Ventilation of Residential Buildings in Alpine Region: A Comparison Between Natural, Mechanical, and Mixed-Mode Strategies

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Abstract

Many studies have shown how controlled natural ventilation has multiple benefits on the health of people and the buildings in terms of indoor air quality (IAQ) and thermal comfort, as well as on the energy consumption of the building.
However, unfavorable outdoor environmental conditions can limit the use of solely natural ventilation and, for this reason, it is often necessary to resort to mixed-mode ventilation.
The aim of this research is to demonstrate the potential of mixed-mode ventilation strategies in comparison with the performance of controlled natural ventilation and mechanical ventilation applied separately, in the context of a dwelling located in a multi-family house in Bolzano (Italy) during the summer season.
Dynamic simulations were performed, developing a room-by-room coupled thermal and airflow model of the dwelling in TRNSYS and TRNFLOW to characterize its thermal behavior and the natural airflows.
The study analyzes and compares three different scenarios: (1) only controlled natural ventilation (CNV), (2) only mechanical ventilation (MVT), (3) a combination of the two (mixed ventilation strategies, MIX).
In this work, the controlled natural ventilation strategies are designed with a twofold aim, which is (a) to improve the indoor thermal comfort, reducing the overheating risk thanks to ventilative cooling, and (b) to improve IAQ by removing indoor airborne pollutants coming from indoor sources.
The first results show that (a) CNV effectively reduces the overheating risk, also achieving excellent IAQ levels; (b) MVT allows acceptable IAQ conditions and good water vapor removal, while overheating could become an issue in terms of duration and intensity. In addition, there is the electricity consumption associated with MVT; (c) in most cases, mixed ventilation provides excellent performance in terms of IAQ and thermal comfort, compared with the former strategies. Overheating is well managed, and the electrical consumption of MVT is limited.

1. Introduction

Many studies have shown how controlled natural ventilation has multiple benefits on the health of people and buildings in terms of indoor air quality (IAQ) and thermal comfort, as well as on the energy consumption of the building (Belleri et al., 2021; Schulze & Eicker, 2013; Schulze et al., 2018). It also has architectural benefits, as it does not require space for duct network to distribute the air within the building, leaving free use of floor-to-ceiling height (CIBSE, 2005). Furthermore, measures to enhance daylight (such as limited penetration depth and increased floor-to-ceiling height) also favor the use of natural ventilation (Carrilho da Graça & Linden, 2016).
However, unfavorable outdoor environmental conditions can limit the use of solely natural ventilation and, for this reason, it is often necessary to resort to hybrid ventilation systems (Ezzeldin & Rees, 2013; Salcido et al., 2016a), or so-called mixed-mode ventilation. There are many studies that have shown the benefits of combining controlled natural ventilation and mechanical ventilation in terms of indoor environment conditions (Arata & Kawakubo, 2022; Hamdy & Mauro, 2019; Kim & de Dear, 2021; Salcido et al., 2016b), but too little is known about the potential of these strategies applied in the South Tyrolean climate context (northern Italy). These strategies must not only be designed with the aim of maximizing IAQ and

Part of
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thermal comfort while reducing energy consumption, but should also take into account the climatic conditions, the typological aspects of the building stock and the habits of the occupants.
The aim of this research is to estimate the potential of mixed-mode ventilation strategies in comparison with the performance of controlled natural ventilation and mechanical ventilation applied separately, in the context of a dwelling located in a multi-family house in Bolzano (Italy) during the summer season.

