energies

MDPI

Article

Ventilation Methods for Improving the Indoor Air Quality and Energy Efficiency of Multi-Family Buildings in Central Europe

Joanna Ferdyn-Grygierek [1,*] and Krzysztof Grygierek [2]

[1] Department of Heating, Ventilation and Dust Removal Technology, Faculty of Energy and Environmental Engineering, Silesian University of Technology, Konarskiego 20, 44-100 Gliwice, Poland
[2] Department of Mechanics and Bridges, Faculty of Civil Engineering, Silesian University of Technology, Akademicka 5, 44-100 Gliwice, Poland; krzysztof.grygierek@polsl.pl
* Correspondence: joanna.ferdyn-grygierek@polsl.pl; Tel.: +48-322372912

Abstract: In Poland and other countries in Central Europe, residential buildings from the second half of the 20th century dominate, which have recently undergone deep thermomodernisation. Research on the retrofitting of residential buildings has focused mainly on energy efficiency, with only a few studies on indoor air quality. The aim of this study was to present a comparative analysis of the impact of five ventilation scenarios (three natural and two mechanical) on CO_2 concentration and energy demand for heating and ventilation in residential spaces of a multi-family building located in Poland. The analyses were based on the results of building performance co-simulation using the EnergyPlus and CONTAM programs carried out under dynamic conditions with a 5 min time step for the entire heating season. The calculations took into account the instantaneous occupancy variability of twenty apartments. In the buildings equipped with new tight windows, the natural ventilation system provided extremely low air exchange (on average 0.1 h^{-1}) and poor indoor air quality (average CO_2 concentration at the level of 2500 ppm). Opening windows to ventilate the rooms generated a multiple increase (up to 8 times) in heating demand during these periods, but average CO_2 concentration was on the level of 930 ppm. The use of mechanical ventilation was profitable both in terms of energy savings (at the level of 50%) and improvement in the indoor air.

Keywords: CO_2 concentration; ventilation; heat demand; multi-family building; energy simulation; indoor air quality

Citation: Ferdyn-Grygierek, J.; Grygierek, K. Ventilation Methods for Improving the Indoor Air Quality and Energy Efficiency of Multi-Family Buildings in Central Europe. *Energies* **2024**, *17*, 2232. https://doi.org/10.3390/en17092232

Academic Editor: Antonio Gagliano

Received: 12 April 2024
Revised: 29 April 2024
Accepted: 3 May 2024
Published: 6 May 2024

1. Introduction

People spend 80–90% of their lives indoors, including two thirds of this time in their homes or apartments [1,2]. Pollutant concentrations in rooms can be two to five times higher than in the outdoor air [3], resulting in unsatisfactory indoor air quality (IAQ). Indoor air quality is one of the most important factors affecting the health of people [4–7], and is associated with sick building syndrome [8].

Ventilation plays an important role in ensuring adequate air quality in buildings. There are various methods of ventilation in buildings, both natural, mechanical, and hybrid. Previous studies comparing the air quality in mechanically and naturally ventilated dwellings located in different climates showed lower concentrations of pollutants such as formaldehyde, volatile organic compounds, carbon dioxide (CO_2), fungi, mold spores, and radon in mechanically ventilated houses [9–11]. In the study [12] based on long-term indoor air monitoring in Tianjin in China, the authors observed even 22.3% higher CO_2 concentrations in apartments with natural ventilation. Kotol [13] assessed indoor air (on the basis of CO_2 and humidity measurements and interviews with residents) in buildings located in the Greenlandic climate that the air quality was significantly improved thanks to the use of sustainable mechanical ventilation with heat recovery. McGill et al. [14] evaluated the CO_2 concentration in the rooms of eight apartments in the United Kingdom, comparing the use of mechanical and natural ventilation systems. Their conclusions included problems with indoor air quality in both natural and mechanical ventilation cases. In turn, Park and Kim [15] assessed residents' ventilation practices and corresponding heating energy consumption in 1390 mechanically ventilated apartments in Seoul. These authors argued that the operation of the mechanical ventilation system significantly affects the perceived acceptability of indoor air.

Sufficient building ventilation can improve occupants' health by 20% or more [16]. However, ventilation increases energy consumption in the building by increasing the cooling or heating demand and the electricity consumption of fans [17]. Although buildings account for approximately 40% of total energy consumption, ventilation systems account for approximately 50% or more of this consumption [18]. Therefore, proper ventilation in the building should aim both at indoor air quality and energy efficiency. The way people ventilate their homes plays a significant role in building energy consumption because the ventilation system replaces heated or cooled indoor air with outdoor air. In Poland and many European countries, the vast majority of residential buildings have natural gravity (stuck) ventilation, and reducing the level of pollution is usually achieved by opening windows. The window is most often tilted inward by 5 to 10 degrees from the base of the frame, which can cause air exchange up to 40 h^{-1} depending on the speed and direction of the wind and the size of the window sash [19]. In the case of natural ventilation, all fresh air must be heated in the room (it is not possible to recover heat from exhausted air), which generates a significant instantaneous heating demand in the winter months, while ineffective and uncontrolled window ventilation does not guarantee good air quality in rooms [20]. The fact that the behaviour of residents in terms of different window opening patterns is crucial to achieve a high IAQ was also confirmed by Pereira et al. [21] for the case of residential buildings located in regions with a mild climate, such as the Mediterranean regions. The results of the research conducted by Galvin [19] suggest the need for more research to quantify energy losses due to poor ventilation management.

There are indications that energy-retrofitted buildings may pose a risk to the indoor air quality and, therefore, to the health and comfort of residents [2]. In Europe, residential building renovations focus mainly on thermal insulation and increasing the airtightness (replacing existing windows) of the building envelope, with limited emphasis on building ventilation. However, achieving energy efficiency does not automatically result in better IAQ. Improved thermal insulation and increased tightness of the building envelope usually worsen IAQ due to reduced ventilation and usually do not lead to expected energy consumption [2]. This is confirmed by research; for example, Coggins et al. [1] evaluated air quality and occupant satisfaction in Irish residences that had been thoroughly modernised. Only 30% of the bedroom met the requirements, and the measured airflow, in most cases, did not meet the minimum performance requirements set out in Irish regulations. Also in Ireland, in the winter periods of 2015 and 2016, the concentrations of air pollutants were monitored in the rooms of fifteen three-storey semi-detached cooperative social apartments before and after thermomodernisation [22]. The increase in pollutant concentrations correlated with lower air change rates in the building after modernisation. Calama-González et al. [23] presented a comparative analysis of the impact of different ventilation scenarios (natural or mechanical ventilation only and natural plus mechanical ventilation) in social housing spaces in Spain before and after modernisation on thermal comfort and indoor air quality. The obtained results showed small differences between ventilation system in terms of human thermal comfort in rooms with low thermal inertia, but indicated energy and economic efficiency of the passive ventilation system. In turn, Măgurean and Petran [24] analysed the indoor environment in sixteen apartments located in Romania in five recently renovated multi-family buildings. Even if the thermal comfort conditions in the rooms increased after modernisation, it was found that almost half of the time the bedrooms had poor indoor air quality due to inadequate ventilation. Thus, it was found that building ventilation is a key issue in the renovation process and is currently not properly addressed in mass renovations of existing multi-family residential buildings. Several other studies also confirmed the negative impact of energy modernisation on IAQ [25–27].

As indicated, insufficient ventilation worsens air quality, which can reduce the comfort of building residents. On the other hand, excessive ventilation may waste energy [28]. Therefore, it is important to use effective control of ventilation systems to supply the appropriate amount of fresh air to each zone to maintain the required air quality while reducing the energy consumption of the ventilation system. Demand-controlled ventilation (DCV) systems can help meet these requirements [29]. DCV systems dynamically adjust ventilation airflow based on occupancy patterns [30], indoor sensors [31], or indoor pollutant concentrations [32,33], which can generate significant energy savings (up to 40%) compared to conventional ventilation systems that provide a constant amount of air [17,34,35]. The most common DCV strategy involves the use of CO_2 concentrations. Lu et al. [36] reviewed several CO_2-based DCV methods and explained the role of CO_2 in ventilation control. The results showed that CO_2-based DCV methods are effective in controlling air quality. Due to the ease and reliability of CO_2 measurements, carbon dioxide is widely used as an air quality indicator [37]; is a suitable indicator of the acceptability of human body odour and environmental comfort. Although CO_2 concentration does not reflect the concentration of other air pollutants, it can help assess air quality in spaces devoid of other major sources of pollution [38].

Improving the energy efficiency of residential buildings has obvious direct benefits in terms of improving occupant comfort [22]. However, few studies have assessed the impact of increased airtightness of the building on the level of ventilation airflow and pollutant concentration. Unlike building energy, the indoor air quality assessment is often voluntary because it is not required by national building regulations and is therefore one of the biggest challenges facing the building sector, especially in the era of widespread thermomodernisation of existing residential buildings. Minimising energy consumption without compromising indoor air quality and thermal comfort would bring health and financial benefits. Therefore, taking into account the significant share of multi-family houses in the total existing building stock in the European Union, the aim of this study was to present a comparative analysis of the impact of different ventilation scenarios (both natural and mechanical) on CO_2 concentration and heating demand in the flats of a multi-family building located in a moderate climate in Poland (Central Europe). The analyses were based on the results of building performance co-simulation using the EnergyPlus and CONTAM programs carried out in dynamic external and internal conditions with a small time step for the entire heating season. Each of the 20 flats with varying degrees of use and the building as a whole were assessed. Many previous studies in this area were based mainly on static calculations [39,40], which did not take into account the instantaneous variability of the ventilation airflow in rooms on different floors of the building and the diversified schedule of occupancy, which did not allow for a reliable assessment of the instantaneous level of indoor air quality. Even if the calculations were carried out in dynamic external climate conditions, most studies assumed a constant infiltration air exchange during the year.

