilation with productivity and health, was published by Chenari et al. [91] in 2016. It was firstly highlighted how ventilation is the key both to provide suitable IAQ and to decrease the energy use. Following conclusions were stated: (1) HV leads to considerable energy savings, while ensuring acceptable IAQ levels. (2) Ventilation of spaces with low or absent occupancy annually leads to considerable energy waste in the world. (3) IAQ and buildings' energy performance are not only affected by characteristics of buildings, but also by methods of ventilation, environmental conditions and controlling behaviors of occupants. (4) Health issues and symptoms, as well as bad occupants' performance, might be provoked by poorly designed ventilation. For this reason, ventilation rates higher than minimum standard requirements are suggested by many studies. Nevertheless, the topic of relation of ventilation rate with indoor health should be further deepened in several types of buildings (offices, day care centers, schools, homes), in several climates and especially in outdoor polluted regions (where more attention to filtration and air cleaning should be paid). (5) Literature lacks of studies regarding HV strategies smart-window based. These strategies could help reducing the energy consumption while maintaining proper IAQ. (6) Energy consumption cannot be reduced under the levels at which discomfort and unhealth are caused to occupants. (7) nZEBs shift the assessment of buildings' energy consumption from a yearly scale to a daily scale, for a balance among demand, storage and production. In this framework, predictive and dynamic control of buildings, comprising HV, can become a winning strategy for a more efficient use of available energy.

Aldawoud (2017) [135] used CFD to study the behavior of several alternative configurations (size and orientation, solar shading) of inlet and outlet openings in a naturally ventilated standard office building in a hot-humid climate. The aim was to maximize wind-driven cross-ventilation by the most efficient design of windows. The paper stated that: (1) Acceptable thermal comfort conditions (thermal regulation perspective) and temperature can be achieved by cross-ventilation. (2) Not adequate outdoor temperatures (too high) and wind conditions (too low) may be present in summer in order to provide enough internal air movement to ensure thermal comfort. Nevertheless, 4 - 8 °C of temperature reduction are achievable. (3) In other seasons (November-April), NV is a valid alternative to air-conditioning. (4) Large inlets and orientations of inlets and outlets are directly proportional with the airflow rate. Larger inlets should be exposed to the main direction of wind. On the contrary, similar small areas of inlets and outlets led to a bigger resistance with lower differences of pressure and less air circulation. Therefore, an important effect on airflow is obtained by building orientation. (5) Airflow is enhanced also by adding horizontal shading devices outside of the outlets. This has the effect of making the differences of pressure higher.

A comparative analysis of the air-change performance of MV and NV was made in two schools in Seville (Spain, dry-summer subtropical-Mediterranean climate) by Gil-Baez et al. (2017) [136]. Levels of humidity, CO_2 and temperature were analyzed in association with occupation, and data obtained were validated with simulations in a third building with cross NV. Here, stack ventilation was tested. The following aspects were pointed out: (1) Based on studies performed in cold climates, MV has been widely adopted in recently built schools, in order to overcome air-tightness to achieve adequate IAQ. Nevertheless, in mild climates the number of hours requiring a heating system is moderate, and near Zero Energy Buildings could be obtained by NV, without compromising indoor comfort. (2) In environments with high occupation and defined schedules (like schools) NV could provide the IAQ necessary for a proper learning environment and remove heat from internal gains such as windows and occupation. (3) Suddenly reduction of CO_2 concentration below the 1000 ppm limit was observed with windows' opening in winter days. Moreover, no parallel temperature reduction was observed. Since heating system was off, this means that internal gains were more significant than NV losses (positive effect of thermal inertia). (4) Usage of NV allowed energy savings between 11 % and 26 % and CO_2 emissions lowering of 31 % - 49 % with respect to MV. Moreover, the NV tested allowed draughts and heat losses to be minimized, due to less presence of air inlets. The socio-economic impact of using NV in schools of Mediterranean regions would be important, due to the high number (87000 schools) in Spain, Greece, France and Italy. This measure would save approximately 46500 tons of CO_2 only in the Andalusia area. (5) A proper design of NV systems, such as windows with automated control, is necessary, since they need to satisfy both energy savings and IAQ requirements. (6) When noise level is low and unpolluted environment is present, NV is a proper solution. Otherwise, with noisy locations or colder weathers, solutions of HV could be implemented (i.e., MV with heat recovery coupled with windows with an automatic control). (7) More research is necessary in mild and Mediterranean climate regions in order to promote the use of NV and develop commercial solutions.

A presentation of a strategy of building design using a HV system to provide energy efficiency measures in a Eighties social housing complex of Modena (Italy) was provided by Barbolini et al. in 2017 [137]. MV (with heat recovery and earth tubes) was used during the heating season. On the other hand, free running use (open trickle ventilators on windows, vertical shaft ventilators, mitigation of heat loads by means of insulation and mass, free night cooling) were used during the non-heating season. Aerodynamic principles to maximize pressure differences due to stack effect were implemented for vertical shafts. Combined heat and power system, solar thermal collectors, PV and solar panels were also used to further minimize the energy demand. Indoor comfort was assessed by the adaptive model during the warm season, and was verified with CFD modeling. It was found out that, in warm season, acceptable indoor conditions can be met in a free running net-zero energy building. For this reason, conversely than the current tendency of using HVAC during hot season, HV ventilation can be suggested, with NV in summer and MV in winter.

In a baseline simulated office building with two floors, a model predictive control (MPC) was built by Chen et al. (2018) [83] in three climate zones of the USA (Atlanta, Los Angeles and San Francisco). The aim was to maintain acceptable indoor conditions with energy consumption minimization, when using HV. Validation showed that occupants' thermal comfort was maintained by MPC, which was therefore performing as expected.

Usman & Bakar (2019) [138] analyzed thermal comfort of a residential premise in Malaysia by means of CFD analysis. The effect of adding a ceiling fan MV system assisting NV was assessed. It was noticed that, by adding this system, there was an improvement in the values of PMV and PPD indexes.

Raji et al. (2020) [82] used CFD and EnergyPlus in order to study six NV strategies in on 12th floor of a 21-storey office building in Delft (Netherlands, temperate maritime climate). It was observed that thermal comfort and fresh air were guaranteed for up to 90 % of occupancy time during summer by NV strategies, and therefore a high share of energy can be saved with this strategy. The different strategies had similar performance, except than the ones combined with a poorly ventilated double skin façade or with atrium design. In fact, double skin façade was observed to have the risk to become too cold or too warm, making it necessary to have a building management system to control vents operation. Minimum temperature set-point is important for windows operation and thermal comfort. For this reason, it needs to be correctly set according to outdoor variations of temperature. Scenarios with vertical shafts (atria or solar chimneys) did not show advantages with respect to the scenarios driven by wind. This might be due to the office geometry (narrow plan) and location (city with high wind velocity along the year). In fact, highest advantages of stack ventilation occur with buildings with a deep plan, where it is difficult for cross ventilation to occur. It was finally highlighted how structure associated or architectural configuration limitations exist for improving or adding NV to existing buildings. Moreover, applying night-time NV during summer could even extend the percentage of hours with comfort conditions. For high-rise buildings, HV is necessary when suboptimal external conditions (wind, temperature or noise) and design failures (architectural design layout or tenancy patterns change) are present.