2. Methodology

The case study building presented in this paper consists of a dwelling located in a multi-family house in Bolzano (Italy). It has a net floor area of 54 m^2 and is occupied by 3 tenants. The model consists of five thermal zones, one for each room of the apartment, i.e., two bedrooms, a living room/kitchen, a bathroom and a small central corridor. Each room, except bathroom and corridor, has only one window. The living area faces south, while the sleeping area faces south and east.
Dynamic simulations and the related analysis were performed, developing a room-by-room coupled thermal and airflow model of the dwelling in TRNSYS and TRNFLOW to characterize its thermal behavior and natural airflows.
We applied the schedules for occupancy, lighting, and electric equipment reported in Wilson et al., 2014, assuming that four occupants are living in the apartment. The total heat gains related to occupants, as well as the CO_2 generation rates, were calculated according to typical metabolic heat generation for domestic activities, namely 1.2 met for occupants in the living area, and 1 met for occupants in the sleeping area. Lighting power density was assumed to be equal to 2.7 W/m^2. When the rooms are occupied, lights are switched on if beam radiation on the room window surface is below 140 W/m^2. Electrical equipment power density was assumed to be equal to 8 W/m^2. If occupants are "sleeping" or "absent", internal loads are considered equal to 2 W/m^2 (20 % of total installed power); if occupants are "active", internal loads are considered equal to 6 W/m^2 (60 % of total installed power, considering a coincidence factor of 0.6). Solar shadings are activated if the zone air temperature is above 24 °C and incident solar radiation on the window is above 140 W/m^2.
The infiltration and ventilation airflows are calculated through the multizone airflow network model coupled to the thermal model through TRNFLOW. The airflow network model includes cracks along the window perimeter and openings at each window and internal door. Fig. 1 also reports a scheme of the airflow network with air nodes, flow paths and flow links. The flow coefficients of the cracks were set in order to have an overall envelope air tightness equal to 0.6 h^{-1} at 50 Pa. No cooling system is considered, but natural ventilation can be activated to provide for ventilative cooling over the warm season. A dual-flow ventilation unit uses supply and return fans to bring fresh air from outside into the living room and bedrooms, and exhausts stale air from the bathroom and kitchen. The ventilation unit is equipped with a high-efficiency passive heat exchanger that allows ventilation thermal losses to be minimized. The heat exchanger can also be bypassed. Each simulation was performed with a timestep of 15 min over the warm season (from May to September). The weather data was generated by Meteonorm using extreme hourly values over a 10-year weather time series for the city of Bolzano. This study analyzes and compares three different scenarios in the climate conditions of Bolzano: (1) only controlled natural ventilation (CNV), (2) only mechanical ventilation (MVT), (3) a combination of the two (mixed ventilation strategies, MIX).

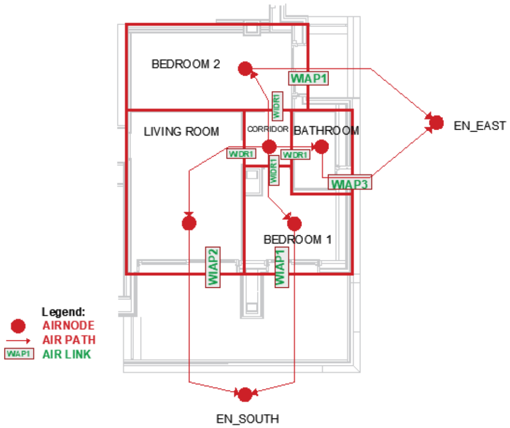

Fig. 1 – Reference building plan, thermal zones, airflow network

2.1 Controlled Natural Ventilation

CNV strategies are designed with a twofold aim, which is (a) to improve the indoor thermal comfort reducing the overheating risk thanks to ventilative cooling, and (b) to improve IAQ by removing indoor airborne pollutants coming from indoor sources.

Two CNV strategies are implemented: a) the single-sided ventilation strategy (CNV-SN) controls the opening and closing of the windows in individual rooms of the apartment independently of the other rooms, while the cross-ventilation strategy (CNV-CR) simultaneously controls multiple rooms. In a real-building application, the opening or closing of the windows could be automated by the application of actuators whose action is guided by algorithms which, based on the internal and external environmental conditions, identify the optimal opening level. The opening or closing of windows is represented in the model by an opening factor, which is a value of between 0 and 1. 0 means total closure and 1 full opening of the window (an opening factor of 0.2 indicates, for instance, a bottom hung window opening) (Table 1). All doors between rooms are assumed to stay half-opened all the time. In order to find the most suitable natural ventilation strategy, internal and external environmental conditions, such as internal temperature and CO_2 concentration, outdoor temperature and relative humidity, are considered in the analysis (Table 2).