2. Methods

2.1. Building Description

A detached multi-family building after thermomodernisation of the external envelope with a total heated area of 1482 m^2 and a cubature of 4151 m^3 was selected for research. The building has a basement and consists of five floors, each with four flats with an area of 54 to 82 m^2 (including two with a bathroom and two with a bathroom and an additional toilet) (Figure 1). The building is constructed using prefabricated reinforced concrete technology. Such shapes and structures were very popular for Polish buildings built in the 1970s and 1980s. Similar buildings are often found throughout Central Europe. The external walls have a three-layer structure, are 30 cm thick, and are additionally insulated with 10 cm of polystyrene (heat transfer coefficient is 0.19 $W/(m^2 \cdot K)$). The roof is also insulated with 20 cm mineral wool and covered with roofing felt (heat transfer coefficient is 0.15 $W/(m^2 \cdot K)$).

Windows with the Pilkington Insulight™ Therm Triple glazing unit (Nippon Sheet Glass Co., Ltd., Tokyo, Japan) [41] and a solar radiation transmittance coefficient of 47% and a heat transfer coefficient of 0.6 W/(m^2·K) do not have any covers. The building has central heating system with water radiators natural gravity ventilation (two or three chimneys in each flat). The basement is not heated.

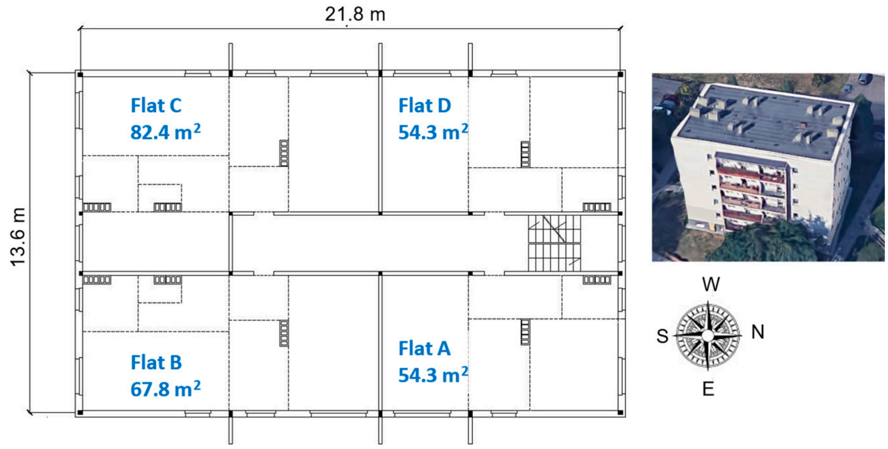


Figure 1. Plan of the floors; flat C on the ground floor is smaller due to the entrance to the building.

2.2. Cases under Consideration

The indoor air quality, ventilation airflow, and thermal efficiency of both individual flats and the entire building were evaluated. Five cases of ventilation systems were analysed (Figure 2). All calculations were performed with a time step of 5 min for the heating period from October to April.

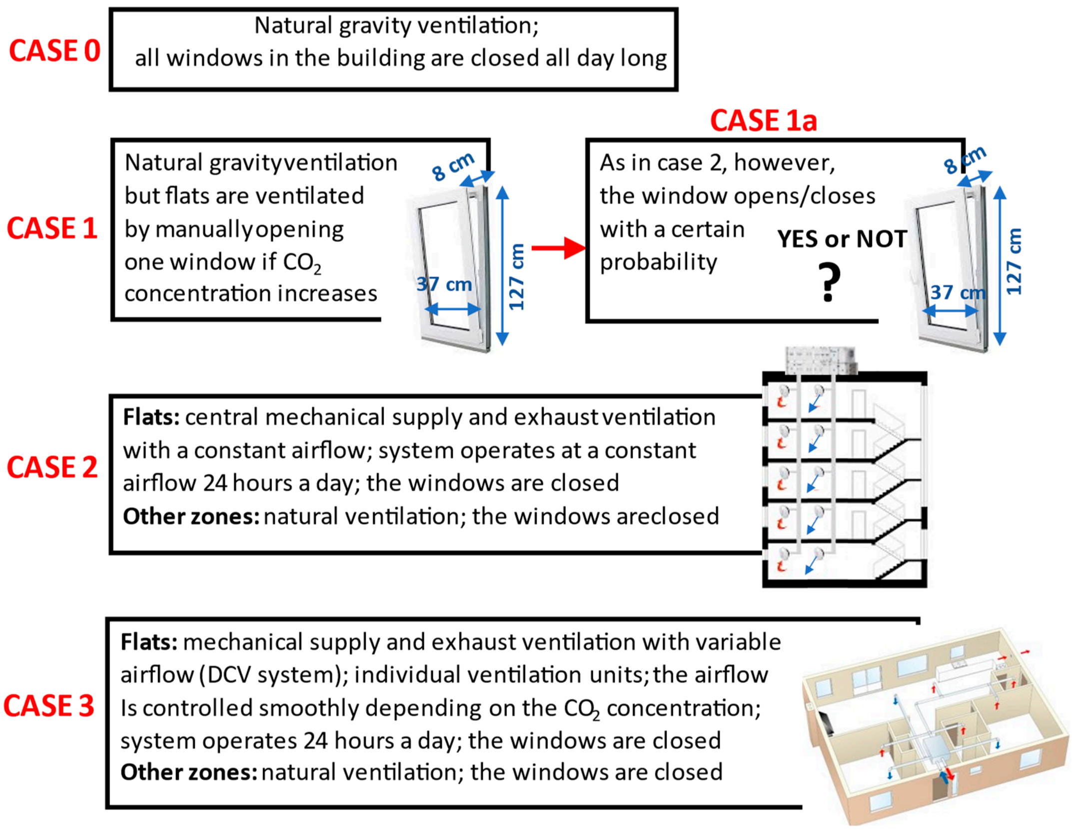


Figure 2. Cases under consideration.

2.3. IAQ and Energy Indicators

In this study, the CO_2 concentration, external airflow, and heating energy consumption were assessed. There are various recommendations and standards that suggest the required levels of CO_2 and ventilation airflow in residential rooms [42,43]. The EN 16798-1:2019 [42] standard suggests default limit values for CO_2 concentration in IAQ categories that correspond to the required airflow per person:

- I category: CO_2 concentration of 550 ppm above the outdoor level (fresh air of 10 dm^3/s per person);
- II category: CO_2 concentration of 800 ppm above the outdoor level (fresh air of 7 dm^3/s per person);
- III and IV categories: CO_2 concentration of 1350 ppm above the outdoor level (fresh air of 4 dm^3/s per person).

A CO_2 concentration of 700 ppm above the outdoor level has been considered an acceptable indoor CO_2 level in the ASHRAE standard [43]. In the scientific literature, a common limit of CO_2 concentration for indoor spaces is also 1000 ppm [44]. It should be noted that the CO_2 concentration levels typically recorded in residential buildings are not harmful to human health and are only used as an indicator of air quality. Carbon dioxide becomes a dangerous pollutant if the concentration exceeds 5000 ppm after exposure for eight hours [45].

In this study, the limits of carbon dioxide concentration in the flats according to the EN 16798-1:2019 standard [42] were used as an air quality indicator. The entire 24 h period on each day was taken into account. The minimum ventilation airflow per person, which was 20 m^3/h, was adopted according to Polish building regulations [46]. In turn, the seasonal heating demand for flats and the entire building (usable energy or its index per m^2) was adopted as an indicator of thermal efficiency. When calculating the indicator for the entire building, the area of the entire building was taken into account; when calculating the indicator for flats, the area of the flat was taken into account.

2.4. Simulation Model

Thermal simulations of the building under dynamic conditions using the EnergyPlus 9.4 (US Department of Energy, Washington, DC, USA) [47] and CONTAM 3.4 (National Institute of Standards and Technology, Gaithersburg, MD, USA) [48] programs were carried out. CONTAM and EnergyPlus were coupled, which allowed for data exchange during calculations (co-simulation) in accordance with the scheme shown in Figure 3.

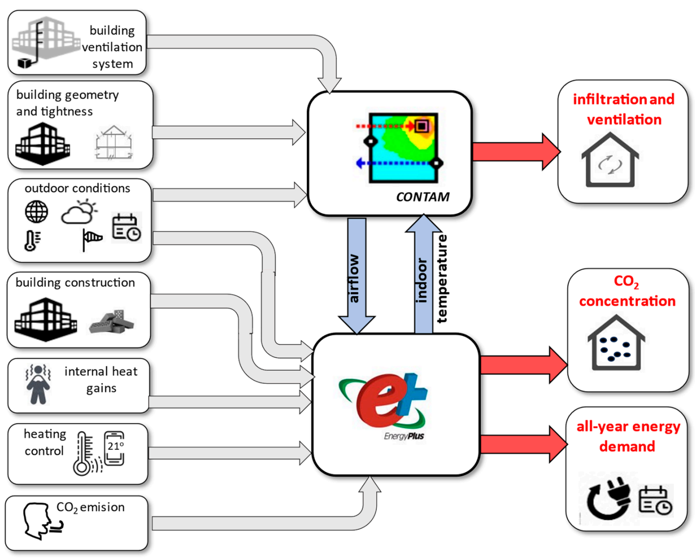


Figure 3. Scheme of energy and airflow simulation.

The building was divided into 31 thermal zones, and the geometry of the rooms was adapted to the dimensions in the axes of the building partitions. It was assumed that each apartment was a separate zone and that there was no uneven temperature distribution inside it. The division of flats into individual rooms was omitted; taking into account the small size of the rooms, it was assumed that they were used as "open spaces". Internal walls in flats were included as additional internal storage mass and added to individual zones.

2.4.1. Infiltration and Ventilation

One-way flow using the powerlaw model was used to calculate infiltration through window and door cracks (Equation (1)):

$$\dot{V} = a \times l \times (\Delta p)^n \quad (1)$$

where: $\dot{V}$—volumetric airflow [m^3/h], a—airtightness factor [$m^3/(m \cdot h \cdot Pa^n)$], l—length of the window cracks [m], n—exponent, and Δp—pressure difference [Pa].

Based on previous studies [49,50], the following values of a and n were adopted:

- for windows, $a = 0.1$ $m^3/(m \cdot h \cdot Pa^{0.67})$ and $n = 0.67$;
- for external entrance doors, $a = 0.1$ $m^3/(m \cdot h \cdot Pa^{0.5})$ and $n = 0.5$;
- for internal doors to flats, $a = 1.0$ $m^3/(m \cdot h \cdot Pa^{0.5})$ and $n = 0.5$.

