Review

Supplementary Materials for: Natural and Mechanical Ventilation Concepts for Indoor Comfort and Well-Being with a Sustainable Design Perspective: A Systematic Review

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Table S1. Studies related with residential environments: summary of key data, comfort domain treated, approach, main conclusions and type of ventilation recommended. JP = journal paper; R = review; CP = conference paper. A.Ch. = air-change; T.R. = thermal regulation; N.C. = night cooling. “T.H.” = thermo-hygrometric; “Vis.” =visual; “IAQ” = indoor air quality; “Ac.” = acoustic; “M.Do.” = multi-domain. NV = natural ventilation; MV = mechanical ventilation; HV = hybrid ventilation; NP = no preference. “Env.” = environment; “Vent. Rec.” = ventilation recommended; “Res.” = residential. T = temperature; RH = Relative Humidity; ACR=air-change rate.

Study	Env.	Place / Climate	Type of NV	Comfort domain treated	Approach	Comfort conclusions	Energy (and other) remarkable conclusions	Vent. Rec.
JP – Yadeta et al. (2022) [94]	Res.	Jimma (South-West Ethiopia) – Warm-temperate climate	T.R.	T.H.	Indoor and outdoor T, RH and air-speed monitoring and questionnaire survey in 104 residential buildings with NV, during the dry season (February – May).	**T.H.:** Neutral T of 20.4 °C and wide comfort range (14.6 - 26.3 °C). In developing countries like Ethiopia, thermal comfort is achievable with larger ranges with adaptive techniques.	In developing countries, NV can be used instead of MV since larger ranges of thermal comfort are present, allowing to save energy. Further studies would be needed in developing countries.	NV
JP - Yin et al. (2022) [104]	Res.	Xi’an (China) - Cold climate and generally serious pollution	A.Ch.	IAQ	$PM_{2.5}$ and CO_2 monitoring in naturally ventilated and mechanically ventilated residential buildings.	**IAQ:** MV combined with short-term NV would control both $PM_{2.5}$ and CO_2 concentration.	/	HV
JP – Torresin et al. (2021) [102]	Res.[1]	Italy (different zones), London	A.Ch., T.R.	Vis., Ac., M.Do.	Online survey on perception of acoustic environment and elements influencing window opening while relaxing or working during winter lockdown.	**Ac.:** The less dominant noises from building services were judged as more appropriate. Occupants tendency to open windows at least sometimes even if in noisy urban areas: possibility of an “adaptive acoustic comfort”. Pleasant outdoor acoustic contexts are not taken into account in present standards. **Vis.:** In Italy, more probability of windows’ opening when a vegetation view was present. **M.Do.:** M.Do. research would be important for ac. criteria definition in NV buildings.	/	HV (and NV)

JP – Mareș et al. (2021) [87]	Res.	Cluj (Romania)	A.Ch.	T.H., IAQ	Numerical energy efficiency assessment, IAQ assessment and evaluation of a MV system (with heat recovery) mitigating air-tightness problems.	**IAQ:** The MV guaranteed a reduction in radon concentration (from 425 to 70 Bq/m^3) and CO_2 concentration (average measurement around 760 ppm). **T.H.:** Thermal comfort was also guaranteed by the system (21 °C).	MV with heat recovery gave an 86 % reduction in energy consumption with respect to NV.	MV
JP – Liao et al. (2021) [88]	Res.	Denmark	A.Ch., T.R.	T.H., IAQ, Ac.	Online survey investigating ventilation type and sleep quality in Danish dwellings during winter 2020 (before COVID-19).	**T.H.:** Thermal discomfort reduced the sleep quality. "Too warm" condition was associated with a more frequent windows' opening. The "too cool" condition was improved by MV. **IAQ:** Stuffy air reduced the sleep quality, especially when NV or carpets were present. This was associated with a more frequent windows' opening. This condition was improved by MV. **Ac.:** Noise reduced the sleep quality.	Limitation: qualitative results which need to be validated with measurements both during winter and other seasons.	MV
CP – Usman & Bakar (2019) [89]	Res.	Malaysia	T.R.	T.H.	CFD analysis of the effects on thermal comfort of NV assisted by a ceiling fan MV system.	**T.H.:** With no wind outside, the ceiling fan gave an improvement in terms of PMV and PPD.	/	HV
CP - Izadyar et al. (2020a) [98]	Res.	Brisbane (Australia) – Subtropical climate	T.R.	T.H.	CFD analysis of single-sided NV depending on balcony's opening and depth in a high-rise building, in terms of thermal comfort.	**T.H.:** Indoor T, air distribution (weaker with shallower balconies) and velocity (acceptable with small openings) depend on balconies' depth and openings.	/	NV
JP - Izadyar et al. (2020b) [99]	Res.	Brisbane (Australia) –	T.R.	T.H.	CFD analysis of single-sided NV depending on balcony's opening and depth in a high-rise building, in terms of thermal comfort.	**T.H.:** Exterior air is transferred farther by smaller openings, which act like nozzles. Extended cold areas are created close to larger openings. Deeper balconies work better in terms of indoor air velocity and thermal	Balconies could improve NV, reducing the dependence on MV.	NV