Table 1 – Range of window opening factor

Output	Description	Value
WIN_LR	Living room window opening factor	0-1[1]
WIN_BR1	Single bedroom window opening factor	0-1
WIN_BR2	Double bedroom window opening factor	0-1

Table 2 - Controlled natural ventilation input

Input	Description	Unit of measurement
TAIR_EXT	Convective outside air temperature	°C
HR_EXT	Relative humidity of the outside air	%
TAIR_LR	Convective air temperature in the living room	°C
TAIR_BR1	Convective air temperature in the single bedroom	°C
TAIR_BR2	Convective air temperature in the double bedroom	°C
CO_2_LR	CO_2 concentration in the living room	ppm
CO_2_BR1	CO_2 concentration in the single bedroom	ppm
CO_2_BR2	CO_2 concentration in the double bedroom	ppm

Table 3 – Control parameters for the activation of controlled natural ventilation

Parameter	Description	Default Value
$TAIR\_EXT_{min}$	Minimum outdoor temperature	16 °C
HR_EXT_{max}	Minimum relative humidity	85 %
$TAIR_{cmf}$	Convective air temperature for the activation of CNV	25 °C
$CO_2\_LR_{min}$	CO_2 concentration limit in the living room	750 ppm
$CO_2\_BR1_{min}$	CO_2 concentration limit in the single bedroom	1000 ppm
$CO_2\_BR2_{min}$	CO_2 concentration limit in the double bedroom	1000 ppm

Assuming that the apartment is equipped with measurement points of the parameters shown in Table 2, these are compared with the threshold values shown in Table 3.

1 In this study 0.2 is considered because of the vasistas opening mode

In Table 4, the control signals are listed, defined as Booleans calculated with logic functions of measured data, control parameters or a combination of other control signals.

Table 4 – Control signals of controlled natural ventilation

Signal	Logic function
Y_SN	SN=1-0
Y_CR	CR=1-0
A	TAIR_EXT > TAIR_EXTmin
R	HR_EXT < HR_EXTmax
G_ZONE	TAIR_EXT < TAIR_ZONE
F_ZONE	TAIR_ZONE > $TAIR_{cmf}$
E_ZONE	CO_2_ZONE > $CO_{2\ min}$[2]
H	MIN(F_LR+F_BR1+F_BR2,1)
L	MIN(G_LR+G_BR1+G_BR2,1)

In Fig. 7 and Fig. 8 the processes that led to the activation of CNV-SN and CNV-CR are summarized. In particular, the activation of the CNV is regulated according to the external environmental conditions (external temperature greater than 16 °C and relative humidity less than 85 %).

2.2 Mechanical Ventilation

A CO_2-based demand-controlled ventilation strategy (DCV) is applied to trigger the operation of the mechanical ventilation unit, which considers the CO_2 concentration threshold value greater than 200 ppm compared with those designed for the activation of the CNV.

More detailed information is reported in Table 5.

Table 5 – MVT properties

Air flow rate per occ [m³/h]	Specific fan pow. [Wh/m³][3]	Heat rec. eff	Free cooling mode ON
36	0.28	70 %	TAIR_EXH[4] >23.5 °C TAIR_EXT<TAIR_ZONE TAIR_EXT>16 °C

2.3 Mixed-Mode Ventilation

Mixed-mode ventilation allows the use of CNV and MVT. There are no conditions imposed a priori on the alternative or simultaneous use of the two ventilation techniques, but the control logic settings of both systems prioritize the use of natural ventilation when the outdoor conditions are acceptable. The activation of CNV occurs after an increase of indoor temperature above the reference comfort temperature or for hygienic ventilation needs, while mechanical ventilation intervenes only when the CO_2 concentration exceeds the threshold and natural ventilation is not effective in providing hygienic ventilation rates. In fact, the pollutant concentration thresholds defined for the activation of controlled natural ventilation and mechanical ventilation are different, with lower threshold values for the activation of CNV. From this perspective, it will be possible to encourage the use of natural ventilation compared with mechanical ventilation, reducing electrical consumption. The performance indicators considered in the analysis of the results are summarized in Table 6 and refer to IAQ, thermal comfort and electricity consumption for MVT.