It was assumed that the doors to the flats were closed all the time. The Darcy–Colebrook model was used to calculate flow resistance through gravity chimneys (made of brick, dimensions of 14 × 14 cm, roughness of 3 mm). For the calculation dynamic losses in ducts, the terminal loss coefficients amounted to 4.0 (grill, elbow, and outlet) [51]. The chimneys extended above the roof to a height of 1.5 m.

Two-way flow model: a single opening was used to calculate the ventilation through an open (ajar) window. The open area is presented in Figure 2. In case 1, if the carbon dioxide concentration exceeded a value of L^{upper}, one window was opened after 15 min. The window remained open until the CO_2 concentration dropped to a value of L^{lower} (it closed 15 min after reaching this level). Taking into account the CO_2 concentration levels calculated with closed windows, the following was assumed:

- value of L^{upper}: 1200 ppm (upper limit of environmental category II);
- value of L^{lower}: 600 ppm (value close to the external background);
- windows could only be opened if at least one person was in the flat;
- between 11 p.m. and 6 a.m., the windows were always closed (the windows were manually operated, and therefore it was assumed that the windows were not opened after going to sleep).

The assumed probability of opening and closing the window for case 1a depending on the external temperature is presented in Table 1 (after leaving the flat during the day and at night between 11 p.m. and 6 a.m., the windows were always closed, as in case 1).

Table 1. Probability of opening/closing the window within 1 h.

External Temperature	<−5 °C	≥−5 °C and <5 °C	≥5 °C
Opening	0.4	0.6	0.8
Closing	0.8	0.6	0.4

The simple air-handling system model was used to calculate the mechanical ventilation (cases 2 and 3):

(1) Case 2: the air handling unit operated 24 h a day at a constant flow of 2700 m^3/h, including:
    - Flats A and D: 120 m^3/h per flat.

- Flats B and C: 150 m^3/h per flat.

(2) Case 3: the air handling units operated 24 h a day with a variable airflow using a DCV system. The efficiency of the fans was controlled proportionally to the carbon dioxide concentration: 400–500 ppm ⇒ 30 m^3/h, 1200 ppm ⇒ 220 m^3/h.

In both cases 2 and 3, supply and exhaust ventilation units with a heat exchanger with a temperature efficiency of 82% were used (based on current data from air handling unit manufacturers).

2.4.2. CO_2 Emission

Based on ASHRAE Standard 62.1-2022 [43], the value of 3.82×10^{-8} $m^3/(s \cdot W)$ was assumed, i.e., 0.0048 dm^3/s per person during the day and 0.0028 dm^3/s per person at night. The concentration of carbon dioxide in the outdoor air was set at 400 ppm.

2.4.3. Internal Heat Gains

Human heat gains were calculated based on ASHRAE Standard 55-2017 [52]:

- between 6:00 a.m. and 11:00 p.m.: total heat was 126 W per person (1.2 met), including sensible heat 70%;
- between 11 p.m. and 6 a.m.: total heat was 73 W per person (0.7 met), including sensible heat 70%;
- there were no heat gains in the staircase.

The number of residents was assumed depending on the size of the flat; however, on the third and fourth floors, the number of residents was reduced and increased by one person, respectively. Occupancy schedules are shown in Figure 4.

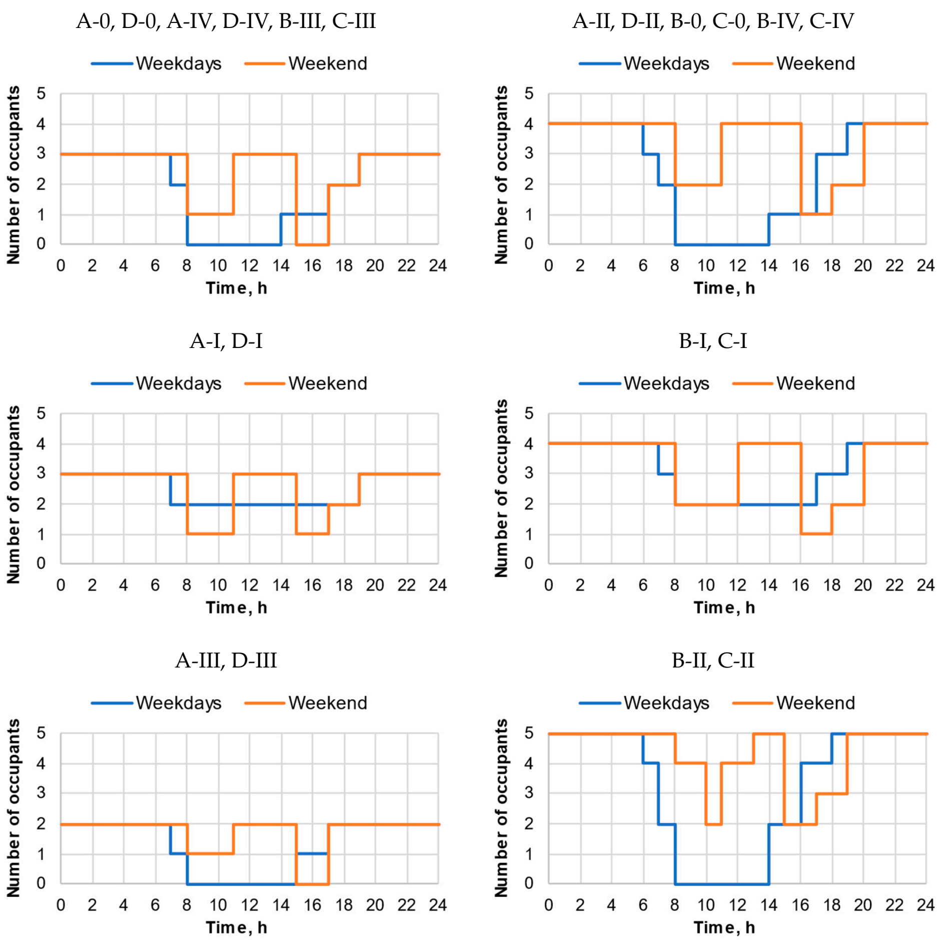


Figure 4. Schedules of people staying in flats; A, B, C, and D—type of flat; 0, I, II, III, and IV—floor.

Lighting in flats was turned on if the natural lighting intensity dropped below 300 lx, assuming a maximum heat gain of 5 W/m^2. The power of the light depended on the intensity of the natural lighting. The lighting could only be turned on at 6 a.m. to 11 p.m. and only if there were people in the flat.

Heat gains from equipment were based on Recknagel and Schramek [53]. It was assumed that each flat was equipped with a hob (cooking), a fridge, a computer, and a TV.

There were no heat gains in the staircase and basement.

2.4.4. Indoor Temperature

It was assumed that flats were 21 °C (whole day), staircases were 16 °C (whole day), and that basements had no heating. The assumption was made for category II thermal environments in accordance with the EN 16798-1:2019 standard [42], for which the operative temperature was 20 °C. The average difference between the air temperature and the operative temperature was assumed to be 1 K [54].

2.4.5. Weather Condition

A typical meteorological year for Warsaw in Poland was used to simulate external conditions [55] with a lowest temperature of –12.3 °C, a highest temperature of 24.5 °C and an average of 4.2 °C in the analysed period from September to April. This location has a moderate transitional climate (Dfb class according to the Köppen–Geiger classification [56]).

3. Results

3.1. Natural Ventilation

Buildings in this group are characterized by the uncontrolled ventilation of rooms and the inability to recover heat from the exhausted air, which affects the building's energy consumption. The airflow from outside is caused by the wind and stack effect and depends on the location of the rooms depending on the cardinal direction and the storey. Therefore, in such buildings, air exchange varies greatly both in the time and space of the building. The average air change rates N in flats during the heating season is given in Table 2.

Table 2. Seasonal average air change rate (N_{avg}), external airflow ($\dot{V}_{avg}$) entering flats, and CO_2 concentration (C_{avg} and C_{max}) in buildings with natural ventilation.

Storey	**Ground Foor**				**I Floor**				**II Floor**				**III Floor**				**IV Floor**			
Orientation	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W
Flat	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
										Case 0										
N_{avg} [h^{-1}]	0.14	0.15	0.15	0.14	0.12	0.13	0.14	0.13	0.11	0.12	0.12	0.11	0.09	0.10	0.10	0.09	0.07	0.08	0.08	0.07
$\dot{V}_{avg}$ [m^3/h]	21	28	29	22	19	25	31	20	16	22	28	17	13	18	23	14	10	15	19	11
C_{avg} C_{max} [ppm]	1768 3162	1718 3459	1652 3040	1709 3153	2429 3812	2330 4014	1970 3219	2349 3901	2871 5451	2872 5638	2411 4641	2786 5624	2094 3680	2180 4252	1829 3482	2068 4070	3767 7316	3658 8760	3012 6746	3860 9158
										Case 1										
N_{avg} [h^{-1}]	0.46	0.48	0.48	0.46	0.60	0.58	0.45	0.60	0.56	0.64	0.52	0.56	0.32	0.36	0.27	0.32	0.42	0.43	0.34	0.42
$\dot{V}_{avg}$, [m^3/h]	70	92	92	70	91	110	104	91	85	122	120	86	49	68	63	49	64	82	79	64
Open time * [%]	19%	19%	19%	19%	29%	26%	23%	28%	27%	31%	28%	27%	16%	17%	14%	15%	24%	25%	23%	24%
C_{avg} C_{max} [ppm]	859 1661	871 1724	869 1713	856 1596	957 1770	972 1796	967 1774	957 1773	961 2364	952 2169	923 1994	958 2218	852 1610	874 1693	886 1580	859 1608	963 2334	981 2363	964 2242	963 2279

Table 2. *Cont.*

Storey	Ground Foor				I Floor				II Floor				III Floor				IV Floor			
										Case 1a										
N_{avg} [h^{-1}]	0.39	0.45	0.47	0.40	0.66	0.66	0.56	0.67	0.52	0.60	0.50	0.54	0.31	0.33	0.27	0.30	0.39	0.45	0.35	0.40
$\dot{V}_{avg}$, [m^3/h]	59	85	89	60	101	126	129	102	79	114	115	82	48	63	63	46	60	85	81	60
Open time * [%]	15%	16%	17%	15%	32%	30%	28%	31%	25%	28%	26%	25%	15%	15%	13%	14%	22%	25%	24%	22%
C_{avg} C_{max} [ppm]	1038 2144	1027 2113	1006 2114	1030 1995	1036 2185	1043 2205	980 1989	1037 2305	1176 3291	1142 2921	1079 2515	1153 2828	1002 2201	1069 2450	1022 2022	1012 2127	1210 3184	1199 3145	1149 2811	1185 3191

* Percentage of window opening time in relation to the entire heating season.

