Article

Humidity-sensitive demand-controlled ventilation applied to multi-unit residential building – performance and energy consumption in Dfb continental climate

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Abstract: A humidity-sensitive demand-controlled ventilation system is known for many years. It has been developed and commonly applied in regions with an oceanic climate. Some attempts were made to introduce this solution in Poland in a much severe continental climate. The article evaluates this system's performance and energy consumption applied in an 8-floor multi-unit residential building, virtual reference building described by the National Energy Conservation Agency NAPE, Poland. The simulations using the computer program CONTAM were performed for the whole hating season for Warsaw's climate. Besides passive stack ventilation that worked as a reference, two versions of humidity-sensitive demand-controlled ventilation were checked. The difference between them lies in applying the additional roof fans that convert the system to hybrid. The study confirmed that the application of demand-controlled ventilation in multi-unit residential buildings in a continental climate with warm summer (Dfb) leads to significant energy savings. However, the efforts to ensure acceptable indoor air quality require hybrid ventilation, which reduces the energy benefits. It is especially visible when primary energy use is analyzed.

Keywords: energy use; demand-controlled ventilation; hybrid ventilation; humidity; multi-unit residential building; simulation; CONTAM

1. Introduction

1.1 Smart ventilation of multi-unit residential buildings

Multi-unit residential buildings (MURBs) are the dominant housing stock in many cities in Europe, Asia, or North America. Occupant comfort is affected by various indoor environmental conditions, outdoor conditions, building characteristics, and occupant-related characteristics. However, thermal conditions and indoor air quality (IAQ) are identified as the most important factors for overall comfort in MURBs [1].

Older buildings were initially equipped with natural ventilation systems, in Europe, most often passive stack ventilation. However, the low investment cost of these systems leads to high operational costs. Different values of pressure observed on various floors result in significant differences in ventilation intensity. Usually, units on the ground floor have much higher air change rates than units located on the highest floor. Moreover, on the highest floor, quite often, reverse flows in ventilation ducts are observed. Because actual airflows are strongly dependent on changing weather conditions, not on users' needs, they often complain about indoor air quality. Paying more attention to energy savings and increasing expectations to comfort calls for smarter solutions.

The key smart ventilation concept is to use controls to ventilate more when it provides either energy or IAQ advantage (or both) and less when it provides a disadvantage. This concept's fundamental goal is to reduce ventilation energy use and cost while maintaining or improving IAQ

relative to a continuously operating system [2]. Systems responding to variable ventilation needs are called demand-controlled ventilation (DCV). In public buildings or office buildings, this control strategy usually supports balanced mechanical ventilation. However, in residential buildings, the DCV concept is preferably applied to natural or hybrid ventilation. The systems usually use trickle vents integrated into façades or window systems, exhaust grilles, and fans supporting naturally driven airflows. The primary design criteria of trickle vents are ventilation capacity, controllability, actuation, thermal insulation, air permeability, water tightness, climatic adaptation, security, and acoustic attenuation [3]. Mijakowski and Sowa described the intervention study in the kindergarten [4]. Initially, the room, with a volume of 138.8 m^3, devoted to 20 children and 2 teachers was ventilated naturally, but no trickle vents were installed in windows. Installing 4 humidity-sensitive demand-controlled trickle vents did not solve the problem of low indoor air quality. The average ventilation rate increased from 0.2 to 0.3 h^{-1} and was still about 10 times lower than required. The study indicated that any control strategy is ineffective in the absence of forces effectively driving air flows.

Besides occupancy, the most common DCV control strategies are sensitive for [5]:

- carbon dioxide (as an indicator of human bioeffluents)
- humidity (as an indicator of human respiration and activities like cooking, bathing, etc.)
- particles (e.g., as an indicator of smoking)
- TVOC (as an indicator of emissions from building materials and different processes.)

These strategies differ in adaptability to variable occupancy in both temporal and spatial scales. The proportional relationship between energy use and occupancy [6], regarded as optimal in public buildings, is more complicated in residential buildings. Such processes as combustion, cooking, washing, or bathing also required ventilation. Controlling humidity is a promising strategy.

WHO guidelines for indoor air quality part dampness and mold [7] states that conclusions from epidemiological studies suggest that dampness related risk factors are associated with a large proportion of human respiratory disease. For instance, residential dampness is associated with a 50% increase in current asthma and substantial increases in other respiratory health outcomes, suggesting that 21% of current asthma in the United States may be attributable to residential dampness and mold.

As many old buildings still wait for revitalization, the solutions enabling the modernization of inhabited buildings are more popular. Such systems usually use the existing ventilation ducts, and the changes are limited to the installation of smart inlet and exhaust elements and the use of chimney caps or fans in the ventilation ducts.

1.2. Humidity based demand-controlled ventilation systems

Humidity-based demand-controlled ventilation is regarded as a simple, smart ventilation system. Air vents used in that system has variable characteristics influenced by relative humidity. For a given pressure drop, airflow is proportional to relative humidity (usually in the range 30÷70%). Characteristics of exhaust grills also depend on relative humidity. If needed, exhaust fans equipped with pressure sensors can be mounted on a roof above exhaust ducts.

Humidity-based DCV systems have been widely used in France for 35 years. Woloszyn et al. [8] presented the study on humidity-sensitive demand-controlled ventilation, concluding that energy savings were mainly related to reducing the mean ventilation rate when the building was not used. In the tested case, due to the application of humidity-sensitive demand-controlled ventilation, the mean ventilation rate was reduced by 30–40% the reference, and as a result, 12–17% of energy savings were observed.

The system in different variants was tested in MURBs in several demonstration projects in several European countries [9]. Long term monitoring campaigns [10] enable observing a significant phenomenon inherent to the humidity-controlled ventilation: its statistical seasonal behavior. The humidity-controlled ventilation saves energy on heat losses, from 30% to 55% in the measured dwellings, giving an average airflow lower in winter than in summer. The monitoring campaigns have also demonstrated that the instantaneous airflow can be very high when needed with this

system, even in winter, where the average airflow is low. A complementary advantage of the demand-controlled ventilation is to reduce the average fan power consumption due to the statistically confirmed low airflow induced by the system. In France, humidity-sensitive ventilation became a reference system, including low-energy residential buildings [11].

However, humidity-sensitive grilles need periodical cleaning. If not cleaned, dust covering the grille flaps decreases airflow, especially for the low openings of the grille [12]. The average in-situ drift of the hygroscopic devices after 9 years of operation is estimated below ± 1.5 %RH and is lower than the announced accuracy of the electronic humidity sensors at installation (± 1.8 %RH) [13].

1.3 Modeling of humidity based demand-controlled natural and hybrid ventilation

Humidity-based demand-controlled hybrid ventilation systems create many problems during modeling. If the system is analyzed in a residential or office building with many rooms, the applied model has to allow the researcher to perform multi-zone simulations. The system's hybrid nature causes natural and mechanical forces driving airflows to be taken into account. The utilization of humidity-based demand-controlled strategies calls for simultaneous humidity ratio calculations in each building zone and airflow calculations between zones. Moreover, modeling has to take into account the behaviors of control elements.

The precise results need detailed modeling of materials moisture buffering properties in contact with the indoor air. During the development of the Humi-Mur model, it has been proved that neglecting hysteresis in the description of the sorption-desorption process leads to significant inaccuracies [14]. Nevertheless, even much simpler models like the simplified two parameters method similar to Thermal Response Factors (TRF) method can give quite good results [15].

The experience gained from many research programs shows that proper modeling of IAQ should include a description of man's activities that have a stochastic nature [16]. Users influence the indoor environment in several ways, divided into three groups: migration between microenvironments, the additional emission of pollutants (including water vapors), and changes in natural and mechanical ventilation characteristics (e.g., through windows opening). Actual behavior depends on many factors, many of which are very subjective, most of which are interrelated.

Usually, in multi-zone airflow analysis, stochastic factors are taken into account by [17]:
- generating the number of input time series with data of stochastic nature
- description of disturbances as Gaussian distributions and the application of Stochastic Differential Equation (SDE) theory,
- multiple generations of sets of input data and the application of a Monte Carlo simulation.

An example of the application Monte-Carlo method to sensitivity analysis while modeling performance of DCV with 4 different demand control strategies were presented in [18,19]. The authors found that the control strategy based on relative humidity affecting exhaust grills was more sensitive to input data than a strategy based on occupancy detection affecting central exhaust fan and strategy based on CO_2 measurements controlling trickle fans supplying air to rooms.

Generalized mathematical models can describe the most straightforward cases. Necessary dependencies for natural ventilation systems can be found, for example, in [20]. Calculations of combined natural and mechanical ventilation systems have been described in technical reports of RESHYVET project [21]. Additionally, Antvorskov [22] listed and described possible renewable energy technologies integrated with hybrid ventilation in residential buildings such as a solar chimney, wind turbine, wind cowl, and windcatcher. A more complex approach is the dimensionless design approach [23].