		Subtropical climate				conditions. The best opening size and depth ratio were found to be 1.1 m and 35 % respectively. Depth impact also depends on buildings' orientation.		
JP – Cardoso et al. (2020) [103]	Res.	Portugal	A.Ch.	IAQ	Transient simulations in a highly permeable apartment with variable ACRs in the mechanical extractor.	**IAQ:** A sweeping effect was observed only when the extractor was on. The ACR depended on the leakage paths. Where NV is extensively used, the influence of air-tightness on ACR needs to be carefully studied.	/	NP
JP - Fernández-Agüera et al. (2019) [96]	Res.	Madrid and Seville (Spain)	T.R., A.Ch.	T.H., IAQ	Study on thermal comfort and IAQ depending on the air-tightness in naturally ventilated residential buildings built before energy efficiency regulations.	**T.H.:** The ACR mainly depended on outdoor T (season), due to the behavior of occupants. This influenced the thermal comfort. Condensation risk was observed in tighter buildings at colder climates (Madrid). **IAQ:** Especially in winter, too high levels of CO_2 (averages of 1900 ppm in Madrid and 1400 ppm in Seville) and unhealthy conditions were observed, due to less frequent ventilation behaviors.	A loss of energy is caused by windows' openings.	NP
JP – Zhao et al. (2018) [95]	Res.	Urumqi (China) - Temperate continental (severely cold winter weather)	T.R., A.Ch.	T.H., IAQ	Preliminary questionnaires on living habits and one-year monitoring in nine differently equipped homes.	**T.H.:** Both NV and MV would need major attention to humidification, especially in winter. Drier conditions were perceived with MV. **IAQ:** Poorer IAQ was observed where air was too humid, due to poor ventilation. Outdoor $PM_{2.5}$ concentration was low in summer, spring and autumn.	When outdoor T are not too extreme and low outdoor $PM_{2.5}$ concentration is present, NV can be exploited to save energy.	NP
JP – Lai et al. (2018) [97]	Res.	China - 5 climate zones: severe cold, cold, hot	T.R., A.Ch.	T.H., IAQ, Ac.	One-year study on NV and MV use in 46 apartments in 10 different cities in China, by means of measurements and questionnaires.	**T.H.:** Priority of occupants was thermal comfort rather than IAQ. The use of NV with respect to MV increased with the outdoor T (climate or season). At cold climates, energy	The three drivers of ventilation behaviors are health, thermal comfort and energy savings.	NP

		summer cold winter, temperate, hot summer warm winter				recovery systems more used than supply MV systems (thermal discomfort). **IAQ:** Priority of occupants was thermal comfort rather than IAQ, but they stated a willingness to spend more on energy if it can provide healthier environments. **Ac.:** Noise reported as a discomfort source, both with NV (from outdoor) and MV (due to the system).		
JP – Lei et al. (2017) [100]	Res.	Beijing (China) – Cold (winter season)	A.Ch., N.C.	T.H., IAQ	One-month IAQ monitoring (O_2, CO_2, T and RH) and survey (thermal comfort and mental state after sleeping) in a students' dormitory.	**T.H.:** Worsening when increasing NV area (T below 20 °C after 4 hours with a ventilation rate of 0.050 m^3/s; RH below 30 % after 4 hours, with a ventilation rate of 0.036 m^3/s). **IAQ:** Improvement when increasing NV area. With less of 6.5 m^2 of space per person, windows' opening is not sufficient.	/	NP
CP – Barbolini et al. (2017) [90]	Res.	Modena (Italy) - Temperate	T.R., N.C., A.Ch.	T.H.	Strategy of building design using HV (MV with heat recovery in winter and NV in summer), with CFD verification of thermal comfort in warm season.	**T.H.:** Adaptive model showed that thermal comfortable conditions can be guaranteed in summer. Suggestion of HV with NV in summer and MV in winter.	/	HV
JP – Grigoropoulos et al. (2016) [91]	Res.	Athens and Thessaloniki (Greece), Larnaca (Cyprus) – Mediterranean (hot summers)	T.R., N.C.	T.H., Ac.	Simulative study about different ventilation strategies to achieve net zero energy balance in three different Mediterranean locations.	**T.H.:** Higher rates of NV associated with thermal comfort improvements (average T reduction of 0.3 °C when increasing the night ACR from 2 to 6 ach). MV provided a better control of T. **Ac.:** Noise is one of the issues to be considered when designing the ventilation.	Despite the better T control, MV produced a higher energy demand (up to 20 %): NV with N.C. is recommended in residential buildings in this climate area. On the other hand, MV (or HV) should be used in larger residential or commercial buildings. Safety, feasibility and life cycle costs need to be considered in the design.	NP