Case 0 should be treated as a theoretical case (complete lack of window opening is unlikely to occur in buildings with natural ventilation). However, it is a reference for other cases and showed the effectiveness of using the proposed solutions. In the case of infiltration only (case 0), the ground floor zones were characterized by a higher average air exchange. In turn, the lowest airflow occurred in flats on the top floor, which was related to the length of the gravity chimney. The instantaneous value of the airflow on the top floor was up to even three times lower than the airflow on the ground floor.

The average air change rates in flats was extremely low; on the top floor it was below 0.1 h^{-1}. The instantaneous fresh airflow ranged from 0 to only 105 m^3/h during windy periods and at low external temperatures in flat C-I on the lowest floor (flat with the largest number of windows). In a small apartment A-IV on the top floor, the maximum calculated airflow did not exceed 50 m^3/h. On average during the season, the airflow does not exceed 20 m^3/h (i.e., approx. 5 m^3/h per person). According to the EN 16798-1:2019 standard [42], the airflow per person should not be less than 4 dm^3/s, i.e., 14.4 m^3/h; however, the building can then be classified into environmental category III. In the case of category I, the required airflow is 10 $dm^3/(s \cdot person)$, i.e., 36 $m^3/(h \cdot person)$. Such diversified air exchange was reflected in the CO_2 concentration in flats. The maximum and average CO_2 concentration calculated in all flats are presented in Table 2. Only in three of them on the ground floor the average CO_2 concentration was below the upper limit of indoor environment category III according to the EN 16798-1:2019 standard [42] (1350 ppm above the background). The calculated maximum CO_2 concentration values were very high, in flats on the top floor they even exceed 8000 ppm. It should also be noted that the CO_2 concentration did not fall to the background level even when people are not in the flat; flats remained empty for only a few hours, and with tight windows limiting the inflow of fresh air, the time to dilute pollutants was too short.

Figure 5a,b show the cumulative distribution of CO_2 concentration in all flats A and C for case 0 (calculated from all 5 min values of CO_2 concentration during the entire analysed season). The indoor air quality in apartments was practically all the time in categories higher than I. At least 50% of the time the air quality was above category III; on the top floor, where the length of the gravity chimney was short, this condition persisted for over 90% of the time. The highest environmental category I could be assigned to rooms on average for less than 5% of the time they were used.

Heat demand index for flats is presented in Table 3. The seasonal heat demand for the entire building was only 7.3 MWh, which gives an index of 4.9 kWh/m^2. The building needed to be heated only for 3 months per year; in October and April, the heat demand is zero, and in November and March, it was negligible. Unfortunately, such low energy consumption was largely caused by the extremely low air exchange in the building. In practice, such large energy savings conceal for users a huge disadvantage, which is a significant deterioration of air quality.

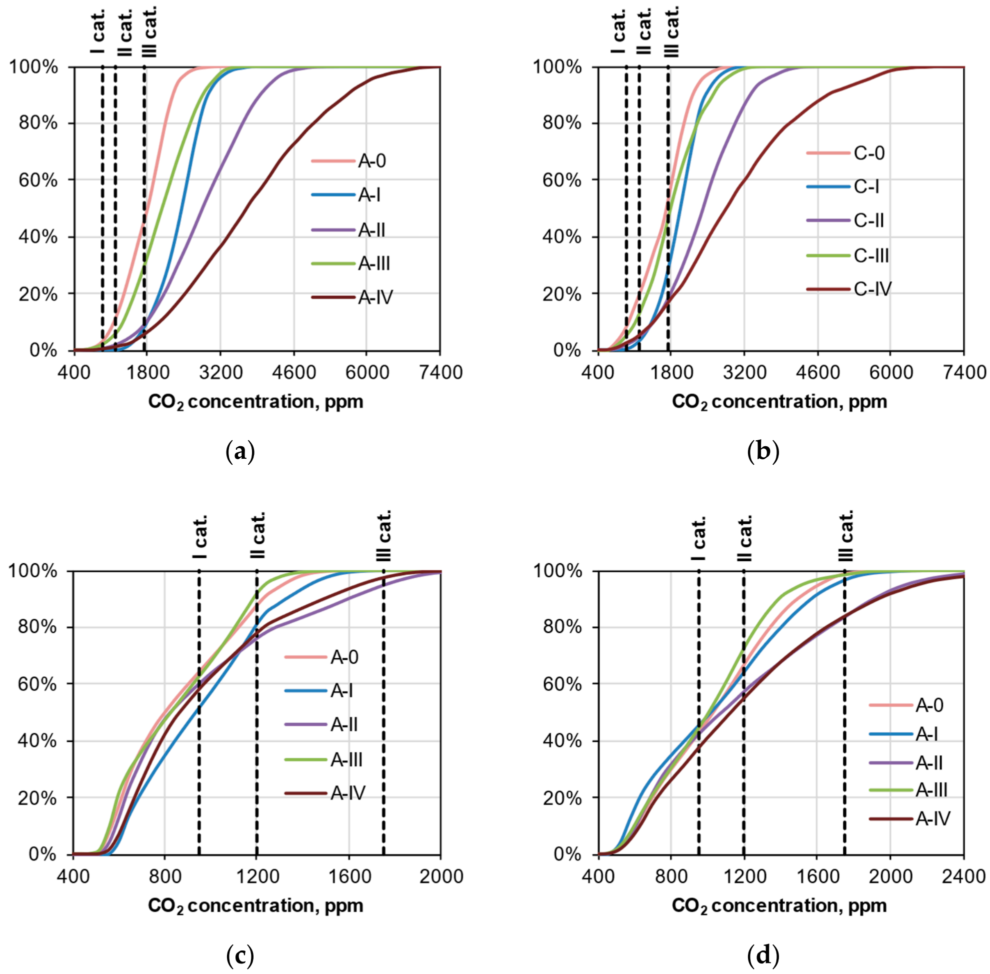


Figure 5. Cumulative distribution of CO_2 concentration for the flats: (**a**) case 0 for flat A; (**b**) case 0 for flat C; (**c**) case 1 for flat A; and (**d**) case 1a for flat A.

Table 3. Heat demand index in flats for all cases.

Storey	Ground Foor				I Floor				II Floor				III Floor				IV Floor			
Orientation	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W
Flat	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Usable energy (heating demand) [kWh/m^2]																				
Case 0	8.0	6.7	8.4	9.4	3.1	2.4	3.9	3.8	3.5	2.4	3.9	4.3	5.4	3.8	5.6	6.6	8.6	6.8	9.1	9.9
Case 1	32.3	31.1	33.0	33.9	32.7	30.4	24.6	34.0	33.0	35.0	29.5	34.3	22.5	22.1	18.6	23.6	34.1	32.1	28.7	35.6
Case 1a	25.7	27.4	30.4	28.0	37.0	35.2	30.8	38.2	28.5	30.9	27.0	30.8	20.3	18.5	17.1	20.9	31.1	31.6	27.4	33.0
Case 2	10.3	8.5	10.3	11.7	4.7	3.5	4.6	5.5	5.5	3.9	5.0	6.6	8.7	6.4	7.6	10.1	13.6	11.0	12.7	15.3
Case 3	8.5	6.4	8.1	9.9	4.1	2.6	3.7	4.9	4.6	2.7	4.0	5.6	6.2	4.1	5.5	7.6	11.4	8.4	10.4	13.0

The instantaneous heating demand in flats was variable, which resulted from the changing load on the rooms during the day and fluctuations in the ventilation airflow. One day for flats B-0 and B-I is shown in Figure 6. In flat B-0, we can observe the moment when the residents left the apartment after 8 a.m. because the CO_2 concentration slowly disappeared until the first person arrived at 2 p.m. Within six hours, the CO_2 concentration dropped by 700 ppm, but unfortunately it did not reach the background level. In flat B-I, where minimum one person was all time (two people during working hours), the CO_2 concentration fluctuated around 1600 ppm. On the other hand, in flat B-I, constant heat gains related to the use of the zone reduced the heating demand during the day.

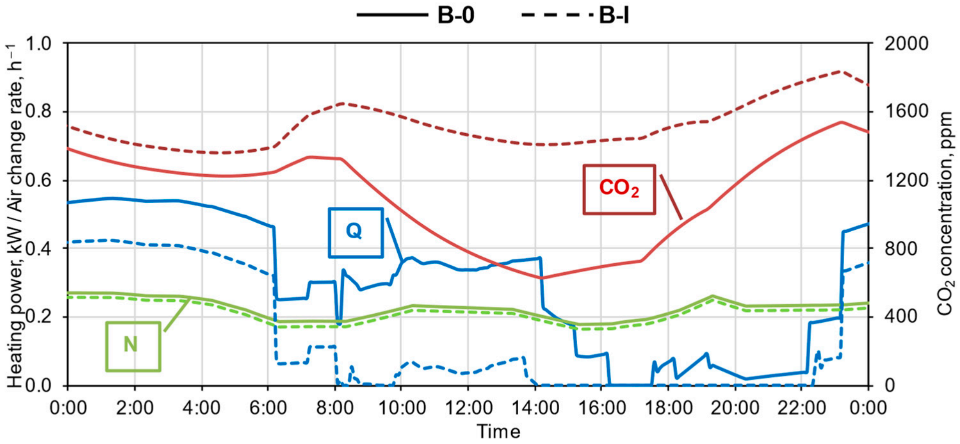


Figure 6. Variability of the heat demand, the air change rates, and CO_2 concentration (case 0) in flat B on the ground floor and on first floor on Monday 9 January.