An investigation on the performance of hybrid ventilation in industrial buildings was performed by Meng et al. (2020) [81], by means of experimental scale model with a heat source in Xi'an University (China). Hybrid NV driven by buoyancy coupled with a mechanical system for exhaust was used. At different velocities of the mechanical exhaust, efficiency of the HV and distributions of temperature were observed. After highlighting how indoor environment and ventilation energy can be optimized by means of HV, the study concluded that an optimal velocity needs to be identified in order to maximize HV efficiency, since non-optimal thermal environment and airflow short circuiting, as well as excessive energy consumption, can be created by a disproportionate MV rate.

Torresin et al. (2021) [139] performed an online survey among 848 people working from home during the COVID-19 pandemic in London and Italy, during winter lockdown. A focus on the perception of the acoustic environment while relaxing or working and on the elements influencing the window opening behavior was given. The HVAC typology did not give any significant difference in soundscape appropriateness for relaxing, and the ventilation strategy did not give any significant difference in soundscape appropriateness for working. Nevertheless, in general, during working and relaxing activities, spaces with less dominant noises from building services were judged as more appropriate. No significancy associated with the sky or building view, noise sensitivity, presence of a quiet side, gender and age were found in the windows opening behavior while working from home. Even if in noisy urban areas, occupants tended to keep open windows at least sometimes when using NV or MMV. In Italy, participants working from home were more incline to open windows when a vegetation view was present. Moreover, higher noise levels were compensated by other benefits from NV in the windows opening behavior. This suggested the idea of the existence of an "adaptive acoustic comfort" in NV facilities [140], [141], to be further investigated in order to define acoustic opportunities for NV in buildings. In fact, elements such as the perception differences between MV and NV and the presence of pleasant outdoor acoustic contexts are not taken into account in present standards.

An empirical study about the change of classrooms environmental conditions during COVID-19 pandemic was performed by Monge-Barrio et al. (2022) [142]. Surveys were conducted during the heating seasons of 2020 and 2021, in nine naturally ventilated secondary/high schools of Pamplona (Spain). Moreover, a detailed building monitoring was implemented in one of the schools. When present, MV was not used due to the high noise produced and the high consumption of energy, so all the facilities where only naturally ventilated during both the periods considered. A mean CO_2 concentration reduction of 1400 ppm (1000 ppm observed) and a mean temperature reduction of 2 °C (18 °C observed) were noticed, with a 31 % increase of the heating energy consumption. The authors highlighted how these lower temperature values can be admissible only during a pandemic situation, without vaccines’ availability. Moreover, they stated that a plan should be prepared by schools, in order to improve indoor conditions, with cross ventilation and installation of CO_2 and temperature monitoring systems. When outdoor conditions require it, complement Heat Recovery Ventilation and thermal envelope improvement would also help in providing healthy and safe classrooms with low CO_2 emissions and low consumption of energy. Therefore, the effects of NV used for air-change were studied with both an IAQ and thermal comfort perspective.

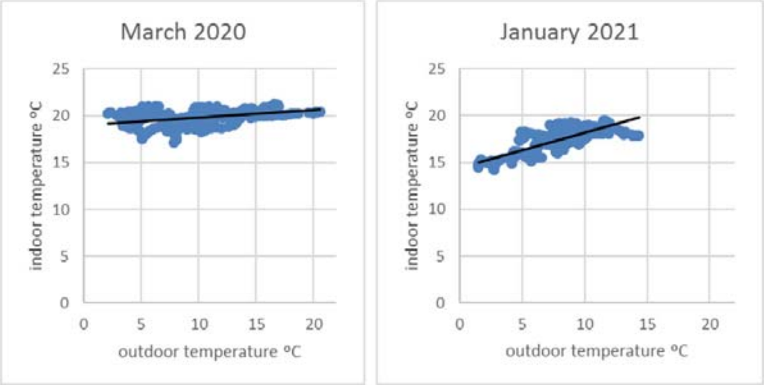


Figure 46: Comparison of temperatures measured in March 2020 and January 2021 as function of outdoor temperature, reproduced from Monge-Barrio et al. (2022) [142]

Another research on an educational building was conducted by Elnabawi & Saber (2022) [143]. The authors evaluated an integrated HV (exploiting NV without compromising comfort) and photovoltaic (PV) system in urban facility in Bahrain (hot-arid climate). The performance was assessed by means of yearly energy savings and CO_2 emissions, as well as the potential to provide comfort on a thermal point of view (thermal regulation perspective). The analysis was made by a dynamic simulation validated using annual consumption data. It was observed that overheating hours (or cooling hours) can be reduced of the 23 % by the automatic operation of windows. Moreover, HV had a better performance in the cool season (33.5 % savings vs. 17.1 % in summer). The annual reduction is equal to 23 % with the hybrid ventilation, and 85 % when adding the PV solar system as a primary energy source. Finally, it was highlighted how extending the upper and lower comfort limits (from 25 °C to 22-29 °C) led to higher energy savings. This can be further enhanced setting the temperature according to the local climate condition instead than using setpoints from international comfort standards.

An evaluation on the particulate matter ($PM_{2.5}$) and CO_2 in seven naturally ventilated and three mechanically ventilated residential buildings was performed by Yin et al. (2022) [144] in China (Xi'an, cold climate and generally serious pollution). This was made by means of a long-term online monitoring (one year). It was observed that, in the most polluted season (winter), NV was not able to remove $PM_{2.5}$ harm for humans: MV was necessary. A significant improvement in air quality could not be obtained by short-term MV if compared with NV, but results improved when the operation duration increased (minimum daily recommendation of 9 hours). The excess of CO_2 concentration (more than 1000 ppm) was greater with MV (26 %) than with NV (9 %). Moreover, a dependence of CO_2 concentration from indoor-outdoor temperature difference was observed. In Xi'an residential buildings, IAQ control could be implemented with a MV system combined with short-term NV in order to both control $PM_{2.5}$ and CO_2 concentration.

Arata & Kawakubo (2022) [145] performed measurement and questionnaire surveys in an office building of Tokyo (humid climate with hot and humid summers and dry and sunny winters with strong North-East monsoons), in order to test the effects of HV on energy consumption, thermal comfort and productivity during springtime (average temperature of 21 °C). The productivity effects were studied by means of a hierarchical linear model (multi-level analysis). The following considerations were made: (1) Mixed mode can decrease the power consumption while improving workers' satisfaction. (2) Windows' opening time depended on weather conditions, varying each day. (3) On floors with HV, savings in the range of 3.1 - 70.6 % were present with respect to floors with MV only (both the systems maintained similar levels of air temperature and PMV). (4) Male participants' productivity improved of 9.1 %, probably because of decreased concentration of CO_2 and higher air flow and air freshness. (5) Since women productivity increased only of the 0.5 % with HV, gender differences might be present. However, a bias could have been given by the small number of female participants.

5.2.4. Studies not clearly stating a preference

Kalamees (2006) [146] monitored the ventilation (measuring exhaust air flows) and the indoor climate (measuring temperature and RH in living rooms, bedrooms and outdoors) of 28 single family lightweight timber-frame houses in Estonia (Nordic climate). The monitoring was performed continuously during 1 year. Questionnaires (one per house) were also administered to occupants. During the hot season, high indoor temperatures highlighted that original design did not consider thermal comfort requirements. Problems in control systems were shown by large temperature variations in winter. Moreover, average daily amplitudes of RH and temperature were strongly influenced by the ventilation performance. Average air-change rates were lower than recommended by standards, but similar to ones measured in other Nordic countries. Questionnaires highlighted that NV was associated with stuffy air, while MV caused noise issues (which limited its use). Moreover, houses with air leakages in envelope caused cold floors, draught from electric sockets and fluctuating room temperatures during winter.