R - Yu & Kim (2012) [92]	Res.	United Kingdom	A.Ch.	T.H., IAQ, Ac.	Review on: 1. regulations and guidelines in relation with heat recovery MV; 2. long-term indoor concentration in super-energy efficient test houses.	**T.H.:** MV is a mean to improve thermal comfort in summer. **IAQ:** Issues (materials, combustion) are present in air-tight buildings. **Ac.:** Noise (fans and forced airflows) is one of the risks in MV performance.	There is need to review ventilation techniques to guarantee both clean air and energy savings (e.g., use of air-cleaners).	NP
CP – Razman et al. (2011) [93]	Res.	Batu Pahat (Malaysia) – Hot and humid	T.R.	T.H.	University hostel field study (measurements and questionnaires) on thermal comfort with NV and ceiling fans.	**T.H.:** Perceived as comfortable, but it would be improved by MV. Comfort was prevented by obstacles to air movement (windows, furniture). 0.19 – 0.24 m/s air-velocity allowed to provide adequate air movement to have a comfortable environment. During afternoon, with T of 27.78 – 29.51 °C, uncomfortable conditions were reported by 70 % of the respondents, who needed the help of actions such as windows and doors openings and ceiling fan operations to restore the comfort conditions.	NV helps achieving energy savings and sustainability.	NP
JP – Kalamees (2006) [101]	Res.	Estonia – Nordic climate	A.Ch., T.R., N.C.	T.H., IAQ, Ac.	One-year exhaust air-flow and indoor conditions (T and RH) monitoring and questionnaires in lightweight timber-frame houses with NV and MV.	**T.H.:** High T in summer in comparison with the Estonian standard, due to design issues; good but too variable T in winter with variations being too high with respect to well insulated envelopes and modern heating systems, due to the control system. T and RH variations influenced by ventilation performance. Cold floors, fluctuating T and draughts caused by air leakages in envelope (winter). **IAQ:** Average ACRs lower than standards (0.39 – 0.41 ach instead of 0.5 ach), but similar	/	NP

	to other Nordic countries. NV associated with stuffy air. **Ac.:** MV caused noise issues, limiting its use.	

Table S2. Studies related with non-residential environments: summary of key data, comfort domain treated, approach, main conclusions and type of ventilation recommended. JP = journal paper; R = review; CP = conference paper. A.Ch. = air-change; T.R. = thermal regulation; N.C. = night cooling. "T.H." = thermo-hygrometric; "Vis." =visual; "IAQ" = indoor air quality; "Ac." = acoustic; "M.Do." = multi-domain. NV = natural ventilation; MV = mechanical ventilation; HV = hybrid ventilation; NP = no preference. "Env." = environment; "Vent. Rec." = ventilation recommended; "Edu." = educational; "Hea." = healthcare; "Wor." = working; "Ind." = industrial; "Amu." = amusement; "Gen." = non-residential in general. T = temperature; RH = Relative Humidity; ACR=air-change rate.

Study	Env.	Place / Climate	Type of NV	Comfort domain treated	Approach	Comfort conclusions	Energy (and other) remarkable conclusions	Vent. Rec.
JP - Arata & Kawakubo (2022) [114]	Wor.	Tokyo (Japan) – Humid climate (hot-humid summers, dry-sunny winters with monsoons)	T.R., A.Ch.	T.H., IAQ	Springtime (average T of 21 °C) questionnaires and measurements in a Tokyo located office building, with the aim of testing energy consumption, thermal comfort and productivity effects of HV.	**T.H.:** Daily variations of windows' openings, depending on outdoor conditions. In both the floors with HV and MV only, similar T (generally in the range of 25 – 26 °C) and PMV (generally in the range of 0.0 – 0.5) levels were maintained. **T.H. and IAQ:** Improvement of productivity of 9.1 % (less CO_2 concentration and higher flow of fresh air) among males with HV. Improvement of 0.5 % among females, with a possible gender dependence (but a possible bias from the small number of female subjects).	Energy savings between 3.1 % and 70.6 % were achieved on floors with HV, with respect to floors with MV only.	HV
JP - Mba et al. (2022) [127]	Edu.	Enugu (Nigeria) – Hot-humid tropical	T.R.	T.H.	Study (experimental and descriptive) on the effect of orientation of 60 school buildings on NV to guarantee thermal comfort.	**T.H.:** the conditions necessary to maintain thermal comfort with NV were studied.	In developing countries, NV in school buildings allows to save energy. Ventilation efficiency dependent on orientation, inlet and outlet positioning and dimensions. Corridors and shading devices can be useful to encourage windows' opening also wen not proper climate conditions are present. Architectural solutions allowing the coupling of wind and stack ventilation are encouraged.	NV
JP – Elnabawi & Saber (2022) [110]	Edu.	Bahrain – Hot-arid climate	T.R.	T.H.	Dynamic simulation (annual energy savings and CO_2 emission) evaluation of an integrated HV and	**T.H.:** Overheating (cooling) hours reduced by windows automatic operations. An expansion of upper and lower comfort limits (22 – 29 °C,	Better performance of HV in cold season in terms of savings. An expansion of upper and lower comfort limits (using local climates conditions instead of international standards) could	HV

		(extremely hot summers and mild winters)			photovoltaic (PV) in a urban University building.	customized for local climate) led to higher energy savings.	lead to higher energy savings. The use of PV and HV allows to save almost the 85 % of the total annual energy demand (36.6 MWh vs. 106.1 MWh).	
JP – Monge-Barrio et al. (2022) [119]	Edu.	Pamplona (Spain)	A.Ch.	T.H., IAQ, Ac.	Empirical study nine naturally ventilated schools (surveys, detailed monitoring in one of the buildings) in during 2020 and 2021 heating seasons, to assess the change of environmental conditions due to the pandemic.	**T.H.:** With the pandemic habits, a mean T reduction (18 °C vs. 20 °C) was observed, with values admissible only during exceptional conditions. Necessity of T monitoring. **IAQ:** With the pandemic habits, a mean CO_2 reduction (1000 ppm vs. 2400 ppm) was observed. Necessity of CO_2 monitoring. **Ac.:** When present, MV was not used due to the loud noise.	When present, MV was not used due to the high energy consumption. A plan involving cross ventilation, CO_2 and T monitoring, envelope improvement and complement heat recovery MV is necessary for healthy and sustainable schools.	HV
R – Ding et al. (2022) [107]	Edu.	/	A.Ch.	T.H., IAQ, M.Do.	Review on IAQ conditions and strategies of ventilation in classrooms, focusing of the aerosol minimizing capability.	**T.H. and IAQ:** Lack of literature on design to avoid airborne transmittable pathogens. Main standards' focus on perceived IAQ and CO_2 concentration. Several reports of IAQ, comfort, performance and health issues. Need to switch from comfort- to health-based design. Benefits on the thermal and IAQ point of views would be obtained by personalized ventilation. **M.Do.:** Potential of IAQ to influence other comfort domains (e.g., higher noise with higher IAQ, surface pollutants' emissions with sunlight, etc.), which should be considered altogether for ensuring occupants' comfort and health.	Main standards' focus on energy consumption and not on health.	MV
R – Wolkoff et al. (2021) [25]	Wor.	/	A.Ch.	T.H., IAQ	Influence of microclimatic parameters (T, RH, ventilation) on health,	**T.H.:** Improved by personal control (physical and psychological impact).	/	NP