As mentioned earlier, case 0 is a theoretical case; in practice, residents open windows less or more often to ventilate rooms. In cases 1 and 1a, the impact of regularly opening (tilting) windows in flats was tested. In real buildings, residents open windows spontaneously when they feel stuffiness or an unpleasant odour. The windows remain open for some time until the residents consider the air quality to be satisfactory or the residents begin to feel thermal discomfort related to the cooling of the room during periods of low external temperature, and the heating system is unable to keep up with the heating needs. Typically, residents close their windows before leaving their flats (e.g., before going to work) and before going to bed. The description provided concerns the behaviour of residents during the heating season; in the summer, the windows usually remain open for most of the day (this aspect was not the subject of this study).

Table 2 shows the average air change rates in the flats for case 1 during the heating season. The average air change rates increased, compared to the case without opening the windows, from three times on the ground floor to even six times on the top floor. With the windows closed, the instantaneous airflow was the same as in case 0, i.e., at the level of 20 m^3/h, while during the window opening time, the airflow always exceeded 200 m^3/h, reaching a maximum value of 1590 m^3/h in flat C-IV, which was almost seven air changes per hour. Even though the airing time was only a small part of the heating season (from 19% to 31% depending on the flat), opening the windows increased the average seasonal external airflow to such an extent that each flat could be classified at least into environmental category III, assuming an average family of four. Flats B-I, C-I, B-II, and C-II could be classified, on average, even into environmental category II. This was caused by opening windows much more often than in other flats. It is also noted that windows were opened much more often in flats with constant presence of people on the first floor, in flats on the second floor with an increased number of residents, and on the top floor where the ventilation airflow was the smallest in the entire building.

Regular airing of flats improved air quality (Table 2). With the exception of flats on the top floor and those with higher loads on the second floor, the maximum carbon dioxide concentration was less than 2000 ppm. The average CO_2 concentration in nine apartments was within the limits of the highest category I of the indoor environment according to the EN 16798-1:2019 standard [42] (550 ppm above background). In the remaining eleven apartments, this limit was only slightly exceeded, never exceeding 1000 ppm.

Figure 5c shows the cumulative distribution of CO_2 concentration in flat A for case 1. The indoor air quality could be classified to at least category II on average 80% of the time; in flats with higher loads or on the top floor, the level of category III was more often exceeded, but only a little over 5% of the time. The air quality in flats was much better than in the case without opening windows.

Opening the window caused the inflow of large amounts of cool air from the outside, and thus a sudden instantaneous increase in heat demand, which is presented in detail for one day in Figure 7. The moment of opening the window is clearly visible, the heat demand then increases up to eight times due to the inflow of large amounts of cold air. This variability is correlated with changes in CO_2 concentration. During periods of lower ventilation, e.g., April (Figure 7b), the CO_2 concentration increased significantly at night, from a low level resulting from evening ventilation to a level exceeding 1200 ppm (the window could only be opened at 6 a.m.). Residents who stay at home during the day were more likely to open their windows in April, when the flow of air infiltrating through leaks was lower.

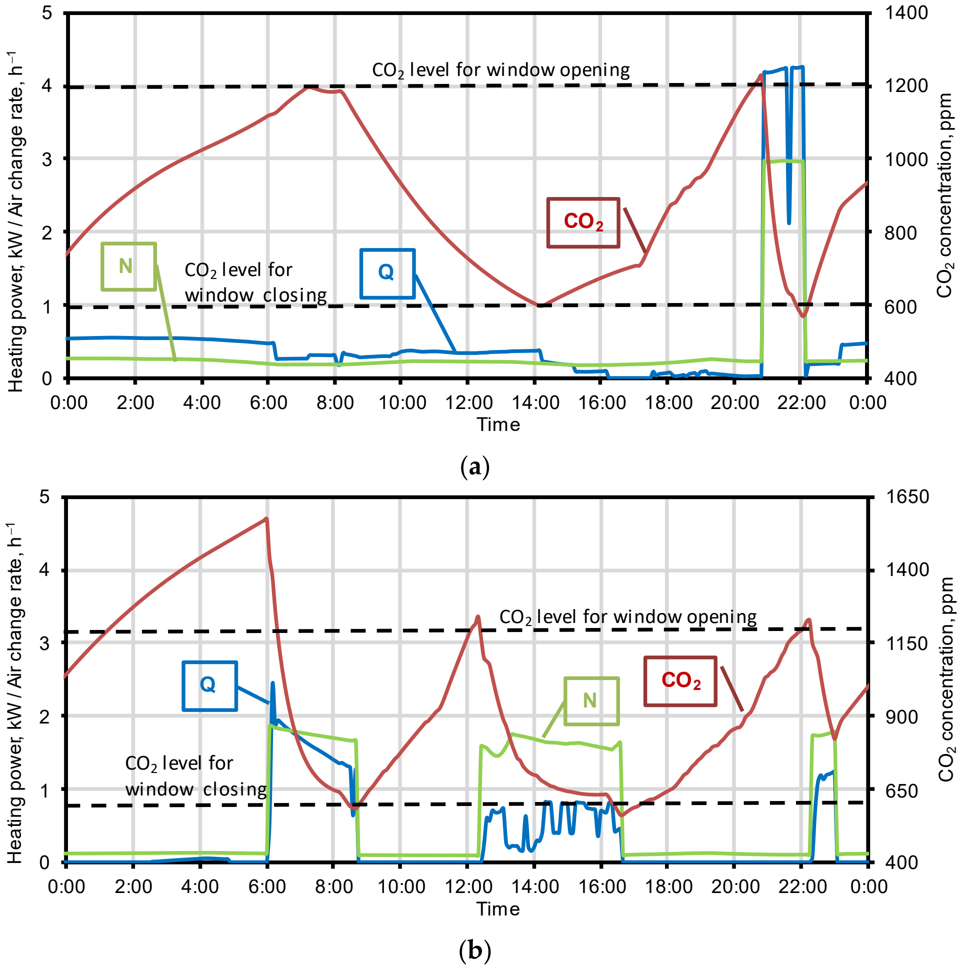


Figure 7. Variability of the heat demand, the air change rates, and CO_2 concentration (case 1) in flat B on the ground floor: (**a**) on Monday 9 January; (**b**) on Sunday 16 April.

The seasonal heat demand in the building increased by as much as five times compared to the case without opening the windows (Table 3) and amounted to 38.0 MWh (25.6 kWh/m^2). The use of airing significantly improved the air quality, but it had a drastic impact on the heating demand, and it also required great discipline; in practice, it is performed very irregularly. The external air change rates reaching the value of 5–6 h^{-1} during window opening time may cause significant local reductions in the indoor temperature during periods of low external temperatures, which may be a source of great local discomfort.

In practice, intermediate ventilation between cases 0 and 1 is used in flats; therefore, additional calculations were made taking into account the probability of opening and closing the window depending on the outside temperature (Table 1)—case 1a. In this case, the windows were not always opened at the assumed threshold CO_2 concentration, the window opening time decreased compared to case 1 (Table 2). This situation resulted in the deterioration of air quality, both the average and maximum CO_2 concentration in flats increased. The average CO_2 concentration value in each flat was above the limit of the highest category I of the indoor environment according to the EN 16798-1:2019 standard [42] (550 ppm above background). The maximum value exceeded the threshold of 3000 ppm (Table 2). Figure 5d shows the cumulative distribution of CO_2 concentration in flats A for case 1a. The indoor air quality could be classified into at least environmental category II on average 60% of the time; in flats with higher loads or on the top floor, the upper level of category III was exceeded more often than in other flats (even almost 20% of the season). Air quality corresponding to category I occurred in flats on average 40% of the season.

On the other hand, residents could forget to close the window after achieving the required air quality, which resulted in a prolonged period of increased heating demand. Although the air quality deteriorated by an average of 16%, the heat demand of the entire building turned out to be lower by only 5%, and the differences in individual flats were at different levels, on the first floor the heat demand even increased (Table 3). The total opening time of windows in the building was at a similar level, as in the case of regular airing according to established rules, but this opening did not always take place at the most favourable time from the point of view of air quality. In this case, the seasonal heat demand in the building was 36.2 MWh, which gave an index of 24.4 kWh/m^2.

3.2. Mechanical Ventilation

In case 3 a central mechanical ventilation system with heat recovery was used, dedicated to multi-family residential buildings, without control of the airflow depending on the needs of individual flats. Table 4 shows the air change rates in flats after implementing mechanical ventilation system.

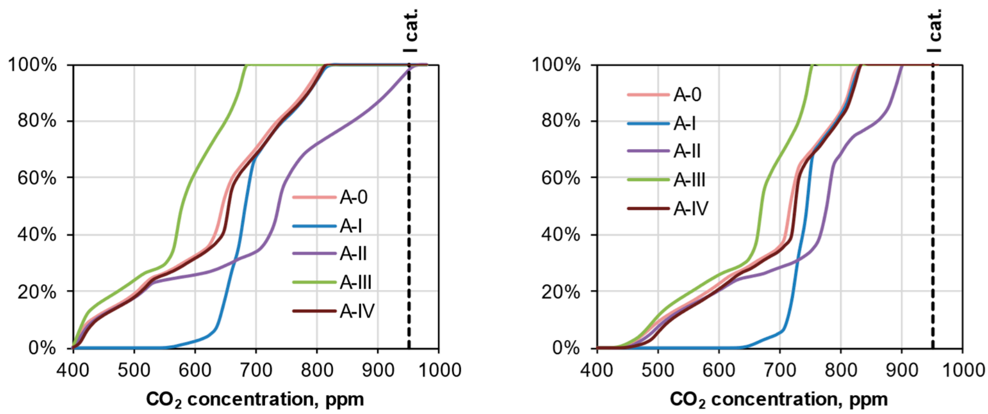
Table 4. Seasonal average air change rate (N_{avg}), external airflow ($\dot{V}_{avg}$) entering flats, and CO_2 concentration (C_{avg} and C_{max}) in buildings with mechanical ventilation.