Ouyang et al. (2006) [147] performed a spectral analysis in five different outdoor locations (building roof, open area outdoor, around buildings, seashore and indoor) to find the characteristics of mechanical and natural wind on the dynamic point of view. It was found that, when mean velocity is not higher than 0.25 m/s, diffusing mechanical wind can reach the characteristics of natural wind. Reaching these characteristics (spectral characteristics of natural wind) can improve occupants’ feeling about mechanical wind.

In 2011, Razman et al. [148] performed a field study in a University hostel in Malaysia (hot and humid climate), in order to identify if thermal comfort can be reached with NV. Measurements were taken for five days between 11:00 and 17:00 and 178 questionnaires' sets were collected. NV helps going for a sustainable environment and saving energy. Thermal condition was perceived as comfortable, but MV would help to make this condition more effective. Thermal comfort was somehow prevented by furniture arrangements and window openings which were an obstacle for adequate air movement.

A review on UK guidelines and regulations in relation to MV systems with heat recovery and a review on the long-term indoor VOC concentrations in super-energy-efficient test houses (considering the effectiveness of trickle ventilators and heat recovery ventilator use) were performed by the study of Yu and Kim (2012) [149]. It was stated that possible high indoor pollution from building materials' emissions and products from combustion can occur in air-tight buildings. Moreover, it was expressed the need to review and examine the several ventilation possibilities to alleviate the indoor pollution while ensuring energy savings. Possible options would be low emission materials or use of air-cleaners to decrease the need of higher air-change rate and thus improve energy savings.

Giridharan et al. (2013) [150] investigated the performance of spaces with MV but passive cooling in a nucleus-type hospital (connected cruciforms blocks with various and little courtyards in between, Figure 4739) in Glenfield (UK). A comparison between thermal comfort criteria and measured temperatures was made during summer 2010, while a prediction of future conditions in ward space was made by means of a calibrated model. The following conclusions were listed: (1) The maximum indoor temperature varied in the range of 27.3 - 29.3 °C, and the nurse station was found to be the warmest zone. Most spaces monitored were found to be within HTM03-01 [151] thresholds in terms of thermal comfort. (2) There is need for adaptive criteria accommodating both cooling and heating conditions, specific for hospitals. (3) The incidence of night-time overheating showed major deviations from criteria of thermal comfort. (4) MV with 1.5 ach^{-1} would provide reasonable conditions of comfort, if good provisions of openings of windows are present. (5) Light touch low carbon interventions may give comfortable conditions in bedrooms in UK Midlands into the 2050s in nucleus-type hospitals, for both extreme and typical years.

Figure 47: Glenfield Hospital aerial view. In yellow the case study wards and waiting area locations Reproduced from Giridharan et al. (2013) [150] (Source: Google Earth image modified [152])

A building model was built by Homod & Sahari (2013) [153] in Malaysia, by means of empirical and physical subsystems model functions. The aim was to focus on the building internal temperature and RH control efficiency by infiltration and ventilation. PMV (as function of HVAC controlled indoor air velocity, temperature and RH) was used to characterize indoor thermal comfort. Twenty-four hours MV simulations with varied flow rate were performed. While highlighting the advantages of MV in guaranteeing thermal comfort, the results point out the possibility of reducing the relying on powered cooling.

Natarajan et al. (2015) [154] used a simultaneous survey among 115 participants and indoor and outdoor measurements, in order to study the applicability of (1) PMV/PPD model (ISO 7730:2005 [155]), (2) adaptive model (ANSI/ASHRAE Standard 55:2013 [156]) and (3) adaptive model (EN Standard 15251 [157]) to assess thermal comfort. The research was performed in three different offices of Bogotà (Colombia, subtropical climate) having three different ventilation regimes (NV, MV and HV). Adaptive and PMV model from Standard 55 was observed to be functional for predicting thermal perception in MV buildings. On the other hand, in NV and HV free-running offices, adaptive models in ASHRAE and EN standards showed less applicability. This was due to a reduced personal control on windows in the two offices part of the survey. PMV model was able to assess conditions of comfort in the HV office, where control conditions were comparable to the MV one. Finally, PMV/PPD and adaptive models' applicability was seen to be strongly dependent on the control possibility which is given to the occupants. For this reason, a classification of environments based on windows' control level (instead of only considering the air conditioning presence) was proposed.

In order to achieve the net zero energy balance, various criteria of ventilation were implemented by Grigoropoulos et al. (2016) [158], in a simulative study (EnergyPlus) of a residential building in a Mediterranean climate (Thessaloniki and Athens, Greece, and Larnaca, Cyprus). In these areas, hot summers are present, with cooling loads prevalent on heating ones, and PV systems are applicable due to high solar irradiance. The base case model scenario was characterized by an air-change rate of 2 air-changes per hour (ACH) during night and early morning. The ventilation rate was gradually increased, also simulating MV, assessing the PV capacity, the primary energy demand and indoor thermal comfort. It was observed that an increase of the ventilation rate to 8 ACH provoked a minor primary energy demand. The energy reduction was never higher than 10 %, and was slightly more marked in Thessaloniki, because of the presence of a milder climate. Moreover, the application of higher rates of ventilation had an even higher impact on thermal comfort, allowing to obtain a 50 % decrease of overheating degree hours in Athens, and a 30 % reduction in Larnaca. MV provided a major control of indoor temperature, but increased the energy demand (20 %) and costs for maintenance. For these reasons, this solution is less applicable in residential buildings in Eastern Mediterranean climates, when microclimate conditions permit the exploitation of night-time ventilation. Other issues (like safety, noise, life cycle costs and feasibility) should be considered when deciding the best solution. In larger multistorey commercial or residential buildings, HV or MV ventilation could be necessary, due to the need of more complicated ventilation techniques for achieving energy savings.

Nardell (2016) [159] provided with a review on the state of possible environmental interventions to overcome the problem of tuberculosis transmission. It was highlighted that interventions to control this illness can also apply to other airborne transmittable diseases. Moreover, measures of environmental control are the most important way of intervention after the identification of unsuspected cases. In fact, transmission is facilitated in overcrowded, congregate and badly ventilated buildings (e.g., prisons, hospitals, refugee camps). Generally, NV is the main air disinfection way, with the advantages of being cheap and broadly available. The drawbacks are the inapplicability under too cold or too hot conditions or other conditions (windows might be closed, for instance, for pest control or security reasons). Moreover, when air conditioning is installed, windows might be kept closed to ensure thermal comfort. MV has the advantage of providing proper disinfection of air, but it might be expensive in the installation, operation and maintenance. Finally, upper room germicidal irradiation was identified as the most cost-effective mean of disinfection.

