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Seasonal Air Quality in Bedrooms with Natural, Mechanical or Hybrid Ventilation Systems and Varied Window Opening Behavior-Field Measurement Results

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Abstract: The article presents the results of measurements of temperature, relative humidity and CO_2 concentration in six single-family houses' bedrooms located in Poland, in Wrocław and vicinity, during two climatic seasons: summer–autumn and winter. Two buildings with natural ventilation (NV) were tested, three with mechanical ventilation with heat recovery (MV) and one with hybrid ventilation (HV)—mixed mode natural and mechanical. The behavior of residents regarding opening windows was analyzed and the influence of the changing internal and external conditions on their active reactions was examined. The analysis confirms and adds to the global discourse on the key impact of user behavior on securing healthy indoor air quality in housing, regardless of ventilation system or building energy standard. A disconnect exists between the observed window opening practices and typical design principles, assuming adjustment to a given ventilation system or changing weather conditions. The observations showed that in both analyzed seasons it was possible to obtain a good quality internal environment, in terms of CO_2 level, regardless of the ventilation system used in the building. However, unfavorable results were observed for one bedroom, in which the inhabitants do not adapt their behavior to local technical conditions. Taking into account the level of relative humidity (RH), much higher values were observed in the NV bedrooms in both analyzed periods. The obtained results were divided into IAQ classes in accordance with the EN 16798-1. The recorded values of the internal temperature confirm the significant influence of the location of the room in the building and the actions taken by the residents.

Keywords: bedroom ventilation; indoor air quality; window opening behavior; hybrid ventilation; MVHR; natural ventilation; housing

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1. Introduction

According to the reports of the Statistics Poland [1], more than 350,000 single-family houses were commissioned for use in Poland over the years 2018–2021. As the mean household size is approx. 2.6 people, it can be assumed that nearly 1 million new bedrooms have been added to single-family housing. According to the Organization for Economic Co-operation and Development (OECD) data, the average sleep time in the 30 member countries is 8 h 24 min [2]. It is relevant to understand the factors that enhance or hinder the safety and comfort of the bedroom environment, where people spend almost 35% of their lives. In recent years, there have been several dozen publications on the bedroom internal environment. Research shows that the effective exchange of indoor air is crucial for sleep quality [3–5]. Sekhar, Akimoto et al. [6,7] provide a rich source of knowledge about relevant standards and research evidence. The authors summarized the findings on the basic bedroom air parameters, i.e., temperature, relative humidity, air exchange rate and carbon dioxide concentration. The research reveals a wide variety of internal conditions worldwide, which, apart from independent factors such as weather, external pollutants (e.g., noise) [8–11] or building characteristics, are also influenced by the residents and their strategies of cooperation with the building and its equipment [12–15]. Our previous research also suggests that the influence of residents is fundamental to the shaping of internal conditions and energy consumption in housing [16–18]. Canha et al. [19] focused on a review of field studies seeking to understand the bedroom environment, and concluded it was essential to provide further evidence from a "wider range of settings (including different countries)" ([19], p. 17). This prompted us to conduct research focused on the conditions of a temperate transitional climate, which is characteristic of Poland. On the one hand, this climate is characterized by the occurrence of cold and hot periods, negatively affecting the internal environment and forcing active methods of its maintenance (heating, cooling). On the other hand, it is distinguished by long periods of mild conditions, allowing for the passive functioning of buildings. Batog and Badura [20] demonstrated exceeded CO_2 concentrations in bedrooms in Poland by analyzing socialist blocks of flats that rely on natural ventilation, which were often inherently weakened by the lack of trickle vents. Our study looks at newly built energy efficient houses, equipped with three types of ventilation systems. Firstly, naturally ventilated homes, i.e., mainstream typology until recently for the Polish residential sector. Secondly, homes relying on whole house mechanical ventilation systems with heat recovery (MVHR), and lastly, those equipped with hybrid ventilation, allowing for a combination of passive and active methods of air exchange.

2. Materials and Methods

2.1. Case Study Characteristics

The reported data was collected as a part of a bigger ongoing research project focused on the influence of user behavior on thermal comfort and energy consumption in energy efficient new-built houses. Within the project, annual data is collected for 10 case studies of voluntarily-participating households. The data includes monitoring of internal environment conditions, focusing on thermal comfort, energy consumption and occupant feedback. Data collection began in the summer of 2021. Key selection criteria for inclusion into the study sample were: occupancy longer than 2 years at the beginning of the study (handover prior to 2019), house energy efficiency standards exceeding targets mandatory at the time of their design, and inclusion of systems supporting low energy goals such as mechanical ventilation with heat recovery, heat pumps or PVs. Location in the vicinity of Wrocław for all case-studies was preferable due to planned repeated on-site visits and similar climatic conditions. All the recruited houses are detached or semi-detached, built in Wrocław and vicinity, up to 40 km away from the city center. All were constructed between 2012 and 2017. The analyses presented in the article were based on the results of measurements collected in the main bedrooms of 6 naturally, mechanically and hybrid ventilated houses. The characteristic parameters of the monitored bedrooms are presented in Table 1.

Table 1. Monitored bedrooms characteristics.

House	**NV1**	**NV2**	**MV1**	**MV2**	**MV3**	**HV1**
Ventilation type *	NV	NV	MV	MV	MV	HV
Floor area, m^2/High, m	19.4/2.62	23/2.80	12/2.70	16/2.70	12/2.70	18.2/2.73
Volume, m^3	50.8	64.4	32.4	43.2	32.4	33.9
No. of occupants	2	2/3	2/3	2	2/1	2/3
Thermal mass	high	high	Low	low	low	medium
Floor	ground floor	ground floor	1st floor	1st floor	1st floor	1st floor
Window orientation	E	W/N	N	S/E	N	W
Noise exposure	medium	low	low	low	low	very low

* NV—natural ventilation, MV—natural ventilation with heat recovery, HV—hybrid ventilation (natural and mechanical change-over system).

For three buildings, the load bearing wall material is ceramic bricks; for four buildings, it is cross laminated timber, which leads to varied thermal mass (Table 1). Two of the analyzed houses rely on natural ventilation, and the rest are equipped with mechanical ventilation with heat recovery. Of the latter group, one house has a hybrid system, where the occupants can choose whether to use MV or to switch to NV. All the houses have floor heating systems and heat pumps. Two bedrooms are on ground floor level and four on the first floor, of which one is adjacent to a pitched roof.