Storey	Ground Foor				I Floor				II Floor				III Floor				IV Floor			
Orientation	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W	N/E	S/E	S/W	N/W
Flat	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Case 2																				
N_{avg} [h^{-1}]	0.83	0.84	0.84	0.84	0.82	0.83	0.69	0.83	0.81	0.82	0.68	0.82	0.81	0.81	0.68	0.82	0.80	0.81	0.67	0.81
$\dot{V}_{avg}$ [m^3/h]	127	159	160	128	125	157	160	126	124	155	158	125	123	154	157	124	122	153	156	124
C_{avg} [ppm]	628	640	638	626	695	695	690	693	707	729	724	705	567	588	586	566	636	648	645	634
C_{max} [ppm]	821	854	853	820	824	853	847	823	967	972	968	966	687	738	733	687	819	853	848	820
Case 3																				
N_{avg} [h^{-1}]	0.59	0.54	0.54	0.59	0.68	0.61	0.51	0.69	0.65	0.61	0.51	0.66	0.49	0.46	0.39	0.49	0.57	0.52	0.44	0.58
$\dot{V}_{avg}$, [m^3/h]	89	102	103	90	104	116	118	104	99	116	118	100	74	88	90	75	87	99	101	88
C_{avg} [ppm]	691	733	730	689	752	792	787	750	739	796	793	738	650	698	696	648	700	742	740	698
C_{max} [ppm]	831	898	897	830	831	899	898	831	899	959	959	899	752	830	829	752	831	897	897	831

The airflow supplied to the flats by the system was constant, but a small amount of air infiltrating through leaks additionally entered the zones, which increased the total ventilation airflow. The air change rates in flats A, B, D, and C on the ground floor was 0.8 h^{-1}, in flat C on the upper floors due to the larger area, 0.7 h^{-1}. The biggest difference in relation to the cases with opening the window occurred on the penultimate floor, which had flats with a smaller number of occupants, in which the window was opened less often, and which now, with a central mechanical ventilation system, have the same ventilation airflow as flats with higher loads. When designing a mechanical ventilation system in residential buildings, the area of the apartment and/or the number of "dirty rooms" (kitchens, toilets) are taking into consideration; the number of residents may change due to a change of owner or tenant; therefore, the current state cannot be a guideline for design (only the minimum criterion specified in the standards must be met). The required ventilation air flow for the highest environmental category I in accordance with the EN 16798-1:2019 standard [42] should not be less than 36 m^3/h. Assuming an average family of four, this condition is met in larger apartments B and C; in smaller apartments A and D, the average air flow is below this limit.

The air change rates in flats during the season was on average level of 0.8 h^{-1} (Table 4), with a maximum value of just over 1 h^{-1}. Air exchange fluctuations resulted from changes in air infiltration through window leaks throughout the season. However, infiltration had a small share in the total ventilation airflow; on average, it did not exceed 10 m^3/h, which was approximately 5% of the total airflow.

The maximum and average CO_2 concentration calculated in the flats are presented in Table 4. The maximum CO_2 concentration only on the second floor (where a larger number of people stay) exceeded 950 ppm (i.e., the upper limit of environmental category I according to the EN 16798-1:2019 standard [42]), but only by a maximum of 22 ppm. The air quality in terms of CO_2 concentration was very good. Figure 8a shows the cumulative distribution of CO_2 concentration in all flats A. With the exception of flats on the second floor, the indoor air quality could be classified to environmental category I by 100% of the time. In flats on the second floor, this limit was exceeded for a maximum of 3% of the season.



(**a**) (**b**)

Figure 8. Cumulative distribution of CO_2 concentration for the flats A: (**a**) case 2; (**b**) case 3.

The use of heat recovery significantly reduced heating demand. Despite the increase in the instantaneous airflow, which allowed maintaining environmental conditions at the required level, the seasonal heat demand in the building decreased by 3.5 times compared to the cases with opening windows. In warm months (October and April), the heating in the flats might be turned off. The total heat demand in this case was 10.4 MWh, which gives a factor of 7.0 kWh/m^2. Energy demand at this level qualified the building as energy-saving with very good indoor air quality. Due to the fact that the heat demand for ventilation in this case did not depend on the floor, the main differences resulted from heat losses through the external partitions, which were the largest, due to the roof, on the top floor. The heating demand on the top floor was even 2–3 times higher than in flats on lower floors. The electricity consumed by fans cannot also be ignored. The use of fans in the supply and exhaust air handling unit increased the building's electricity demand during the heating season to 5.1 MWh, which constitutes 50% of the usable energy for heating and ventilation of the building.

The mechanical ventilation system discussed above provided a constant amount of fresh air to the rooms 24 h a day, regardless of whether the flats were occupied. The introduction of a system that would take into account the variable load in rooms could be a source of additional energy savings. Therefore, the last case considered was a decentralized mechanical ventilation system with heat recovery, dedicated to a single flat, with airflow depending on the instantaneous CO_2 concentration in the individual flat. Such a system provides the required amount of fresh air, with minimal energy consumption by the ventilation system.

Table 4 shows the average air change rates in flats during the heating season in cases with smooth control of the supply airflow depending on the CO_2 concentration. The average air change rates in flats decreased, compared to the case with a constant airflow, by 17–43%, depending on the flat, while ensuring air quality at a similar very good level. The greatest effect was achieved in flats on the third floor with fewer occupants. The maximum air change rates in flats was 1 h^{-1}, which was higher than the design airflow for case 2. However, the average airflow supplied by the mechanical ventilation system to flats was as much as 27% smaller than the average design value in case 2 and was 98 m^3/h. Only in two flats with higher loads on the second floor did the maximum CO_2 concentration slightly exceeded (by 9 ppm) the upper limit of environmental category I according to the EN 16798-1:2019 standard [42] (Table 4). The average values in case 3 were more similar to each other in individual flats compared to case 2. The maximum difference in average values in flats was 148 ppm; in case 2, it was 163 ppm. The control system adjusted the airflow to the needs, which provided environmental benefits, especially in flats with higher loads. Figure 8b shows the cumulative distribution of CO_2 concentration in flat A. The indoor air quality of most flats can be classified into environmental category I by 100% of the time. In more occupied flats on the second floor, this limit was exceeded for a maximum of 4% of the season. On average, the air quality was slightly worse compared to case 2, but still remained in the middle of the indoor environment category I.

The use of additional follow-up control of the fans resulted in energy savings in the building at an average level of 21% throughout the heating season compared to the case with a constant ventilation airflow. The total heat demand was 8.3 MWh, which gives an index of 5.6 kWh/m^2. Energy demand at this level qualified the building as an energy-saving building with very good indoor air quality. Unfortunately, the electricity consumed by the fans of twenty individual units was higher (by approximately 60%) than in the case of one large central unit and was at the level of 8.1 MWh, which is 100% of the usable energy for heating.

4. Discussion

Fresh air is a basic requirement for human health and well-being. The key to protecting health against the negative effects of air pollution is to improve ventilation. Unfortunately, in order to reduce energy consumption, the possibility of reducing the amount of air is often considered, so an important problem is finding a compromise between indoor air quality and energy consumption.

In this study, the ventilation air flow, carbon dioxide concentration, and heat demand were compared for an exemplary multi-family building for five cases of various ventilation systems. Figure 9 shows the seasonal heat demand of the building and the average carbon dioxide concentration in flats at subsequent stages of ventilation modernisation. Figure 10 shows the frequency of carbon dioxide concentrations in the ranges I, II, and III of indoor environmental quality categories, as the total number of hours from all 20 flats during the entire heating season from October to April; the total number of hours in the season is 101,760 h (212 days × 24 h × 20 flats).

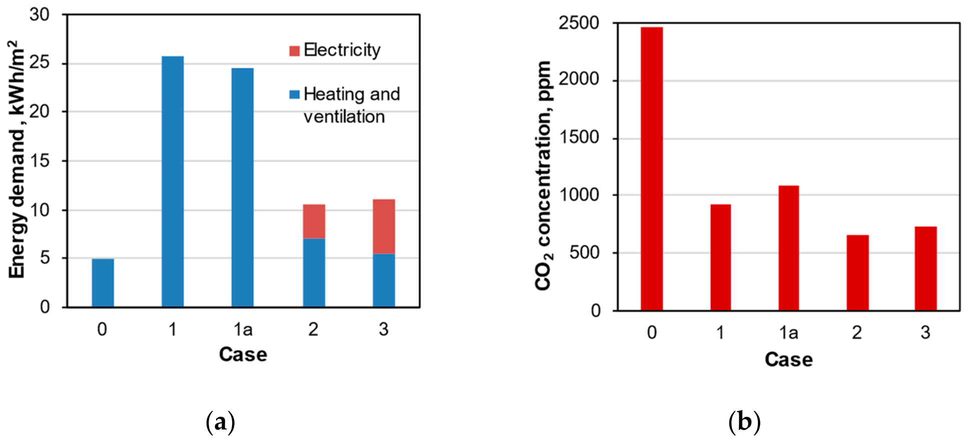


Figure 9. (**a**) Seasonal heat demand of the entire building and (**b**) average CO_2 concentration in flats.

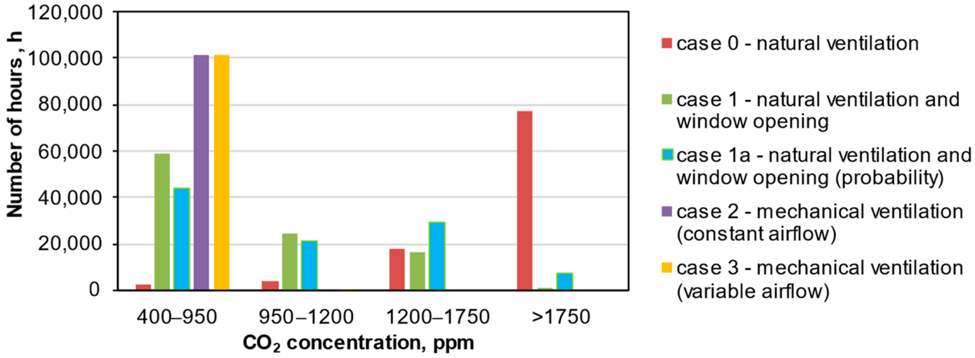


Figure 10. Frequency of CO_2 concentration in the various categories of the indoor environment (total value from all 20 flats during the entire heating season).