In practice, when modeling multi-unit buildings, researchers usually use computer programs based on multi-zone macro-scale models. The literature review indicates that many different computer programs have been used for that purpose. Jeong and Haghighat [24] presented the usefulness of simulation package ESP-r for modeling a hybrid-ventilated building. The authors concluded that modeling of hybrid ventilated buildings using this type of approach is possible, and the resultant outputs are feasible and practical in terms of both the thermal and ventilation points of view. However, at the same time, limitations exist when someone attempts to model complicated

building systems or model CO_2 based control systems. The study by Zhai et al. [25] analyzed the impact of natural and hybrid ventilation models on whole-building energy simulations using EnergyPlus. Simulation results were very accurate only for one building out of three modeled, while the other two buildings were less promising. The authors defined the imperfections of the EnergyPlus network model related to natural and hybrid ventilation. IDA ICE 4 simulation software was used to analyze the impact of demand-controlled ventilation installed in new residential buildings on indoor air quality and energy savings [26]. In that study, the energy demands for heating air and electricity consumption for the ventilation fan were decreased by 20% and 30%, respectively.

Numerical simulations of a ventilation system controlled by relative humidity can also be conducted using Clim2000 [27]. Savin and Laverge [28] claim that also other programs as SIREN (developed by CSTB, France) and WUFI® Plus (developed by Fraunhofer IBP, Germany) have proven their reliability to assess demand-controlled ventilation.

In several already published papers, the analysis of the performance of humidity based ventilation was based on simulations performed in the multi-zone airflow simulation package CONTAM (developed by NIST, USA) [29, 30]. The validation of this indoor air simulation tool against, e.g., tracer gas measurements, is well documented in the literature [31-33]. CONTAM has been used in many studies devoted to demand-controlled ventilation controlled by indoor contaminants (e.g. [34]). Although water vapor is not typically thought of as an indoor contaminant, it was also demonstrated that CONTAM could be used to predict water vapor concentrations in each zone by applying mass balance equations that incorporate water vapor sources and sinks [35]. However, when simulating fast transport mechanisms, such as high air change rates, sorption, and chemical reactions, typical solvers used by CONTAM may have difficulty accurately predicting transient contaminant concentrations or humidity ratio. Therefore it is recommended to use solver CVODE that adjusts its time steps to control errors, freeing users from selecting an appropriate time step. This solver can predict pollutant dynamics on time scales shorter than the one-second limit imposed by the legacy solver [36].

Constantly developed CONTAM is now prepared for coupling the multi-zone airflow and contaminant transport analysis with energy simulations computer programs Energy Plus [37], and TRNSYS [38]. In fact, the airflow results obtained from CONTAM can be used as input data for any building's energy model. Such approach was presented by Sowa and Mijakowski [39], while the authors performed airflow analyses using CONTAM (calculations with 1 min time step, exported data with 15 min time step) while energetic hourly calculations were performed using 6R1C energy model [40]. The model developed at Warsaw University of Technology is based on the simple hourly method described in ISO FDIS 13790:2008 [41]. An essential modification is splitting airflow between outdoor and indoor into controlled airflow (with known or calculated supply temperature) and uncontrolled infiltration/exfiltration. Similarly to 5R1C, the model allows supplying the heat energy to three nodes – to the interior of building construction, to the internal surface of building construction, and to indoor air. The developed model has been successfully verified with the BESTEST [42].

Emmerich [43] presented simulated performance of natural, hybrid, and mechanical ventilation systems in an office building. The analysis compared the performance of the virtual building in American towns with a different climate. Simulations were performed using CONTAMR, a CONTAM multi-zone IAQ modeling program that provides coupled thermal/airflow modeling. The performance of natural ventilation occurred unacceptable in challenging climates of Boston, Minneapolis, and Miami. The mechanical system provided more consistent control, as expected. The hybrid system saved significant amounts of fan energy, reduced cooling loads, or reduced fan and cooling loads in all climates but often resulted in higher heating loads.

Sensitivity analysis by varying some of the most significant parameters in mixed (hybrid) ventilation systems was presented by Pinto et al. [44]. The study is based on simulations using the CONTAM modeling program and experimental data of air permeability of the building envelope and ventilation devices' performance characteristics.

2. Materials and Methods

2.1. Analyzed building

The procedure for ventilation system recommendations developed by the National Energy Conservation Agency (NAPE) [45] uses two types of virtual reference buildings: 8-floor multi-unit residential building (Figure 1) and 2-floor single-family building. This study describes simulations performed in a virtual MURB, according to the following assumptions:

- 8-floor building with a basement,
- three small apartments M1, M2, and M3 (Figure 1). on each floor (and appropriate assumptions regarding the use of the apartments),
- flat roof,
- thermal parameters of building partitions (minimum requirements according to Polish building codes and related ministerial ordinance [46] for newly erected buildings), central hydronic heating with convection heaters,
- heat source - district heating network.

The building has a total volume of V_e = 5865 m³, surface of envelope A_e=2028.5 m² (shape ratio A_e/V_e = 0.35) and usable area A_f = 1634 m². Altogether there are 23 units, occupied by 47 persons.
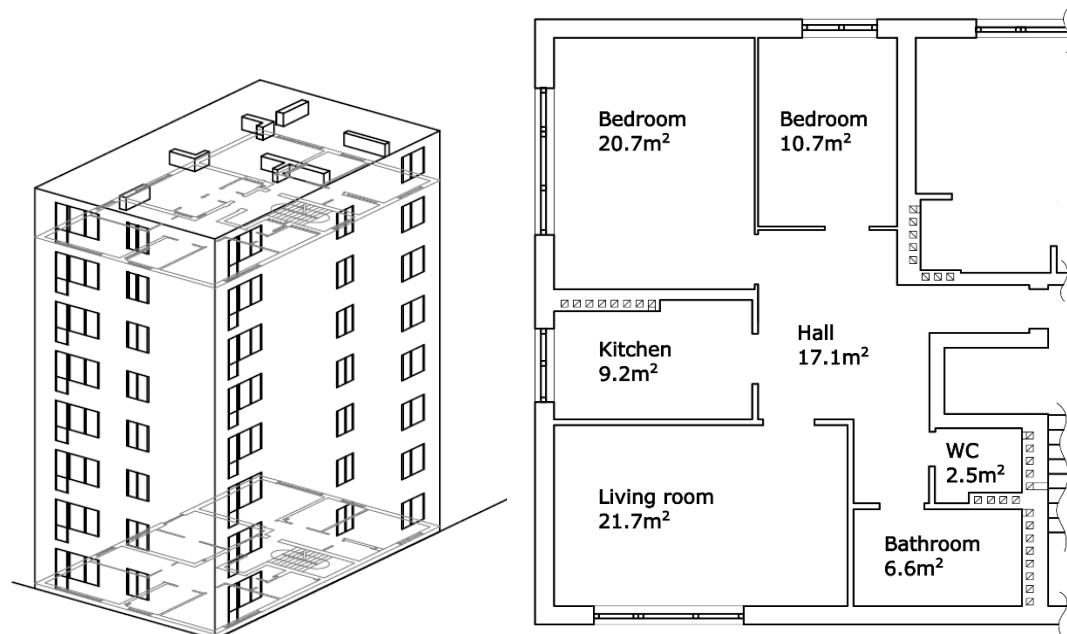

Figure 1. The NAPE 8-floor multi-unit residential reference building and one of the apartments subjected to detailed analysis.

In each unit type, a time pattern of emission of moisture gains related to people's presence and activity (cooking, washing dishes, shower) was defined. The walls and ceiling have gypsum plaster that has been taken into account modeling of moisture buffering.

The NAPE reference building is equipped with two optional ventilation systems: mechanical exhaust ventilation and passive stack ventilation. Mechanical exhaust ventilation is designed just to meet the minimal requirements of the Polish ventilation standard [47]. Air is exhausted from kitchens (70 m³/h for kitchens equipped with gas cooker), bathrooms with or without a toilet (50 m³/h), and separate toilets (30 m³/h). In that case, the supply is through trickle vents, which provide 30 m³/h of air when tested with 10 Pa pressure difference.

According to regulations, passive stack ventilation should ensure identical airflows as mechanical exhaust ventilation. In practice, air change rates driven by natural forces are not verified by any calculations. The model applied in the NAPE reference building assume that air is supplied to the units through trickle vents installed in each window. In test conditions at 10 Pa pressure

difference, these vets provide 50 m³/h [47]. Exhaust grills connected to individual stacks with cross-section 14x14 cm are located in kitchens, bathrooms, toilets. Outlets are placed above the roof.

According to the Polish ventilation standard, the following airflows should be exhausted: unit M1 - 100 m³/h, unit M2 – 80 m³/h, and unit M3 – 130 m³/h. For all units, the required airflow is 2380 m³/h.