All the bedrooms have openable and easily accessible windows. In terms of external noise, i.e., a factor potentially limiting night-time windows opening, all the houses are located in quiet neighborhoods, with NV1 relatively most exposed to potential noise from a nearby road and HV1 least exposed to noise. In terms of external air quality, four houses are located in Wrocław, and thus are exposed to poor air quality, mostly in the heating season [21]. HV1 and NV1 are located within villages with some buildings in the vicinity relying on solid fuel for heating and hot water. There are times of day when windows need to be closed to prevent polluted air from entering the house; however this is typically not during the analyzed hours of the night. NV2 is located min. 2 km away from any solid fuel heating sources and close to a wooded area, suggesting it has the lowest air pollution in the studied sample.

2.2. Methods

The analysis was performed for two periods covering the warm season (summer–autumn), when free running mode was allowed (22 August–31 October 2021) and winter (9 January–15 March 2022), when active heating season was required. The weather data was obtained from the weather station in the center of Wrocław [22]. Temperature, relative humidity and carbon dioxide concentration loggers have been installed in each bedroom. HOBO MX1102A and Comet Vision U3430 meters with parameters listed in Table 2 were used. The parameters of the measuring devices are presented in Table 2.

Table 2. CO_2, temperature and relative humidity (RH) monitoring equipment used in the study.

	Data Logger HOBO MX 1102A	**Data Logger Comet Vision U3430**
Measuring range	Temperature: 0–50 °C RH: 1–90% CO_2: 0 ppm–5000 ppm	Temperature: −20–60 °C RH: 0–100% CO_2: 0 ppm–5000 ppm
Accuracy	Temperature: ±0.21 °C from 0 °C to 50 °C RH: ±2% from 20% to 80% typical to a maximum of ±4.5% including hysteresis at 25 °C; below 20% and above 80% ± 6% typical CO_2: ±50 ppm ± 5% of reading at 25 °C, less than 90% RH non-condensing and 1013 mbar	Temperature: ±0.4 °C RH: ±1.8% CO_2: ±(50 ppm + 3% from reading) at 25 °C and 1013 hPa
Resolution	Temperature: 0.024 °C at 25 °C RH: 0.01% CO_2: 1 ppm	Temperature: 0.1 °C RH: 0.1% CO_2: 1 ppm
Sampling interval	15 min	15 min

After a walk-through accompanied by the residents, magnetic reed switches were installed in the windows indicated as those used to ventilate the bedrooms. Magnetic reed switches developed and manufactured by Efento were used for the tests. In five houses, reed switches were installed directly in the bedrooms. In one house, a reed switch was installed in the corridor in the immediate vicinity of the bedroom, as according to the residents, the bedroom window is always kept closed overnight. The reed switches record information on the opening of the windows in a 5 min time step (information on the opening status of the window in successive 5 min periods, not the actual duration of the opening). Table 3 summarizes the basic information on the location of the measuring equipment and the operating mode of the ventilation system in the analyzed measurement periods, and Figure 1 shows their location in buildings. All sensors were located at the height 0.6–0.7 m above floor level.

Table 3. Measuring equipment and operating mode of the ventilation system in buildings.

House	Type of Data Logger	Magnetic Reed Switch Location	Ventilation Operation Mode	
			Warm Season Summer–Autumn 22 August–31 October 2021	Heating Season Winter 9 January–15 March 2022
NV1	HOBO MX1102A	corridor	NV	NV
NV2	Comet Vision U3430	bedroom	NV	NV
MV1	Comet Vision U3430	bedroom	MV	MV
MV2	Comet Vision U3430	bedroom	MV	MV
MV3	Comet Vision U3430	bedroom	MV	MV
HV1	HOBO MX1102A	bedroom	HV-NV	HV-MV

Figure 1. Location of measuring equipment: (**a**) NV1; (**b**) NV2; (**c**) HV1; (**d**) MV1; (**e**) MV2; (**f**) MV3.

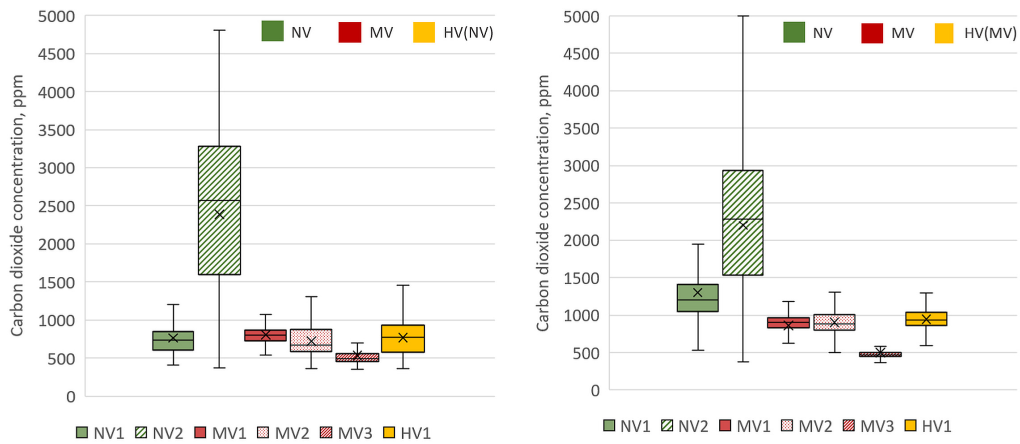
For the analyzed periods, the bedroom occupancy hours were assumed to be between 11 p.m. and 7 a.m. The registered air parameters were compared for the selected hours. In the next step, four periods covering three consecutive days were selected, for which a detailed profile of individual parameters was presented against the windows opening behavior.

The level of carbon dioxide concentration and the relative humidity (RH) in rooms were compared to the EN 16798-1 standard [23]. In terms of the level of CO_2, it classifies bedrooms in four IAQ categories depending on the internal increase in concentration in relation to the atmospheric air. The internal increase in value does not exceed 380 ppm for Category I and 950 ppm for Category IV. Assuming the average CO_2 concentration in the outside air is 400 ppm, it gives the final achieved concentration in the range of 780–1350 ppm. The EN 16798-1 standard does not classify residential buildings as requiring air humidification or dehumidification, however, for the purposes of this article, the measured values were compared with categories of rooms with controlled relative humidity. The highest Category I includes rooms with a RH from 30% to 50%, Category II from 25% to 65%, and the lowest Category III from 20% to 70%.

