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Comparative Air Quality Study of Bathroom Use in Residential Bedrooms

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Highlights

- This study focuses on the effect of the use of the bathroom in the bedroom on the quality of air.
- A long-term measurement method was used to determine the effect of bathroom use.
- The air quality is influenced by the planning of the bathroom and the ventilation of bedrooms.

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Abstract

Indoor air quality in bedrooms, where most people spend around a third of their day, has a significant impact on human health through the quality of sleep. Studies on air quality in residential bedrooms have examined factors affecting air quality, such as the relationship between occupancy patterns and ventilation routines, and the impact of planning has not yet been assessed. This study analyzes how different master bathroom designs affect the air quality in the bedroom. To assess the effect of bedroom air quality, this study compares summer and winter measurements from two dwellings with similar floor areas and occupant types, but with different bathroom-to-bedroom relations. In addition, satisfaction with indoor air quality, an important indicator, was questioned and its connection with sleep quality was evaluated. It was found that the layout of bathrooms in bedrooms is affected by indoor air quality, especially in winter when ventilation is reduced, and that bathrooms leading directly into the bedroom are detrimental to air quality.

1. INTRODUCTION

The main purpose of bedrooms is to provide a suitable space for sleeping and relaxing. Today, however, in addition to sleeping, bedrooms are also used for dressing, personal hygiene, and even working. Along with the changing functions, the duration of stay in bedrooms increases, and one-third of the day is spent in these rooms, even just for sleeping. Sleep, which is the main function of bedrooms, is defined as the transition to a different state of consciousness and is not just a state of inactivity for rest, but a period of active renewal for the body. For this reason, sleep is vital for health and affects people's physical, cognitive, emotional health, and daily life performance [1]. When an adequate amount and good quality sleep is not taken, the risk of heart attack, diabetes, and obesity increases in people, and it also causes attention deficit in daily performance, slowing memory, cognitive loss, and depression [2].

People use approximately 3840 liters of air per day during 8 hours of sleep (when resting, inhale and exhale about 7 or 8 liters of air per minute), and the quality of this air consists of many variables. One of the factors influencing sleep quality is the condition of the sleeping environment, i.e. the thermal, acoustic, lighting, and ventilation performance of the bedroom. Indoor environmental conditions affect people both during the transition to sleep and in sleep. They also play an essential role in determining the satisfaction level of people with their bedrooms. Many studies on the effects of these factors on sleep quality are carried out in laboratory conditions [3, 4], but there are few field studies [5-7] on the quality of bedrooms. In research conducted in the laboratory environment, the sleep state of individuals is observed and the physical characteristics with the indicators explain sleep quality. Laboratory studies are not long-term and do not reflect real environmental conditions, so they are not conducted to determine air quality factors [8, 9].

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Ventilation and thermal environmental factors play a part in determining indoor air quality. Acceptable air quality is defined as a situation where no harmful pollutants are detected by the standards, and 80% of users do not feel dissatisfied [10]. It is thought that air is polluted with changes in the proportions of outside air gases other than natural air components and steam. Air temperature, radiant temperature, air velocity, and relative humidity are four key parameters that define the thermal environment, which are the elements of indoor air quality. Most studies on air quality in bedrooms are for temperature control and include changes in sleep phases with the temperature variables [11, 12]. In addition, it has been determined that a change in humidity in sleeping affects various physiological systems [13]. As a result of ventilation, the concentration of gases in the indoor air also affects the air quality [14, 15]. The CO_2 level [16] and the consideration of particulates [17] are influencing indoor air quality, especially in living spaces. It is seen that the effect of ventilation systems used in bedrooms [18], the ventilation habits of users, and personal variables play a role in indoor air quality [19, 20]. The openings are used for temperature and air exchange control [15, 21, 22], and the quality of the outside air is a factor in the utilization of the outside air [23, 24]. The studies mostly consist of temperature, humidity, air exchange rate, CO_2, particulate measurements and some questionnaires that evaluate the user's sleep quality [25, 26].

In new housing planning approaches, bathrooms and dressing rooms are added to bedrooms and designed as integrated. This study evaluated the effect of the additional function (personal cleaning) of the bedrooms on the air quality. A review of the literature shows that although the effect of bedroom air quality on the control of openings or on sleeping habits has been investigated, there is no research on the effect of the design relationship on air quality. Specifically, few studies assess normal occupant use in real buildings and include long-term summer and winter measurements. Within the scope of this study, the factors affecting the air quality in the bedrooms were measured in the context of standards and evaluated together with the usage variables. The design of the bathroom area in the bedrooms has been discussed according to the results of the measurements and interviews. In this way, air quality evaluation of bedrooms will be included in the literature in terms of planning. The study will provide an indication for the planning of spaces and their relationships. Understanding the impact of bathroom use on indoor air quality can raise awareness of potential health risks that can affect respiratory health and general wellbeing. The study can inform better ventilation strategies in bedrooms areas that help to reduce the humidity and pollutants generated by bathroom use. Insights from such research can guide architects and builders in designing residential spaces that minimize air quality issues, such as strategically placing bathrooms away from bedrooms or using better ventilation strategies.

2. MATERIAL AND METHOD

In this study, the air quality of a bathroom directly connected to the bedroom and a bedroom connected to the bathroom from the dressing room was evaluated through long-term measurements and interviews. These are the most common types of master bedroom layouts. This study was carried out by comparing the measurement values of the building belonging to two plan types. This research cannot be carried out in many buildings and cannot provide more general information because of the long duration of the study, the limited number of measuring instruments and the problems of obtaining permission from the houses where the measurements are to be taken. This should be seen as preliminary research, providing the basis for further study.

The buildings selected as case studies are in Konya, Turkey. Since Konya is a lowland surrounded by mountains, especially in winter, foggy and misty weather can be felt in the city with poor wind and air currents. There are eight stations to measure air quality in the city and PM_{10}, $PM_{2.5}$, CO, NO_2, NOX, NO and O_3 measurements are taken in the city centre station. The selected housing examples are 4 km away from this station. Figure 1 presents the outdoor air quality values taken from the air quality center station for the measurement dates. There are some gaps, especially in summer data based on the station's measurements. The data indicates that the air quality in the area is generally satisfactory. However, individuals with sensitivities may occasionally experience some discomfort. The national limit values weren't exceeded during the measurement period, and only a few days might cause moderate health concern for some pollutants.