3. Results and Discussion

The study examines and compares three different scenarios: (1) only CNV, (2) only MVT, (3) a combination of the two (mixed ventilation strategies).

2 It refers to CO_2_LRmin - CO_2_BR1min - CO2_BR2min

3 "SIA-Shop Produkt - 'SIA 2024 / 2015 D - Raumnutzungsdaten Für Energie- Und Gebäudetechnik (Normenwerk => Architekt).'" n.d. Accessed March 31, 2022. http://shop.sia.ch/normenwerk/architekt/sia 2024/d/2015/D/Product.

4 TAIR_EXH = exhaust air temperature

Table 6 – Performance indicators

Symbol	Unit of measurement	Description
N_{on}	h	No. of hours of activation of the CNV and MVT strategies
D_{op}	h	Avg duration of window opening
N_{att}	No	No. of actv. of the window actuators
W_{MVT}	kWh	Electricity consumed by the MVT
W_{MIX-SN}	kWh	Electricity consumed by the MIX-SN
W_{MIX-CR}	kWh	Electricity consumed by theMVT-CN
OH_h	%	% of occ. hours Tair>26 °C (Nicol, 2013)
OH_i	K	Avg. intensity OH during occ. hours
CO_2, C_{1-4}	%	% of occ. hours CO_2 (cat I-IV)[5]
HR, C_{1-4}	%	% of occ. hours HR (cat I-IV)[6]

The results of the simulation model are analyzed in terms of IAQ, thermal comfort and electricity consumption connected to ventilation. Fig. 2 shows the average distribution of occupied hours of the three thermal zones (living room, single bedroom, double bedroom) in the four categories of environmental quality ("CEN/TR 16798-2:2019 Energy Performance of Buildings - Ventilation for Buildings - Part 2: Interpretation of the Requirements in EN 16798-1 - Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indo" 2019) defined by concentration of CO2 in the thermal zones during the summer period (May-September). As regards CNV, it guarantees excellent levels of IAQ in terms of CO_2 concentration for the greatest number of hours (55 % of occupied hours fall into category I), while, for the remaining part of the time, the IAQ falls in category IV (where Category I corresponds to a high level of expectation, Category II to a medium level). This is probably due to the fact that the activation of the CNV is regulated according to the external environmental conditions (external temperature and relative humidity, see Fig. 7 and Fig. 8), which, if they were not favorable, would not allow the opening of the windows for the correct hygienic replacement.

The optimal results are those obtained from the use of mixed-mode ventilation strategies, able to exploit the potential of natural ventilation strategies and to use MVT as a backup if the activation of natural ventilation is not convenient.

Compared to CNV, MVT guarantees a greater number of occupied hours in which the CO_2 concentration level corresponds to the one required by categories I and II of indoor environmental quality (IEQ).

Focusing on controlled and mixed-mode natural ventilation strategies, Fig. 3 shows the distribution of the activation hours of the strategies in the living room for the summer season by type of ventilation.

Only with controlled natural ventilation strategies are the windows open for about 60 % of the summer hours, while for about 40 % of the hours natural ventilation cannot be activated, despite the need for ventilation, because of unfavorable outdoor conditions. In the case of mixed ventilation, this eventuality is considerably reduced to about 15 % of the total summer hours, thanks to the contribution of mechanical ventilation, which is active for about 30 % of the hours. It is also observed that the number of hours in which both natural and mechanical ventilation are active is very low (about 2 % of the hours).