3. Analysis and Results

3.1. Carbon Dioxide Concentration

Figure 2 shows the concentration of carbon dioxide in bedrooms recorded in two measurement periods, between 11 p.m. and 7 a.m. During the warm period, three buildings were ventilated naturally and three were mechanically ventilated. In the cold period, two buildings were ventilated naturally and four mechanically (Table 3).



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

Figure 2. Bedroom carbon dioxide concentration, hours 11 p.m.–7 a.m.: (**a**) summer–autumn; (**b**) winter.

In the warm season, apart from the NV2 building, low levels of CO_2 concentration in the rooms were maintained. Average values for NV1, MV1, MV2, HV1 ranged from 763 ppm to 805 ppm, and for MV3 533 ppm. Maintaining the level I category according to EN 16798-1 was achieved 62% (NV1), 40% (MV1), 65% (MV2), 93% (MV3) and 51% (HV1) of the time. The periods of exceeding the level of IV category were much shorter—2% (MV1) and 3% (NV1). In MV2 and HV1, the period of exceeding class IV was <0.3% of the time, and in MV3, no exceeding was recorded. In the cold season, in mechanically ventilated buildings, CO_2 concentrations were lower than in the naturally ventilated NV1 building, but a general upward trend was observed in all buildings except MV3. Average values for MV1, MV2 and HV1 ranged from 861 ppm to 942 ppm, for NV1 it was 1299 ppm, and for MV3 it was 497 ppm. Class I maintenance was observed for 8% (NV1), 20% (MV1), 22% (MV2), 98% (MV3) and 10% (HV1) of the time. For all bedrooms with the MV system, the period of exceeding the IV category was $\leq$ 1%, while for the NV1 building it was 28%.

The maximum values of CO_2 concentration were recorded in the NV2 house. Regardless of the season, it remained at a very high level. The average value for the warm season was 2384 ppm, and for the cold season was 2197 ppm. Meeting the conditions of category I was achieved for 18% of measurements in the warm season and 12% of measurements in the winter. Exceeding the IV category was observed for 79% of the time, both in the warm and cold period. Several measuring points reached the value of 5000 ppm, which is the maximum recorded by the measuring device.

3.2. Temperature

Figure 3 shows the temperature in bedrooms recorded in two measurement periods, between 11 p.m. and 7 a.m.

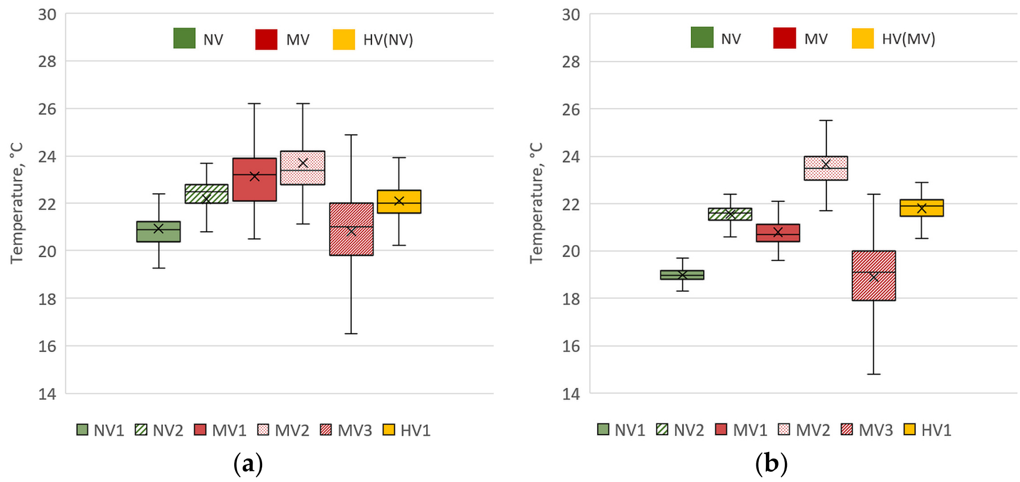


Figure 3. Bedroom temperature, hours 11 p.m.–7 a.m.: (**a**) summer–autumn; (**b**) winter.

The lowest average air temperatures in the bedrooms were recorded in the NV1 and MV3 buildings and are, respectively, 21.0 °C and 20.8 °C for the warm season and 18.8 °C and 18.9 °C for the winter season. The largest temperature fluctuations occurred in the MV3 building, which resulted from the frequent opening of windows by residents, discussed later in the study. The low average temperature in the NV1 bedroom has different contributing causes for each of two periods analyzed, with the exception of its ground floor location, previously linked with overall more stable and lower internal temperatures [16] than on higher floors. Otherwise, for the heating season, it was the NV1 residents' preference for lower temperatures than in the other five households that explains the lowest mean temperature in the sample. In the free-running season, two factors seem to underpin the NV1 indoor environment: architectural design (e.g., high thermal mass, relatively small window area) and residents' practices of keeping both internal bedroom doors open, thus allowing cross-ventilation into other cool spaces. Further analysis of the factors other than window opening within the bedrooms spaces is beyond the scope of this paper. The contribution of door opening is not represented in the window opening time analysis; however, it is possible that open doors together with the unsealing of the windows, not registered by the reed switch, is sufficient to ensure high air exchange in the room. The second room located on the ground floor is the NV2 bedroom, where the average temperature in the analyzed periods is close to 22 °C. Here, however, the sealing of the room for the night (both internal doors and windows) prevents proper air exchange, which is confirmed by the other recorded parameters. Similar internal temperatures in both seasons were maintained in the HV1 facility (approx. 22 °C). Bedrooms MV1, MV2, MV3 and HV1 are located on the 1st floor, of which MV2 is the only room with a window facing south. This results in the highest average temperature of 23.7 °C for both periods. The most pronounced differences in the measurement results for individual seasons were observed for bedroom MV1—the average of the warm period was 23.1 °C, and for the cold period was 20.8 °C.

3.3. Relative Humidity

Figure 4 shows the relative humidity in bedrooms recorded in two measurement periods, between 11 p.m. and 7 a.m.

