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An Experimental Study of Thermal Comfort and Indoor Air Quality—A Case Study of a Hotel Building

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Abstract: Ensuring the comfort and health of occupants is the main objective of properly functioning building systems. Regardless of the season and building types, it is the priority of the designers and building managers. The indoor air parameters affect both the well-being and health of users. Furthermore, it could impact the effectiveness of their work and concentration abilities. In hotel facilities, the guests' comfort is related directly to positive opinions or customer complaints, which is related to financial benefits or losses. The main goal of this study is the analysis of the indoor environmental quality in guests' rooms, based on the example of a hotel in Poland. The article assesses the variability of air parameters, including temperature, humidity, and carbon dioxide concentrations, and the acceptability of indoor conditions. The research was carried out in November 2020. Based on the collected data, the dynamics of changes of selected air parameters were analyzed. The article analyzes the comfort indicators inside guest rooms, including the Predicted Mean Vote (PMV) and Predicted Percentage of the Dissatisfied (PPD) index. The obtained results were compared with the optimal conditions of use to ensure the guests' comfort. As the analysis showed, the temperature and humidity conditions are maintained at a satisfactory level for most of the time. It was noticed that the CO_2 concentrations temporarily exceeded the value of 2000 ppm in two of the analyzed guests' rooms, which could cause discomfort to hotel guests. In these rooms, the increase in the volume of ventilation airflow should be considered. The measured parameters dynamically varied over time, and there was no repeatability or clear patterns of variation. This is due to the individual preferences and behavior of users. A detailed analysis is extremely difficult due to the possibility of opening windows by users, the irregular presence of hotel guests in the rooms, and the inability to verify the exact number of users in the room during the measurements.

Keywords: indoor environmental quality; thermal comfort; air quality; carbon dioxide concentration

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1. Introduction

Indoor environmental quality (IEQ) is essential for people's health, well-being, and work performance. It is especially relevant due to the high percentage of time spent indoors by the average person [1,2]. IEQ depends on many factors, including air quality, temperature and humidity conditions, and lighting [3,4]. The indoor environment is very complex, and building occupants may be exposed to variations in parameters that define thermal comfort and air quality.

Thermal comfort is a state in which a person feels that their body is in a heat balance, i.e., does not feel hot or cold. The assessment of thermal comfort is very complicated because of the number of environmental and personal factors that can affect it. There are seven main factors to include when considering human thermal comfort: air temperature, humidity, radiation temperature, air velocity, metabolic heat related to the activity, clothing insulation, and adaptation possibilities [5]. The calculation of the heat exchange between the human body and its environment is a basis of thermal comfort evaluation. Therefore, the balance equations of heat gains and losses should be built and solved for the analyzed case. It should be preceded by measuring or assuming the physical quantities that characterize the case. For the purpose of simplifying analyzes, thermal comfort indices are used [6,7]. Indices have been developed using heat-balance equations as a function of the parameters describing the human–environment system. The result of the analysis using the thermal comfort indices is a number that indicates the level of thermal comfort or discomfort in the assumed scale. It is calculated based on factors that influence thermal comfort. The classification introduced by McPherson [5] allows three categories to be distinguished based on the measurement of physical factors, physiological strain, and the calculation of heat exchange. Another division has been proposed by Parson [8]. The classification includes three categories: empirical, which is based on a collection of user opinions; rational, which uses calculations of heat exchange between the body and the environment; and direct indices responding to parameters influencing thermal comfort.

One of the most popular indicators of indoor thermal comfort is the Predicted Mean Vote (PMV). Indicator PMV predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale (−3, cold; −2, cool; −1, slightly cool; 0, neutral; +1, slightly warm; +2, warm; +3, hot) [9]. The PMV model is based on a thermodynamic equilibrium between users and their immediate thermal environment. It assumes that, for the users' comfort, the amount of generated heat by the body should be balanced by the amount released to the environment through radiation, convection, and conduction. The primary purpose of the PMV index is to determine the average thermal impression score for a group of people. It is calculated based on four physical parameters (air temperature, humidity, air velocity, and mean radiant temperature) and two personal factors (clothing and activity). Analytically, the value of this parameter can be calculated with Equation (1) [10]:

$$PMV = (0.303 \cdot e^{(-0.036 \cdot M)} + 0.028) \cdot \left\{ \begin{array}{c} (M-W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M-W) - p_a] - 0.42 \cdot \\ [(M-W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot \\ [(t_{cl}+273)^4 - (t_{rm}+273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{array} \right\} \quad (1)$$

where:

M—the metabolic rate (W/m^2);
W—the external work (W/m^2);
p_a—the partial vapor pressure (Pa);
f_{cl}—the ratio of the area of the body covered by clothing to the area of the exposed body;
h_c—the convective heat transfer coefficient;
t_{cl}—average temperature of the human body surface covered with clothing (°C);
t_a—the air temperature (°C);
t_{rm}—the mean radiant temperature (°C).

An inherent element of thermal comfort assessment using PMV is the determination of the Predicted Percentage of Dissatisfied (PPD) index. It complements the analysis by the estimated percentage of occupants dissatisfied by the thermal conditions in the analyzed space. Based on statistical research, the relationship between PMV and PPD was created, as it is presented in the diagram in Figure 1. The minimum value of the PPD index is 5%, which means that it is not possible to adjust the parameters inside the room to satisfy all occupants.

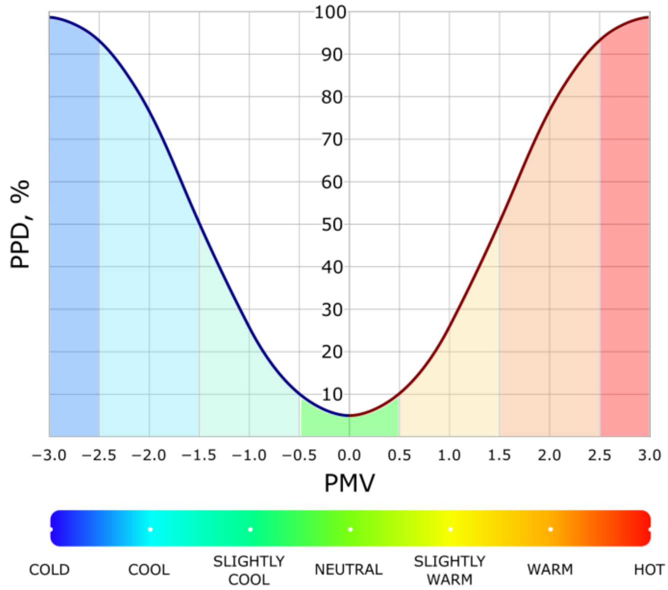


Figure 1. Graphical interpretation of the relationship between PMV and PPD.