					performance, office work and risk of infections.	**IAQ:** Chronic and acute illnesses can be decreased by ventilation, especially MV. Poorly designed NV and poorly operated or maintained MV can lead to poor IAQ. Dry air in winter can lead to viruses transmissions. Health-based ventilation design would be needed.		
JP – Cai et al. (2021) [105]	Edu.	Beijing (China)	A.Ch.	T.H., IAQ, Ac.	Monitoring (CO_2, T, $PM_{2.5}$, RH, efficiency of air cleaners) in classrooms with MV and NV with air-cleaners.	**T.H.:** With both NV and MV, T values under the 18 °C recommended by Chinese standard were found close to the beginning and the end of the running period of heating. **IAQ:** Both NV and MV did not provide environments with low enough $PM_{2.5}$.. Benefits in increase of ventilation rate CO_2 reduction are present with MV. Negative air ion purification possibly associated with oxidative stress. **Ac.:** Noise (together with thermal comfort and IAQ) is one of the constraint conditions to choose the best ventilation system.	NV had a higher energy efficiency in removing $PM_{2.5}$.	NP
JP - Scheuring & Weller (2021) [115]	Wor.	3 different climates: 1. Wiegendorf (Germany), European continental; 2. Madrid (Spain), Mediterranean;	T.R., A.Ch.	T.H., IAQ	Simulation with EnergyPlus to analyze comfort and energy effects of different strategies of ventilation based on windows' opening (T and CO_2 dependent) and MV (CO_2 dependent).	**T.H.:** In colder months (below 7 °C) at moderate climates, it was not possible to use long windows' openings due to thermal discomfort. In other conditions, NV outperformed MV. **T.H. and IAQ:** NV and MV control strategies were based on T and CO_2 concentration in the simulation.	Energy savings can be achieved by NV, but not-proper behavior can lead to energy waste (and not proper IAQ).	NP

		3. Hanoi (Vietnam), subtropical.						
JP – Abdul Hamid et al. (2020) [60]	Wor.	Sweden	T.R., A.Ch., N.C.	T.H., IAQ	Questionnaires, measurements and simulations (CO_2, ACRs, RH and T) in twelve heritage office buildings, to assess the effect of dampers for ACRs reduction (system A) and chimney-hidden MV with heat recovery (system B).	**T.H.:** Indoor conditions dependent on outdoor T (and opening behavior). Too cold and draught conditions in winter, too warm, dry and stuffy in summer. **IAQ:** Stuffy environment in summer. Potential reduction of CO_2 from system B.	The two solutions gave a potential energy reduction of: 16 kWh/m^2 (12 %) with system A and 39 kWh/m^2 (47 %) with system B.	NP
JP – Zender-Swiercz (2020) [120]	Wor.	Poland – Moderate climate (low winter T and high summer T)	A.Ch.	T.H., IAQ	Twenty-six weeks monitoring (indoor: CO_2; indoor and outdoor: T, RH) in a façade ventilation device equipped office.	**T.H.:** 20 – 22 °C of T and 27 – 43 % of RH maintained, local draughts. Recommendation of air humidification, electric heater and exhaust heat recovery (avoid local discomfort). **IAQ:** With high insulation and sealed windows, insufficient air exchange might be present with NV.	MV cannot be installed always, due to architectural difficulties: decentralized façade units can be a solution.	MV
JP – Raji et al. (2020) [67]	Wor.	Delft (Netherlands) – Temperate maritime	T.R., A.Ch., N.C.	T.H., IAQ, Ac.	Six strategies of NV studied on the 12th floor of a 21-storey office building, by means of CFD and EnergyPlus.	**T.H. and IAQ:** Thermal comfort and fresh air guaranteed for all configurations except than the ones combined with poorly ventilated double skin façade (not adequate management and outdoor T dependent windows' operations) and atrium (stack ventilations advantages occur with deep plans). Night-time ventilation would extend the hours with comfort conditions.	NV has the potential to reduce the energy demand. In high-rise buildings, HV might be necessary when design failures (e.g., tenancy patterns change or layout of architectural design) are present.	HV and NV