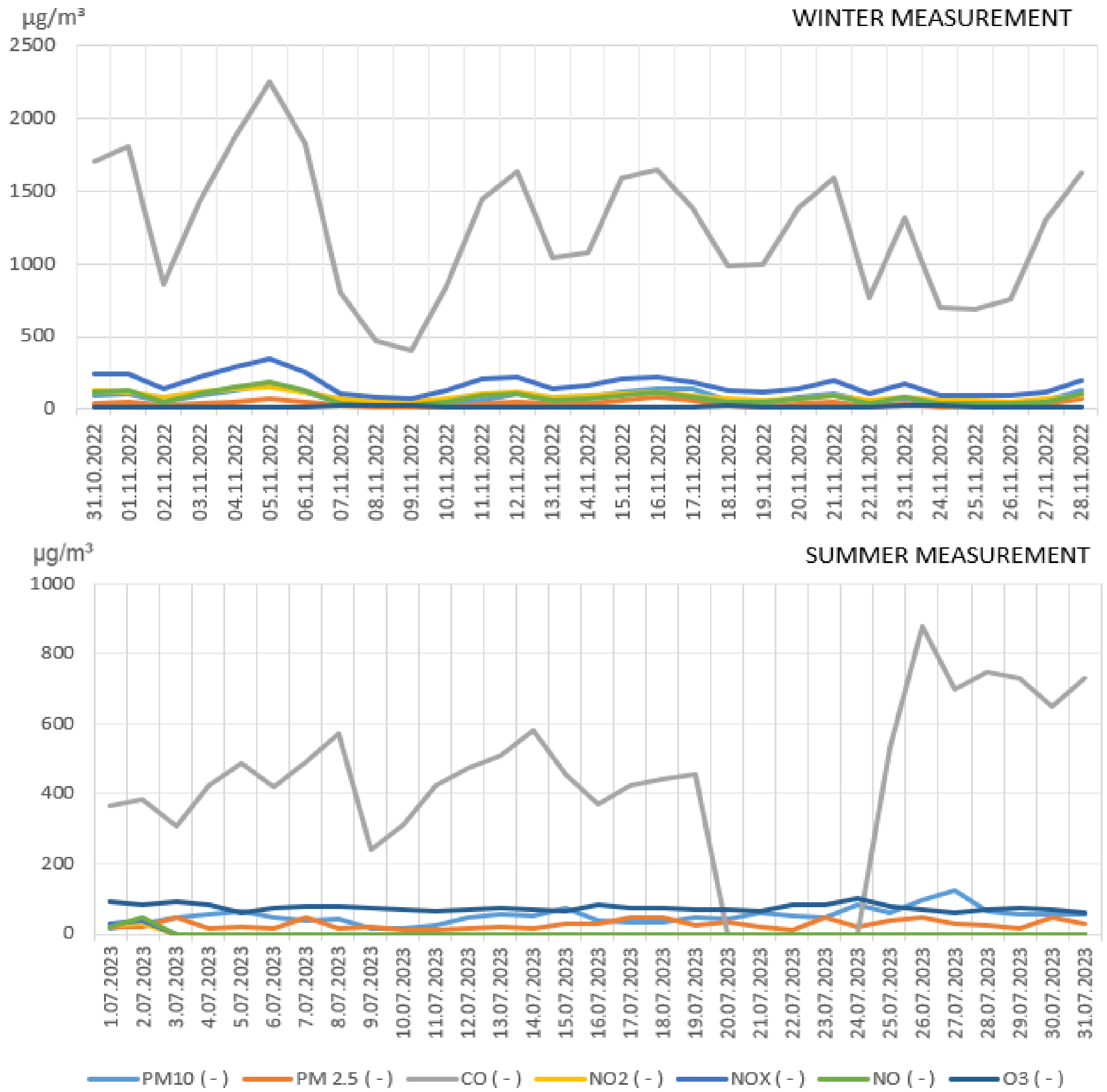

Figure 1. *Outdoor air quality values (PM_{10}, $PM_{2.5}$, CO, NO_2, NOX, NO, O_3) of Konya in measurement period*

2.1. Indoor Air Quality Monitoring Plan

Since the comparative research method was used, an evaluation was made on two examples to obtain the effects of differences. Two flats in a residential area were selected as a sample to compare the impact of bedroom planning. In these cases, while air quality measurements were made in winter and summer for a month, the bathrooms of the sleeping rooms were not used in the first 15 days, and they were used in the last 15 days. Particulate matter ($PM_{2,5}$), carbon dioxide (CO_2), temperature, relative humidity, and air pressure measurements in the houses were carried out between October 31 and November 28 and between July 1 and July 30 with the "PCE-AQD 20 Particle Measurement Device". It was ensured that the devices had approximately the same surface area and different master bedroom plans were selected from the same place in the designated areas in the bedroom and bathroom as in Figure 2. The devices were placed close to the head of the bed and on the counter in the bathroom. The bedsides were chosen to get the air quality at the level of sleeping.

The measuring device was chosen to be put on the counter as a commonplace in the master bathrooms where it could remain motionless. The measuring device that is supplied with a calibration certificate can measure particulate matter ($PM_{2.5}$) in the range of 0-250 $\mu m/m^3$ with an accuracy of ± (10% of rdg. + 15 µm), and carbon dioxide (CO_2) in the range of 0-10000 ppm with an accuracy of < 1000 ppm: ± 40 ppm; 3000 ppm: ± (50 ppm + 3% of rdg.); > 3000 ppm: ± (50 ppm + 5% of rdg.). Additionally, the temperature can be measured within the range of 0-50 °C with ± 0.8°C accuracy, humidity in the range of 5-95% RH with >70% RH: ± (3% of the prev+1% RH) <70% RH: ± 3% RH accuracy, and air in the range of 10-1100 hPa pressure with ± 1.5 hPa accuracy. Measured values are automatically stored by the devices on an SD memory card in Excel format. PCEAQD 20 device recorded the data at 60-second intervals. The data obtained due to the measurements were compared with the determined standards.

Figure 2. *Photographs of the installed instrument*

2.2. Case Studies

The selected residences have 4 bedrooms, and one of the bedrooms has a bathroom. There are planning differences between the examples studied. In one of the rooms, the bathroom opens directly onto the bedroom, while in the other, it opens first onto the dressing area in space. The distance between the two cases is 500 m as shown in Figure 3.