In the case of a building with natural ventilation without opening windows, high energy savings for heating are caused by extremely low air exchange in the building (on average 0.1 h^{-1}), which is the result of tight windows; the situation is the worse the higher the floor and the shorter the gravity ventilation duct. Therefore, natural ventilation systems used in residential buildings (especially during periods without wind) are unable to provide the required air exchange, and the CO_2 concentration may periodically reach up to 9000 ppm if the windows are not opened all day long. Similar conclusions were drawn based on measurements by Alonso et al. [57]. The situation can be improved by regular airing of living areas. The maximum carbon dioxide concentration falls below 2500 ppm, but for more than 20% of the season it exceeds 1200 ppm, which is the limit of category II of the indoor environment. Moreover, ventilation significantly increases the instantaneous heating power in the rooms, and during periods of low external temperatures it may cause a local decrease in the indoor temperature in the rooms. Since regular airing of flats requires great discipline, in practice we are dealing with an intermediate case in which residents do not always open the window in the event of deterioration of air quality, and may also forget to close it despite achieving good air quality. This results in a deterioration of air quality and an increase in heat demand in the case of prolonged periods with the window open; therefore, with a significant deterioration of air quality, the heat demand decreases by only 5%. In the case of manual control, the windows are not opened at night when the residents are sleeping. Despite lower CO_2 emissions during sleep, the concentration of CO_2 in the bedroom air in the morning often exceeds 3000 ppm, which consequently causes a feeling of lack of rest and a bad mood during the day [58].

For the ventilation system to fulfil its purpose, it must be configured with appropriate mechanical ventilation devices and operate when people are present in the room (also at night). However, designing ventilation systems for residential buildings has significant limitations. The basic problem in many, even highly developed, countries is the limited financial resources for their implementation. As a rule, funding can be obtained for replacing windows and insulating external walls; the remaining part of the investment—the modernisation of the ventilation system—must be covered from own funds. An investment that allows maintaining high air quality in existing residential buildings should be treated as necessary for the health and well-being of residents. Such modernisation will reduce the heating demand by more than three times compared to the case with airing by opened windows, but the indoor environment will meet the conditions of category I.

The load on the flats varies throughout the day, so the use of mechanical ventilation with variable airflow (DCV system) gave good results and allows us to reduce the heating demand by 20% while maintaining the same high air quality. It should be emphasized, however, that mechanical ventilation systems require additional electricity to operate the fans, which will have a noticeable impact on the cost of maintaining the building. Despite this, the sum of energy for heating and electricity when using mechanical ventilation is more than two times smaller than the energy for heating in case of opening windows. To sum up, a supply and exhaust ventilation system with heat recovery is currently the best way to ensure adequate air quality in flats. The choice of a system with a constant or variable airflow will be influenced by the investment cost and the possibility of installing ducts and air handling units in the building. Installing individual systems in apartments requires adequate space in the apartment, and the system itself will generate additional noise. Noise from ventilation systems is an important risk factor. The most common sources of noise in homes are fans and ducts. Evidence suggests that people turn off the systems that generate these noises due to the annoyance that they cause [2].

5. Conclusions

The research allowed for a quantitative assessment of the instantaneous values of the ventilation airflow, indoor air quality, and energy demand for heating and ventilation in individual flats of a multi-family building typical of Central Europe. The research showed differences depending on the floor of the building (owing to the different stack effect caused by changing the length of gravity chimneys), the intensity of the use of the flats (uneven CO_2 emissions), and the period of year (instantaneous and seasonal changes in external conditions). The main conclusions from the conducted research are as follows:

- In buildings equipped with new tight windows (without additional air vents), the natural gravity ventilation system is unable to ensure the required air exchange and, therefore, the indoor air quality in the flats; large energy savings related to heating a small amount of ventilation air (average air change rate at the level at 0.1 h^{-1}) cannot cover up the huge disadvantage of such buildings, which is the low indoor air quality (average CO_2 concentration in flats at the level of 2500 ppm, with a maximum value even above 6000 ppm on the top floor, where the gravity ducts are short). The average CO_2 concentration on the top floor (3600 ppm) is twice as high compared to the mixtures on the ground floor (1700 ppm).
- Lack of mechanical ventilation with a tight building envelope encourages users to open windows to ventilate the rooms; this generates a multiple increase (even eight times) in heating power during these periods with the risk of local thermal discomfort. Therefore, the assumed effects of reducing heat demand after thermal modernisation of the building are often not achieved.
- By using mechanical supply and exhaust ventilation with heat recovery, good indoor air quality can be maintained in flats (average carbon dioxide concentration at the level of 700 ppm). The use of mechanical ventilation can be profitable both in terms of energy savings (at the level of 50%, due to heat recovery from the exhaust air) and improvement of the indoor air, which affects the health and well-being of residents; a significant drop in operating costs related to heating and ventilation should be expected. However, the electricity consumption in the building will increase, which is related to the need to provide energy to drive the fans (in the case of individual air

handling units in each flat, the demand for electricity may be as high as the energy demand for heating and ventilation). In this case, installing photovoltaic panels to produce electricity for fans should be consider.

- Integrated simulation of heat demand and air exchange in dynamic conditions, with a small time step, taking into account instantaneous heat loads, airflow, and pollutant emissions, allows for the analysis of various heating and ventilation systems in a manner sufficient for the correct assessment of heat demand and indoor air quality in multi-family buildings when making investment decisions regarding the design and modernisation of these buildings. Only such simulation allows for a comprehensive analysis of the conditions in rooms in terms of energy efficiency and indoor air quality.

Future Research

Poorly organized inflow of large amounts of external air into rooms in the case of natural ventilation may cause drafts to occur in certain zones. To prevent this phenomenon, research should be carried out regarding the type of air vents, their location, and possible additional heating of the incoming air.

Author Contributions: Conceptualization, J.F.-G. and K.G.; methodology, J.F.-G. and K.G.; software, K.G.; formal analysis, J.F.-G.; writing—original draft preparation, J.F.-G.; writing—review and editing, K.G.; supervision, J.F.-G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The work was supported by the Polish Ministry of Science and Higher Education within the research subsidy.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Coggins, A.M.; Wemken, N.; Mishra, A.K.; Sharkey, M.; Horgan, L.; Cowie, H.; Bourdin, E.; McIntyre, B. Indoor air quality, thermal comfort and ventilation in deep energy retrofitted Irish dwellings. *Build. Environ.* **2022**, *219*, 109236. [CrossRef]
2. Ortiz, M.; Itard, L.; Bluyssen, P.M. Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: A literature review. *Energy Build.* **2020**, *221*, 110102. [CrossRef]
3. Pitarma, R.; Marques, G.; Ferreira, B.R. Monitoring indoor air quality for enhanced occupational health. *J. Med. Syst.* **2017**, *41*, 23. [CrossRef]
4. Logue, J.M.; Price, P.N.; Sherman, M.H.; Singer, B.C. A method to estimate the chronic health impact of air pollutants in U.S. residences. *Environ. Health Perspect.* **2011**, *120*, 216–222. [CrossRef]
5. Cao, S.J.; Ren, C. Ventilation control strategy using low-dimensional linear ventilation models and artificial neural network. *Build. Environ.* **2018**, *144*, 316–333. [CrossRef]
6. Khovalyg, D.; Kazanci, O.B.; Halvorsen, H.; Gundlach, I.; Bahnfleth, W.P.; Toftum, J.; Olesen, B.W. Critical review of standards for indoor thermal environment and air quality. *Energy Build.* **2020**, *213*, 109819. [CrossRef]
7. Shin, M.S.; Rhee, K.N.; Lee, E.T.; Jung, G.J. Performance evaluation of CO_2-based ventilation control to reduce CO_2 concentration and condensation risk in residential buildings. *Build. Environ.* **2018**, *142*, 451–463. [CrossRef]
8. Wargocki, P.; Wyon, D.P.; Sundell, J.; Clausen, G.; Fanger, P.O. The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. *Indoor Air* **2000**, *10*, 222–236. [CrossRef] [PubMed]
9. Du, L.; Leivo, V.; Prasauskas, T.; Taubel, M.; Martuzevicius, D.; Haverinen-Shaughnessy, U. Effects of energy retrofits on indoor air quality in multifamily buildings. *Indoor Air* **2019**, *29*, 686–697. [CrossRef]
10. Yang, S.; Pernot, J.G.; Jorin, C.H.; Niculita-Hirzel, H.; Perret, V.; Licina, D. Energy, indoor air quality, occupant behaviour, self-reported symptoms and satisfaction in energy-efficient dwellings in Switzerland. *Build. Environ.* **2020**, *171*, 106618. [CrossRef]
11. Wallner, P.; Munoz, U.; Tappler, P.; Wanka, A.; Kundi, M.; Shelton, J.F.; Hutter, H.-P. Indoor Environmental Quality in Mechanically ventilated energy efficient buildings vs. conventional buildings. *Int. J. Environ. Res. Public Health* **2015**, *12*, 14132–14147. [CrossRef]
12. Zhao, L.; Liu, J.; Ren, J. Impact of various ventilation modes on IAQ and energy consumption in Chinese dwellings: First long-term monitoring study in Tianjin, China. *Build. Environ.* **2018**, *143*, 99–106. [CrossRef]
13. Kotol, M. Current ventilation strategies in Greenlandic dwellings. *J. Build. Eng.* **2021**, *39*, 102283. [CrossRef]
14. McGill, G.; Oyedele, L.O.; McAllister, K. Case study investigation of indoor air quality in mechanically ventilated and naturally ventilated UK social housing. *Int. J. Sustain. Built Environ.* **2015**, *4*, 58–77. [CrossRef]