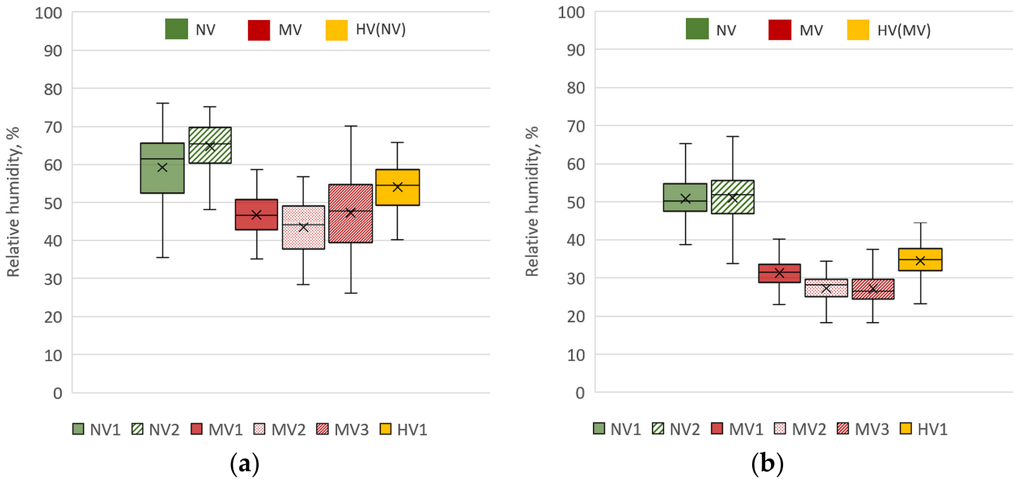


Figure 4. Bedroom relative humidity, hours 11 p.m.–7 a.m.: (**a**) summer–autumn; (**b**) winter.

Both in the warm and cold season, naturally ventilated bedrooms were characterized by higher values of relative humidity. This is most clear in the case of the NV1 and NV2 buildings, where the average relative humidity in the warm season was 59% and 65%, and 51% in the cold season for both buildings. The EN 16798-1 classifies rooms with normalization of relative humidity to the lowest, III category, if RH levels of 20–25% and 60–70% are observed. The lower and higher values went beyond the lowest class. NV1 and NV2 bedrooms would belong to the 3rd room category for 52% and 53% respectively in the warm season, while the time of moving beyond the lowest category was 5% and 24%. In winter, the relative humidity in these buildings was lower—exceeding 60% was observed for 2% and 3% of the time, and no measurements exceeding 70% was observed. There was also no relative humidity lower than 30% in any of the periods. In the HV1 building, which was also naturally ventilated at that time, the average relative humidity in summer was 54% and was higher than in buildings with the MV system. The period of exceeding the relative humidity of 60% in the warm season was 18% for HV1, and no measurements exceeding 70% were recorded.

In the MV bedrooms, the average relative humidity in the warm season ranged from 44% to 47%, and in the cold season from 27% to 31%. Category III in this period was observed only in the MV3 building for 13% of the warm season, and in the cold season in the MV2 and MV3 buildings for 2% of the measurement period. However, the time of failure to maintain the relative humidity of 30% was long—in the MV1, MV2 and MV3 buildings, it was, respectively, 34%, 80% and 80% of the time. In the HV1 building, mechanically ventilated at that time, the RH was higher and amounted to 35%. No relative humidity <20% was observed, and the values of 20–30% represented only 13% of the measuring points. The MV1, MV2 and MV3 buildings were equipped with air handling units with plate heat exchangers; only in the HV1 building was there an air handling unit with a rotary heat exchanger, which enables partial transfer of moisture between air streams.

3.4. Residents' Behavior

Figure 5 shows the share of registered window opening cycles in two analyzed measurement periods. The applied reed switches register whether a window is in the closed position for each 5 min cycle. They record "alarm" whenever a window is open wide, slightly tilted or only its air tightness is released. No indication of opening time is recorded. Presented results show how many of all cycles were those during which the window opening state was recorded. It is not a precise information about the duration of the opening, but it illustrates the trend in the behavior of householders, which affects the above-mentioned measurement results.

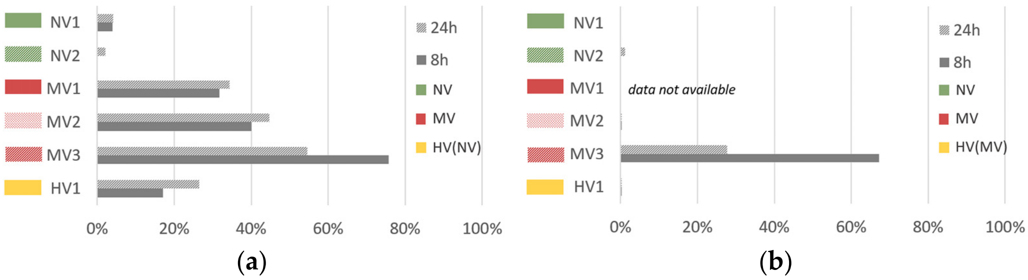


Figure 5. Share of cycles with an open window: (**a**) summer–autumn; (**b**) winter.

In the warm period, the lowest number of window opening cycles was recorded in bedrooms NV1 and NV2. The inhabitants of these buildings also did not open their windows in the winter season. These buildings are naturally ventilated and the windows are not equipped with air inlets. NV1 and NV2 bedrooms have the largest cubature of all analyzed rooms and are the only ones on the ground floor. In the warm season, only 2% of opening cycles were registered in the NV2 building throughout the day, almost none of which occurred at night (<0.1%). The behavior of the inhabitants is clearly reflected in the measurement results, especially in the concentration of CO_2 and relative humidity. In the NV1 building, window opening cycles in the warm season accounted for only 4%, but most of it took place at night. During the cold season, the inhabitants of the NV1 building occasionally opened their windows during the day (<0.1%), but no opening was recorded during the night. The results of CO_2 concentration measurements in this room did not differ so drastically from other buildings, but the level of relative humidity was high. In the HV1 facility, which was naturally ventilated in the warm season, the share of window opening cycles throughout the day was 26%, while 17% were at night. In addition, no drastic differences in the concentration of CO_2 were observed here, and the relative humidity level, compared to other measurements, had an average value. The largest number of window opening cycles was recorded in continuously mechanically ventilated buildings. In the warm season, in MV1 and MV2 buildings, window opening was recorded in 33% and 45% of measurement cycles during the day and in 32% and 40% of night cycles. Interesting results were observed in the MV3 building. The share of window opening time here was the highest of all buildings, and mostly concerned the night time. In the warm season, the opening cycles accounted for 55% of the entire day and 76% of the night time. In winter, it was 28% and 67%, respectively. The behavior of users is reflected in all previous results of internal parameters measurements—the lowest observed CO_2 concentrations and its slight fluctuations, the largest temperature fluctuations and its drops to a value deviating from what is commonly considered comfortable, and significant fluctuations in relative humidity in the warm season. In the cold season, smaller fluctuations in the internal relative humidity result from slight fluctuations in the moisture content in the external air. In summer, fluctuations in the moisture content in the outside air are greater, and these phenomena are typical for the Polish climate.