5 CO_2 categories were defined according to EN16798-1 Annex B assuming 400ppm as the average outdoor concentration ("EN 16798-1:2019 Energy Performance of Buildings - Ventilation for Buildings - Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acous" 2019)

6 relative humidity cat. were defined according to EN16798-1 Table I.11

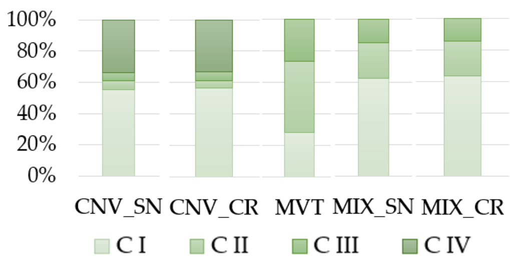

Fig. 2 – Distribution of IAQ categories (C I–C IV) for the CO_2 concentration during the occupied hours considering the five ventilation strategies during the summer period (May-September)

Even if the two control systems do not communicate with each other, their control prevents their simultaneous activation, allowing the two types of ventilation to alternate with each other. In addition, Fig. 4 shows the influence that outdoor temperature and humidity conditions (see Table 3) have on the activation of CNV strategies. As the figure shows, the outdoor temperature is the most critical parameter (higher than 70 % of hours during the summer period), when the outside temperatures are lower and, during the night, they can drop below 16 °C. In general, no significant improvement occurs by activating the CNV-CR strategy, probably due to the fact that air mixing within the apartment was ensured by an open door all the time. As regards the hygrometric results, Fig. 5 shows the distribution of the relative humidity in the four categories of environmental quality during the occupied hours considering all the ventilation scenarios.

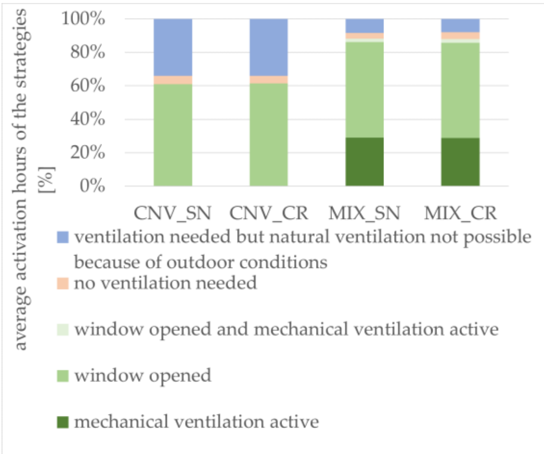

Fig. 3 – Average activation hours of the strategies in the LR during the summer period

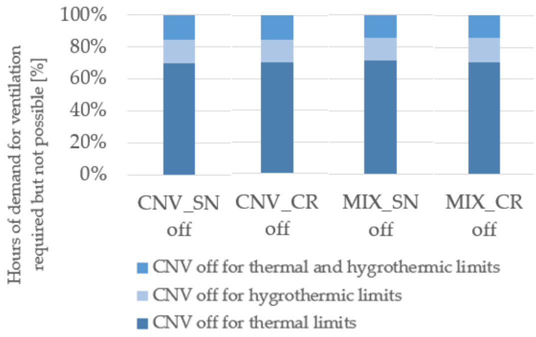

Fig. 4 – LR % of hours in which it is not possible to take advantage of CNV due to the thermal and hygrometric limits imposed on its activation [%]

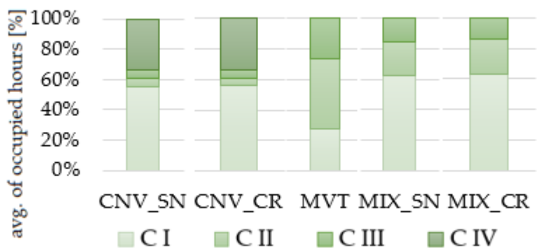

Fig. 5 – Distribution of hygrometric categories (C I – C IV) for the relative humidity assessed during the occupied hours considering the five ventilation strategies during the summer period

In all scenarios, most of the occupied hours fall into category I or II, i.e., with a relative humidity of between 25 % and 60 %. Only the MVT scenario guarantees better results, probably due to the fact that the air intake with MVT is localized in the rooms where there is the greatest generation of water vapor. A percentage of hours greater than 0 % falls into categories III-IV, assuming that unfavorable external conditions do not allow the opening of the windows.

As regard overheating, the graph in Fig. 6 shows the average percentage of occupied hours with overheating risk (reference temperature equal to 26 °C) and the average intensity. As the figure shows, the highest overheating occurs in the MVT case with monthly average overheating hours of 80 % and monthly average intensity of 2.7 °C.