Lei et al. (2017) [160] monitored the IAQ (O_2, CO_2, temperature and RH) in a students' dormitory of Beijing during winter (January). Questionnaires' surveys were used to analyze mental state and thermal comfort after 7 hours sleeping. A model predicting temperature and IAQ while variating the open area during winter was proposed. The study also aimed to prove that, in dormitories, NV is necessary even in cold climates. It was concluded that increasing the NV area improved IAQ, but decreased thermal comfort. During winter, 0.055 m^2 (giving 0.036 m^3/s of NV) was found to be the proper area of ventilation in dormitories with 10-12.5 m^3 of space per person. With open area bigger than 0.077 m^2, the temperature decreased under 20 °C only after 4 hours. An increase in the students' number should be accompanied with an increase of the open area. Nevertheless, with less than 6.5 m^3 per person, windows' opening is insufficient.

Heebøll et al. (2018) [161] performed a four weeks monitoring of four different Danish classrooms (Atlantic temperate climate) in the winter season (January), one year after a retrofitting was performed. Temperature, CO_2 concentration, use of energy and behavior in door and windows opening were recorded. The rooms, located in Copenhagen, were equipped as follows: (A) decentralized, balanced supply and exhaust MV unit with heat recovery; (B) automatically operable windows with an exhaust fan; (C) automatically operable windows with alternating counter-flow heat recovery through slots in the outside wall; (D) visual feedback display unit showing the current classroom carbon dioxide concentration, thus advising when the windows should be opened. Original approach of manual windows opening was retained in one class, for comparison. The paper allowed to list the following observations: (1) The presence of a CO_2 feedback display caused the opening time to be longer (during occupancy hours including breaks), but this did not cause the decrease of CO_2 concentration to be significant. (2) With automatic opening and exhaust fan, the opening period was 71 % of occupancy time (breaks included), also causing CO_2 concentration to be significantly lower with respect to classrooms with only manual operations. (3) With automatic opening and heat recovery, opening period was 49 %, with no significant lower CO_2 concentration with respect to "only-manual" rooms. (4) In the rooms with MV and with automatic windows and the exhaust fan, the lowest concentrations of CO_2 were measured. (5) No remarkable differences were observed in indoor temperatures of classes with automatic opening of windows and classes with no retrofit. Temperature was generally within comfort ranges in both cases. A significantly warmer temperature was observed in rooms with the display for visual CO_2 feedback or with MV (maybe caused by a valve defect and radiator thermostats' setting). (6) In temperate areas, MV or automated windows opening systems are recommended for classrooms.

An investigation on the use of MV and NV in 46 apartments in 10 cities in China, located in 5 different climate zones (severe cold, cold, hot summer cold winter, temperate, hot summer warm winter), was performed by Lai et al. (2018) [162]. The houses were monitored for one year, and questionnaires were administered to gain information about residents' choices. It was stated that MV, even if more controllable, reliable and comfortable, could generate secondary air pollutants, noise and energy consumption. Moreover, it was found out that average ventilation duration was shorter for MV (7.2 hours vs. 11.0 hours). NV duration increased and MV duration decreased with: warmer climates, warmer season and higher average outdoor temperatures. In colder regions, when temperature reached 24 °C, NV duration began to decrease. When dealing with colder climates, use of supply MV was less than energy recovery ventilation systems, probably due to thermal discomfort. Moreover, MV and NV durations were highly variable and people were not active in the change of the status of ventilation. Noise was reported as a source of discomfort both in case on NV (outdoor) and MV (system). Finally, it was observed that the priority of occupants was thermal comfort instead than healthy IAQ. Nevertheless, when MV allowed to provide healthy indoor conditions, they stated their willingness to spend money on energy. Thus, energy savings, health and thermal comfort were proposed to be the three drivers of ventilation behaviors.

MV and NV effects on indoor climate (thermo-hygrometric and IAQ, thermal regulation and air-change perspectives) of nine homes in Urumqi (China, temperate continental climate with severely cold winters) was investigated by Zhao et al. in 2018 [163], by means of preliminary questionnaires on living habits and one-year indoor monitoring. Four of the houses considered were equipped with NV, four with MV with heat recovery, and one with MV without heat recovery. It was observed that winter indoor climate was dry, but comfortable during the rest of the year. In this season, MV was observed to possibly cause a lower temperature reduction and a lower humidity reduction with respect than a 25 minutes long NV. Both MV and NV would need attention to humidification, especially in the colder season. Moreover, indoor conditions were perceived drier by people living in environments with MV, who also expressed preference for humidifying the rooms: this did not prevent humidity to be lower than in houses with NV. In houses with NV, IAQ was observed to worsen because of too humid conditions when poor ventilation was present. $PM_{2.5}$ concentration was low outside in summer and transition seasons. Moreover, not too hot or too cold temperatures were present. These last aspects make it suitable to improve indoor environmental conditions by NV, saving MV energy.

Fernández-Agüera et al. (2019) [164] studied IAQ and thermal comfort in two different climates in Spain (Seville and Madrid). The investigation was conducted in residential buildings constructed before regulations on energy efficiency (1939-79). The case studies were not equipped with a MV system and had various levels of air-tightness. The IAQ was compared with the air-tightness and a comparison of the behavior in day- and night-areas was performed. It was firstly stated that, in these buildings, NV behavior (and therefore outdoor temperature) was the main driver for the air-change. Indoor-outdoor concentration of CO_2 were similar in spring, summer and autumn in Seville, and only in summer in Madrid. In Seville, this was associated with the behavior of occupants trying to lower the temperature during less irradiated times. In Madrid, poorer thermal comfort was also detected during summer. In both climates, during winter, levels of CO_2 above 1200 ppm were recorded in both Madrid (1900 ppm) and Seville (1400 ppm). Higher values were recorded during night. During this season, occupants, being aware of the of the MV lack, ventilated their flats mainly in the morning, primarily relying on infiltration during the rest of the time. This was the main reason why unhealthy indoor air and poor air quality (both in terms of CO_2 land RH levels) were observed. In fact, low air-change rate and air-tightness both concur in creating high concentrations of CO_2. In areas with warmer climates, this association is less evident, due to the major influence of individual behaviors in terms of ventilation. Healthy conditions could not be maintained, with the consequent risk of condensation, especially in colder climate (Madrid) and in buildings with the highest air-tightness (where windows had been substituted). The practice of windows' openings was observed to cause also a loss of energy. Improvement of ventilation practices and MV systems would ameliorate the IAQ in both locations. In Seville, comfort standards could be met raising winter internal temperatures by means of a more effective heating.

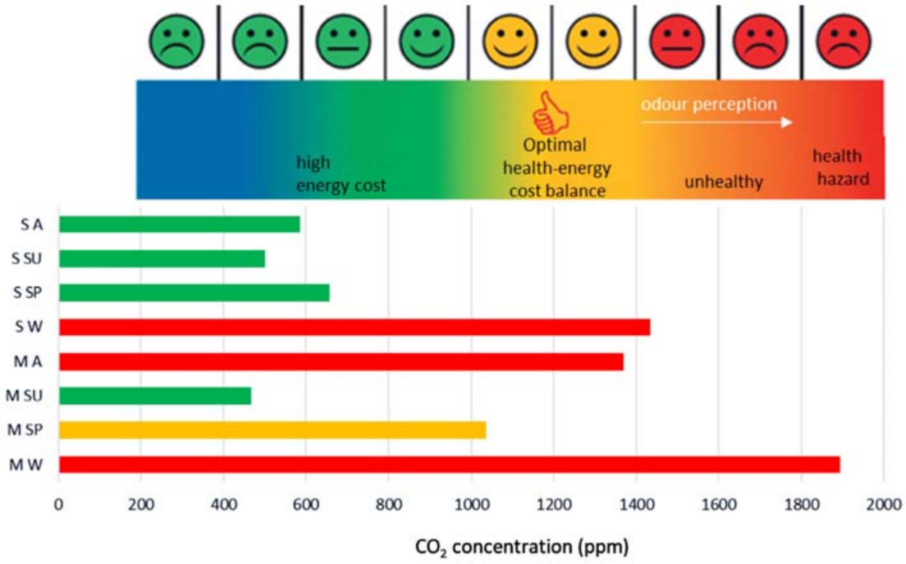


Figure 48: IAQ and balance with ventilation energy consumption. S = Seville; M = Madrid; A = autumn; SU = summer; SP = spring; W = winter. Reproduced from Fernández-Agüera et al. (2019) [164]