						T.H., IAQ and Ac.: In high-rise buildings, HV necessary with not-optimal outdoor conditions (T, noise or wind).		
JP - Meng et al. (2020) [66]	Ind.	Xi'an (China)	T.R.	T.H.	Investigation on HV (buoyancy NV + exhaust MV) performance in industrial buildings, using an experimental scale model with heat source.	**T.H.:** Need of optimal exhaust velocity to maximize efficiency and thermal comfort, without creating short circuiting. In this light, the definition of ventilation efficiency by [156] was used: $$\boldsymbol{E_T} = \frac{\boldsymbol{T_{out}} - \boldsymbol{T_{in}}}{\boldsymbol{T_{occupied\ zone}} - \boldsymbol{T_{in}}}$$ Using two different internal heat sources of 200 W and 500 W, the critical exhaust velocities were found to be respectively equal to 1.4 m/s (E_T = 24.4) and 1.0 m/s (E_T = 6.69).	Need of optimal exhaust velocity to maximize efficiency and minimize energy consumption.	HV
JP – Maas et al. (2019) [125]	Edu.	Luxembourg	T.R., A.Ch.	T.H., IAQ	Monitoring (periodic indoor and energy measurements and questionnaires) in a MV seminar room in a 70ies building with no major retrofitting.	**T.H.:** No relationship between perceived percentage of dissatisfied and perceived climate. **IAQ:** Small (not perceived by occupants) improvements in CO_2 concentration when the MV system was "on".	Higher energy consumption when the MV system was "on". Shut down or semi-automatic control (+ a low-cost retrofit) might constitute an advantage in this type of rooms in older buildings.	HV (and NV)
JP – Stabile et al. (2019) [121]	Edu.	Cassino (Central Italy)	A.Ch.	IAQ	Monitoring of CO_2 concentration and indoor and outdoor particle number in a school before (NV) and after (MV with a 1000 ppm CO_2 setpoint) retrofitting.	**IAQ:** CO_2 was reduced with longer airing periods, but no change in indoor generated PM_{10} and increase of sub-micron particles from outside were present in the same conditions. MV gave improvements on all pollutants measured.	MV gave improvements on energy consumption (presence of a heat recovery).	MV
JP – Heebøll et al. (2018) [122]	Edu.	Denmark – Atlantic temperate	T.R., A.Ch.	T.H., IAQ, Ac.	Four-weeks monitoring (T, CO_2, energy, opening behavior) of four classrooms with different ventilation equipment.	**T.H.:** T within comfort ranges (20 – 24 °C) both with automatic windows opening and with no retrofit. **IAQ:** CO_2 depended on the ventilation type, with the lowest concentration with MV and	Respective corrected heating energy use in the measurement period (07/01 – 02/02) were 646 kWh with MV (even if it might be affected by a malfunctioning valve), 372 kWh with automatic windows and exhaust fan and 287 kWh with automatic windows and alternating counter-flow heat recovery through outside wall slots.	NP

						with automatic windows and exhaust fan (mostly under 1000 ppm). MV or automated windows are recommended in temperate areas. **Ac.:** Noise level of MV was in line with what specified by the manufacturer.		
JP – Guo et al. (2018) [108]	Amu.	/	T.R.	T.H.	Buoyancy driven ventilation in a large-ceiling ocean park analysis, by means of reduced-scale model, full-scale numerical simulation and similarity analysis.	**T.H.:** MV is needed to ensure thermal comfort.	/	MV
CP – Chen et al. (2018) [64]	Wor.	USA – Warm-humid (Atlanta), dry (Los Angeles and S.Francisco)	T.R.	T.H.	Model predictive control in a simulated office in three climatic zones, when using HV.	**T.H.:** Thermal comfort was maintained.	/	HV
JP – Rasheed et al. (2017) [111]	Wor.	Auckland (New Zealand) – Oceanic subtropical	T.R., A.Ch.	T.H., Vis., IAQ, Ac., M.Do.	Investigation (literature and questionnaires) on reasons on unpopularity of NV in New Zealand.	**T.H.:** No specific preference of a ventilation typology among workers. Highest impact among workers by T extremity and control over T. NV negative impact on productivity still under debate. **Vis., IAQ, Ac., M.Do.:** Other comfort aspects connected with NV need deeper studies.	NV not encouraged by New Zealand green certification system, which might obstruct decision changing in designers and occupants.	NV
JP – Gil-Baez et al. (2017) [118]	Edu.	Seville (Spain) –Mediterranean	T.R., A.Ch.	T.H., IAQ, Ac.	Comparative MV and NV analysis (T, RH and CO_2) in two schools; implementation of cross ventilation NV through simulation.	**T.H.:** No T reduction with windows openings in winter (due to internal gains). In colder locations, HV is advisable.	Energy and CO_2 emission reduction with NV (primary energy savings of 18 – 33 %). Proper NV design (e.g., automated windows) necessary. In Mediterranean areas, NV and HV use in schools would have a strong socio-economic impact and save a lot of energy.	HV (and NV)