The relationship between these two coefficients can be determined directly using Equation (2):

$$PPD_{PMV} = 100 - 95 \cdot \exp\left(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2\right) \quad (2)$$

There are also studies of perceived air quality (PAQ) based on the air enthalpy. Fanger found a linear relationship between the acceptability of conditions and the enthalpy of air at different levels of pollution [11,12]. For empirical research, a three-level scale was used, where +1 means "clearly acceptable" conditions, 0 corresponds to the assessment as both "just acceptable" and "just unacceptable", and the value −1 describes the conditions as "clearly unacceptable". The acceptability of the conditions can be determined using Equation (3):

$$Acc = a \cdot h + b \quad (3)$$

where h is the air enthalpy expressed in kJ/kg, and the coefficients a and b depend on the source of pollution in the room. In further calculations, the coefficients for clean air were used, where $a = -0.033$ and $b = 1.662$ [11], while the percentage of dissatisfaction on this basis may be calculated from the dependence in Equation (4) [12,13]:

$$PPD_{Acc} = \frac{\exp(-0.18 - 5.28 \cdot Acc)}{1 + \exp(-0.18 - 5.28 \cdot Acc)} \cdot 100 \quad (4)$$

There are many standards and guidelines regarding thermal comfort. On an international scale, standards for the parameters of the internal environment, such as ASHRAE Standards 62.1 [14] and 62.2 [15], ASHRAE Standard 55 [9], and International Standards EN 16798-1: 2019 [16] and ISO 7730 [10], are commonly used. According to standard EN 16798-1: 2019 [16], four categories of rooms can be distinguished depending on various environmental criteria. Category I includes spaces with a high level of expectation and are recommended to be occupied by very sensitive and fragile persons with special requirements. Rooms with a medium level of expectation are applied for most buildings and are included in category II. Category III represents the moderate air quality level that could affect the performance of users. Additionally, category IV includes values that represent the poor quality of spaces that are occupied for short periods. For each of the described categories, the recommended ranges for the PMV and PPD ratios were defined. Table 1 presents detailed information.

Table 1. Indoor Environmental Quality categories for thermal comfort requirements for residential building and living spaces with sedentary activities [16].

Cat.	Applicability	PPD	PMV
I	High expectation of good quality (this level should be considered when occupants have special needs, for example small children, elderly people, or people with disabilities).	<6	$-0.2 < PMV < +0.2$
II	Medium expectation of good quality (this level is the normal situation that should be applied for buildings).	<10	$-0.5 < PMV < +0.5$
III	Moderate expectation of good quality (while acceptable IAQ will still be delivered, there is an increased risk of IAQ sometimes affecting occupant performance).	<15	$-0.7 < PMV < +0.7$
IV	Low expectation of good quality (should only be considered for building areas that are only occupied for short periods of time, only by a small fraction of building occupants or only during exceptional circumstances that do not occur for prolonged periods).	<25	$-1.0 < PMV < +1.0$

The cleanliness of the supply air is one of the basic parameters of air quality, especially in industrial and urbanized areas. Users should not feel unpleasant odors or be exposed to air pollution indoors. At the design stage of installation, the potential sources of pollution and their harmfulness to the human body are analyzed. All contaminants in the room should be identified, eliminated, or minimized and their amount should be minimized. The assessment of air quality is based on the measurement of the concentration of pollutants in the room. Particulate matters have detrimental effects on human health. These fine pollutants could irritate mucous membranes and cause dermatitis and problems of the respiratory system. One of the most popular gaseous pollutants that characterizes the air quality is carbon dioxide [17]. This component is an inseparable element of the respiration process, and its concentration in the internal air is not a constant value. The concentration of CO_2 may vary in time. The main factors that can affect it are the airtightness of the room, the number of users, and the type of ventilation. It is a relatively easy-to-measure substitute for indoor pollutants and correlates with human metabolic activity. A high concentration of carbon dioxide causes the exchange of air in the lungs to happen more frequently and may cause an increase in blood pressure and heart rate as well as being able to cause drowsiness, headaches, concentration drops, human perception changes, and overall malaise. The prolonged stay in a room with a high concentration of carbon dioxide may be accompanied by headaches, watery eyes, and even nausea. The concentration of carbon dioxide in the atmospheric air is 0.04% and a concentration above 2.5% may cause harmful effects for users. In the literature, the concept of "Pettenkofer number" [18], i.e., the concentration of carbon dioxide in the room, which is acceptable for hygienic reasons, is defined. Max Joseph von Pettenkofer claimed that poor indoor air quality is not the cause of diseases, but it impairs human immunity and, consequently, increases the possibility of disease. To assess indoor air quality, Pettenkofer used carbon dioxide concentration measurements. CO_2 was supposed to reflect the content of other harmful substances for humans. Pettenkofer believed that a carbon dioxide concentration above 1000 ppm is not suitable for users. For permanent occupancy, the CO_2 concentration should not exceed 700 ppm. As described above, the standard EN 16,798 [16] presents the division of a building into four categories depending on the degree of comfort, expectations, and set requirements. Table 2 below shows the recommended design increase of the carbon dioxide concentration in the room above the outdoor concentration for all buildings categories. Values were proposed both for living rooms and bedrooms. These values are used to calculate energy balances and regulate the ventilation system.

Table 2. Building categories and recommended design of an increase in CO_2 concentration in the room air above the level outside the building [16].

Category	Design ΔCO_2 for Living Rooms, ppm	Design ΔCO_2 for Bedrooms, ppm
I	550	380
II	800	550
III	1350	950
IV	1350	950

The ASHRAE Standard 62.1 [14] also notes the risk to users' health connected with high CO_2 concentrations. In the case of sedentary work (activity level of 1.2 met), the CO_2 generation rate is 0.31 L/min. Research measurements have shown that, for sedentary persons, a supplied airflow of 7.5 L/s per person could dilute bio-odors to a level that satisfies about 80% of users. This airflow also allows maintaining a steady-state CO_2 concentration in a space no greater than about 700 ppm above outdoor air levels. Typically, the concentration of carbon dioxide in the outside air is 300–500 ppm. High levels may indicate an imminent source of contamination. The document assumes that a carbon dioxide concentration in the range of 1000–1200 ppm ensures user satisfaction concerning air freshness.