Cardoso et al. (2020) [165] used transient simulations in order to compare scenarios with different possible air paths configurations in a Portuguese apartment with highly permeable envelopes and highly variable air-change rate. Both natural and mechanical scenarios were included. A MEV (mechanical extraction ventilation) was present in bathroom and kitchen. On the other hand, unintentional air leakage paths constituted the source for air supply. Only when the MEV was on, a sweeping effect from bedroom to bathroom was observed. Moreover, equivalent air leakage area distribution through different leakage configuration paths was impactful on the air-change rate. It was concluded that the dependence of air-change rates from air-tightness is worth to be studied in Southern Europe, since NV is widely used. IAQ, energy efficiency and comfort strongly depend on it.

Abdul Hamid et al. (2020) [55] monitored air temperature, air humidity, air-change rates and CO_2 in twelve heritage buildings with offices of Sweden. Measurements were coupled with questionnaires to the occupants. The effects of a MV ventilation system with a heat recovery located in a chimney pot (hidden) and of dampers for air-change rate reductions (installed on the pathways for natural airflows, on the chimney tops) were studied. This was done by means of field measurements and energy simulations in two of the buildings. It was observed that, in this type of building, indoor climate is highly dependent on outdoor conditions. In fact, air-change rate is higher during working hours (window openings), higher during working time in summer than in winter (window openings), lower during after-hours in summer than in winter (smaller indoor-outdoor temperature difference). Too cold and draught conditions were observed in cold season, while too warm, dry and stuffy environments was seen in summer (with acceptable CO_2 conditions). Moreover, the two proposed solutions were observed to give a potential reduction in the energy use (also

CO_2 concentration in case of chimneypot MV with heat recovery). Finally, the authors recommend to make other investigations, specific for each building (e.g., thermography with air-tightness testing, emissions, particulate and moisture safety assessments), before taking decisions on the measures to apply. Profitability of measures should be taken into account, as it is fundamental in decision-making processes.

A real-time investigation of $PM_{2.5}$ and CO_2 concentrations in 33 classrooms located in 21 different schools of Beijing, comparing MV systems and NV with air cleaners, was performed by Cai et al. (2020) [166]. Air temperature, humidity and effectiveness of air-cleaning were also monitored. Too low ventilation rates were observed with NV in days of high $PM_{2.5}$ concentration. Nevertheless, both NV and MV were not sufficient to lower enough the $PM_{2.5}$ concentration. MV ensured temperature to be not too low during winter. Nevertheless, during days of central heating switching on or off, indoor temperature was found to be sometimes lower than the 18 °C recommended by Chinese standards, with both NV and MV. NAI (negative air ion) purification modules were observed to tend to elevate the levels of biomarkers related with a higher possibility of oxidative stress. MV had a lower energy efficiency in removing $PM_{2.5}$, but was more effective in the CO_2 reduction.

Scheuring & Weller (2021) [167] performed an EnergyPlus simulation in an office room, in order to study the comfort and energy implications of four strategies of window openings (based on CO_2 and temperature) and one intake/exhaust MV system (based on CO_2), at the three different climates of: (1) Wiegendorf (Germany) - moderate (European continental); (2) Madrid (Spain) – Mediterranean; (3) Hanoi (Vietnam) – subtropical. The paper led to the following considerations: (1) NV can be an alternative to save energy in non-residential buildings, ensuring less costs of maintenance and positive psychological feelings of freshness of air. Nevertheless, NV might lead to higher energy consumption and less IAQ, due to behavior of users. Therefore, controls of NV based on concentration of carbon dioxide and room temperature are needed. (2) In the cold months at moderate climate, long openings could not be used due to thermal discomfort. In the other conditions, NV outperformed MV.

The review by Wolkoff et al. (2021) [47] investigated the influence of microclimatic parameters (room temperature, indoor air humidity, ventilation) on human health, cognitive performance, infection risk and work in offices. It was highlighted that acute and chronic health issues can be reduced by ventilation, which can also enhance the work performance. This is due to control strategies of general emission source and the indoor air pollutants (comprising pathogens) dilution. MV helps diluting and removing the indoor air pollutants, thus giving better comfort and less health risks. When devices like efficient filtration and air cleaning systems are implemented, also exposure to size dependent ambient particles can be reduced. Satisfaction on thermal comfort and overall microenvironment is improved by personal control of ventilation, due to positive physical and psychological impact. Nevertheless, an increased exposure to air pollution, pathogens and allergens (from indoor or outdoor) can occur due to ventilation itself, being cause of health risks. This happens with NV or when not properly designed, maintained or operated MV is present. Deterioration of IAQ perception and harm from new chemicals exposure can also occur due to ozone surface-initiated reactions from systems maintained improperly. Moreover, in the cold season, dry outdoor air can enhance the viability of virus droplets: high ventilation rate with no humidification has to be avoided. Therefore, WHO's air quality guidelines should be met by a "health-based ventilation rate", with an acceptable perception of IAQ by diluting human bio-effluents.