Figure 3. *The location of the cases in the layout plan (redrawn from Konya City Information System [27])*

One of the apartments subject to measurement is on the second floor and on the heavily used main street. The apartment has East-South and West facades. The master bedroom is located on the west side of the apartment. The main area of the bedroom is 20.1 m^2, the dressing room opening to the bedroom is 5.4 m^2, and the en-suite bathroom opening to the dressing room is 3.8 m^2. 6.3 m^2 glazed balcony is at the front of the bedroom facing the outside. The clear height is 2.8 m. Balcony windows are 5.06 m^2, of which a single wing of 1.76 m^2 in the corner can be opened. It was learned from the users that the house is ventilated regularly, and a vacuum cleaner is used once a week for cleaning purposes. The heating system is operated between 21-25 degrees. The drawing of the first case is shown in Figure 4.

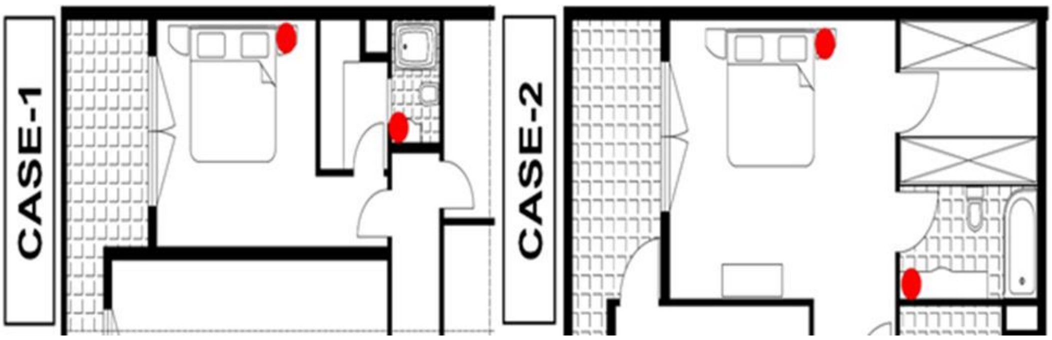

Figure 4. *The bedroom plan and measurement points of Case-1 and Case-2*

The other residence is on the fourth floor, on the heavily used main street, and has two facades in the East-West direction. The master bedroom is located on the west side of the apartment. The main area of the bedroom is 16.9 m^2, the dressing room opening to the bedroom is 5.4 m^2, and the en-suite bathroom is 2.9 m^2. The 13,7 m^2 glazed balcony overlooking the outside is at the front of the bedroom. Balcony windows are 7 m^2, of which a single wing of 1.15 m^2 in the corner can be opened. The clear height of second case is 2.82 m. It was learned from the users that the house is ventilated regularly, and a vacuum cleaner is used once a week for cleaning purposes. When operating the heating system, the residents preferred that the underfloor heating system be activated when the temperature dropped below 25 degrees. The dressing room and the en-suite bathroom open directly to the bedroom. The drawing of the second case is also shown in Figure 4.

2.3. Driving Factors

In either case, the bedrooms and bathrooms are only used part-time during the week as the owners are at work. Due to regular morning ventilation, air exchange occurs in the rooms from outside. The activities in the bathroom (hand washing, washing, etc.) and cleaning activities at home were noted, and their effects on the measurements were examined. Although the children living in the house are rarely in the room, they did not have long-term effects on the measurements. Due to the use of underfloor heating systems in buildings, the humidity levels in the room were affected by this.

2.4. User Evaluation of Air Quality

Bedroom users were also asked to evaluate the air quality after these measurements. After asking for demographic information, the survey asked respondents to rate their problems with air quality levels and whether it affected their sleep. The interview questions are based on the Pittsburgh Air Quality Index (PSQI). Users were asked to answer 39 questions in the interview. PSQI is a self-report questionnaire that assesses sleep quality over a one-month period. The measure was developed by Daniel Buysse et. all at the University of Pittsburgh in 1989 [28]. Ağargün et al. [29] conducted the validity and reliability study of PSQI in Türkiye. This index, widely used in various fields of study related to sleep, has formed the methodology of numerous studies on a global scale.

3. THE RESEARCH FINDINGS AND DISCUSSION

Particulates (PM $_{2,5}$), carbon dioxide (CO_2), temperature, and relative humidity measurements were made with two PCE-AQD 20 Particle Measurement Devices at the bedside in the bedroom and on the bathroom counter in the master bathroom. In the evaluation, a comparison was made between the bathroom and bedside readings in winter conditions, followed by summer readings.

3.1. Results of Winter Measurement

It is presented in Figure 5 that the ASHRAE recommended maximum limit value of 60% was never exceeded for the relative humidity values, which is one of the measured comfort parameters, in the bedroom measurements of Case-1 taken both when the bathroom was used and when it was not used. It was determined that the measured values fell below the recommended minimum limit of 30% for 11 days when the bath was used and 13 days when it was not. In the graph, the instantaneous increases in the humidity values coincide particularly with the days of bathroom and room cleaning. In Case 2, the recommended maximum limit value of 60% of the humidity in the bedroom measurements was never exceeded. While the bathroom was not in use, the humidity level was between the ASHRAE recommended minimum and maximum values for two days. Bathroom measurements were taken while the bathroom was in use; four days were below the recommended minimum value of ASHRAE 55 [30]. It is clearly observed that humidity values in spaces increase with bathroom use in winter measurements, and for residences with very dry outdoor air conditions, the humidity values of the bedroom are positively affected by the bathroom connection.