Fanger [19] proposed a relationship between the percentage of dissatisfied people and the concentration of pollutants. The relationship between PPD and the concentration of CO_2 in the air can be determined by Equation (5) [20]:

$$PPD_{CO_2} = 395 \cdot e^{\left[-15.15 \cdot (\Delta C)^{-0.25}\right]} \tag{5}$$

where ΔC is the difference between indoor and outdoor carbon dioxide concentration in ppm. The assumed CO_2 concentration in the atmospheric air was at the level of 400 ppm.

The topic of users' comfort and the variability of indoor parameters is often discussed in the literature [21,22]. Buildings with different functionalities, structures, and in many different climates are analyzed in these papers. Interesting results, on the example of a commercial passive office building with a thermally activated system, are presented in the article by Michalak [23]. Based on measurements taken during standard operation, the authors presented an analysis of thermal comfort parameters, including the vertical temperature profile, floor surface temperatures, and the PMV and PPD index. The research confirmed that good thermal conditions were maintained. A detailed analysis of the measurement data showed the possibility of overheating, resulting in unnecessary cooling increasing operating costs. Measurements in this area are also often carried out in medical facilities [24], where internal conditions are crucial for limiting the spread of viruses and bacteria and the quick recovery of patients. Increased interest can also be observed in the indoor air quality of educational facilities [25–29]. As numerous studies showed [30–32], improper indoor air conditions, including temperature, humidity, and carbon dioxide concentration, could affect the concentration ability, learning performance, and creativity of students. The results of the research by Vimalanathd and Ramesh Babu [33] showed that both temperature and lighting influence the productivity of office workers. Interesting measurements were also carried out in historical buildings [34–38]. In these cases, the modernization and changes of the building structures are extremely limited due to historical values and cultural heritage. Increasingly, artificial intelligence (AI) methods [39–41] can be found as a competitive approach to the analytical method of comfort analysis using well-known relationships. Karyono et al. [42] proposed an adaptive approach using AI to minimize errors resulting from individual preferences, behavior patterns, and metabolic variability. According to the authors, including differences in the thermal comfort requirements between different groups of people (young, elderly, disabled, and sick) is one of the advantages.

The problem of designing installations in hotel facilities is related to the unevenness and difficulty in determining the occupancy level of the rooms. The subject of air parameters control and thermal comfort in hotel buildings has already been discussed in the literature [43–52]. A properly functioning ventilation system in a hotel should ensure air exchange and maintain comfort conditions for users. It should provide appropriate conditions, but, at the same time, be profitable from an economic point of view. The comfort of the hotel's customers is strictly determined by the parameters of the air in the rooms, including its thermal parameters and air purity. It is crucial to provide a fresh air stream and maintain thermal comfort parameters. One of the essential issues during the design stage is to propose an appropriate solution for hotel rooms. These are the crucial spaces for customers expecting a high standard and comfort of use [43]. Kim et al. [44] characterized the variations in the indoor temperature and humidity profiles of changes in twenty guest rooms in a case-study hotel in Washington. The research included one-minute temperature, relative humidity, and occupancy measurements. The authors noticed that the implementation of uniform, steady temperatures across all guest rooms caused uncomfortable conditions in some periods. This is due to the different dynamic heat balance of the twenty guest rooms, which resulted from the combined effects of several factors, such as the location of the guest rooms, ventilation rates, vacant periods, other conditioning mechanisms, and external weather conditions. This potential discomfort was also identified from the collected thermal comfort survey. During the heating season, about 57% of the surveyed discomfort sources were related to the thermostat, including the mechanical system not responding quickly to the thermostat changes. Kuo et al. [45] identified four major problems of one five-star international hotel in Taiwan based on the comprehensive IAQ audit of the guest rooms. The measurements included ambient temperature, relative humidity, and air velocity. In addition, chemical and biological indicators, e.g., the concentrations of carbon dioxide, suspended particulate matter, and formaldehyde, were measured. The authors noted that, with a high outside temperature (over 30 °C), the temperature in the rooms is significantly low. Moreover, the air exchange rate was insufficient, and formaldehyde contamination and microbial pollution were too high. Research in hot climates was also carried out by Sahid et al. [46]. The indoor air temperature of the observed five hotels was between 28.85 °C and 29.54 °C, while the outdoor air temperature was in the range between 28.42 °C and 40.52 °C. This study was conducted in five hotels and both questionnaires for guests and measured instruments indoor were used. The authors noticed that the layout of the hotel building had an impact on the difference in air temperature. Furthermore, solar radiation influences the occurrence of temperature changes in the rooms. A 4-star hotel building in Portugal was used for a comprehensive IAQ audit by Asadi et al. [47]. The proposed approach included the measurement of physical parameters and the monitoring of the concentrations of selected chemical and biological indicators. Four of the main observed problems included insufficient ventilation rate, poor filtration effectiveness, high particle concentration, and Legionella contamination of the sanitary hot-water circuit. Surveys completed by guests are a frequently used method of assessing the quality of the environment in hotel facilities [46,48–51]. The paper by Shen et al. [48] aimed to identify IEQ problems in budget hotels in China by improving indoor conditions. The analysis was based on the online review data collected on the reservation website. According to the results, the IEQ complaint rate is very high, with criticisms being mostly related to acoustic parameters. The authors also noted the impact of the seasons and climate zones on the complaints about environmental quality.

The present article presents an analysis of the air parameters, including temperature, relative humidity, and carbon dioxide concentration, in hotel rooms of a building located in southern Poland. The considerations are based on experimental measurements carried out in the normal operating conditions of the facility in November 2020.