5.3. Further statistics about literature analysis

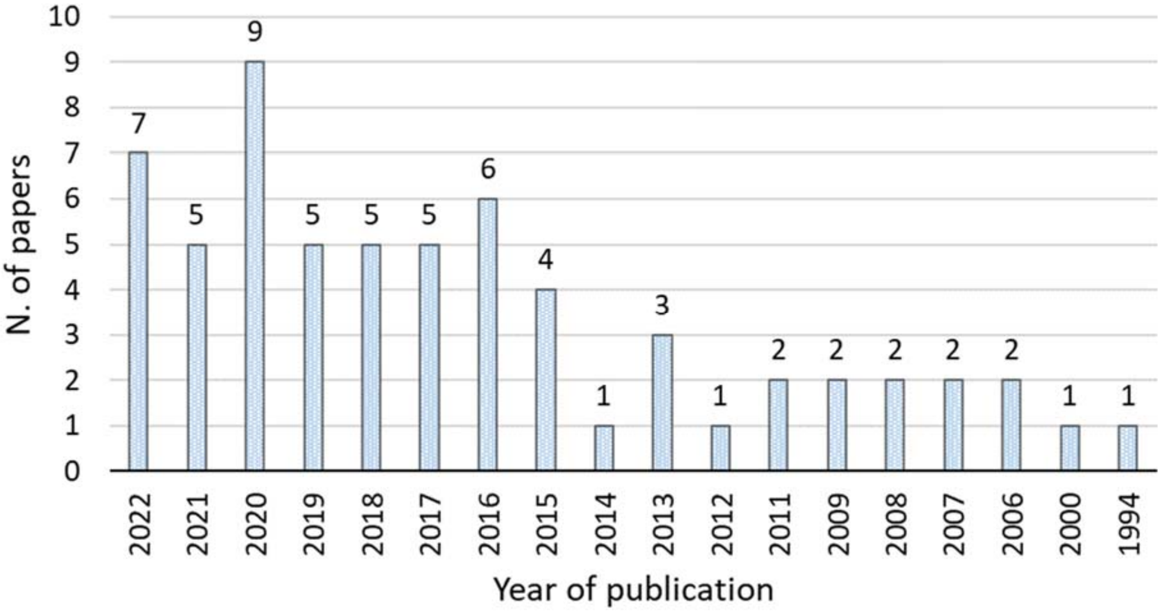


Figure 49: Number of articles for each year of publication

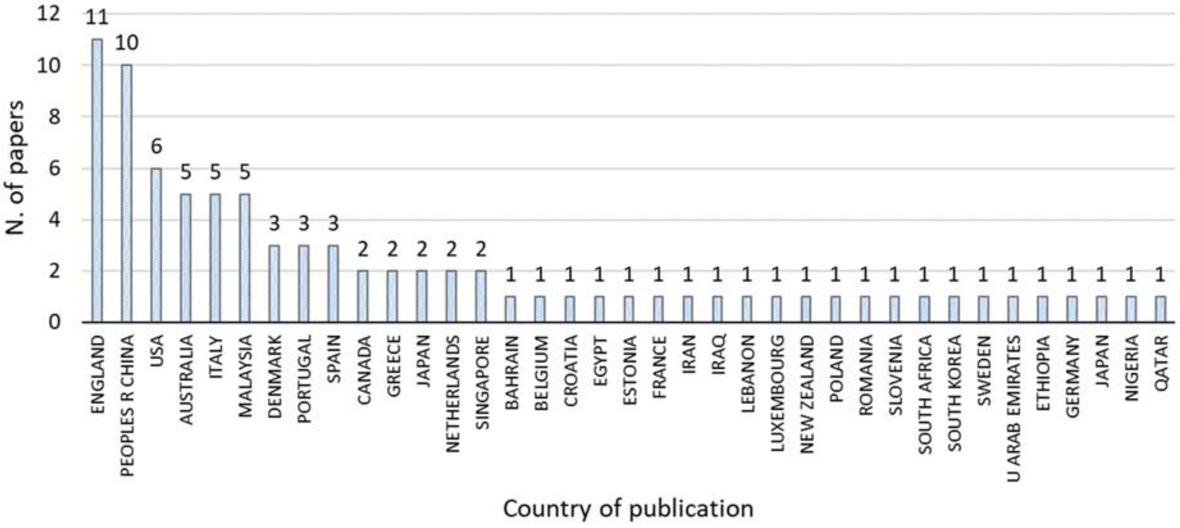


Figure 50: Number of articles for each publication country/region

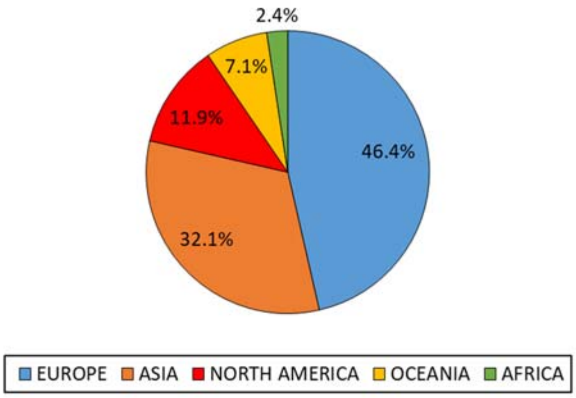


Figure 51: Percentage of articles per continent

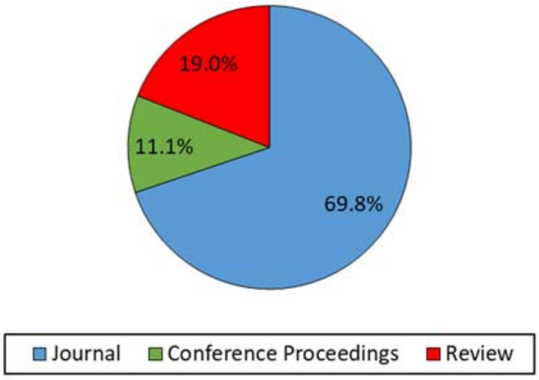


Figure 52: Percentage of articles per type

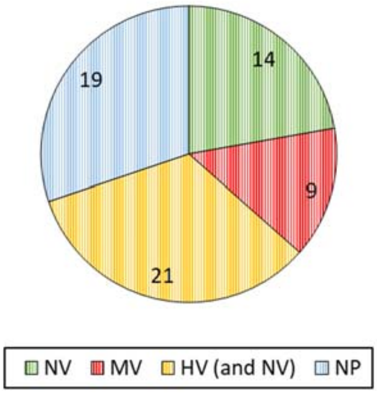


Figure 53: Number of articles per type of ventilation recommended. NV = natural ventilation; MV = mechanical ventilation; HV = hybrid ventilation; NP = no clear preference