						IAQ: Reduction of CO_2 levels with windows' openings in winter. NV is a proper solution when outside pollution is low. **Ac.**: NV is a proper solution when outside noise is low, otherwise HV is advisable.		
JP – Aldawoud (2017) [109]	Wor.	Dubai (UAE) - Hot-humid	T.R.	T.H.	CFD study of several configurations of openings in a NV standard office building.	**T.H.:** Cross ventilation can give acceptable conditions. Too high T (which can reach the upper 40s) and too low wind are present outdoors in summer, even if a T reduction of 4 – 6 °C below exterior air is possible. In other seasons NV can work instead of air-conditioning.	Larger inlets should be exposed in the wind direction. Horizontal shading devices outside of the outlets also improve the pressure difference.	HV
R – Salcido et al. (2016) [29]	Wor.	/	T.R., A.Ch., N.C.	T.H., IAQ	Review of 1996-2006 literature on HV use in offices.	**T.H.:** Influenced by people behavior and occupancy. Cooling efficiency depends on the climatic area. **IAQ:** Influenced by people behavior and occupancy.	Energy consumption is influenced by people behavior and occupancy. HV design should be optimized (e.g., wind speed and direction) to minimize MV energy.	HV
JP - Da Graça & Linden (2016) [30]	Gen.	/	T.R., N.C.	T.H., Vis., Ac.	Ten open questions about NV design in non-residential buildings.	**T.H.:** NV preferred by most people (higher thermal tolerance), due to higher users' control. NV can be applied in the outdoor T range 10 – 25 °C: hours with exploitable NV will diminish in hotter climates, but rise in mild and cold ones. Innovative approaches (e.g., N.C.) can be usefully exploited. **Vis.:** NV and daylight benefit of similar constructive techniques (e.g., high windows, operable skylights, etc.), and both overheating and glare are led by direct sunlight and large glazed façades.	NV should be further exploited in non-commercial buildings due to its strong potential in terms of energy savings.	NV

						IAQ.: NV will benefit of less polluting mobility solutions (electric vehicles). **Ac.:** NV will benefit of less noisy mobility solutions (electric vehicles).		
JP – Natarajan et al. (2015) [116]	Wor.	Bogotà (Colombia) – Subtropical highland	T.R.	T.H.	Study of applicability of comfort models by means of indoor and outdoor measurements and questionnaires in three offices with different ventilation techniques (NV, MV and HV).	**T.H.:** Adaptive and PMV models applicability highly dependent on the control of occupants on windows (reduction of thermal comfort with lack of control).	/	NP
JP – Montgomery et al. (2015) [126]	Wor.	Vancouver (Canada)	A.Ch.	T.H., IAQ	IAQ investigation (TVOCs, CO_2 and PM) in an office design to work with both NV and MV.	**T.H.:** Indoor and outdoor T within bands of adaptive model. **IAQ.:** More variable pollutants' concentration with HV. $PM_{2.5}$ were higher with NV, while TVOC depended on ACR of NV.	HV suggested to save energy while ensuring to meet good IAQ and benefitting technology solutions (occupancy sensors, PM and regional meteorological data, etc.).	HV
JP – Dhalluin & Limam (2014) [117]	Edu.	La Rochelle (France) – Mild-oceanic climate	T.R., N.C., A.Ch.	T.H., Vis., IAQ, Ac.	Comparison of four ventilation modes (natural or mixed mode) in two adjacent classroom of a university building, using questionnaires and measurements.	**T.H.:** Self-Opening and Shading System (SOS) gave satisfactory conditions when well controlled. With extreme conditions, HV is necessary. Due to the low ACR, manual NV provided the lowest IEQ. Draughts required to manually close windows in winter. Mixed modes gave the lowest comfort perception. Homogeneous RH and air velocity evaluations with the different modes (low occupants' sensitivity to these parameters). **Vis.:** Homogeneous lighting level evaluations with the different modes (low occupants' sensitivity to this parameter).	SOS gave low consumption when well controlled. Mixed modes gave the lowest energy savings.	HV

						IAQ: SOS gave satisfactory conditions when well controlled. With extreme conditions, HV is necessary. Due to the low ACR, manual NV provided the lowest IEQ. Mixed modes gave the lowest comfort perception despite the best IAQ conditions. **Ac.:** Quite good for all modes, even if the intermittent noise by SOS system was better tolerated than the MV continuous one.		
JP - Giridharan et al. (2013) [106]	Hea.	Glenfield (United Kingdom)	T.R., N.C.	T.H., Vis.	Thermal comfort criteria and T comparison + future conditions predictions with a calibrated model in a nucleus-type hospital (cruciform blocks with courtyards in between), mechanically ventilated but passively cooled.	**T.H.:** Most spaces within British standards for hospitals (major deviations with night-time overheating). Maximum temperatures indoor were in the range of 27.3 – 29.3 °C. Necessity of specific adaptive criteria for hospitals. 1.5 ach^{-1} MV would provide comfort conditions with adequate windows' openings provisions. In this type of facilities, light touch carbon interventions would provide comfortable conditions in bedrooms. **Vis.:** The conversion of internal courtyards into additional wards, causes daylight to be reduced.	The conversion of internal courtyards into additional wards, causes cross ventilation to be reduced.	NP
CP – Azarbayjani (2013) [112]	Edu.	Eugene (Oregon, USA) - Mediterranean	T.R., N.C.	T.H., Vis.	CFD investigation on stack effect and 2-driving -forces-wind ventilation comfort performance in a double-skin façade university building.	**T.H.:** Comfort conditions provided by NV, with cool air removing heat during night (max average dry bulb T equal to 27 °C, in the afternoon in June). NV benefitted on the building orientation.	/	NV