2. Materials and Methods

2.1. Investigated Building

The hotel building is an accurate recreation of the historic Turówka saltworks, including the shape of the body and dimensions in the outline. The parameters of the windows and the thickness of the walls are also similar to the original dimensions. The building materials used aimed to recreate the building as accurately as possible. Due to the historical character of the building, all modernization actions were carried out under the supervision of the conservator. The facility consists of four above-ground stories and an underground. The usable area of the hotel facility is 4620.00 m^2, with a built-up area of 1370.00 m^2. The total volume of the building is 19,300.00 m^3. Ventilation is provided by several air handling units, operating the rooms with similar functionality. The air handling unit for hotel rooms is equipped with a regenerative counter-flow exchanger with controlled humidity recovery. The air is supplied to individual zones using separate systems. Grouping was based on the functional and technological aspects of the rooms. The ventilation system works in a balanced mode. Air handling units do not recirculate the air and conditions 100% outside air. In the case of the system for guests' rooms, it was assumed that the supplied airstream was 60 m^3/h for each room. The entire building is heated in winter with central heating radiators. In the summer period, the temperature in hotel rooms is kept within the range of 23–25 °C, depending on the individual setting, with the use of fan coil units. In winter, the temperature is maintained by central heating radiators.

2.2. Methods for Measuring and Calculation

The subject of the research is the assessment of the air quality in hotel rooms. The measurements were carried out continuously during the standard operation of the hotel. Three measurement weeks from 5 November to 26 November 2020 were adopted for the analysis. The measurement reading period was adapted as 1 min. The analysis included five rooms located on the first and second floors of the building. All rooms are double bedded. The detailed layout of the rooms, along with the most relevant information, is summarized in Table 3.

Table 3. Detailed information on the analyzed rooms.

Room	Area, m^2	Windows	Floor	Comments
Room A	31.32	3	1st	-
Room B	21.70	1 (balcony)	1st	-
Room C	26.74	2	1st	living room in a two-room apartment; corner room
Room D	34.00	1	2nd	-
Room E	18.63	1	2nd	-

The appearance of the building and the exact location of the analyzed rooms is shown in Figure 2.

Measuring devices located directly in the analyzed rooms were used to measure the air temperature, relative humidity, and concentration of carbon dioxide. The measuring range and accuracy were 0 to 50 °C (±0.3 °C) for the temperature; from 0% to 100% (±2%) for relative humidity (measured in non-condensing conditions); and from 0 to 10,000 ppm (±3%) for the concentration of carbon dioxide. Air temperature in the room, relative humidity, and CO_2 concentration were recorded at one-minute intervals. The most important research question was to examine the conditions of the rooms during the presence of hotel guests. At the same time, the measurements could not disturb hotel guests' stay. The conditions under which the tests were carried out forced the simplification of the measurement system. The measuring system had to be relatively small and did not require long cable connections. For the same reason, no spherical radiation sensors were used. Therefore, the measuring devices were located behind the desks at a height of about 70 cm, as shown in Figure 3. During the operation of the hotel rooms, users stayed, for most of the time, on the bed or at the desk. Thus, the location of sensors, at a relatively low height and behind the desk, should not adversely affect the analysis of the obtained results.

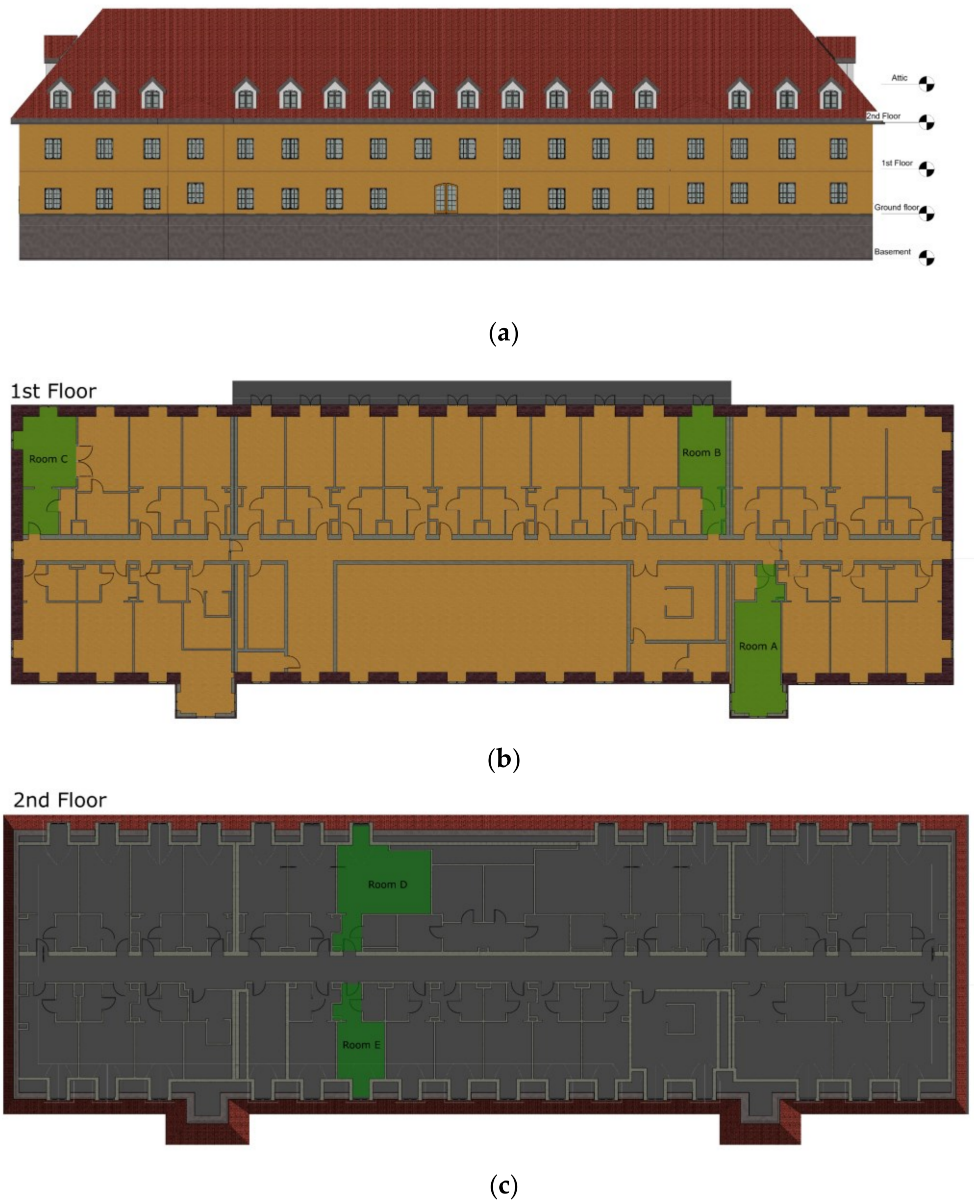


Figure 2. Plans and architectural section of the building: (**a**) Appearance of the facade; (**b**) 1st floor plan; (**c**) 2nd floor plan.