3.5. Daily Variability of Registered Parameters

Figures 6–9 show the detailed variability of the recorded parameters in selected periods lasting three consecutive days. The selection of the dates was based on the assessment of internal conditions. Periods selected:

- warm season, high value of the external temperature T_e and significant fluctuations between the time of day and night: $T_{e,max}$ = 29.2 °C, $T_{e,min}$ = 7.6 °C (Figure 6),

- warm season, smaller fluctuations in external temperature T_e between day and night: $T_{e,max}$ = 24.5 °C, $T_{e,min}$ = 12.1 °C (Figure 7),
- mild season, small fluctuations in external temperature between day and night: $T_{e,max}$ = 16.1 °C, $T_{e,min}$ = 2.6 °C (Figure 8),
- cold season, the lowest recorded temperature values: $T_{e,max}$ = 3 °C, $T_{e,min}$ = −8.3 °C (Figure 9).

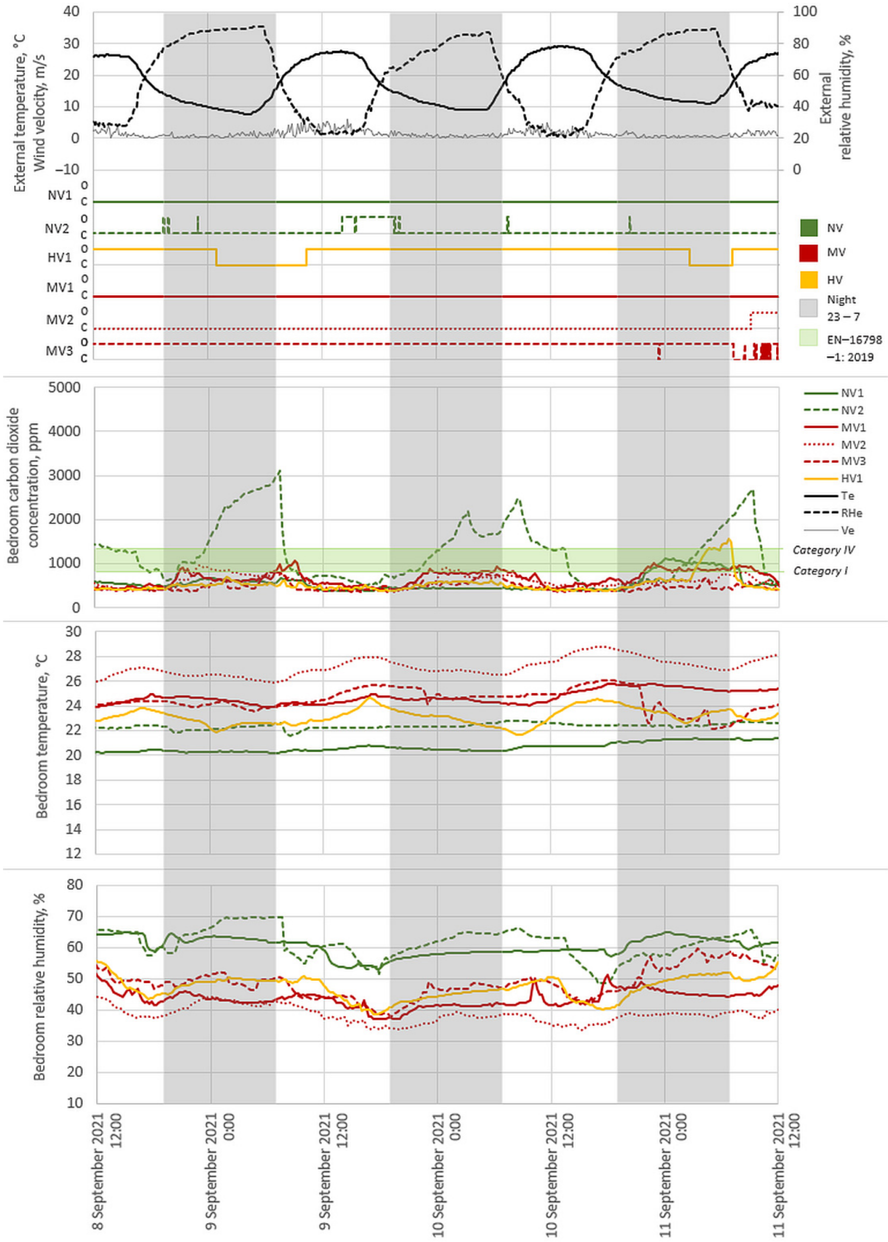


Figure 6. Detailed variability of the measured parameters over the period 8–11 September 2021.