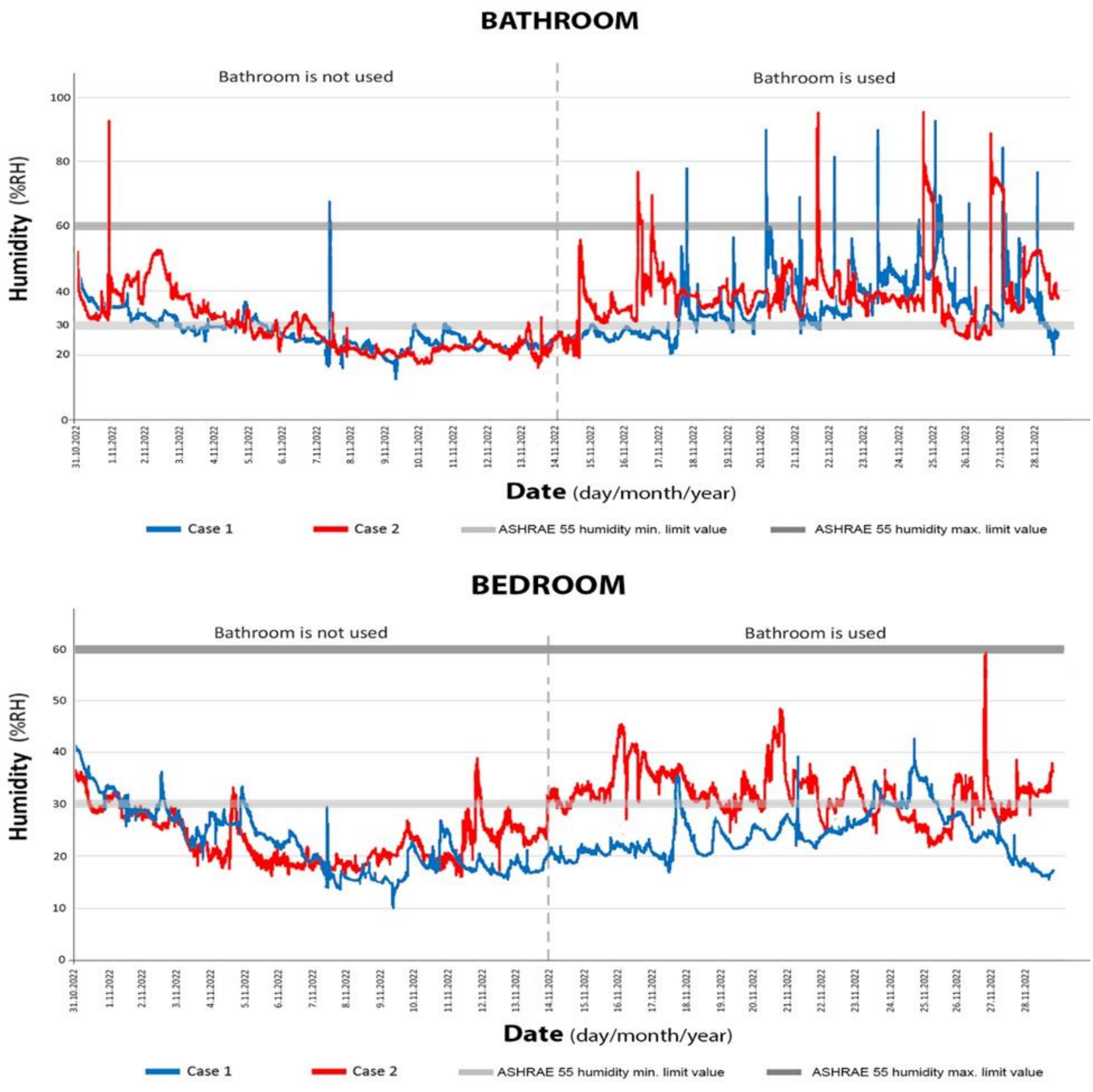

Figure 5. *Humidity measurement results from bedroom and bathroom in winter*

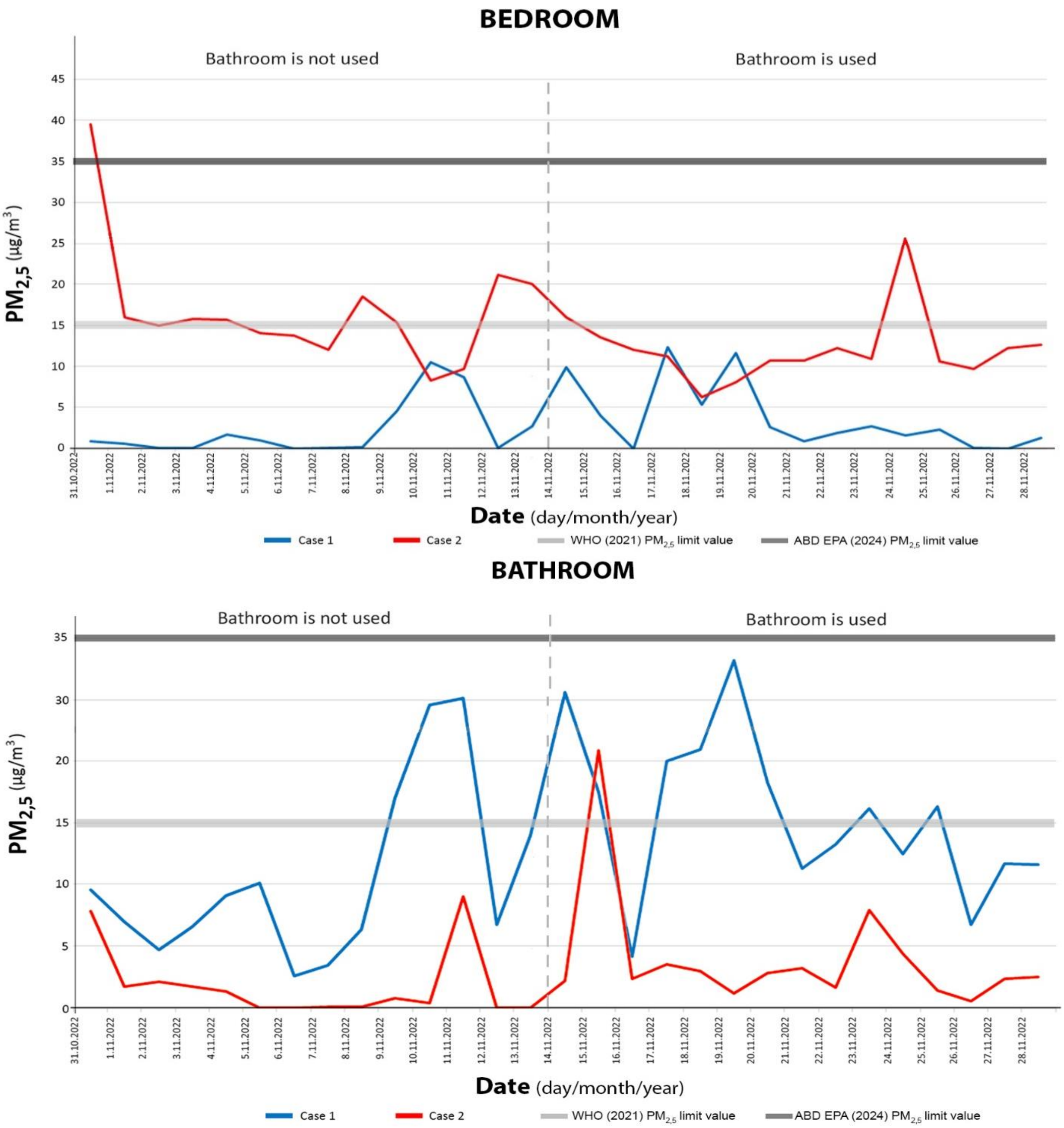

Figure 6. *$PM_{2.5}$ measurement results from bedroom and bathroom in winter*

According to $PM_{2.5}$ measurements in the bedroom made with/without using a bath in Case-1, the maximum limit value determined by WHO [31], 15 µg/ m^3, and the maximum limit value established by EPA [32], 35 µg/m^3 during a 24-hour period were never exceeded in the measurements as seen in Figure 6. While no problematic levels of $PM_{2.5}$ particles were detected in the bedroom of Case-1 in the winter measurements, higher values were obtained in the bathroom measurements.$PM_{2.5}$ measurements in the bedroom made without using a bath in Case-2 showed that the maximum limit value determined by WHO, 15 µg/m^3 was exceeded for 5 days, and the maximum limit value established by EPA, 35 µg/m^3, was exceeded for 2 days. It is observed that the $PM_{2.5}$ concentration measured in the bedroom when using the bathroom reached the maximum limit value determined by WHO, 15 µg/m^3 for once. Consequently, the impact of bathroom usage on PM $_{2.5}$ levels over time was examined in the winter measurements.

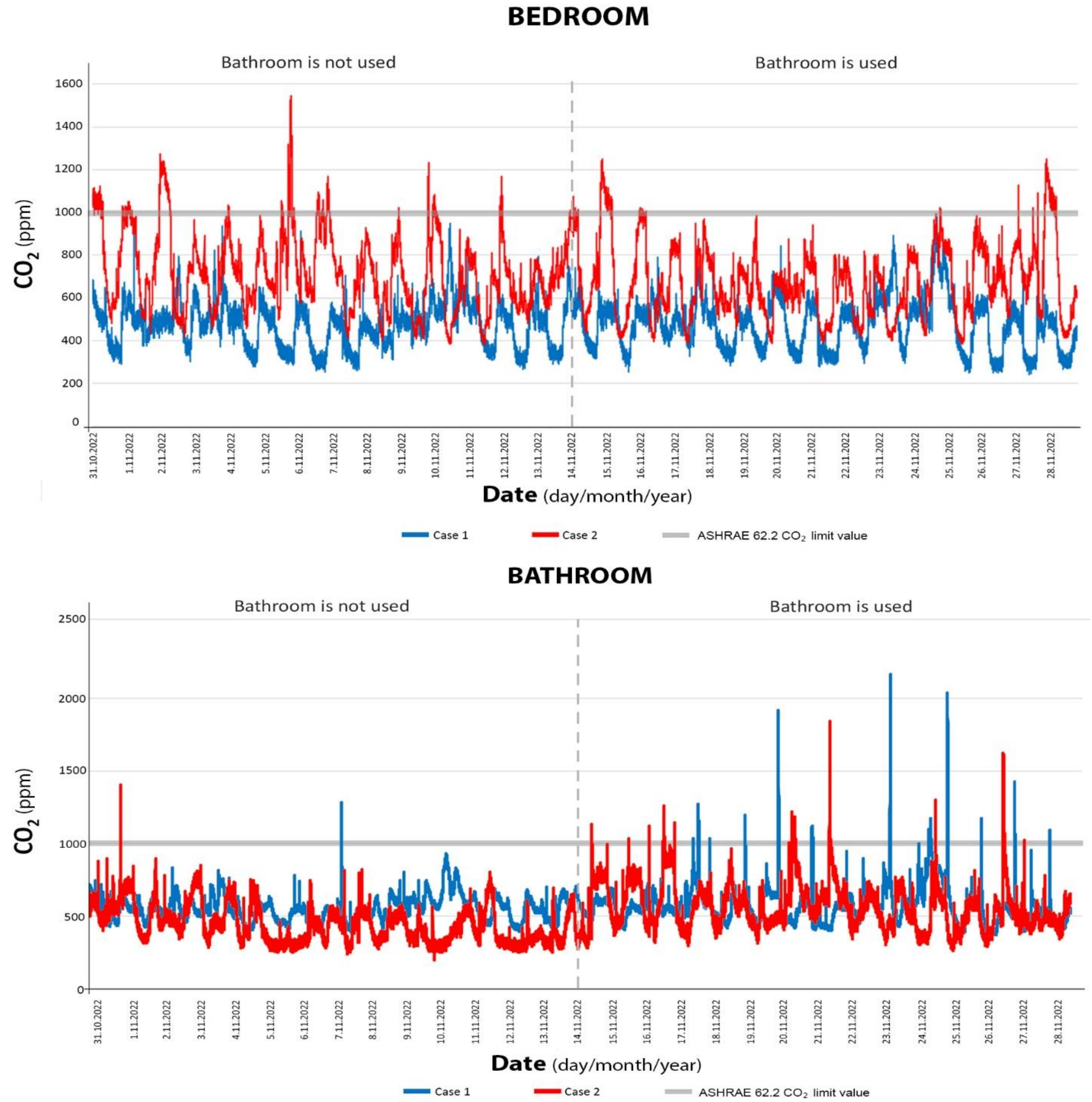

Figure 7. *CO_2 measurement results from bedroom and bathroom in winter*