In the further analysis of simulation results, special attention will be paid to the unit M3. The unit has a floor area of approximately 88.9 m² and is used by two adults and a child. Space is divided into a living room and two bedrooms, a kitchen, bathroom, separate toilet, and a hall. Schedules of occupancy define in which room each person is present on typical workdays and weekends. One adult and child are out of the home during mid-day on workdays. Figure 2 presents a pattern of moisture emission for a working day and a weekend.
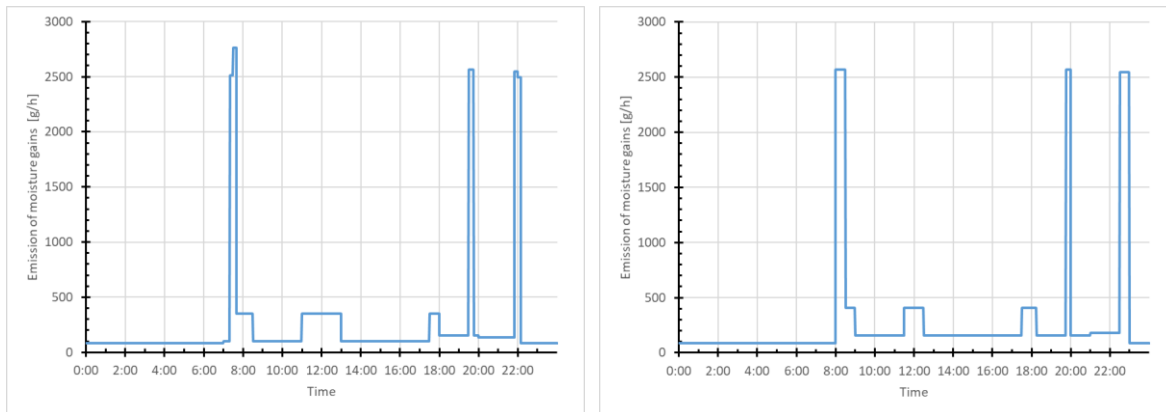

Figure 2. Assumed daily variations of moisture gains in unit M3 work days (left) and weekends (right).

2.2. Investigated ventilation options

Option 1 is a reference passive stack ventilation described above.

Option 2 is a passive stack ventilation equipped with humidity-sensitive trickle vents and exhaust grilles. As described earlier indoor relative humidity affects the characteristics of these elements. Additionally, exhaust grills mounted in bathrooms and toilets are equipped with presence sensors that force a control damper to open when users are in space (delay for switching off is 20 min).

Option 3. Trickle vents and exhaust grilles have identical characteristics like in option 2, but exhaust fans mounted on a roof above individual exhaust ducts support airflows induced by natural forces when needed. They are equipped with pressure sensors that control fan speed.

2.3. Climatic data

The building is virtually located in Warsaw, Poland. The vast majority of studies on humidity-driven DCV systems were performed in countries (France, Belgium, Netherlands) that lies in the region of temperate maritime climate (According to the European Environmental Agency -EEA). Using Köppen-Geiger climate classification, this climate is described as Cfb - Oceanic climate - Marine west coast climate. This study is conducted in the temperate transitional climate (EEA classification). The Köppen-Geiger classification regards Warsaw as a town with warm summer continental or hemiboreal climates – Dfb. According to Eurostat, averaged heating degree-days for Poland equals 3315. Similarly, calculated average degree days for France represent approximately 70% of Poland's value, while for Belgium and the Netherlands, around 80%.

Having access to the long-term metrological data, researchers can produce their own Untypical Meteorological Years (UMY) that are variations of the Weather Year for Energy Calculations 2 (WYEC2) reference year calculated with different than standard weighting indices. In such a situation, different weather parameters are less or more important during the selection of typical

months [48]. It is possible to develop UMY best suitable for modeling natural or hybrid ventilation systems. However, a need to compare results between studies encourage scientists to use mainly measured meteoroidal data or standardized ISO or WYEC2 typical years. All analyses are performed using a typical meteorological year for Warsaw Airport Okęcie (52° 10'N; 020° 58'E), published by the Polish Ministry of Infrastructure (https://archiwum.miir.gov.pl/media/51889/wmo123750iso.txt). This file complies with rules described in EN ISO 15927-4, [49]. According to these data, Warsaw ambient temperature varies from -12 °C to +34 °C, while the span of daily average temperature is -7 °C to +24 °C (Figure 3).
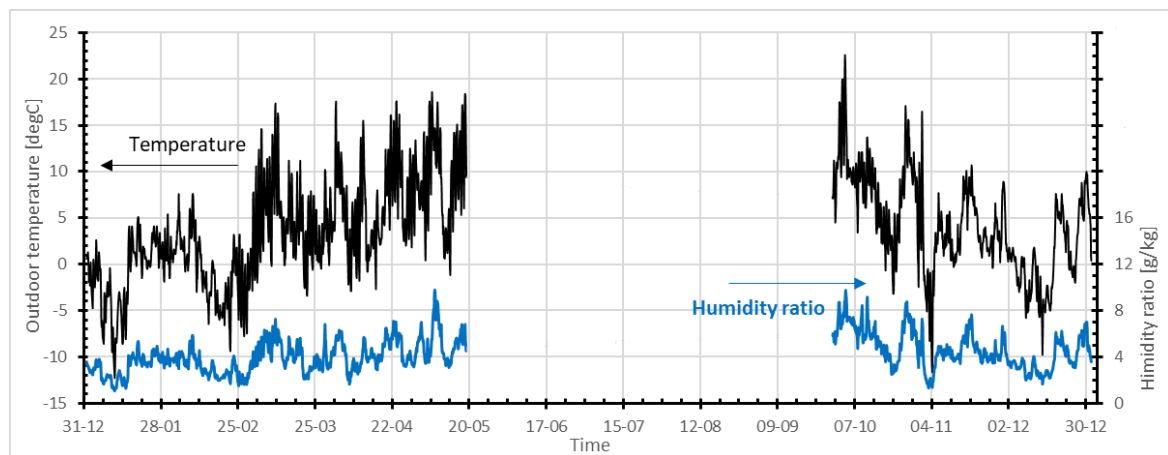

Figure 3. Ambient temperature and humidity ratio for Warsaw.

As during summer, buildings are not heated, and users significantly change their behavior related to opening windows, the calculations were performed only for the heating season. According to Polish tradition, it has been assumed that the heating season starts in autumn when the daily average temperature drops below +12 °C and the heating period stops when the daily average temperature exceeds +12 °C in spring. For selected weather file corresponding date for starting/ending heating season are September 29th and May the 18th.

2.4. Software used

Airflow simulations were performed using the computer program CONTAM. In the CONTAM environment, the building, together with the analyzed ventilation system, has been idealized as 97 zones, 715 flow paths, 56 ducts, and 126 junctions/terminals. Additionally, in humidity-based demand-controlled hybrid ventilation systems, the model takes into account controls (in the analyzed case, humidity influences characteristics of air vents, exhaust grills, and exhaust fans). It should be pointed out that a real control network is more complex than presented on a sketchpad as some nodes can be so-called super elements that represent subnetworks. Figure 4 presents Sketchpad (CONTAM) of the eight floor of the analyzed building for Option 3.
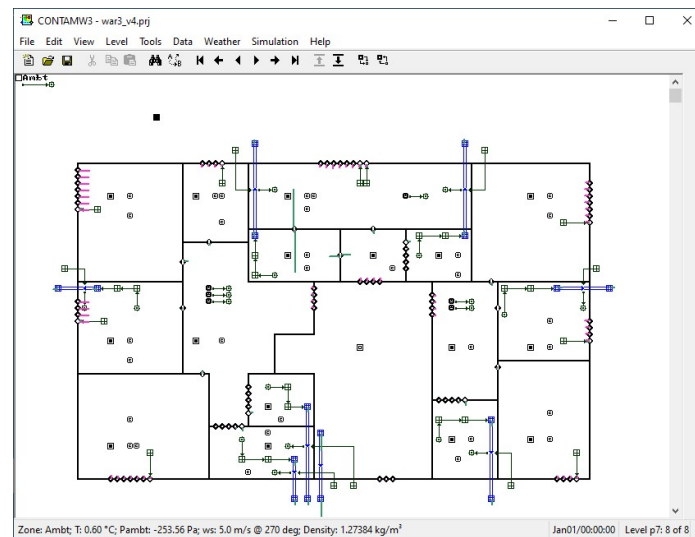
Figure 4. Sketchpad (CONTAM) presenting the eight floor of the analyzed building for Option 3.

Most airflow elements in CONTAM environment are based on the following empirical (powerlaw) relationship between the flow and the pressure difference across a crack or opening in the building envelope:

$$Q = C(\Delta P)^n, \tag{1}$$

The volumetric flow rate, Q [m³/s], is a simple function of the pressure drop, ΔP [Pa], across the opening. Powerlaw equation coefficients C and n used during modeling in this article are presented in Table 1.

Table 1. Coefficients C and n of the used during modeling different options of ventilation systems.

Flow element	C	n
	m³/(s·Pa^n)	-
Window gap (1m)	1.80E-05	0.67
Trickle vent (passive stack ventilation)	1.25E-03	0.50
Exhaust grill (passive stack ventilation)	(Added as loss coefficient in the duct)	
Higro-sensitive trickle vent (<35%RH)	5.83E-04	0.50
Higro-sensitive trickle vent (>65%RH)	2.50E-03	0.50
Higro-sensitive exhaust grill (<30%RH)	3.30E-04	0.50
Higro-sensitive exhaust grill (>75%RH)	2.20E-03	0.50

Airflows were analyzed using CONTAM with 1 min time step (results were stored with 15 min time step). A boundary layer diffusion model was used to simulate the effect of moisture buffering.