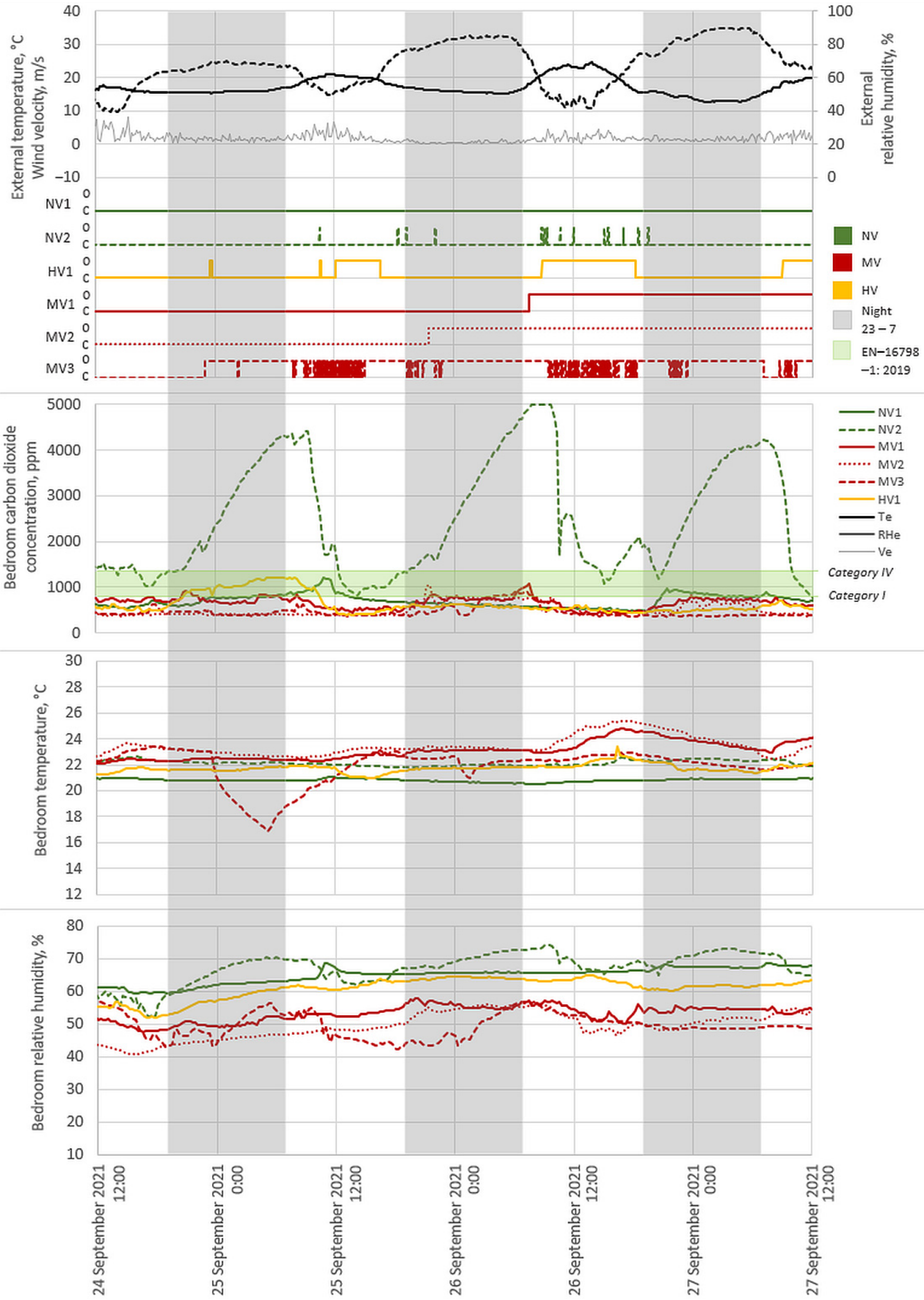


Figure 7. Detailed variability of the measured parameters over the period 24–27 September 2021.

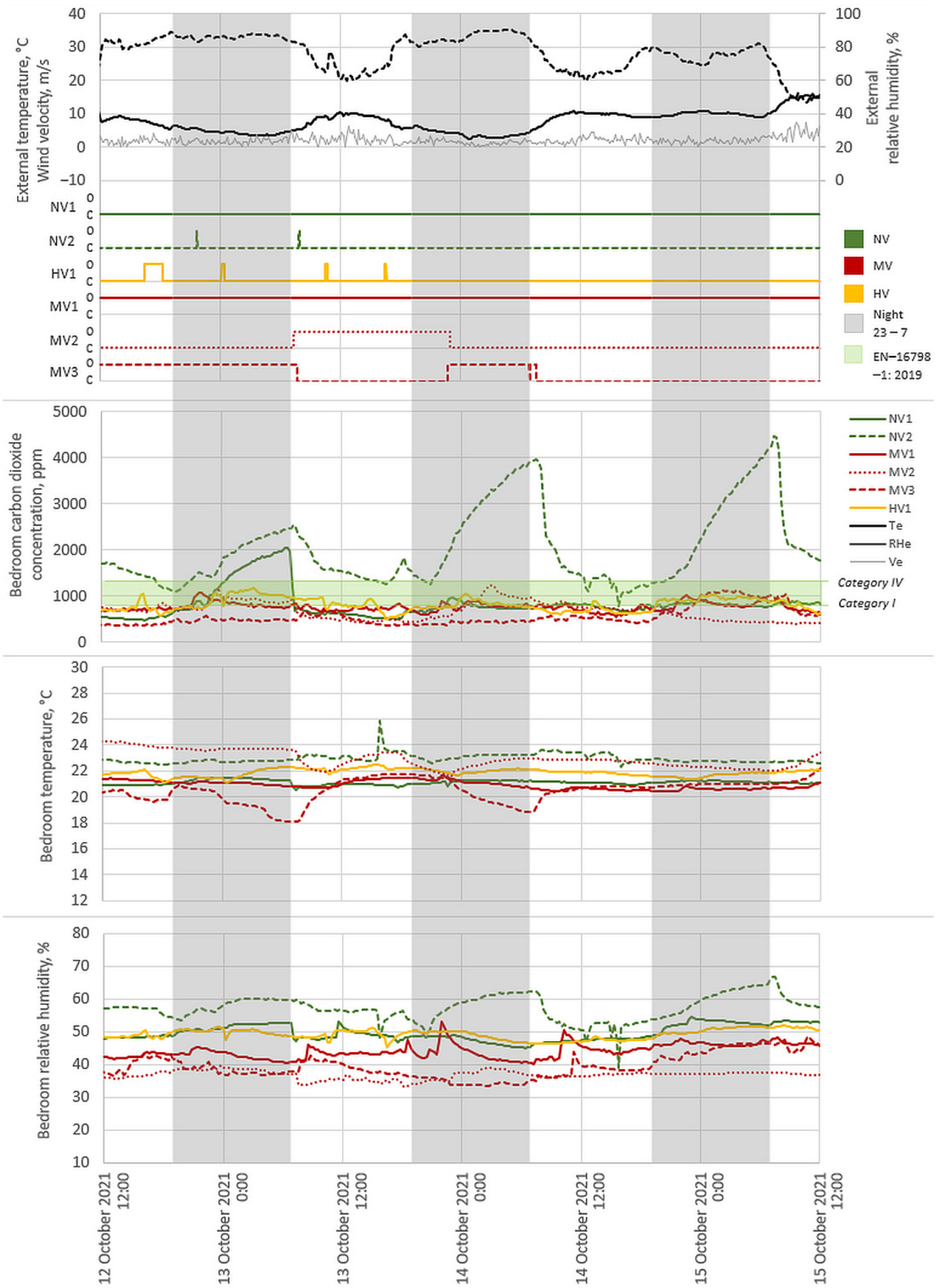


Figure 8. Detailed variability of the measured parameters over the period 12–15 October 2021.