As can be seen in Figure 7, the CO_2 concentration in Case-1, which is another indoor air quality determining parameter measured in the bedroom, did not exceed the maximum value of 1000 ppm set by ASHRAE 62-2019 [33] standard; however, the value of 800 ppm, which is considered a dangerous value for indoor environments such as residences, was exceeded for 5 days when the bathroom was not used. It was exceeded for 4 days when the bathroom was used. The maximum CO_2 level was recorded as 977 ppm, and the minimum CO_2 level was measured as 243 ppm on the days when the bathroom was used. The CO_2 concentration in the bedroom of Case 2 without using the bathroom, especially at nighttime was always above 800 ppm and was above 1000 ppm for eight days. When the bathroom was used, it was over 800 ppm for 12 days and over 1000 ppm for 6 days. On the other hand, in the bathroom measurements without using the bathroom, the CO_2 concentration was exceeded for one day in both cases. The CO_2 concentration nearly every day reached the maximum value by using the bathroom. There was a good correlation between the CO_2 concentration and bathroom use. In these measurements, it is observed that the bedroom air quality is affected by the bathroom, especially due to the architectural planning effect. In Case-2, there is a correlation between cleaning days and $PM_{2.5}$ levels. In case 1, it is thought that the dry vacuuming process, especially in the bedroom, is effective in increasing the instantaneous value. Preliminary findings suggest that CO_2 levels are approaching the established limit values, a phenomenon that may be attributed to reduced ventilation during the winter months.