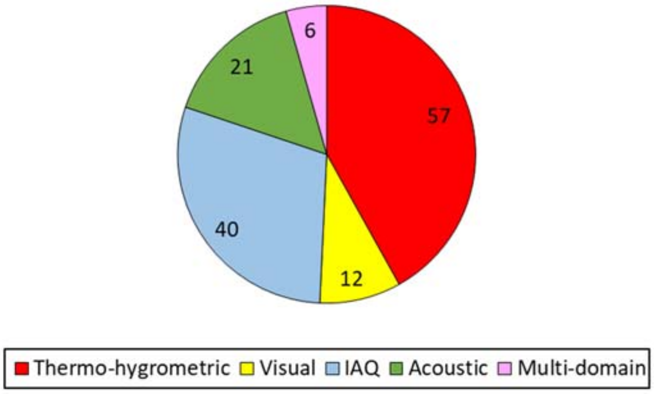


Figure 54: Number of papers treating each comfort domain

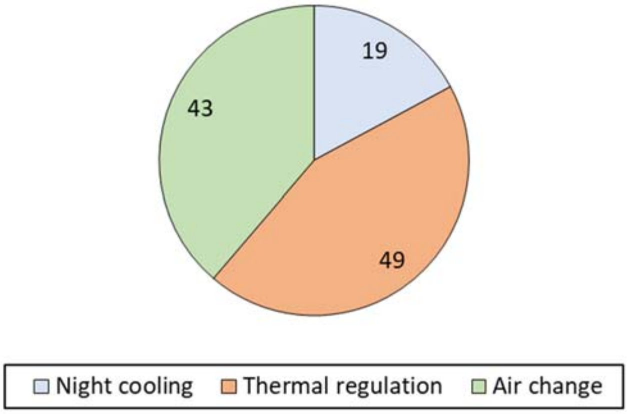


Figure 55: Number of articles considering each ventilation aim

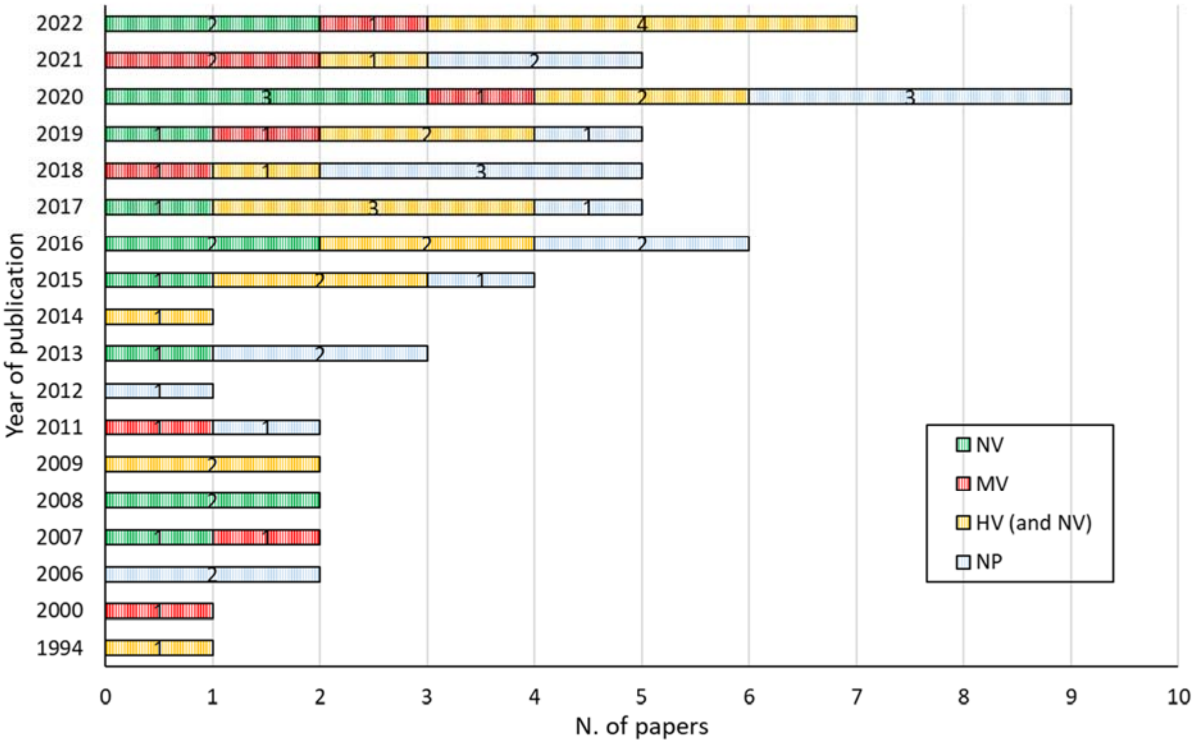


Figure 56: Association between publication year and type of ventilation recommended

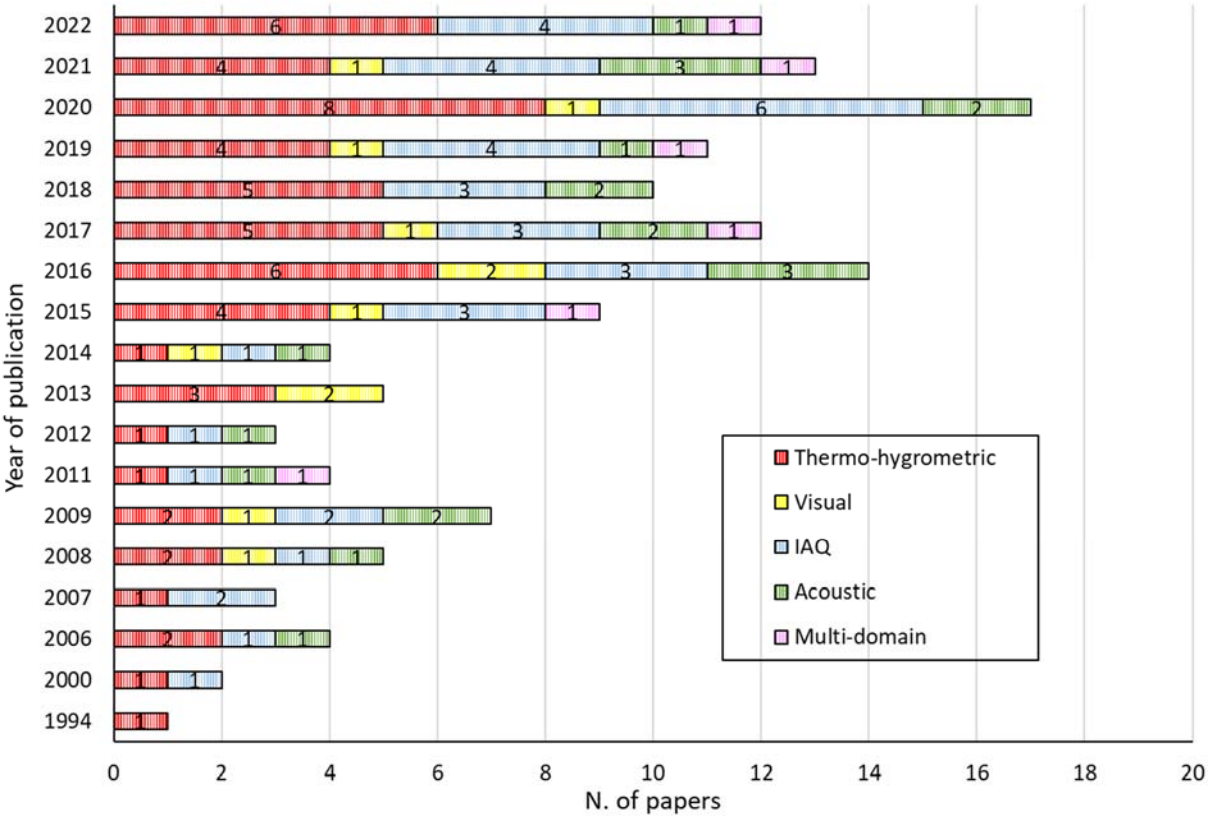


Figure 57: Association between publication year and comfort domain treated

Table 1: Number of articles per type of environment considered

Type of environment	Number of papers
Residential	18
Educational	12
Healthcare	1
Working	14
Industrial	1
Amusement	1
Non-residential (unspecified)	3
Inapplicable (various, unspecified, …)	13

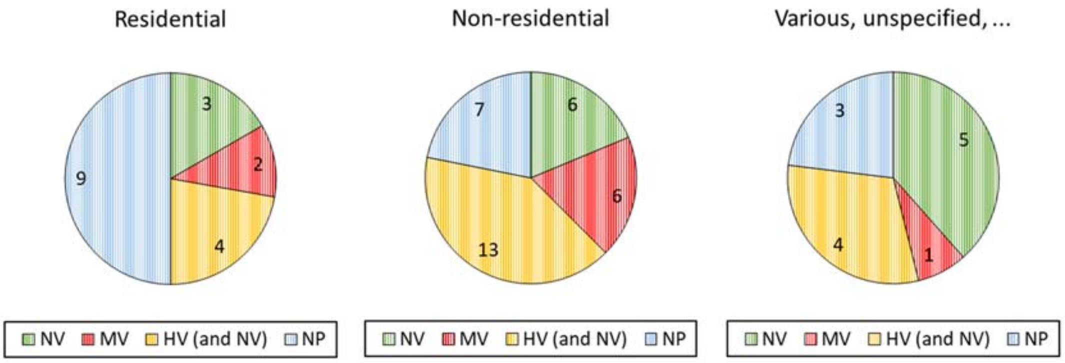


Figure 58: Number of papers per type of ventilation recommended, divided by type of environment. NV = natural ventilation; MV = mechanical ventilation; HV = hybrid ventilation; NP = no clear preference