3. Results and Discussion

3.1 Airflow simulations

Detailed simulations during heating season (between September 29th and May the 18th) provided a massive set of results to compare the behavior of the analyzed ventilation systems for the whole building and different units located on a different floor. However, in this paper, three ventilation options would be discussed, especially for the unit M3. As units on the ground floor differ from units on higher floors, detailed comparisons will be presented for the units located on the second and eighth floors.

The relationships air flow rates vs. outdoor temperature for 3 ventilation options are presented in Figure 5. The most significant difference between the second and eighth floors can be observed for passive stack ventilation. Second-floor performance is strongly dependent on temperature and for very low temperatures (< -3°C) are higher than required by the Polish ventilation standard. On the eight-floor, airflows are much lower, and the impact of outdoor air temperature can be observed for very low outdoor temperatures (< -5°C). Moreover, quite often, reverse flows in ventilation ducts have been observed (red dots in Fig. 5). Air supply to the toilet or kitchen would disperse smells and odors on the whole unit. Due to small pressure values caused by thermal buoyancy, the effect caused by wind is higher than for the unit located on the second floor. Occasional reverse airflows are also observed on the 2nd floor but only for outdoor air temperatures higher than 15°C.

For option 2 air flows are smaller than for option 1 and never reach the required 130 m³/h. The differences between the second and eighth floors are significantly lower. The dependence of air flows on outdoor temperature is hardly noticeable, even on the second floor. As warmer outdoor air has higher moisture content than cold air, humidity-sensitive trickle vents and exhaust grilles remain open, increasing airflow rates.

For option 3, the second floor's air flows are almost identical but are still higher on the second floor. An increase of airflows in a mild period is observed, and required 130 m³/h are observed quite often. Reverse airflows do not appear.
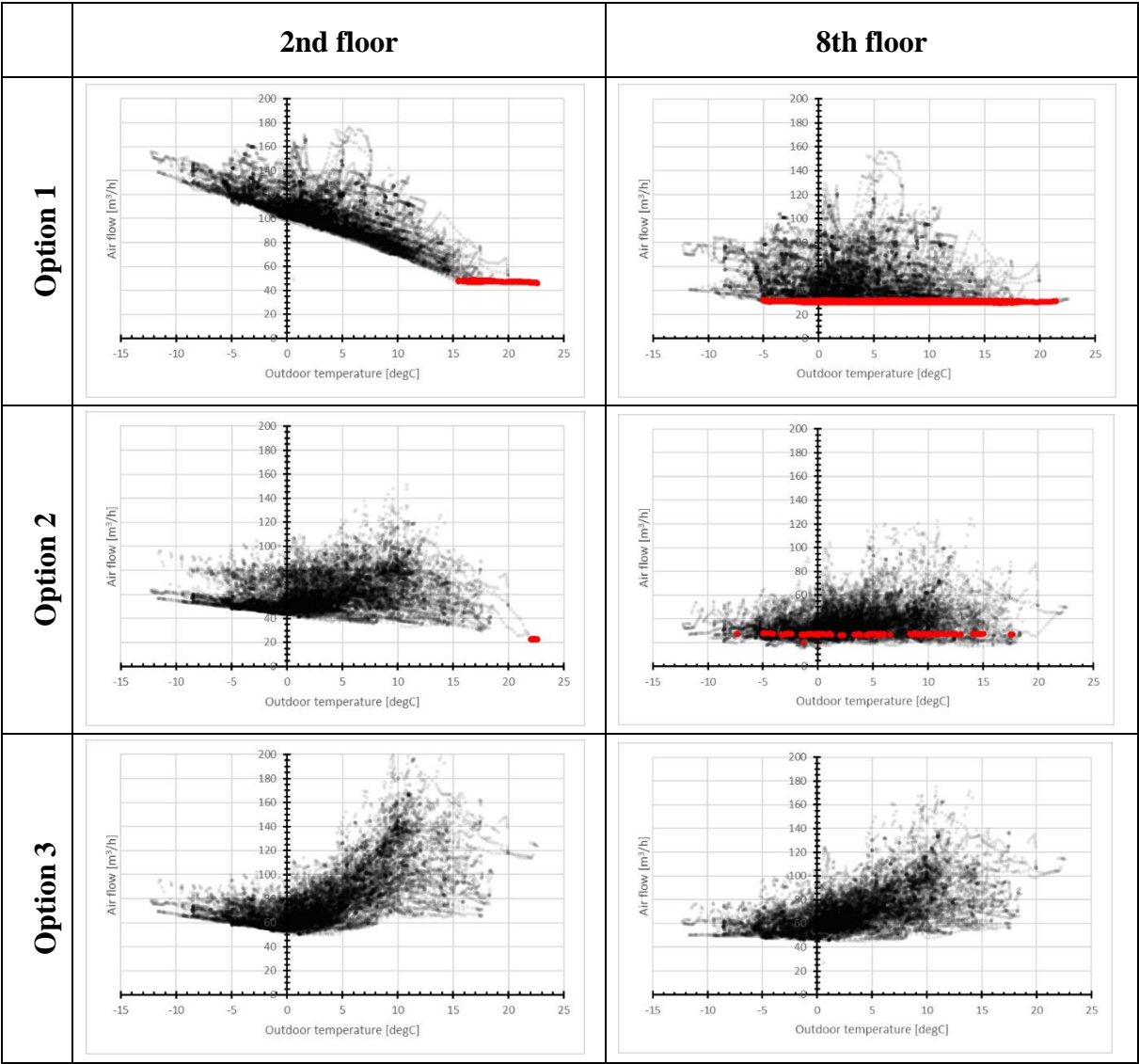

Figure 5. Comparison of air flows for units M3 located on the 2nd and the 8th floors for three optional ventilation systems (red dots indicate opposite air flow in ventilation ducts).

Figure 6 presents the airflows through unit M3 observed during workdays. For option 1, the average air flows do not depend on the time of day. The average value for the second floor (approx. 110 m³/h) is only slightly lower than the required 130 m³/h. On the 8th floor, the average air flows are only 50 m³/h. The plotted lines showing average values +/- standard deviation and the maximum values indicate a considerable variation of the intensity of ventilation depending on the weather.

In options 2 and 3 there are periodic changes in the intensity of ventilation, following the assumed time variation of moisture gains. The average values of the flows are lower in comparison with option 1. At the same time, noticeable differences between the second and the eighth floors decrease.
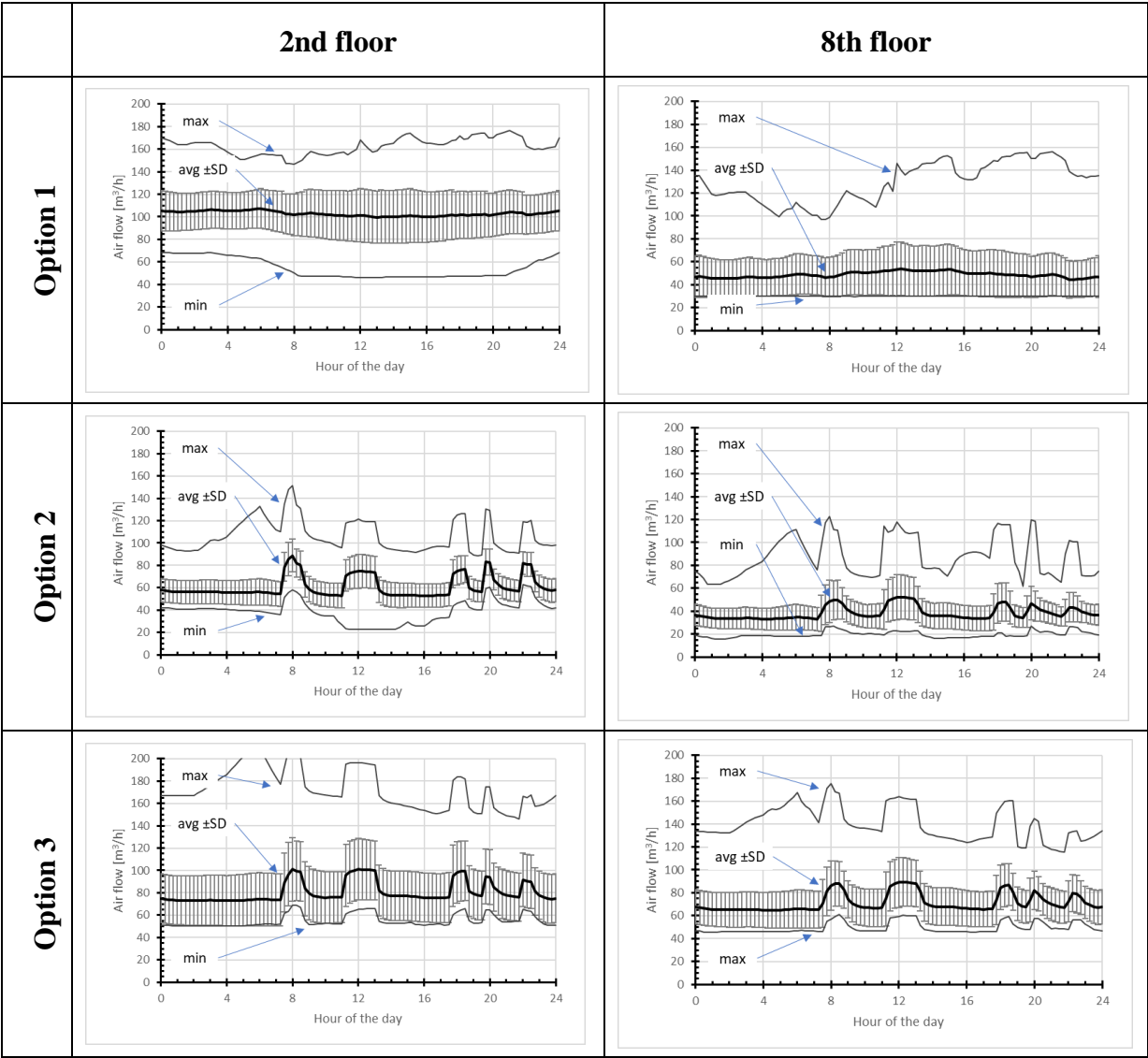