Data analysis was performed using an MS Excel spreadsheet and Statistica program. The values were averaged over five minutes to simplify the further analysis and minimize the impact of momentary signal disturbances and no readings. For the analysis of air quality regarding carbon dioxide concentrations, a scale, as shown in Table 4, was adopted. This scale was created based on the review of existing guidelines and limit concentrations for CO_2 in indoor environments prepared by Lowther et al. [53]. As several sources have assumed, the limit value for good air quality is 1000 ppm. A level above 2000 ppm indicates poor and unacceptable air quality.

(a) (b)

Figure 3. Example of the analyzed hotel room: (**a**) Appearance of the room; (**b**) Location of the measuring device.

Table 4. Air quality scale according to carbon dioxide concentration.

Air Quality Level	Concentration, ppm
Very good	<800
Good	800–1000
Moderate	1000–1400
Acceptable	1400–2000
Bad	2000–3000
Very bad	>3000

The PMV and the corresponding PPD index were calculated based on the known standards according to Equations (1) and (2), using Excel software. For occupants engaged in the resting activity described as "seated, quiet" and "standing, relaxed", the metabolism rate amounted to 1.0 met and 1.2 met, respectively. Thus, in this study, the value of 1.1 met was assumed. The metabolic rate of 1 met corresponds to the produced heat flux 58 W/m^2 of the skin area. The value of 1.0 clo was adopted for the insulation of the clothing for the entire research period. According to ASHRAE standard 55 [9], this insulation level is typical of clothing for the winter outdoor environment. The air velocity was assumed to be 0.1 m/s. The values of these parameters were selected based on the ASHRAE standard 55 [9] and other papers [54–56]. In several papers [57–59], the mean radiant temperature was assumed to be equal to the air temperature. The above assumption was used in this article for the PMV model. The PDD coefficient based on the acceptability coefficient and the concentration of carbon dioxide was calculated using Equations (4) and (5), respectively, as mentioned in the first section.

3. Results

Three weeks in November 2020 during the heating season were analyzed. Due to the amount of data obtained from the measurement system, the 5 min average of the measurements was analyzed. Basic statistics of the collected data are summarized in Table 5.

As can be seen in the table, in rooms B and D, the minimum recorded temperatures are below 17 °C, which could lead to a feeling of coolness in the room. Such low temperatures may result from the periodical lack of use of the rooms, when the hotel management, to reduce operating costs, limits the heating power in individual rooms. The humidity characteristics are similar for individual rooms. Only room D is different, where the relative humidity is 5–10 percentage points higher than in other rooms. Regarding the concentration of carbon dioxide, a significant difference between the characteristics of individual rooms can be seen. It is especially noticeable in the case of the maximum values, which in rooms B and C exceed 3000 ppm. Further data analysis covered the distributions of the measured parameters over the entire measurement period for each of the rooms. Figure 4 contains the variability charts.

Table 5. Basic statistical data of the collected data for individual rooms.

Room	Temperature, °C			Relative Humidity, %			CO_2 Concentration, ppm		
	Min.	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**
A	21.7	24.1	23.2	30.0	51.0	39.4	400.0	869.0	502.0
B	16.8	25.6	23.5	24.0	46.0	34.7	400.0	3884.6	669.7
C	19.5	25.4	23.4	24.0	45.0	35.3	400.0	3126.6	603.1
D	16.2	22.9	19.4	39.0	59.0	46.7	400.0	1082.0	553.8
E	20.7	23.7	22.3	31.0	49.0	39.9	400.0	1330.5	646.9

As the above graphs show, significant fluctuations in the concentration of carbon dioxide, temperature, and relative humidity in each room are visible. There was no visible impact of the day of the week on the variability of these values. As the weekly analysis did not reveal any clear trends of variability, it was decided to check the dynamics of the changes during the day. For this purpose, one representative day was selected. The dynamics of changes on this day for each of the rooms were presented. Figure 5 shows the daily distribution of values on the example of 16 November.

At a further stage, the individual values of carbon dioxide concentrations were assigned to the appropriate categories, according to Table 4. Then, the PMV indices were calculated. Figure 6 shows the percentage share of the values for both indicators according to the assumed scales. The charts present results for each of the analyzed rooms in the period from 5 to 26 November 2020.

In the next stage of the analysis, the predicted percentage of dissatisfied (PPD) indices were calculated using three different methods. The first one is based on the relationship (2) between the PMV and PPD coefficients. The second one uses the determined relationship (4) between the PPD coefficient and the enthalpy of air. In the last approach, Equation (5), including the concentration of carbon dioxide, was used. All equations are described in the first chapter, with the literature review. The calculated PPD values are presented as a function of time. Figure 7 presents the results.