3.2. Results of Summer Measurement

In the summer measurements, the minimum humidity value determined by ASHRAE 55 was exceeded for 10 days in bedroom measurement without using the bathroom for Case 1, and the humidity level dropped intensely after not using the bathroom as shown in Figure 8. While the bathroom was used, the values were getting higher than before, but they were still below the minimum value of the ASHRAE most of the time.

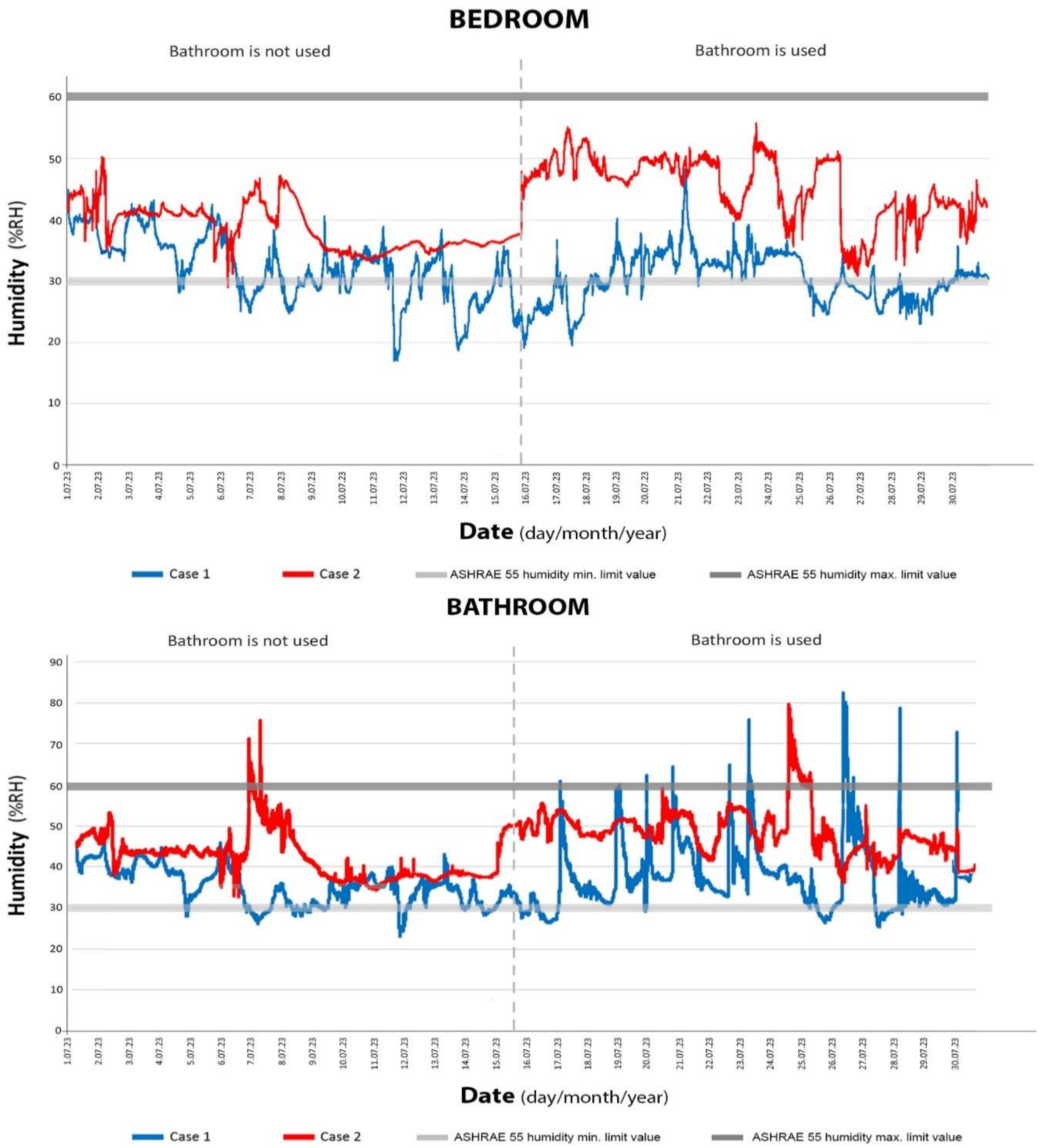

Figure 8. *Humidity measurement results from bedroom and bathroom in summer*

In the bathroom measurement for Case-1, the humidity level behaved like in the bedroom, reaching a value below the minimum value determined by ASHRAE, and then with the use of the bathroom, this value increased and sometimes exceeded the maximum value determined by ASHRAE. More frequent use of showers, especially in the summer months, is seen as the main reason for this. The humidity level of the bedroom for Case-2 is below the minimum humidity value for only one time, and the basic reason behind that is not operating any heating system. The maximum humidity level was also within the measurement period. This is due to the longer ventilation periods in the summer. On the other hand, while the bathroom was used, the humidity level of the bedroom was higher, but it was still not below or over the limit values of ASHRAE 55. It is observed that the sudden increases in humidity coincide with the days when the bathroom and room are cleaned. A discernible escalation in humidity levels is evident in both samples during the summer measurements. However, a notable observation is that the humidity levels in the bathroom sample, which faces the bedroom, consistently exhibit higher values.