Figure 6. Comparison of daily airflows in units M3 located on the 2nd and the 8th floors for 3 optional ventilation systems (workdays).

For ventilation systems sensitive to humidity (options 2 and 3), airflows through units are slightly different for workdays and weekends. It is the result of different shapes of moisture emission. Figure 7 presents the variability of daily airflows observed in unit M3 during weekends for hybrid ventilation (option 3).
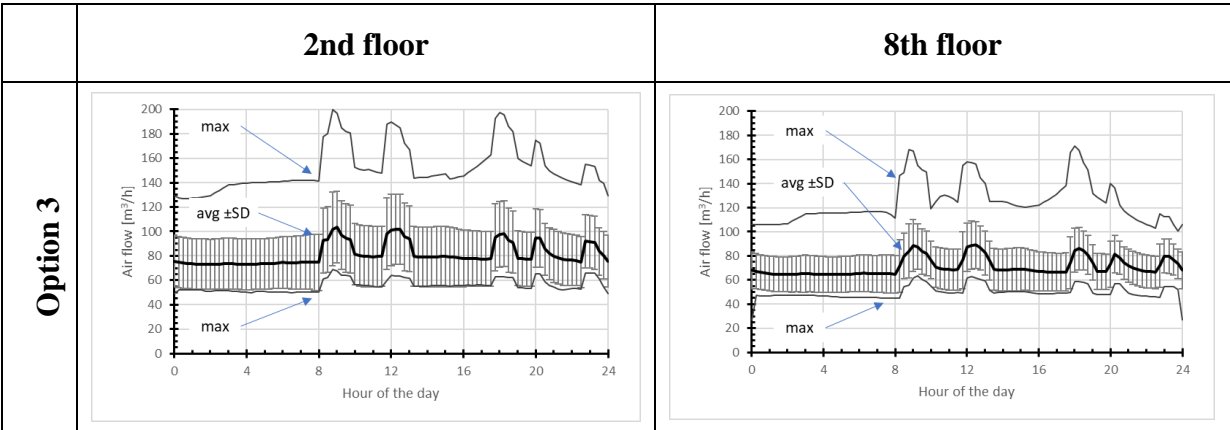
Figure 7. Daily airflows in units M3 located on the 2nd and the 8th floors for ventilation system in option 3 (weekends).

Figure 8 presents histograms of relative humidity that is a control system used in options 2 and 3. The graphs contain data simulated for halls that correspond to "spatially averaged" humidity. Distributions of relative humidity for three options for unit M3 on the 2nd floor are very similar. Simulated values lie between 20% and 60%, with the most common values below 40%.
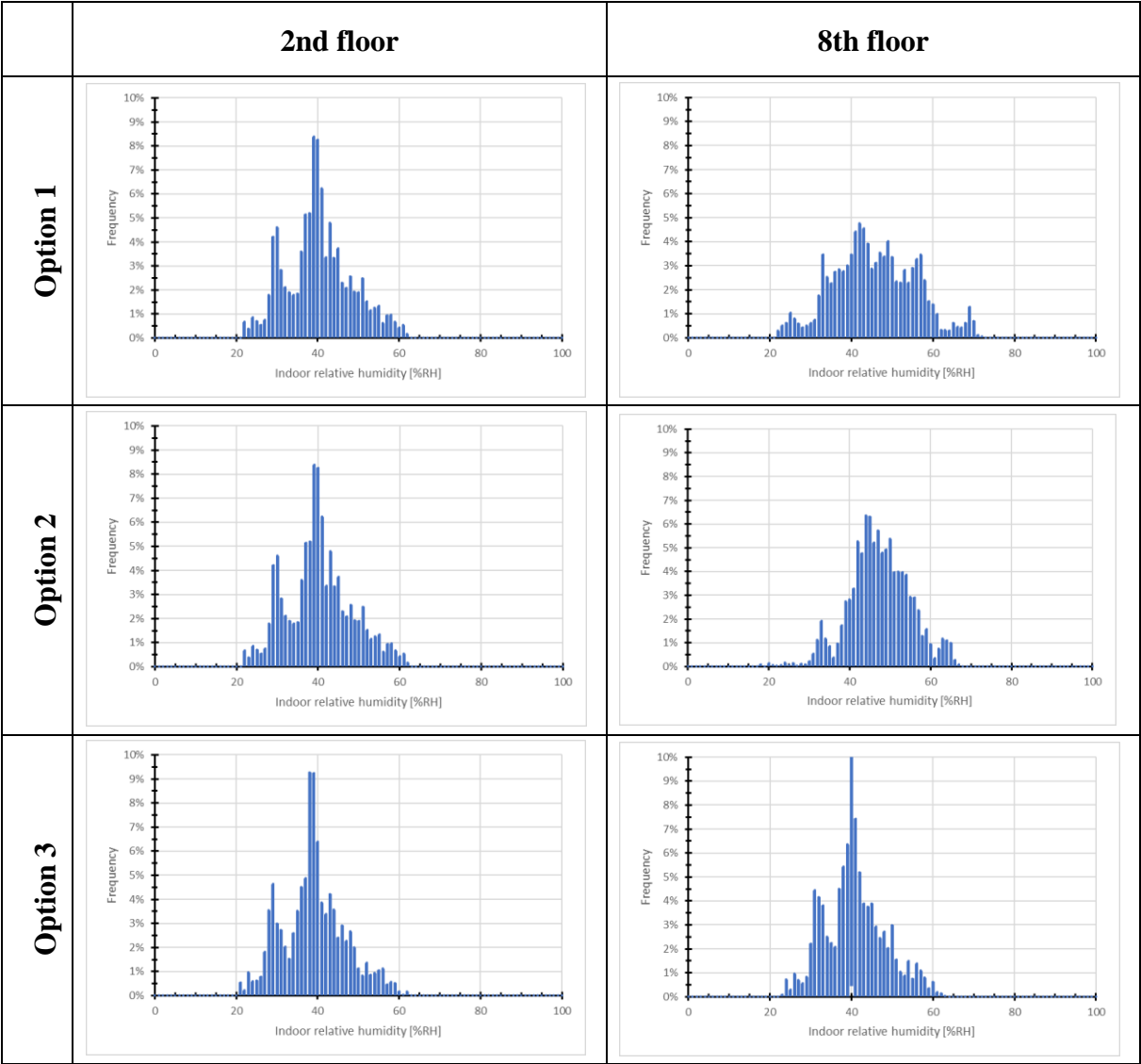

Figure 8. Comparison of indoor relative humidity histograms for units M3 located on the 2nd and the 8th floors for three optional ventilation systems.

As unit M3 located on the 8th floor is less intensively ventilated, simulated relative humidities are higher. For passive stack ventilation (option1), the frequency of occurrence relative humidities > 50% is much higher than in the unit on the 2nd floor. The maximum values of relative humidity exceed 70%.

The application of humidity-sensitive trickle vents and exhaust grilles reduce differences between the 2nd and the 8th floors. For hybrid mode (option 3), relative humidity histograms for the 2nd and the 8th floors are very similar.