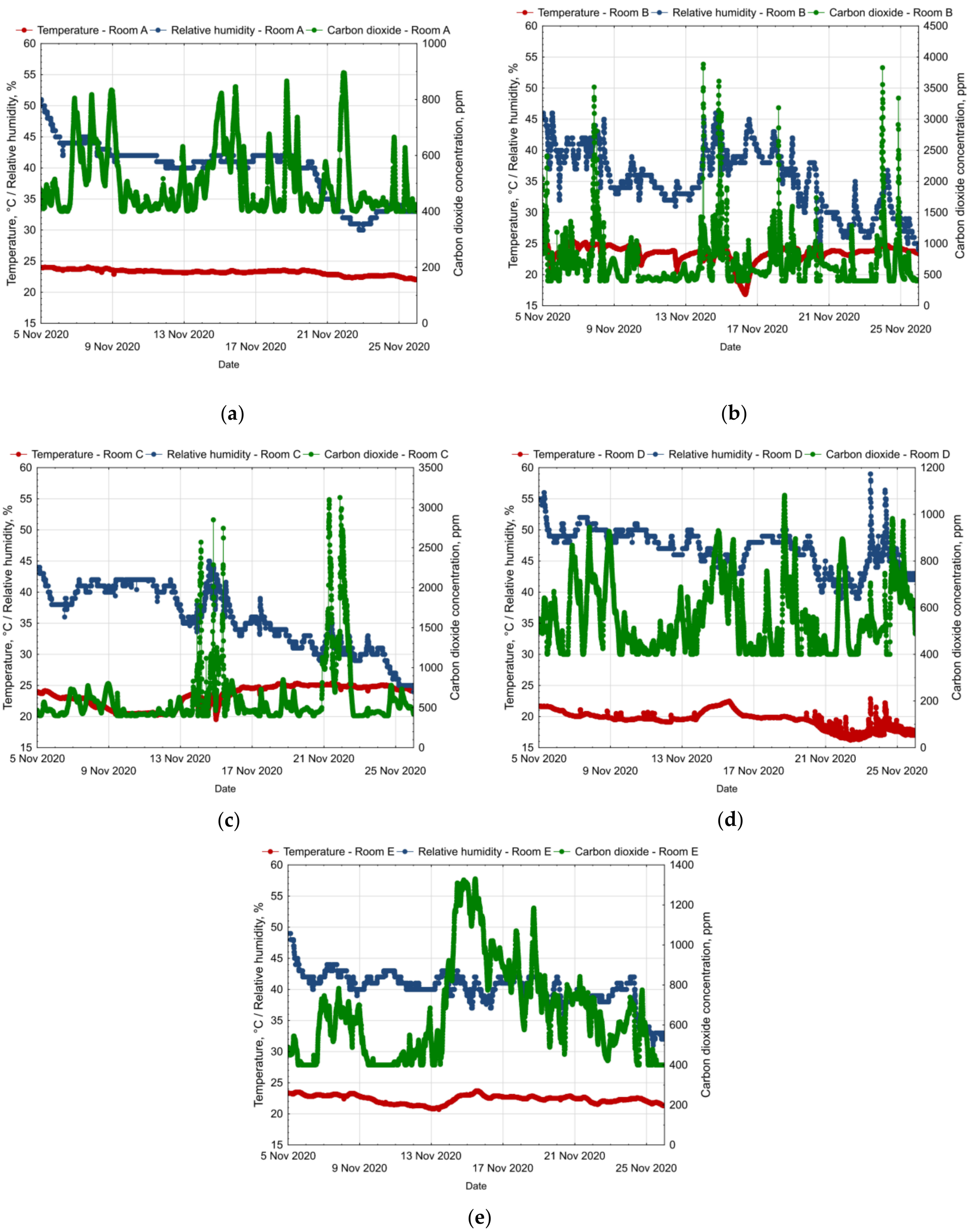


Figure 4. Variability distribution of the temperature, relative humidity, and carbon dioxide concentration in each of the analyzed rooms over three weeks: (**a**) Room A; (**b**) Room B; (**c**) Room C; (**d**) Room D; and (**e**) Room E.

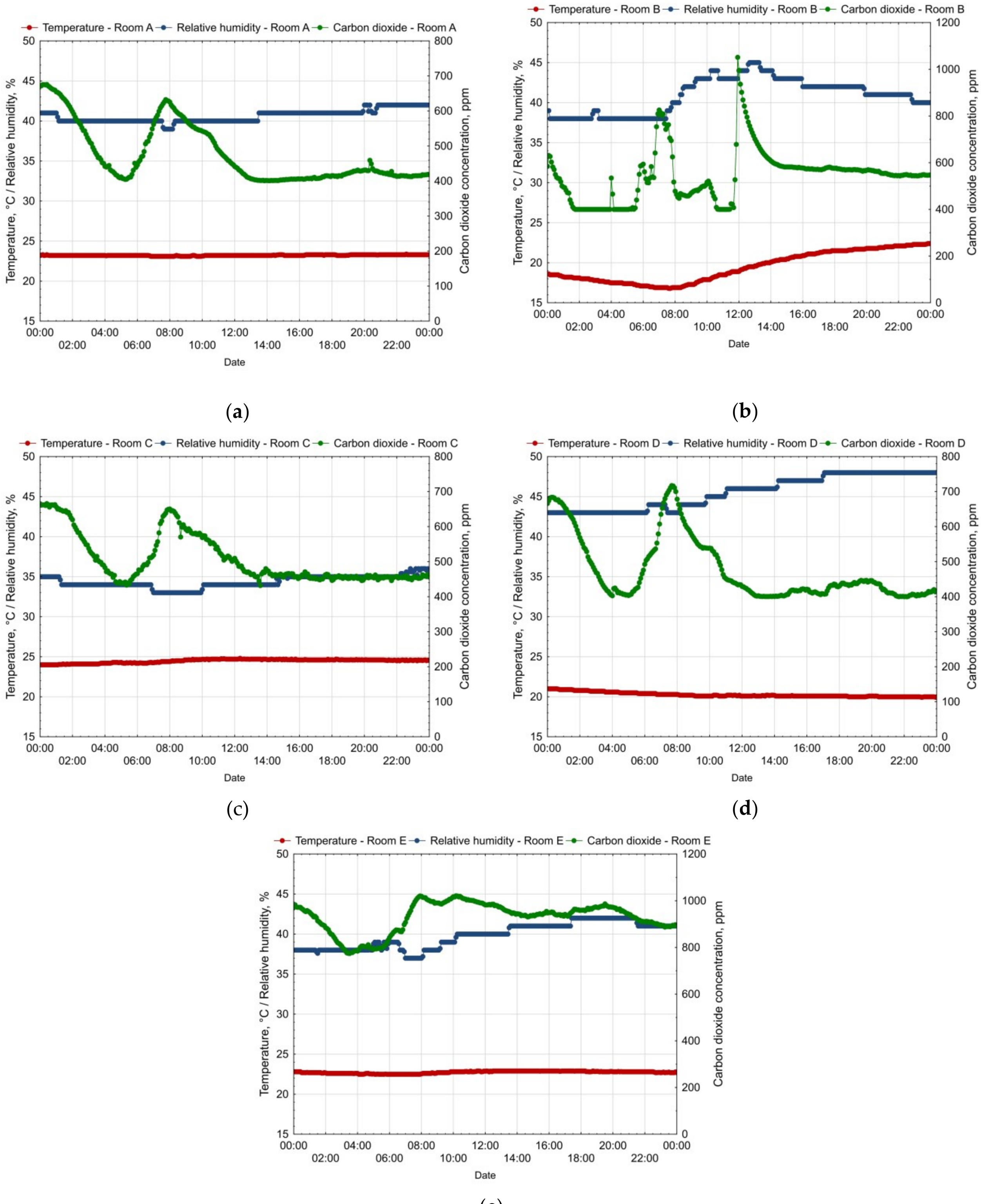
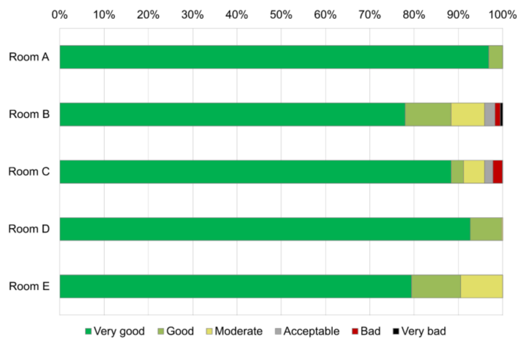
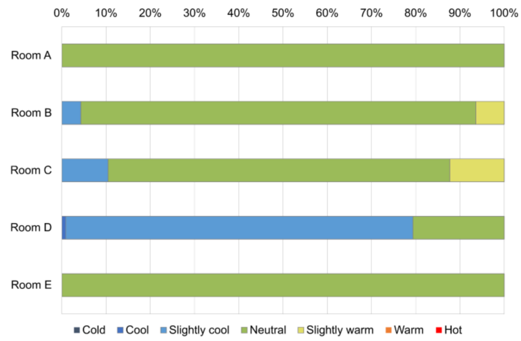