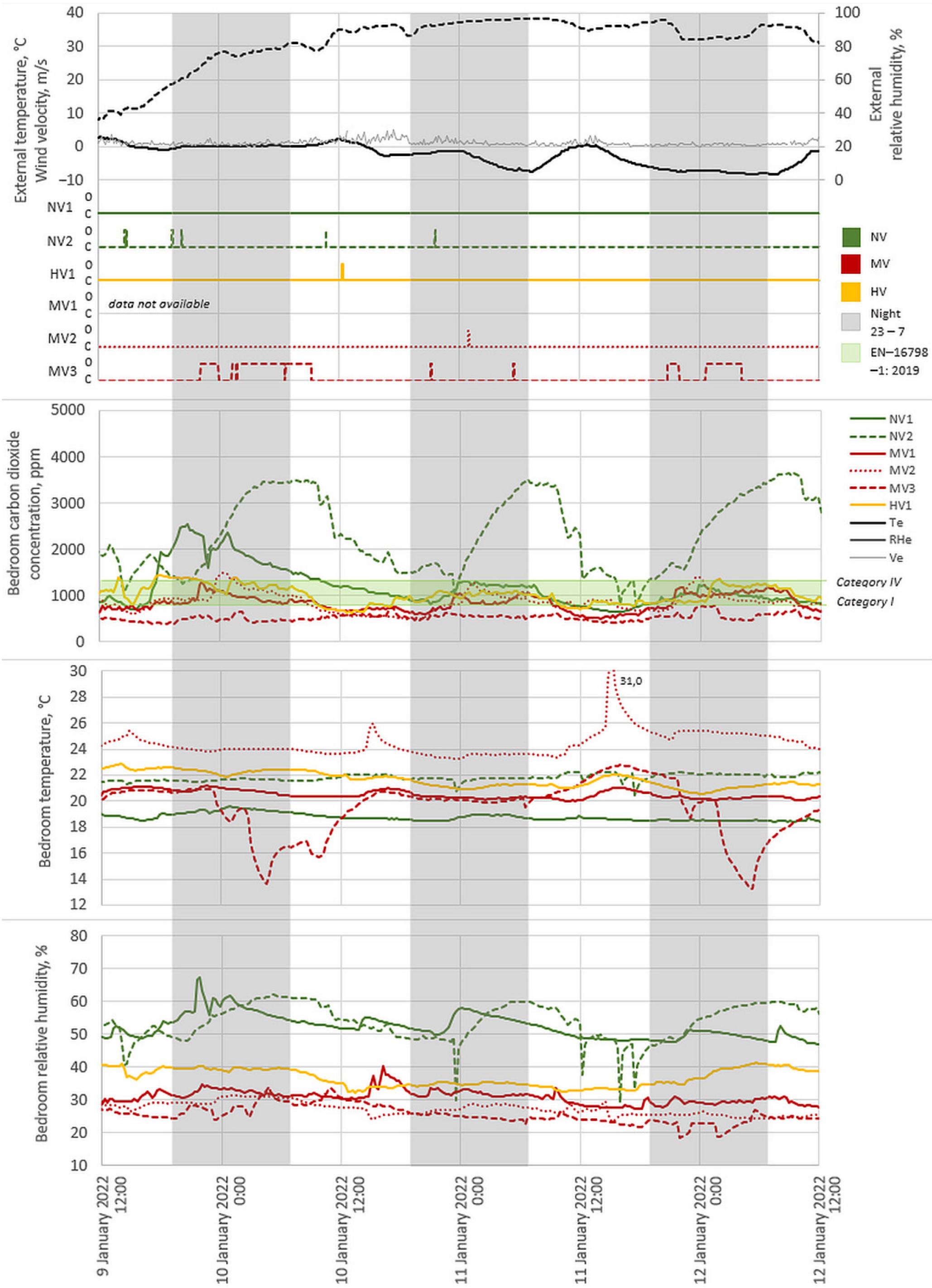


Figure 9. Detailed variability of the measured parameters over the period 9–12 January 2022.

For selected periods, the reaction of residents to changing external and internal conditions was analyzed. Symbols on the chart "O" and "C" next to the names of objects mean the position of the window "open" and "close".

During the period of the highest recorded values of the outside air temperature (Figure 6), the windows in the NV1, MV1 and MV2 buildings were closed. The residents' reaction to changing external conditions were not observed. The residents of MV2 did not use the window to cool the bedroom naturally, despite the high temperature inside. In the NV2 bedroom, a temporary window opening was observed during the night periods and one longer period of opening during the daytime. The inhabitants undertook actions that were likely to improve the internal conditions, but the procedure did not bring tangible results. Windows remained closed even at high CO_2 and relative humidity levels. In the HV1 building, the window was open for most of the period, but the reaction of the residents to the drop in temperature in the room was recorded—when the internal temperature dropped to approx. 22 °C at night, the window was closed. This resulted in a significant increase in CO_2 concentration on the morning of 11 November 2021. In the MV3 building, the window was mostly open. In the morning hours of 11 November 2021 there were problems with the reed switch. This period was excluded from the window position data analysis.

During the warm period with a lower amplitude of the external air temperature (Figure 7), the windows in the NV1, MV1 and MV2 buildings still remained in the closed position. The temperature in the rooms decreased compared to the previous period, so the energy accumulated in the building during warm periods was partially discharged. In the NV2 building, no changes in the behavior of users were observed—short periods of window opening occurred mainly during the day, with no reaction of residents to deteriorating internal conditions. In the HV1 building, the residents actively reacted to the changing external conditions. They chose not to open the window at night, but the CO_2 concentration was in the range of category IV. The MV3 reed switch indications were once again partially excluded from the analysis, but it can be noticed that a significant drop in internal temperature did not cause any reaction in the inhabitants.

During the mild period with a small amplitude of the outside temperature (Figure 8), most of the windows remained closed. Longer periods of opening were registered only in the buildings MV2 and MV3. Concentrations of CO_2 in closed spaces, apart from NV2, increased, but still allowed at least category IV to be maintained. The conditions in the NV2 bedroom did not change significantly, but a reduction in the number of cycles of airing the room was observed.

During the period of the lowest recorded values of outside air temperature (Figure 9), most windows remained closed. Due to the failure of the reed switch, no data on the opening of the MV1 bedroom window are available, but the lack of significant drops in the internal temperature suggests that it was also closed. During this period, the HV1 building operated in the mechanical ventilation mode, which had a noticeable effect on the reduction of window opening times. In the MV3 mechanically ventilated bedroom, the windows were still partially open despite periodic drops in the internal temperature to approx. 14 °C, but these periods were significantly shortened. In addition, no apparent changes in user behavior were recorded.