15. Park, S.; Kim, H.J. A field study of occupant behavior and energy consumption in apartments with mechanical ventilation. *Energy Build.* **2012**, *50*, 19–25. [CrossRef]
16. Fisk, W.J. How home ventilation rates affect health: A literature review. *Indoor Air* **2018**, *28*, 473–487. [CrossRef]
17. Zhang, S.; Ai, Z.; Lin, Z. Novel demand-controlled optimization of constant-air-volume mechanical ventilation for indoor air quality. *Appl. Energy* **2021**, *293*, 116954. [CrossRef]
18. Cui, C.; Zhang, X.; Cai, W. An energy-saving oriented air balancing method for demand controlled ventilation systems with branch and black-box model. *Appl. Energy* **2020**, *264*, 114734. [CrossRef]
19. Galvin, R. Impediments to energy-efficient ventilation of German dwellings: A case study in Aachen. *Energy Build.* **2013**, *56*, 32–40. [CrossRef]
20. Ai, Z.T.; Mak, C.M.; Cui, D.J.; Xue, P. Ventilation of air-conditioned residential buildings: A case study in Hong Kong. *Energy Build.* **2016**, *127*, 116–127. [CrossRef]
21. Pereira, P.F.; Ramos, N.M.M.; Almeida, R.M.S.F.; Simoes, M.L.; Barreira, E. Occupant influence on residential ventilation patterns in mild climate conditions. *Energy Procedia* **2017**, *132*, 837–842. [CrossRef]
22. Broderick, Á.; Byrne, M.; Armstrong, S.; Sheahan, J.; Coggins, A.M. A pre and post evaluation of indoor air quality, ventilation, and thermal comfort in retrofitted co-operative social housing. *Build. Environ.* **2017**, *122*, 126–133. [CrossRef]
23. Calama-González, C.M.; León-Rodríguez, Á.L.; Suárez, R. Indoor environmental assessment: Comparing ventilation scenarios in pre- and post-retrofitted dwellings through test cells. *J. Build. Eng.* **2021**, *43*, 103148. [CrossRef]
24. Măgurean, A.M.; Petran, H.A. Analysis of Measured CO_2 Levels through Long-Term Monitoring in Renovated Multifamily Buildings: A Common Case. *Buildings* **2023**, *13*, 2113. [CrossRef]
25. Collignan, B.L.E.; Ponner, E.; Mandin, C. Relationships between indoor radon concentrations, thermal retrofit and dwelling characteristics. *J. Environ. Radioact.* **2016**, *165*, 124–130. [CrossRef]
26. Coombs, C.; Chew, G.L.; Schaffer, C.; Ryan, P.H.; Brokamp, C.; Grinshpun, S.A.; Adamkiewicz, G.; Chillrud, S.; Hedman, C.; Colton, M.; et al. Indoor air quality in green-renovated vs. non-green low-income homes of children living in a temperate region of US (Ohio). *Sci. Total Environ.* **2016**, *554–555*, 178–185. [CrossRef] [PubMed]
27. Prasauskas, T.; Martuzevicius, D.; Kalamees, T.; Kuusk, K.; Leivo, V.; Haverinen-Shaughnessy, U. Effects of energy retrofits on indoor air quality in three Northern European countries. *Energy Procedia* **2016**, *96*, 253–259. [CrossRef]
28. Fix, A.J.; Pamintuan, B.C.; Braun, J.E.; Warsinger, D.M. Vapor-selective active membrane energy exchanger with mechanical ventilation and indoor air recirculation. *Appl. Energy* **2022**, *312*, 118768. [CrossRef]
29. Zhuang, C.; Shan, K.; Wang, S. Coordinated demand-controlled ventilation strategy for energy-efficient operation in multi-zone cleanroom air-conditioning systems. *Build. Environ.* **2021**, *191*, 107588. [CrossRef]
30. Ye, Y.; Chen, Y.; Zhang, J.; Pang, Z.; O'Neill, Z.; Dong, B.; Cheng, H. Show more. Energy-saving potential evaluation for primary schools with occupant-centric controls. *Appl. Energy* **2021**, *293*, 116854. [CrossRef]
31. Lu, X.; O'Neill, Z.; Li, Y.; Niu, F. A novel simulation-based framework for sensor error impact analysis in smart building systems: A case study for a demand-controlled ventilation system. *Appl. Energy* **2020**, *263*, 114638. [CrossRef]
32. Kim, M.K.; Baldini, L.; Leibundgut, H.; Wurzbacher, J.A. Evaluation of the humidity performance of a carbon dioxide (CO_2) capture device as a novel ventilation strategy in buildings. *Appl. Energy* **2020**, *259*, 112869. [CrossRef]
33. Li, C.; Cui, C.; Li, M. A proactive 2-stage indoor CO_2-based demand-controlled ventilation method considering control performance and energy efficiency. *Appl. Energy* **2023**, *329*, 120288. [CrossRef]
34. Merema, B.; Delwati, M.; Sourbron, M.; Breesch, H. Demand controlled ventilation (DCV) in school and office buildings: Lessons learnt from case studies. *Energy Build.* **2018**, *172*, 349–360. [CrossRef]
35. Wang, W.; Wang, J.; Chen, J.; Huang, G.; Guo, X. Multi-zone outdoor air coordination through Wi-Fi probe-based occupancy sensing. *Energy Build.* **2018**, *159*, 495–507. [CrossRef]
36. Lu, X.; Pang, Z.; Fu, Y.; O'Neill, Z. The nexus of the indoor CO_2 concentration and ventilation demands underlying CO_2-based demand-controlled ventilation in commercial buildings: A critical review. *Build. Environ.* **2022**, *218*, 109116. [CrossRef]
37. Schibuola, L.; Tambani, C. Indoor Environmental Quality Classification of School Environments by Monitoring PM and CO_2 Concentration Levels. *Atmos. Pollut. Res.* **2020**, *11*, 332–342. [CrossRef]
38. Fisk, W.; Wargocki, P.; Zhang, X. Do Indoor CO_2 Levels Directly Affect Perceived Air Quality, Health, or Work Performance? *ASHRAE J.* **2019**, *61*, 70–77.
39. Michalak, P.; Szczotka, K.; Szymiczek, J. Audit-Based Energy Performance Analysis of Multifamily Buildings in South-East Poland. *Energies* **2023**, *16*, 4828. [CrossRef]
40. Alsabry, A.; Szymański, K. Energy Analyses of Multi-Family Residential Buildings in Various Locations in Poland and Their Impact on the Number of Heating Degree Days. *Energies* **2023**, *16*, 4648. [CrossRef]
41. Pilkington. Available online: https://www.Pilkington.Com/Pl-Pl/Pl/Produkty/Funkcje-Szkla/Izolacja-Cieplna/Pilkington-Insulight-Therm (accessed on 15 January 2024).
42. *EU Standard 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 Acoustics-Module M1-6. European Committee for Standardization: Brussels, Belgium, 2019.
43. *ANSI/ASHRAE Standard 62.1-2022*; Ventilation and Acceptable Indoor Air Quality. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.: Atlanta, GA, USA, 2022.

44. ASHRAE Position Document on Indoor Carbon Dioxide. Approved by ASHRAE Board of Directors February 2, 2022. Available online: https://www.ashrae.org/file%20library/about/position%20documents/pd_indoorcarbondioxide_2022.pdf (accessed on 10 April 2024).
45. Polish Ministry of Family, Labor and Social Policy. *Regulation of the Minister of Family, Labor and Social Policy of 12 June, 2018 on the Highest Permissible Concentrations and Intensities of Factors Harmful to Health in the Work Environment*; Journal of Laws of the Republic of Poland Item. 1286, (with Recast); Polish Ministry of Family, Labor and Social Policy: Warsaw, Poland, 2018. (In Polish)
46. Polish Ministry of Infrastructure. *Regulation of the Minister of Infrastructure of 12 April 2002 on the Technical Conditions That Should Be Met by Buildings and Their Location*; Journal of Laws of the Republic of Poland No 75, Item. 690, (with Recast); Polish Ministry of Infrastructure: Warsaw, Poland, 2002. (In Polish)
47. Engineering Reference. *EnergyPlusTM*; Version 9.4.0; Documentation; US Department of Energy: Washington, DC, USA, 2020.
48. Dols, W.S.; Polidoro, B.J. *CONTAM User Guide and Program Documentation Version 3.4*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2020.
49. Blaszczok, M.; Baranowski, A. Thermal improvement in residential buildings in view of the indoor air quality—Case study for Polish dwelling. *ACEE Archit. Civ. Eng. Environ.* **2018**, *11*, 121–130. [CrossRef]
50. Ferdyn-Grygierek, J.; Baranowski, A.; Blaszczok, M.; Kaczmarczyk, J. Thermal diagnostics of natural ventilation in buildings: An integrated approach. *Energies* **2019**, *12*, 4556. [CrossRef]
51. American Society of Heating, Refrigerating and Air Conditioning Engineers. *ASHRAE Handbook*; American Society of Heating, Refrigerating and Air Conditioning Engineers: Atlanta, GA, USA, 2005.
52. *ANSI/ASHRAE Standard 55*; Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE): Atlanta, GA, USA, 2017.
53. Recknagel, H.; Schramek, E.R. *Handbook. Heating, Air Conditioning, Domestic Hot Water, Refrigerator Technology*; Omni Scala: Wrocław, Poland, 2008; ISBN 978-83-926833-6-0. (In Polish)
54. Kaczmarczyk, J.; Ferdyn-Grygierek, J.; Baranowski, A. The impact of building parameters and way of operation on the operative temperature in rooms. *ACEE Archit. Civ. Eng. Environ.* **2018**, *11*, 107–114. [CrossRef]
55. Typical Meteorological Years and Statistical Climatic Data for the Area of Poland for Energy Calculations of Buildings-Open Data. Available online: https://www.gov.pl/web/cyfryzacja/portal-danych-danegovpl (accessed on 15 January 2024).
56. Koppen Climate Classification | Definition, System, & Map | Britannica, (n.d.). Available online: https://www.britannica.com/science/Koppen-climate-classification (accessed on 12 January 2024).
57. Alonso, C.; de Frutos, F.; Martín-Consuegra, F.; Oteiza, I.; Frutos, B. Energy consumption and environmental parameters in Madrid social housing. Performance in the face of extreme weather events. *Build. Environ.* **2024**, *254*, 111354.
58. Umeda, A.; Ishizaka, M.; Ikeda, A.; Miyagawa, K.; Mochida, A.; Takeda, H.; Takeda, K.; Fukushi, I.; Okada, Y.; Gozal, D. Recent Insights into the Measurement of Carbon Dioxide Concentrations for Clinical Practice in Respiratory Medicine. *Sensors* **2021**, *21*, 5636. [CrossRef]