Figure 5. Example of the daily variability of the tested parameters for each room: (**a**) Room A; (**b**) Room B; (**c**) Room C; (**d**) Room D; and (**e**) Room E.

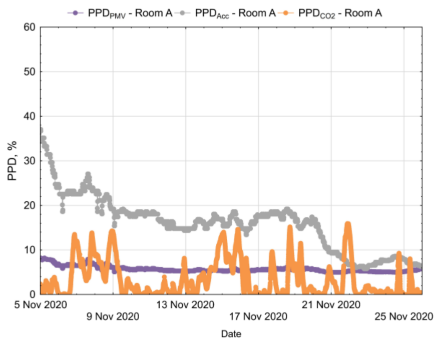


(**a**)



(**b**)

Figure 6. Percentage share of individual categories in the assessment of air quality: (**a**) by carbon dioxide concentration (Table 5); (**b**) assessments according to the PMV indicator (as shown in Figure 1).



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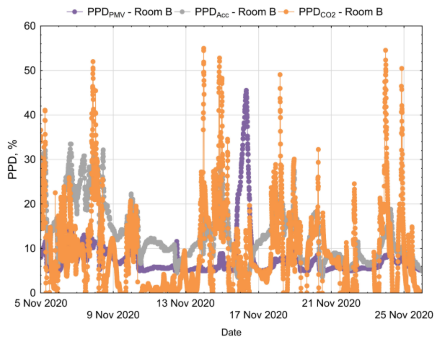

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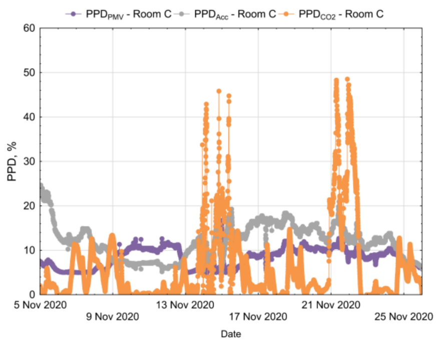
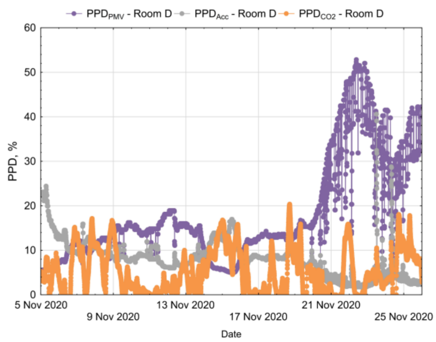
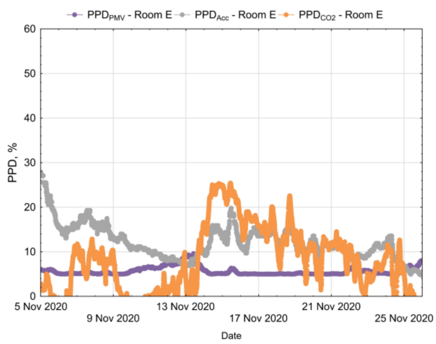


(**c**)



(**d**)



(**e**)

Figure 7. Variability of dissatisfaction indices calculated according to the PMV index, carbon dioxide concentration, and enthalpy relationships: (**a**) Room A; (**b**) Room B; (**c**) Room C; (**d**) Room D; and (**e**) Room E.

4. Discussion

The analysis of the quality of the internal environment in the rooms of the Turówka hotel in Poland was carried out based on daily and weekly measurements. Three measurement weeks in November 2020 were selected for the analysis. As shown by the results, the best conditions in terms of carbon dioxide concentration occurred in rooms A, D, and E (Figure 6a). Particularly comfortable conditions were noticed in room A, where the temporary values did not exceed 1000 ppm. The highest concentrations observed in rooms B and C exceeded 3000 ppm. Such CO_2 concentration levels during prolonged exposure may cause drowsiness, headaches, or a lack of concentration. When analyzing the graphs of variability over time, it can be noticed that the high values of carbon dioxide concentration persisted only for short periods. The duration of the period with an increased concentration of carbon dioxide (at the level above 2000 ppm) does not exceed two hours for room B and 5 h for room C. The low CO_2 concentrations in room D can be related to the low temperatures that were recorded in that room. Other authors noticed similar conditions in hotel rooms. Asadi et al. [47] stated excessive CO_2 concentrations in guest rooms with measurements as high as 1710 ppm. During the night hours, the concentration level of CO_2 increased due to the constant metabolic emissions by the guests. The authors proposed the increase in the supply airflow to improve the IAQ in hotel rooms. On the other hand, Zani et al. [52] recorded much lower concentrations during the operation of hotel rooms. The authors proposed implementing a smart IAQ monitoring network. This approach may be crucial, especially during a pandemic. The authors developed a case study of a major hotel facility in Turin. They highlighted the need for long-term research to support the understanding of the characteristics of the building. According to the paper, the application of advanced techniques allows detecting patterns of changes and gathering information about the influence of specific human activities on indoor air quality. The results showed that the concentration of carbon dioxide in each of the analyzed rooms was kept within the assumed limits and did not exceed the value of 800 ppm.