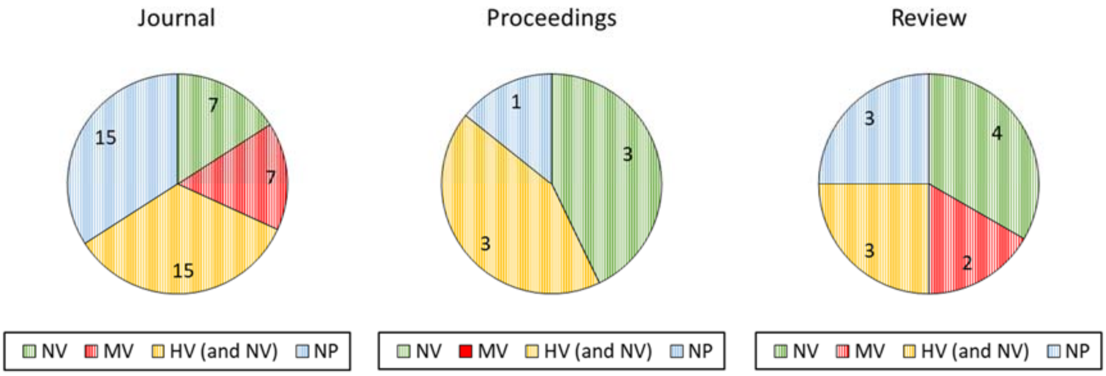


Figure 59: Number of articles per type of ventilation recommended, divided by type of document. NV = natural ventilation; MV = mechanical ventilation; HV = hybrid ventilation; NP = no clear preference

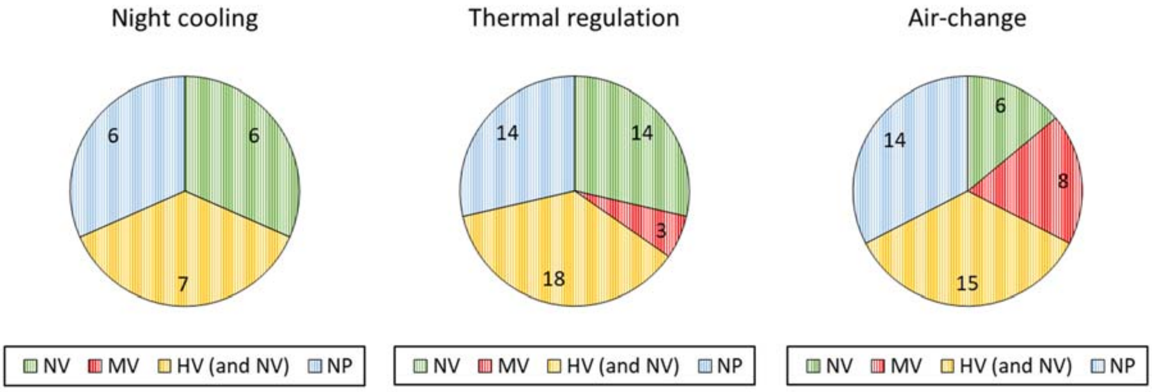


Figure 60: Number of articles per type of ventilation recommended, divided by aim of ventilation considered. NV = natural ventilation; MV = mechanical ventilation; HV = hybrid ventilation; NP = no clear preference

5.4. Main outcomes of literature analysis

Main outcomes are summarized and listed here below:

1. Not many studies comparing NV and MV in terms of indoor comfort and well-being were found. Especially, literature lacks of comparison of NV and MV in some non-residential facilities, such as healthcare ones.
2. The number of papers on the topic is growing in time. A sudden increase is present in 2020.
3. Most papers deal with thermo-hygrometric or IAQ comfort. Other domains are named marginally in less recent papers, and more frequent in the most recent years as part of a multi-domain framework.
4. In most cases, papers dealing with visual or acoustic comfort, or dealing with multi-domain, treat them only marginally (e.g., highlighting that their connections with other domains are important in future research).
5. The necessity to study the lighting and the noise domains connected with NV is pointed out by some papers.
6. When there is a preference of occupants for NV, this is mainly due to control, air movement and access to the outside.
7. Main disadvantages of NV are dealing with the ability to guarantee IAQ and desired comfort conditions. In this sense, main obstacles in using NV are outside pollution, outside noise and outside temperature (too high or too low). Climate change will further limit the NV useful time in warmer regions, but will expand it in colder regions.
8. Nevertheless, there is the need to further deepen the effects of pleasant sounds from outside on indoor comfort. This aspect is not taken into account in standards by now.
9. In many cases, the ability to precisely control the environmental conditions by MV was not perceived by occupants.
10. Another limit of NV is that it might be too dependent on people behavior (in opening windows).
11. Main disadvantages of MV are dealing with the energy consumed, the lack of control and plant's noise. MV systems needs to be properly design in order to minimize these problems.
12. Some papers argue that, if using solutions like heat recovery, MV can save energy with respect to NV.
13. In general, indoor environment and energy consumed are strongly influenced by behavior.
14. Different solutions give different impacts, which can be observed on different indicators of IAQ (CO_2, PM, VOC, …).

15. Attention to elements such as air-tightness of the facility and buildings' materials emissions should also be paid, when designing the ventilation system.
16. Some architectural characteristics like building orientation, position, size of openings, façades, etc., are very important in the design of NV. These elements need to be carefully designed. In this sense, the use of CFD is used or encouraged by many studies.
17. NV and daylight do not compete, but can benefit from similar architectural elements.
18. The type of ventilation to be used is dependent on climate (e.g. use of air conditioning in tropical areas, due to high humidity) as well as economic conditions (two papers stressing the dependence on NV of developing countries). Nevertheless, a proper design and the coupling with other techniques can optimize comfort and energy consumption.
19. HV can be a proper solution to save energy and allow control, using backup MV solutions when proper conditions cannot be maintained by NV alone. Moreover, it permits to use NV when season or time of the day allow it. For these reasons, most studies recommend HV in order to maximize energy efficiency guaranteeing comfort and IAQ in all seasons.
20. The share of papers suggesting NV alone was growing until 2020, mostly because of energy efficiency reasons. After COVID-19 pandemic, this proportion seems to have decreased. In fact, the importance of MV or HV for health and air purification reasons are often emphasized later, especially in some non-residential environments. The need to move the ventilation design from a comfort-based to a health-based approach is sometimes highlighted.
21. MV alone is mostly recommended in non-residential environments. In both residential and non-residential, a considerable share of papers recommend the use of HV. It is also interesting to notice that in papers speaking about ventilation with a general point of view (not referring to a specific environment), NV and HV are mostly recommended.
22. Some papers highlight the necessity of changing standards and guidelines in order to decrease energy consumption, improve comfort and encourage NV. For instance, a classification of environments based on windows' control level instead than considering only air conditioning presence, was proposed by one paper.
23. Not many studies dealing with night cooling were found. The necessary of further studies in the field was highlighted also by some articles. Moreover, when considered, night cooling was mostly treated marginally and within some general considerations.
24. No clear trends in the type of ventilation suggested were observed categorizing the papers per type of document or per aim of ventilation considered. The only remarkable observation is that no conference papers recommending MV only were found.

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