3.2 Indoor air quality analysis

CONTAM allows users to simulate the existence of occupants within a building. It is possible to simulate occupants' movement throughout the building and determine each occupant's contaminant exposure. Occupant exposure is determined by integrating the contaminant concentration to which the occupant is exposed over a period of time [30]. As carbon dioxide is commonly used as a simplified indicator of IAQ, often without a full appreciation of the links between indoor CO_2 and ventilation [50], it was also adopted in the described study. Figure 9 compares daily fluctuations of CO_2 concentrations inhaled by the inhabitants on workdays in units M3 located on the 2nd and the 8th floor for three optional ventilation systems.
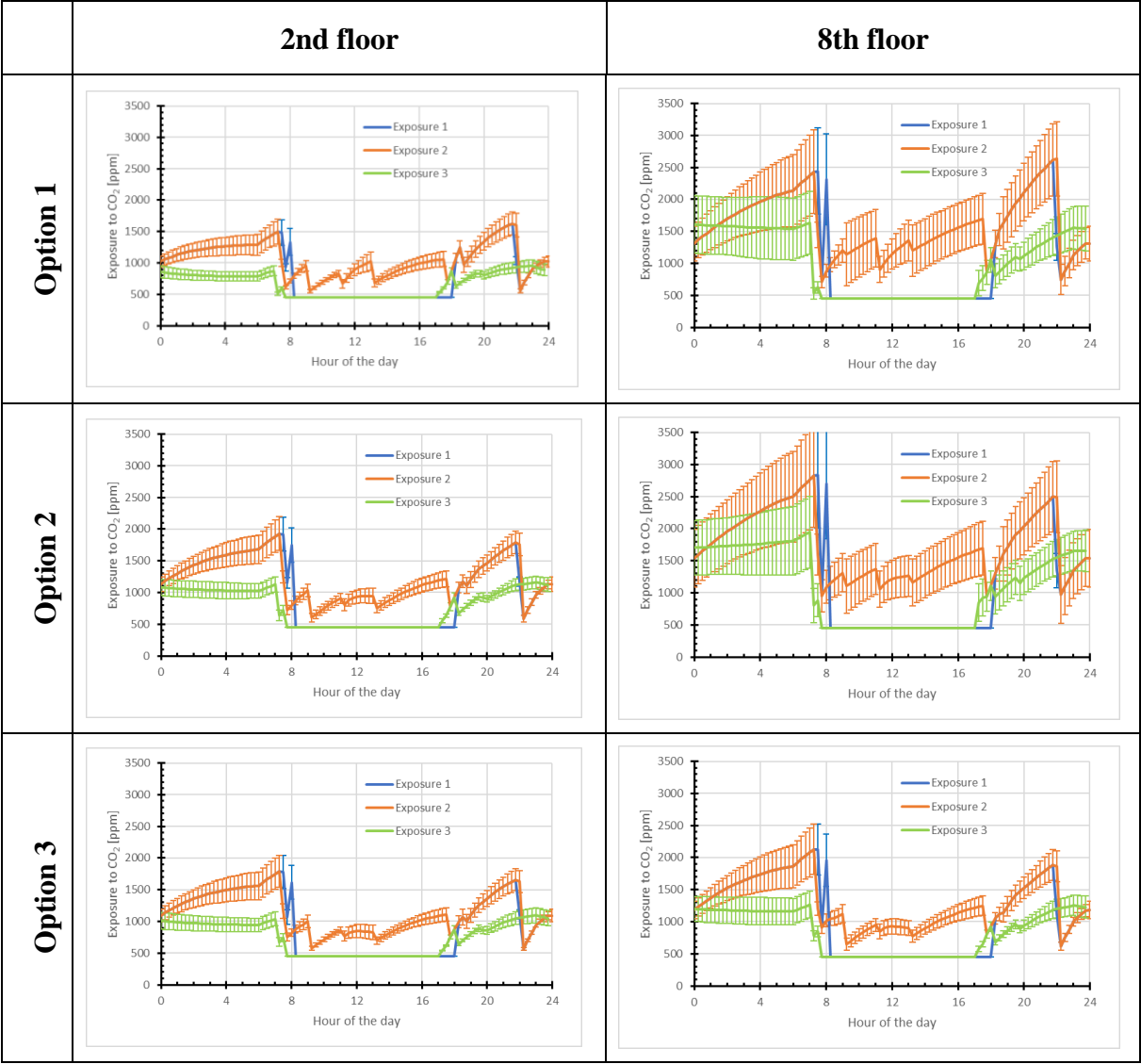

Figure 9. Comparison of exposures to CO_2 in units M3 located on the 2nd and the 8th floor for three optional ventilation systems (work days).

Due to the more stable work of ventilation, the variability of the exposure is smaller for unit M3 on the second floor. The identical time pattern of using the apartment on the 8th floor leads to much higher exposure to CO_2. It is caused by worse performance of ventilation (regardless of the analyzed option). Figure 10 shows the analogous weekend CO_2 concentration for hybrid ventilation.
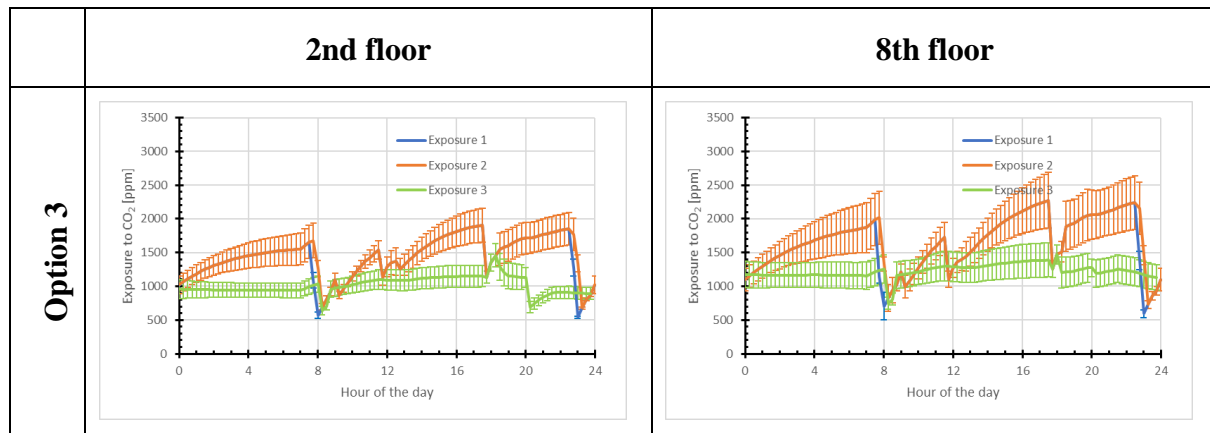
	2nd floor	8th floor
Option 3		

Figure 10. Exposure to CO_2 concentrations in units M3 located on the 2nd and the 8th floor for ventilation system in option 3 (weekends).

The average exposure to CO_2 concentration in the entire building for the reference variant is 1146 ppm, while in the unit M3 on the 2nd and the 8th floors, they are 974 ppm and 1540 ppm, respectively. These values confirm quite large differences in the performance of passive stack ventilation on floors 2 and 8.

The introduction of humidity sensitive air trickle vents and exhaust grilles, consequently limiting air flows, leads to an increase in CO_2 exposure. In the entire building, the average exposure to CO_2 is 15.5% higher. For the units M3 located on the 2nd and 8th floors, the increases are 15.71% and 5.39%, respectively. In the unit M3 located on 8th floor, the average CO_2 concentration would be 1623 ppm, which would be considered unacceptable for approx—30% of people entering the unit.

The use of humidity-sensitive hybrid ventilation would mean that the average exposure values for the M3 apartment on both floors and the entire building would be similar. The M3 apartment on the 8th floor would still have a slightly higher concentration of CO_2 than its counterpart on the 2nd floor, but the difference would be the smallest among the options considered.

Table 2. Exposure to CO_2 energy consequences of three ventilation systems applied in NAPE reference building.

	Exposure		Unit M3 2nd floor	Unit M3 8thfloor	All units in the building
	Average	ppm	974	1540	1146
Option 1	Min (16.7%)	ppm	450	450	450
	Max (83.3%)	ppm	1351	2305	2803
	Average	ppm	1127	1623	1289
Option 2	Min (16.7%)	ppm	450	450	450
	Max (83.3%)	ppm	1638	2480	3029
	Average	ppm	1050	1194	1053
Option 3	Min (16.7%)	ppm	450	450	450
	Max (83.3%)	ppm	1517	1744	2116

3.3 Energy consumption related to ventilation

In simple ventilation systems used in residential buildings, energy is used to heat the cold air supplied to the rooms and to induce forced using fans. In the analyzed humidity-sensitive demand-controlled ventilation systems, it is impossible to recover heat from the exhaust air to heat the supplied air, which means that energy consumption is quite significant.

When analyzing primary energy, the source of energy used is also essential. The NAPE reference building is supplied with heat from the municipal heating network (heat is produced in cogeneration) and is connected to the national power grid. In Poland, the primary energy factor for district heat produced by cogeneration from hard coal or natural gas is 0.8, while electricity supplied by the national electricity network is multiplied by factor 3.0. Table 3 presents the differences in energy demand in the analyzed optional ventilation system.

Table 3. Energy consequences of optional ventilation systems applied in NAPE reference building.