During the period with a lower occupancy, some rooms remained empty. Therefore, to reduce the operating costs of the entire building, the heat output of radiators in individual rooms is reduced. Room D is such an example as it is visible in the second part of the analyzed period. The temperature then dropped below 17 °C, and CO_2 concentrations remained relatively low. The most optimal thermal conditions were observed in rooms A and C, where the average temperature exceeded the value of 23 °C and did not drop below 19.5 °C. As mentioned earlier, the indoor temperature depends on the presence of users, their individual preferences, and the settings of heating devices for a particular room. The humidity conditions inside the rooms were similar in all rooms. Room D was an exception. As mentioned above, this room was periodically out of use, and a higher humidity was observed there. Nevertheless, the humidity did not exceed 59%, which can be considered comfortable conditions. For comparison, the paper by Kim et al. [44], mentioned in the first section of this article, stated that, for occupied hotel rooms, temperature and humidity differences between rooms are higher during the cooling season than in other seasons. Values varied for the temperature from 21.1 °C to 26.1 °C and for the relative humidity from 44.2% to 56.0%. For the heating season, the temperature and humidity variations were from 22.6 °C to 24.6 °C and from 31.6% to 39.5%, respectively. During the transitional season, parameters took values from 22.4 °C to 25.5 °C and from 39.9% to 47.8%, respectively. Significant differences were observed in the average temperatures of the checked-in rooms between the occupied and unoccupied periods. During the heating season, the values varied from 0.3 °C to 1.7 °C by room. The authors noticed that the temperature measured during the heating season tended to have a larger dispersion than in the cooling season.

As shown in Figure 6b, the results of the PMV calculations indicate that some rooms may be perceived as "slightly cool". However, this may be a result of periodic non-use. November is the autumn month in which temperatures in the Polish climate vary widely from −5 to +20 °C. Therefore, the clothing of users, and more precisely the thermal insulation of their clothing, has a significant impact on the users' feelings. Room A and

E, throughout the measurement period, provided comfort requirements, with PMV index values ranging from −0.5 to 0.5. Room B and C, on the other hand, may periodically be perceived as quite cool or quite warm, which may also result from the individual settings of the users.

In the next stage, the predicted percentage dissatisfied (PPD) indices as a function of various parameters were analyzed. Lower values of the PPD index mean better indoor conditions. Even a preliminary analysis shows significant differences between the used coefficients. The most comfortable conditions were observed in rooms A and E, where PPD indices did not exceed 40 and 30%, respectively. In both cases, when comparing the PPD_{Acc} and PPD_{PMV} indications, it can be seen that the results obtained with the use of air acceptability and enthalpy take much higher values, often even twice as high. In both cases, however, it can be assumed that the conditions provided to the users were optimal. The situation is different in the case of other rooms. In rooms B and C, due to the high concentration of carbon dioxide, the temporary PPD indices increase temporarily above the value of 50 or 60%. On 16 November, a sudden drop in temperature to a value below 17 °C was visible in room B. It directly affected the increase in the PPD_{PMV} coefficient to the value of over 40%. Such a situation may be a result of the window opening. As in the previous examples, the enthalpy-related coefficient also takes higher values. In the case of room D, this relationship is reversed, and the PPD_{PMV} coefficient takes higher values than PPD_{Acc}. This is a direct consequence of the temperature decrease below the value of 17 °C. A significant increase in the PPD_{PMV} index can be seen in the third week when the temperature reaches its lowest values, and the results of the calculations are 30–60%.

The analysis of the results included differences between the particular rooms. Room C has the largest area of the analyzed species and was the only room not used as a bedroom. It is the living room in the apartment and may serve as a meeting place. The indoor carbon dioxide level depends upon the number of people, and ventilation with a constant volumetric flow rate may not be sufficient. Rooms B and E have a similar area, layout, and the number of windows, yet the conditions in room B are less comfortable, both in terms of temperature and carbon dioxide concentration. While analyzing the temperature variability in room B, it was noticed that the value drops are very dynamic, which in the authors' opinion may be related to the opening of the windows by users. Comparing the temperature records in rooms B and C, significant temperature changes are noticeable. The values changed in a wide range and smoothly over the period. It is a corner room, and thus heat losses are higher. Consequently, in the absence of users and limited heating power, the temperature in the room may decrease. As previously noted, rooms A and E have the most comfortable indoor conditions. Both rooms differ in terms of area and the number of windows. The only common point is the location of the rooms on the northwest side. The remaining rooms are located on the south-eastern side. The prevailing winds in Poland blow from the west, south-west, and north-west. This may affect the carbon dioxide concentration in the rooms due to the infiltration of outdoor air.

5. Conclusions

Analyzing the quality of the indoor environment is crucial, especially in rooms where users spend a significant part of their day. A hotel is a specific type of facility, as the time of use and user behavior are time varying. Moreover, these values are hard to predict or assumed at the initial stage of calculations. The quality of the environment in hotels' rooms is essential, as it determines the popularity of the hotel, thus the number of guests and the resulting economic benefits. As shown in the sections above, the measured parameters, i.e., temperature, humidity, and carbon dioxide concentration, varied over time, and there was no repeatability or clear patterns of variation. This is due to the individual preferences and behavior of users. As the analysis showed, the temperature and humidity conditions were maintained at a satisfactory level for most of the time. The exception was room D, which was temporarily out of service. The calculated PMV index indicated that users could have felt cold in this room. While analyzing the carbon dioxide concentration, it was noticed that the CO_2 concentrations exceeded the value of 2000 ppm in rooms B and C, which could cause discomfort to hotel guests. In these rooms, the increase in the volume of ventilation airflow should be considered. Many factors affect the conditions inside the rooms, especially in such dynamic spaces as guest rooms. A relationship between the location of rooms and indoor air quality was observed. However, the verification of this dependence could be possible if more hotel rooms are included in the analysis. A detailed analysis is extremely difficult due to the possibility of opening windows by users, the irregular presence of hotel guests in the rooms, and the inability to verify the exact number of users in the room during the measurements.

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