						Vis.: A large amount of natural light is provided by the façade, if controlled carefully with sunshades.		
JP – Khaleghi et al. (2011) [123]	Edu.	Vancouver (Canada)	A.Ch.	IAQ, Ac., M.Do.	IAQ (VOC, ultrafine particles and respirable-fibre), ventilation rates and acoustic (noise and reverberation) comparison of "green" and "non-green" campus study rooms, both with MV and NV.	**IAQ:** Generally better with MV. **Ac.:** Lower sound pressure and low-frequency noise by NV. Issues with poorly designed MV. With NV, higher noise with higher ventilation rates (windows' openings). **M.Do.:** Direct association between IAQ and noise level with MV.	MV suggested for proper building design, with careful attention to noise.	MV
JP – Brager & Baker (2009) [55]	Gen.	USA	T.R., A.Ch.	T.H., Vis., IAQ, Ac.	Web-based survey in twelve HV buildings (with operable windows), compared with a database of 43000 surveys performed in 370 buildings. Investigations on IAQ, thermal comfort, lighting, acoustics, cleanliness, spatial layout, maintenance, furnishing and overall satisfaction were made.	**T.H. and IAQ:** Two of the categories receiving the lowest score in the entire database (too low air movement and control lack). Much better performance in HV buildings, with a relationship of the satisfactions with the two parameters and climate (moderate climates are better) or buildings' age (newest are better). Previous research: operable windows preferred because of personal control, major air movement, connection with the outdoor and perceived fresh air. **Vis.:** One of the environmental categories the survey referred. It was not among the categories which received the lowest score in the entire database. **Ac.:** One of the categories receiving the lowest score in the entire database. It had a slight improvement in mixed-mode buildings: only one occupant indicated open windows as an	Proper HV design necessity (with good MV and NV integration) was stressed: occupants should able to ignore automatic controls if needed.	HV (and NV)

						issue, the other problems were probably due to hard-finish materials characterizing the "green" buildings designed for good IAQ and daylight.		
JP – Butala & Muhic (2007) [113]	Wor.	Slovenia	T.R., A.Ch.	T.H., IAQ	Comfort analysis in three office buildings (two with MV and one with NV) during winter, using measurements and questionnaires.	**T.H.:** Deviations between subjective evaluations and predicted conditions (influence of psychological factors). Neutral conditions expressed by a higher percentage in NV building. **IAQ:** Higher dissatisfaction in MV buildings.	/	NV
R – Braham (2000) [124]	Wor.	United Kingdom – Temperate maritime	T.R., A.Ch., N.C.	T.H., IAQ	Review on performance data of low-energy office buildings, with a focus on fabric energy storage and ventilation strategies.	**T.H.:** Better comfort can be assured by MV than NV, if fabric energy storage and efficient energy storage are used. **IAQ:** MV can provide the highest possible IAQ.	Lower energy consumption can be assured by MV than NV, if fabric energy storage and efficient energy storage are used. Moreover, less maintenance and, in temperate marine climate, minimal supplementary heating and cooling demand are necessary. N.C. coupled with massive elements is useful in summer.	MV

Table S3. Studies not related with a specific type of environment: summary of key data, comfort domain treated, approach, main conclusions and type of ventilation recommended. JP = journal paper; R = review; CP = conference paper. A.Ch. = air-change; T.R. = thermal regulation; N.C. = night cooling. “T.H.” = thermo-hygrometric; “Vis.” =visual; “IAQ” = indoor air quality; “Ac.” = acoustic; “M.Do.” = multi-domain. NV = natural ventilation; MV = mechanical ventilation; HV = hybrid ventilation; NP = no preference. “Env.” = environment; “Vent. Rec.” = ventilation recommended; “Var.” = Various/Inapplicable. T = temperature; RH = Relative Humidity; ACR=air-change rate.

Study	Env.	Place / Climate	Type of NV	Comfort domain treated	Approach	Comfort conclusions	Energy (and other) remarkable conclusions	Vent. Rec.
R – Izadyar et al. (2020c) [136]	Var.	/	T.R., A.Ch., N.C.	T.H., Vis., IAQ, Ac.	Review on occupants’ perception influenced by façades’ openings and balconies’ geometry.	**T.H., IAQ, Vis. and Ac.:** All the four domains were used for categorization of post-occupancy evaluations studies considered in the review.	More studies related with balconies’ design to optimize NV should be addressed. More post-occupancy evaluations should be done.	NV
R – Mukhtar et al. (2019) [138]	Var.	/	T.R., A.Ch., N.C.	T.H., Vis., IAQ, Ac., M.Do.	Review on underground building optimization and passive strategies.	**T.H., Vis., IAQ, Ac. and M.Do.:** Specifically designed passive design strategies would improve IEQ in this type of buildings. Elements like availability of daylight (also related with heat load) and thermal mass and night ventilation (related with cooling load) are fundamental for thermal comfort, as well as pollution sources (e.g., materials) for IAQ.	Integration of passive systems in the design of underground buildings is fundamental for energy savings. Energy consumed can be diminished by using soil and natural ventilation.	NV
R - Nardell (2016) [128]	Var.	/	T.R., A.Ch.	T.H., IAQ	Review on possible environmental measures against tuberculosis transmission.	**T.H.:** NV might be inapplicable due to too warm or too cold outdoor conditions, or because of running air conditioning. **IAQ:** Interventions can be applied also to other airborne transmittable diseases. NV is the main and cheapest disinfection way. MV would provide proper disinfection.	MV might have the disadvantage of being expensive (installation, management and operation).	NP
R – Chenari et al. (2016) [31]	Var.	/	T.R., A.Ch., N.C.	T.H., Vis., IAQ, Ac.	Literature study on energy efficient ventilation methodologies, taking into account behavior-energy association and correlation with health and productivity.	**T.H. and IAQ:** Ventilation energy cannot be reduced under the threshold at which occupants’ discomfort is present. **IAQ:** HV (e.g. smart-windows based) can ensure good IAQ, which is also influenced	HV (e.g., smart-windows based) can lead to remarkable energy savings. Considerable energy is wasted due to ventilation of low-occupied or unoccupied spaces. Literature lacks of studies on smart-windows based HV.	HV (and NV)