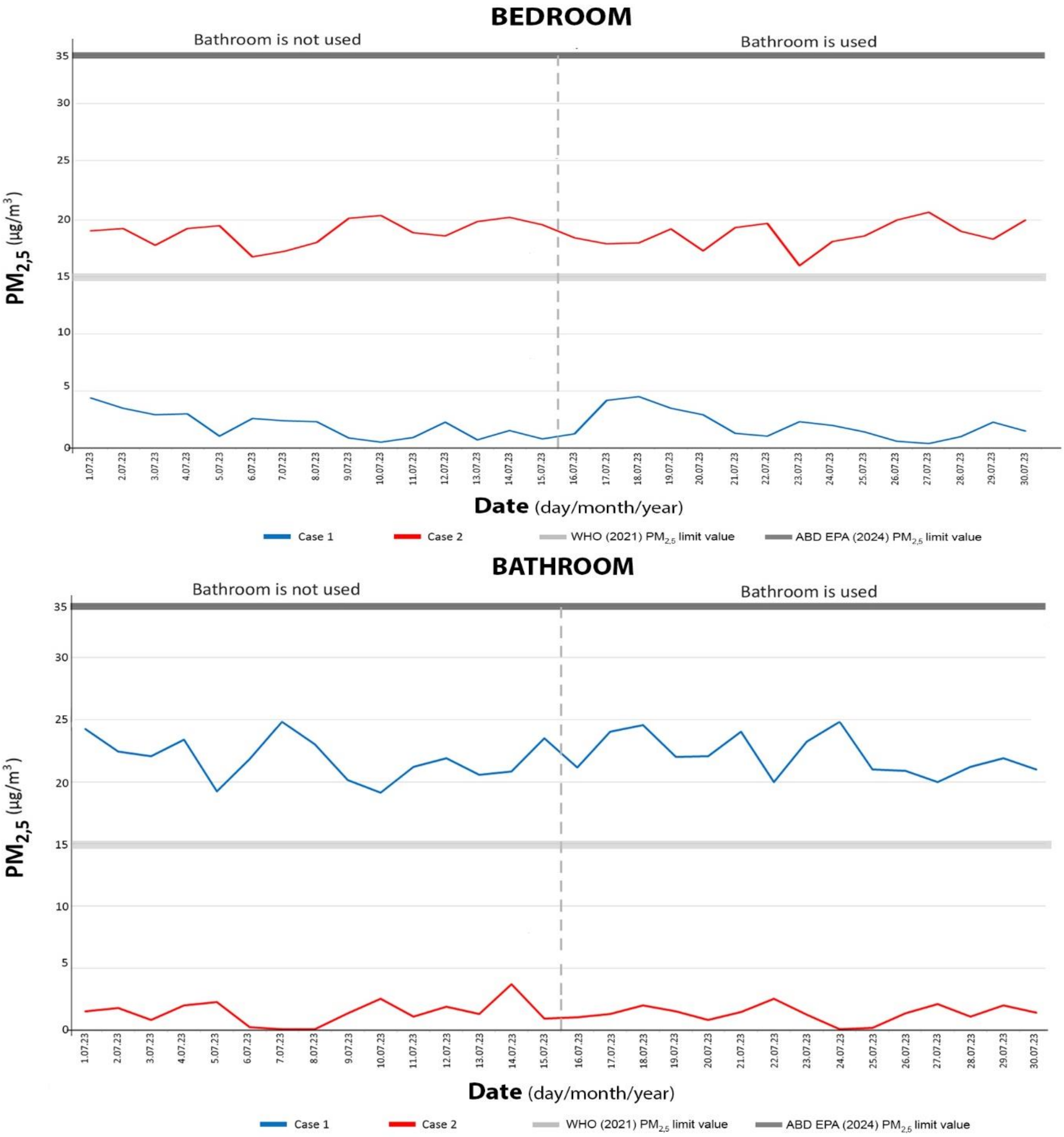

Figure 9. *$PM_{2.5}$ measurement results from bedroom and bathroom in summer*

According to the summer measurements shown in Figure 9, $PM_{2.5}$ measurements never reached the limit value of EPA limit values. The main reasons for this could be better outdoor air quality, cleaning conditions, and room design. On the other hand, the results of the bedroom and bathroom measurements showed different dispositions for the cases. In Case-, $PM_{2.5}$ measurements in the bedroom were lower than in the bathroom. Controversially, in Case-2, the $PM_{2.5}$ measurements of the bedroom were higher than those of the bathroom. In summer, the $PM_{2.5}$ measurements were not much influenced by bathroom use. In Case-1, the air quality in the bathroom was not influenced by the quality of the outside air due to the room layout. On the other hand, in Case-2, the air quality in the bathroom could be influenced by the air quality in the bedrooms. Consequently, despite the higher $PM_{2.5}$ measurements recorded in the bathroom in Case-1, it is hypothesized that the bedroom's less exposure to these values can be attributed to its design.