The higher overheating rate in the MVT case is probably due to (1) the presence of the heat recovery unit, which has an undesirable recovery effect even in free cooling mode, (2) the limited air flows moved by the ventilation and finally (3) the lack of forced ventilation control dedicated to ventilative cooling. The scenarios with CNV and MIX strategies show a lower overheating rate, even if lower percentages of monthly average overheating hours and monthly average overheating intensity are noted in the second case.

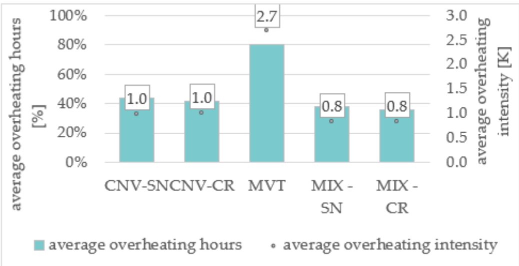

Fig. 6 – Average overheating hours and overheating intensity across all the model zones

As regards electricity consumption, with MVT only this is equal to 75 kWh, MIX-SN to 35 kWh and MIX-CR to 34 kWh. MIX therefore allows a saving of approximately 40 kWh of electricity to be achieved, which corresponds approximately to a reduction of 54 % of electricity consumption for ventilation compared with the case of MVT only.
In the case of CNV, during the cooling season, it is relatively lower than MVT, since the only energy use is for opening and closing the windows.

4. Conclusion

The aim of this research is to demonstrate the potential of mixed-mode ventilation strategies in comparison with the performance of CNV and MVT (without free-cooling option) applied separately, in the context of a dwelling located in a multi-family house in Bolzano (Italy) during the summer season.
This study analyzes and compares three different scenarios in the climate conditions of Bolzano during the cooling season: (1) only CNV, (2) only MVT, (3) a combination of the two (mixed-mode ventilation strategies).
The main results show that CNV and MIX allow a reduction in the overheating risk and an excellent level of IAQ to be achieved, although inadequate outdoor conditions may prevent window opening. MVT allows acceptable IAQ and humidity levels. However, overheating can occur up to 80 % of the time over the summer period due to: (1) the presence of the heat recovery unit, which has an undesirable recovery effect, even in free cooling mode, (2) the limited amount of air flows moved by the ventilation machine and (3) the lack of a forced ventilation control for the ventilative cooling. MIX provides excellent performance in terms of IAQ and overheating control, compared to the former strategies. The lower use of MVT makes it possible to achieve a saving of approximately 40 kWh of electricity for the summer season, which corresponds approximately to a reduction of 54 % of electricity consumption for ventilation compared with the case of MVT only. As shown in the system activation trends, the greater use of natural ventilation corresponds with less frequent use of mechanical ventilation, with a very reduced number of hours of simultaneous activation of the two (approximately 2 % of the total hours).
More in-depth analyses will be carried out on overheating to compare strategies in summer conditions, through an adaptive analysis of thermal comfort.

Acknowledgement

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Appendix

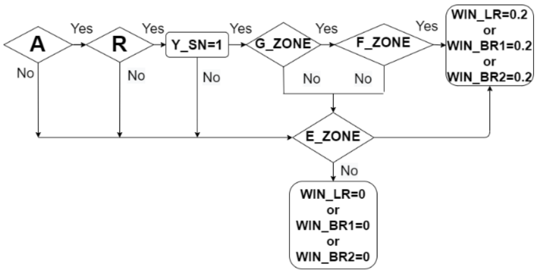

Fig. 7 – CNV-SN

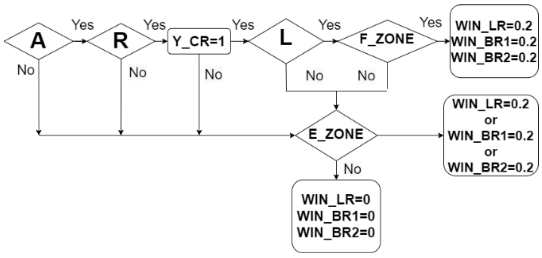

Fig. 8 – CNV-CR