Energy			Unit M3 2nd floor	Unit M3 8th floor	All units in the building
Option 1	Ventilation heat loss	kWh/year	3361	1529	50992
		kWh/(m²year)	37.98	17.28	31.21
	Electricity consumption	kWh/year	0	0	0
		kWh/(m²year)	0	0	0
	Sum of above converted to primary energy	kWh/year	2689	1224	40793
		kWh/(m²year)	30.39	13.83	24.97
Option 2	Ventilation heat loss	kWh/year	1878	1144	27231
		kWh/(m²year)	21.23	12.92	16.67
	Electricity consumption	kWh/year	0	0	0
		kWh/(m²year)	0	0	0
	Sum of above converted to primary energy	kWh/year	1503	915	21785
		kWh/(m²year)	16.98	10.34	13.33
Option 3	Ventilation heat loss	kWh/year	2357	2117	40404
		kWh/(m²year)	26.63	23.92	24.73
	Electricity consumption	kWh/year	122	158	2245
		kWh/(m²year)	1.38	1.78	1.37
	Sum of above converted to primary energy	kWh/year	2252	2166	39057
		kWh/(m²year)	25.45	24.48	23.90

The introduction of humidity-sensitive air inlets and air exhaust grilles leads to a reduction in the difference in ventilation operation on individual floors, while ventilation intensity is far from the minimum requirements. However, a periodic increase in ventilation intensity caused by high moisture emission can be observed. Desirable limitations of airflow in winter are observed on the lowest floors. The airflow increases slightly during transitional periods. Consequently, the energy needed to heat the ventilation air is reduced by as much as 47%. The exposure of residents to the concentration of CO_2, treated as an air quality indicator is higher than in option 1, which means that reducing energy consumption is accompanied by deterioration of air quality in the building.

Replacing the natural ventilation system with hybrid ventilation by introducing roof fans supporting the airflow in low thermal buoyancy values reduces the ventilation operation differences on individual floors. The average value of the air stream is higher than in option 2 but still lower than required. The consequence of the use of hybrid ventilation is the improvement of indoor air quality. Average CO_2 concentrations for all inhabitants of the entire building are approximately

600-650 ppm above the concentration in the outside air. However, this is related to the additional consumption of electricity to drive the fans. For the entire building, the consumption is 2245 kWh/year (1.37 kWh/(m^2year)). If electricity from the national energy grid is used, this corresponds to a 6735 kWh/year of primary energy (4.11 kWh/(m^2year)).

4. Conclusions

The performance of gravity ventilation in multi-unit medium-high buildings in a continental climate Dfb is highly unsatisfactory. In winter, the apartments on the lowest floor are excessively ventilated, which leads to high demand for energy necessary to heat the ventilation air. At the same time, the apartments on the top floors are not adequately ventilated. The ventilation airflows are small, and often the opposite of the airflow direction in the ventilation ducts is observed. As a result of differences in the intensity of ventilation of individual units, the exposure of residents to the concentration of CO2, treated as an indicator of air quality, varies significantly. Obtained results indicate that the application of humidity sensitive demand-controlled ventilation systems can significantly reduce the amount of energy in residential buildings. However, the recommendations should look not only at energy but also at indoor air quality. Figure 10 summarizes the results presenting the comparison of exposure to CO_2 concentrations vs. normalized primary energy. Significant differences in energy use and indoor air quality between units for options 1 and 2 can be easily observed. Only humidity-sensitive hybrid ventilation creates almost uniform conditions in the whole buildings.
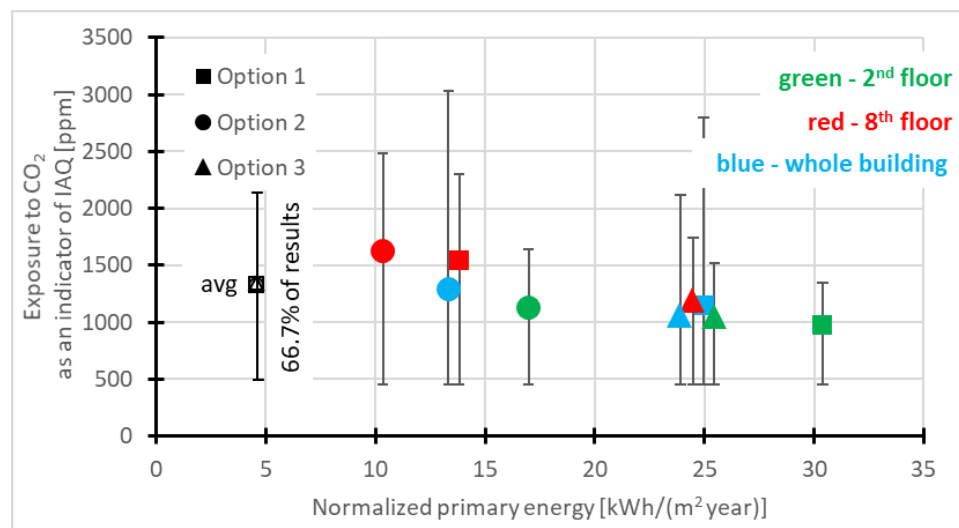

Figure 11. Comparison of exposure to CO_2 concentrations vs. normalized primary energy in units M3 on the 2nd and the 8th floors, and the whole building.

The study confirmed that the application of demand-controlled ventilation in multi-family residential buildings in a continental climate with warm summer Dfb leads to significant energy savings. However, the efforts to ensure adequate air quality require hybrid ventilation, which reduces the energy benefits. In the case of on-site renewable energy generation, this value might not be included in the building's energy balance. In such a case, the use of primary energy for ventilation could be reduced to 19.78 kWh/(m^2year).

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References

1. Andargie, M. S.; Touchie, M.; O'Brien, W. A review of factors affecting occupant comfort in multi-unit residential buildings. *Build. Environ.* **2019**, *160*, 106182. [Google Scholar][CrossRef]

2. Guyot, G.; Sherman, M. H.; Walker, I. S. Smart ventilation energy and indoor air quality performance in residential buildings: A review. *Energ. Buildings* **2018,** *165*, 416-430. [Google Scholar][CrossRef]

3. Biler, A.;, Unlu Tavil, A.; Su, Y.; Khan, N. A review of performance specifications and studies of trickle vents. *Buildings*, **2018,** *8(11)*, 152. [Google Scholar][CrossRef]

4. Mijakowski, M.; Sowa, J. An attempt to improve indoor environment by installing humidity-sensitive air inlets in a naturally ventilated kindergarten building. *Build. Environ.* **2017**, *111*, 180-191. [Google Scholar][CrossRef]

5. Fisk, W. J.; De Almeida, A. T. Sensor-based demand-controlled ventilation: a review. *Energ. Buildings*, **1998**, *29(1)*, 35-45. [Google Scholar][CrossRef]

6. Ouf, M. M.; O'Brien, W.; Gunay, B. On quantifying building performance adaptability to variable occupancy. *Build. Environ.*, **2019**, *155*, 257-267. [Google Scholar][CrossRef]

7. WHO (2009), WHO guidelines for indoor air quality: dampness and mould. Heseltine, E., & Rosen, J. (Eds.). WHO Regional Office Europe, Copenhagen, Denmark [link]

8. Woloszyn, M.; Kalamees, T.; Abadie, M. O.; Steeman, M.; Kalagasidis, A. S. The effect of combining a relative-humidity-sensitive ventilation system with the moisture-buffering capacity of materials on indoor climate and energy efficiency of buildings. *Build. Environ.* **2009**, *44(3)*, 515-524. [Google Scholar][CrossRef]

9. Guyot, G.; Sherman, M. H.; Walker, I. S. Smart ventilation energy and indoor air quality performance in residential buildings: A review. *Energ. Buildings*, **2018**, *165*, 416-430. [Google Scholar][CrossRef]

10. Savin, J. L., Berthin, S., & Jardinier, M. (2014). Demand-controlled ventilation. 20 years of in-situ monitoring in the residential field. The proceedings of the 35th AIVC Conference "Ventilation and airtightness in transforming the building stock to high performance", Poznań, Poland, 24-25 September 2014. [Google Scholar]

11. Guyot, G. Lessons learned from a ten-year monitoring in residential buildings equipped with humidity based demand controlled ventilation in France. The Proceedings of the 40th AIVC - 8th TightVent - 6th venticool Conference: "From energy crisis to sustainable indoor climate - 40 years of AIVC" Ghent, Belgium 15-16 October 2019. [Google Scholar]

12. Berthin, S.; Savin, J. L.; Jardinier, M. Measurements on humidity controlled ventilation systems in 55 occupied apartments. IEA ANNEX 41 meeting, Florianópolis, Brazil, April 2-4, 2007. [Google Scholar]

13. Guyot, G.; Melois, A.; Bernard, A. M.; Coeudevez, C. S.; Déoux, S.; Berlin, S.; Parent E.; Huet, A.; Berthault, S.; Jobert, R.; Labaume, D. Ventilation performance and indoor air pollutants diagnosis in 21 French low energy homes. *Int J Vent*, **2018**, *17(3)*, 187-195. [Google Scholar][CrossRef]

14. Kwiatkowski, J.; Woloszyn, M.; Roux, J. J. Modelling of hysteresis influence on mass transfer in building materials. *Build. Environ.*, **2009**, *44(3)*, 633-642. [Google Scholar][CrossRef]