4. Discussion

Case studies were conducted on a small group of carefully selected sample buildings [24]. As such, they provided a chance to explore the rich context underpinning observed measurements, but they do not allow for drawing universal conclusions that can be fully translated into the entire typology of single-family buildings. However, the dependencies observed during the analyses confirm and build on the results recorded by scientists in other countries and other climates, concerning the significant impact of the way the building is used on the internal conditions it achieves.

Research on internal conditions in bedrooms ventilated with various systems, both mechanical and natural, was presented by Sekhar, Bivolarova et al. [25]. On the basis of measurements carried out during the heating season, they noticed that in a naturally ventilated bedroom, the concentration of CO_2 was usually 2.5–3 times higher than in a mechanically ventilated bedroom. Mechanical ventilation guaranteed good air mixing and dilution of CO_2 concentration to the level of approx. 1000 ppm. They also analyzed the influence of door opening and closing on the air exchange rate. In a naturally ventilated bedroom, despite the use of air inlets, this coefficient was very low and amounted to $<0.15\ h^{-1}$ with the door closed and $0.3\ h^{-1}$ with the door open. For a mechanically ventilated bedroom it was $0.6\ h^{-1}$.

The results of tests in the cold period presented in the article also covered the heating period. The CO_2 concentrations observed in the two naturally ventilated bedrooms (NV1, NV2) exceeded the values observed in all buildings with MV. In the NV1 building, the average value was approx. 1.5 times the value for MV1, MV2 and HV1 buildings, and the period of maintaining at least category IV lasted over 70% of the registered time. In the NV2 building, the average value of CO_2 concentration was approx. 2.5 times the value for buildings with MV1, MV2 and HV1, and the maintenance period of at least category IV was only approx. 20% of the registered time. In mechanically ventilated bedrooms, the maintenance period of at least category IV was over 99% of the time, which proves the higher efficiency of air exchange by MV systems. The values observed in the MV3 building differ from other mechanically ventilated rooms, which is related to the frequent opening of the windows, as shown in Figure 5. Apart from the higher CO_2 concentration in the NV buildings, there are also diametrical differences between recorded values in NV1 and NV2. The observed discrepancies confirm the fundamental influence of the way the interior is used and the awareness of the inhabitants. The broad range of CO_2 concentrations in naturally ventilated interiors confirms the results also observed in other studies [26–29].

Information on the internal environment and the opening of windows in naturally ventilated bedrooms was also provided by Heide, Skyttern and Georges [30]. For 10 bedrooms located in six detached houses in Trondheim, they measured temperature, relative humidity, CO_2 concentration, particulate matter, formaldehyde and TVOC. The research was conducted in March and April. Most of the bedroom windows were open during the research. CO_2 concentrations exceeding the external concentration by over 950 ppm (category IV) were observed only in two bedrooms, and it lasted for 70% and 80% of the night period (the analyzed time range was 23:00–6:00). In the remaining bedrooms, the exceedance time was shorter and amounted to 10% or less. Six bedrooms had an average daily temperature of <18 °C, and the remaining four were >21 °C. Among the cooler bedrooms, the mean RH varied between 32% and 49%, while in three of the four warmer rooms it was <20%.

The research results for the warm period presented in the article also show a low level of CO_2 in the bedrooms, regardless of the ventilation system. The maximum observed time of exceeding the IV IAQ category was 3%. The exception is the NV2 facility, where the lowest category was not met for almost 80% of the time, and the problem was probably the lack of awareness of its inhabitants. The values of temperature and relative humidity do not meet the comparative conditions due to the discrepancy in the analyzed seasons. These parameters can be compared with the summary of the analysis by Sekhar, Akimoto et al. [6]. The authors found that in the analyzed bedrooms, the internal temperature range in the heating season was from 20 °C to 25 °C, and in the cooling season from 25 °C to 30 °C, with the greatest temperature variation occurring in facilities ventilated in a natural way. Relative humidity ranged from 40% to 80%, and the differences between the heating and cooling seasons were less pronounced. In the presented case study, the average indoor temperatures ranged from approx. 19 °C to approx. 24 °C in the heating season and from approx. 21 °C to approx. 24 °C in the warm season (but mostly outside the cooling season). Average values of relative humidity for the heating period were from 27% to approx. 50% in the heating season and from 43% to 65% in the warm season.

Satisfactory results of hybrid ventilation bedroom measurements provide the basis for further research on the validity of using such a solution, as global studies [31–36] show a significant impact of the use of natural ventilation in various climates on reducing energy demand and internal comfort.

5. Conclusions

This field study covered six energy efficient houses in and around Wrocław, Poland. Several key conclusions emerged:

- the fact that a bedroom is ventilated by natural means is not synonymous with the impossibility of maintaining a high-quality internal environment; other important factors are the heating season, bedroom size and door opening behavior,
- maintaining a high-quality internal environment using natural ventilation is, however, more reliable in warm and transitional periods,
- natural ventilation of rooms may increase the relative humidity to a level deviating from comfort standards, and carries the risk of the development of pathogenic organisms (e.g., fungi, mold),
- mechanical ventilation of rooms may cause the relative humidity to drop below the standard of comfort conditions,
- it is possible to effectively ventilate rooms with the use of hybrid ventilation systems, combining mechanical and natural systems in the "change-over" mode,
- effective natural ventilation of rooms requires knowledge, awareness and taking up activity by the residents,
- mechanical ventilation systems are more consistent in shaping the internal environment of a bedroom and are more resistant to the passivity of residents,
- the habits and preferences of the residents in many cases do not correspond to the activities expected for a given building standard.

The conducted analyses also allowed for the formulation of questions, and the answers to them will be sought during further exploration of the issue:

- Is it possible to determine which of the internal parameters is the main trigger of the residents' adaptive behaviors?
- What is the impact of active residents' responses to improve the quality of the indoor environment on the buildings' energy consumption?
- How does a hybrid ventilation system perform compared to mechanical or natural one in terms of household internal air quality and energy consumption?
- What is the influence of the location of the room in the building, and its location in relation to CO_2 emission sources, on the observed measurement results?
- What non-technical factors underpin residents' practices related to IAQ control in the bedrooms?
- Does the use of a rotary heat exchanger for heat recovery avoid unfavorable drops in internal relative humidity during the heating season?

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