						by ventilation method, environmental conditions and occupants' behavior. Poorly designed ventilation might provoke health issues. **Vis.:** Atriums and double-skin façades can be exploited for both NV and daylight. **Ac.:** Noise is one of the parameters affecting occupants' behavior. Double-skin façades and atriums can be used for NV protecting from noise.		
R – Daghigh (2015) [131]	Var.	Malaysia and nearby area - Tropical (hot and humid)	T.R., A.Ch., N.C.	T.H., IAQ, M.Do.	Review of thermal comfort and ventilation in residential, office and classrooms buildings.	**T.H.:** In hot-humid climates, the thermal comfort range is wider than one indicated in international standards. **IAQ:** Healthy IAQ influence thermal perception. **M.Do.:** Healthy IAQ influence thermal perception.	More studies in the field would improve T.H. comfort, IAQ and energy efficiency. Ventilation techniques should be coupled with other active and passive strategies in order to decrease the energy consumption.	HV
R – Aflaki et al. (2015) [132]	Var.	Tropical (hot- and humid)	T.R., A.Ch., N.C.	T.H., Vis, IAQ	Review on studies supporting solutions and architecture to maximize NV efficiency in tropical climate buildings.	**T.H. and IAQ:** Due to high T and RH, MV is widely used, but better conditions have been shown by many researches with NV. **Vis.:** Apertures (windows, vents, louvres and doors) are significant for daylight and NV.	Lower consumption have been shown by many researches with NV. Studies on louvered windows (for N.C.) and vernacular apertures and elements would be needed.	NV
JP – Homod & Sahari (2013) [129]	Var.	Kuala Lumpur (Malaysia) - Abundant rainfalls, hot and humid	T.R., A.Ch., N.C.	T.H.	PMV model used to assess internal T and RH control efficiency by infiltration and ventilation, by means of 24-hours simulations of MV with variable flow rate.	**T.H.:** Results highlight MV advantages in ensuring thermal comfort.	Results point out that it would be possible to reduce the relying on powered cooling.	NP

		climate throughout the year						
JP – Perino (2009) [133]	Var.	/	T.R., A.Ch.	T.H., IAQ, Ac.	Test lab investigation and numerical models (control strategies) about buoyancy driven single-sided NV for management of IAQ.	**T.H. and IAQ:** Single-sided buoyancy-driven NV can guarantee proper ACRs, controlling T and IAQ. Models are useful for control strategies. **Ac.:** Outdoor noise can be one of the factors limiting airing use, being easier to be controlled by MV.	/	HV
R – Omer (2008) [130]	Var.	/	T.R., A.Ch., N.C.	T.H., Vis., IAQ, Ac.	Description of low-energy solutions in buildings' design.	**T.H.:** Wind towers can help maintaining thermal comfort in arid regions. Too high outdoor air can cause discomfort and draught (carefulness to poor design). **IAQ:** Poor IAQ can be caused by too little inflow. Ventilation design need to take into account outdoor pollution. **Ac.:** Ventilation design need to take into account outdoor noise. **Vis.:** Daylight named as another passive technique.	Maximum share of natural energy should be used in order to maintain thermal comfort without wasting energy. Passive cooling (climatic design) and MV operations' optimization can help in this way. Architectural elements, building location, orientation and materials (e.g., night cooling) need to be taken into account for proper ventilation design. CFD is a useful tool for airflow control and air movement in rooms design.	NV
JP – Stavrakakis et al. (2008) [134]	Var.	Rural Greece	T.R.	T.H.	Test-chamber measurements (air speed and T) and CFD analysis of cross NV with non-symmetrical openings, by means of PMV and adaptive models.	**T.H.:** Not-symmetrical openings' locations can provide well mixed conditions, minimizing T differences and local draughts.	/	NV
JP – Sultan (2007) [137]	Var.	Singapore	A.Ch.	IAQ	Estimation of mortality and morbidity by outdoor PM under different	**IAQ:** Nationwide NV adoption in residential buildings is associated with higher morbidities (13 – 38 % higher) and	/	MV

					buildings' filtration and ventilation conditions.	mortality (28 % higher). Less asthma cases in schools associated with adoption of MV and filtration from current NV. Lower mortality and morbidities in workplaces by better filtration.		
JP – Ouyang et al. (2006) [135]	Var.	China	Inapp-licabe	T.H.	Spectral analysis on the characteristics of natural and mechanical wind on the dynamic point of view.	**T.H.:** With a mean velocity of 0.25 m/s, diffusing mechanical wind can reach the characteristics of natural wind, improving occupants' feeling.	/	NP
JP – Mathews et al. (1994) [65]	Var.	/	T.R., N.C.	T.H.	Proposal and validation of a procedure for the verification of load prediction for thermal analysis, in order to assess comfort at the design stage.	**T.H.:** MV cooling techniques should be used only when desired thermal comfort cannot be provided.	The combination of mechanical and passive cooling and different control strategies, more than a 60 % reduction of system size and energy use could be achieved.	HV