15. Mijakowski M.; Kwiatkowski J. (2010), Moisture flow between indoor air and porous materials – simplified two parameters method and detailed TRNSYS simulation, Proceedings of the 1st Central European Symposium on Building Physics, 13-15 September 2010, Cracow - Lodz, Poland, Gawin, D.; Kisilewicz, T. Eds. pp. 395-400,

16. Sowa, J. Man as a stochastic factor in indoor air quality predictions. *Indoor Environ.*, **1994**, *3(3)*, 119-122. [Google Scholar]

17. Sowa, J. Comparison of methods of including stochastic factors into deterministic models of indoor air quality. *Energ. Buildings*, **1998**, *27(3)*, 301-308. [Google Scholar][CrossRef]

18. Van Den Bossche, N.; Janssens, A.; Heymans, N.; Wouters, P. Performance evaluation of humidity controlled ventilation systems in residential buildings using Monte Carlo Analysis. IAE/ECBCS-Annex 41 MOIST-ENG. 2007 Paper A41-T4-B-07-3. [Google Scholar]

19. Laverge, J.; Van Den Bossche, N.; Heijmans, N.; Janssens, A. Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies. *Build. Environ.*, **2011**, *46(7)*, 1497-1503. [Google Scholar][CrossRef]

20. Heiselberg, P. Natural ventilation design. International journal of ventilation, *Int J Vent*, **2004**, *2(4)*, 295-312. [Google Scholar][CrossRef]

21. Op't Veld, P. Introduction to EC RESHYVENT–EU cluster project on demand controlled hybrid ventilation for residential buildings. *Build. Environ.* **2008**, *43(8)*, 1342-1349. [Google Scholar][CrossRef]

22. Antvorskov, S. Introduction to integration of renewable energy in demand controlled hybrid ventilation systems for residential buildings. *Build. Environ.* **2008**, *43(8)*, 1350-1353. [Google Scholar][CrossRef]

23. Yang, D.; Li, P. Dimensionless design approach, applicability and energy performance of stack-based hybrid ventilation for multi-story buildings. *Energy*, **2015**, *93*, 128-140. [Google Scholar][CrossRef]

24. Jeong, Y.; Haghighat, F. Modelling of a Hybrid-Ventilated Building–Using ESP-r. *Int J Vent*, **2002** *1(2)*, 127-139. [Google Scholar][CrossRef]

25. Zhai, Z. J.; Johnson, M. H.; Krarti, M. Assessment of natural and hybrid ventilation models in whole-building energy simulations. *Energ. Buildings*, **2011**, *43(9)*, 2251-2261. [Google Scholar][CrossRef]

26. Hesaraki, A.; Holmberg, S. Demand-controlled ventilation in new residential buildings: consequences on indoor air quality and energy savings. *Indoor Built Environ*, **2015**, *24(2)*, 162-173. [Google Scholar][CrossRef]

27. Woloszyn, M., Shen, J., Mordelet, A., & Brau, J. (2005). Numerical simulations of energy performance of a ventilation system controlled by relative humidity. The 26th AIVC Conference, Ventilation in relation to the energy performance of buildings, was held in Brussels, Belgium, 21- 23 September 2005 (pp. 295-300). [Google Scholar]

28. Savin, J. L., & Laverge, J. Demand-controlled Ventilation: an outline of assessment methods and simulations tools. The Proceedings of the 32nd AIVC Conference " Towards Optimal Airtightness Performance", Brussels, Belgium, 12-13 October 2011. [Google Scholar]

29. Walton, G.; Dols, W. S. CONTAM 2.4 user guide and program documentation (No. NIST Interagency/Internal Report (NISTIR)-7251), US Department of Commerce, National Institute of Standards and Technology, USA, 2005 [link]

30. Dols, W. S.; Polidoro, B. J. CONTAM User Guide and Program Documentation Version 3.4. NIST Technical Note 1887, Revision 1 US Department of Commerce, National Institute of Standards and Technology, USA, 2020 [link]

31. Delsante A.; Aggerholm S. The use of simulation tools to evaluate hybrid ventilation control strategies. Annex 35 Hybvent technical report: International Energy Agency, Energy Conservation in Buildings and Community Systems, 2002

32. Emmerich, S. J. Validation of multi-zone IAQ modeling of residential-scale buildings: a review. *ASHRAE Tran.* **2001**, *107(2)*, 619-628. [Google Scholar]

33. Emmerich, S. J.; Nabinger, S. J.; Gupte, A.; Howard-Reed, C. Validation of CONTAMW predictions for tracer gas in a townhouse. Building Simulation 2003, Eighth International IBPSA Conference Eindhoven, Netherlands August 11-14, 2003 (p. 299-306). [Google Scholar]

34. Persily, A.; Musser A.; Emmerich, S.; Taylor, M. Simulations of indoor air quality and ventilation impacts of demand controlled ventilation in commercial and institutional buildings. NISTIR 7042, US Department of Commerce, National Institute of Standards and Technology. USA, 2003 [link]

35. Emmerich, S. J., Persily, A., & Nabinger, S. (2002). Modeling moisture in residential buildings with a multi-zone IAQ program. Proceedings, 9th International Conference on Indoor Air Quality and Climate, Monterey, California, June 30-July 5, 2002, Levin H. Ed. [Google Scholar]

36. Lorenzetti, D. M.; Dols, W. S.; Persily, A. K.; Sohn, M. D. A stiff, variable time step transport solver for CONTAM. *Build. Environ.* **2013**, *67*, 260-264. [Google Scholar][CrossRef]

37. Dols, W. S.; Emmerich, S. J.; Polidoro, B. J. Coupling the multi-zone airflow and contaminant transport software CONTAM with EnergyPlus using co-simulation. *Build. Simul.* **2016**, Vol. 9, No. 4, pp. 469-479). Tsinghua University Press. [Google Scholar][CrossRef]

38. Dols, W. S.; Emmerich, S. J.; Polidoro, B. J. Using coupled energy, airflow and indoor air quality software (TRNSYS/CONTAM) to evaluate building ventilation strategies. *Build Serv Eng Res T*, **2016**, 37(2), 163-175. [Google Scholar][CrossRef]

39. Sowa, J., & Mijakowski, M. Whole year simulation of humidity based demand controlled hybrid ventilation in multiapartment building. The Proceedings of the 32nd AIVC Conference "Towards Optimal Airtightness Performance", Brussels, Belgium, 12-13 October 2011 (pp. 12-13). [Google Scholar]

40. Mijakowski, M.; Narowski, P.; Sowa, J. Integrated calculations of thermal behaviour of buildings and processes in AHU - the tool for assessment of energy performance of complex buildings. Building Simulation 2009, Eleventh International IBPSA Conference, Glasgow, Scotland July 27-30, 2009, p. 875-882. [Google Scholar]

41. ISO-FDIS 13790:2008 Energy performance of buildings - Calculation of energy use for space heating and cooling. [link]

42. Narowski, P., Mijakowski, M., Panek, A., Rucińska, J., & Sowa, J. Proposal of simplified calculation 6R1C method of buildings energy performance adopted to Polish conditions. The Proceedings of the Conference Central Europe Towards Sustainable Building 2010 - CESB10 Prague, Czech Republic, 30th June - 2nd July 2010 Hájek, P.; Tywoniak, J.; Lupíšek, A.; Růžička, J.; Sojková, K. Eds. [Google Scholar]

43. Emmerich, S. J. Simulated performance of natural and hybrid ventilation systems in an office building. *HVAC&R Res*, **2006**, *12(4)*, 975-1004. [Google Scholar][CrossRef]

44. Pinto, M.; Viegas, J.; Freitas, V. Performance sensitivity study of mixed ventilation systems in multifamily residential buildings in Portugal. *Energ. Buildings*, **2017**, *152*, 534-546. [Google Scholar][CrossRef]

45. Sowa J.; Panek A.D.; Mijakowski M. A method to analyse the performance of residential ventilation systems, *REHVA J.* **2013**, *50 (4)*, 23-26. [Google Scholar]

46. Regulation of the Minister of Infrastructure of 12 April 2002 on the technical conditions that should be met by buildings and their location paragraph, Journal of Laws of the Republic of Poland, with recast on 18 September 2015, (Rozporządzenie Ministra Infrastruktury z dnia 12 kwietnia 2002 r. w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie, Dziennik Ustaw Rzeczypospolitej Polskiej,zmienione dnia 18 września 2015 r.). [link]

47. PKN, PN-83/B-03430/Az:3 2000, Ventilation in Dwellings and Public Utility Buildings, 2000. Specifications (in Polish). [link]

48. Narowski, P., Janicki, M., & Heim, D. Comparison of Untypical Meteorological Years (UMY) and their influence on building energy performance simulations. In Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28. 2013, Wurt, E. Ed. International Building Performance Simulation Association (pp. 1414-1421). [Google Scholar]

49. EN ISO 15927-4:2005 – Hygrothermal performance of buildings -- Calculation and presentation of climatic data -- Part 4: Hourly data for assessing the annual energy use for heating and cooling. [link]

50. Persily, A.; de Jonge, L. Carbon dioxide generation rates for building occupants. *Indoor Air*, **2017,** *27(5)*, 868-879. [Google Scholar][CrossRef]