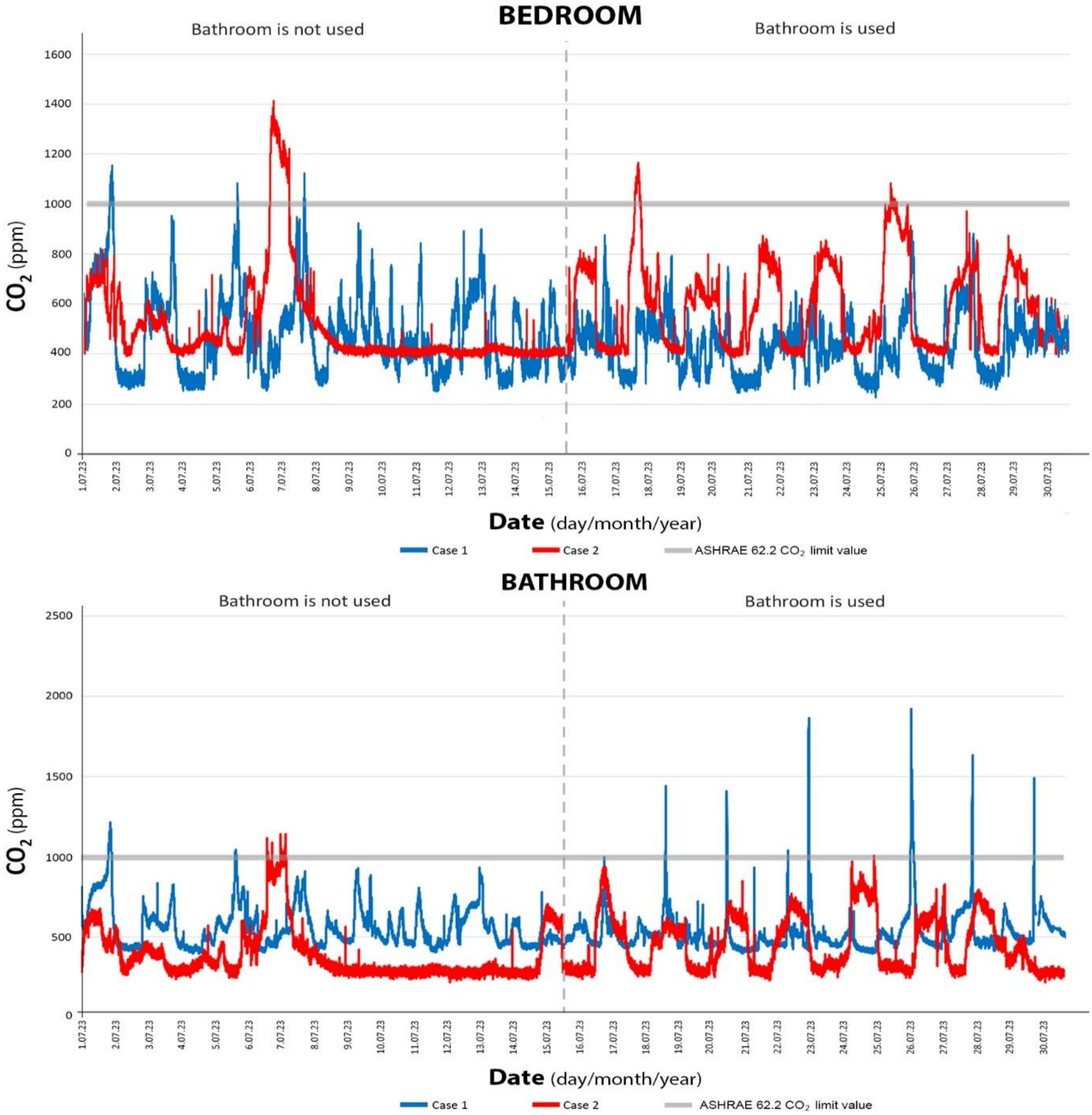

Figure 10. *CO_2 measurement results from bedroom and bathroom in summer*

The results of CO_2 concentration measurements in summer are presented in Figure 10. Measurements are very similar characteristics to winter results. The maximum value of 1000 ppm was exceeded 3 times, and 800 ppm was exceeded 7 times in the bedroom measurements without using the bathroom for Case-1. When the bathroom was used, 1000 ppm was never exceeded, and 800 ppm was exceeded 3 times in bedroom measurements. In bathroom measurements of Case-1, when the bathroom was not used, the maximum value of 1000 ppm was exceeded 2 times, and 800 ppm was exceeded 4 times. While the bathroom was in use, the maximum value of 1000 ppm exceeded 6 times, and 800 ppm was exceeded 9 times. The CO_2 concentration in the bedroom of Case-2 without using the bathroom, the maximum value of 1000 ppm, and a dangerous value for indoor environments of 800 ppm were exceeded for only one day. When the bathroom was in use, the maximum value of 1000 ppm was exceeded 2 times, and 800 ppm was exceeded 3 times. The reason for better results is the night ventilation of the room in the summertime. The CO_2 concentration in the bathroom of Case-2 without using the bathroom behaves similarly to the bedroom, and the maximum value of 1000 ppm and a dangerous value for indoor environments of 800 ppm was exceeded for one day, which was the same day in bedroom measurements. On the other hand, the CO_2 concentration in the bathroom was higher than when the bathroom was not used, but 1000 ppm was never exceeded, and 800 ppm was exceeded 3 times. It is assumed that the air quality in the bathroom is better because of room layout and ventilation. Despite the elevated levels of carbon dioxide (CO_2) resulting from extended bedroom usage relative to bathroom usage, night ventilation during summer months has been shown to positively impact the overall CO_2 levels in all indoor environments.

3.3. Results of Interview

As seen in Table 1, the bedroom users in both houses are between 35 and 40 years old, married, and university educated. They said they used the bedroom for at least 4 to 8 hours. Female occupants of both houses have allergic disorders, and all users are non-smokers. Both bedroom users have similar demographic characteristics. In addition, both bedrooms are of similar size, the current equipment (furniture, carpet, etc.) is of similar quality, and the bedroom usage routine is also similar.

Table 1. *Interview summary table of user sleeping quality*

	Gender	Age	Time spent asleep	Falling asleep time	The Pittsburgh Sleep Quality Index score
Case 1	Female	38	5-6 hours	45 minutes	14
	Male	41		60 minutes	23
Case 2	Female	35	6-7 hours	15-30 minutes	15
	Male	38		15 minutes	9

The occupants in Case-1 complained of sleepiness, drowsiness, and headaches. They also mentioned problems with nose and throat allergies. They stated that these symptoms improved when they did not use the bedrooms. They also reported they were uncomfortable with the odor coming from the bathroom. They said the increasing natural ventilation reduced their discomfort, especially in the summer. The users expressed satisfaction with the indoor air, temperature, and humidity, but the interviews revealed that they didn’t know the cause of their problems. Both users reported falling asleep in 45-60 minutes. The users complained of waking up frequently in the middle of the night or early in the morning with excessive heat, bad dreams, and pain. Both users described their sleep quality as poor during the measured month. In addition, the male user reported loud snoring, leg twitching and jumping during sleep, and restlessness when rated by their partners. In general, they reported sleeping between 5 and 6 hours. The Pittsburgh Sleep Quality Index score was 23 for the male user, and 14 for the female user. This score was described as poor according to the index. In Case-2, it was noted that complaints such as headaches, dizziness and drowsiness were rare for both users and none during the month. They stated nothing changed when they did not use the bedroom. There was also a complaint about the bathroom smell in this dwelling. They reported that they were satisfied with the indoor air quality due to the natural ventilation in summer. Both users stated that they fall asleep in 15-20 minutes. In general, they said they slept between 6 and 7 hours. The users reported they sometimes woke up in the middle of the night or early in the morning and felt warm. Both users described their sleep quality as quite good during the measured month. In the mutual evaluation of their partners, the male user complained of loud snoring, leg twitching, and jumping while sleeping. The male user's Pittsburgh Sleep Quality Index value was 9, and 15 for the female user. Although both were described as poor, it was determined that they had better sleep quality than the other case. Consistent with the findings, an examination of the data reveals a positive correlation between user complaints and the quality of sleep, as measured by the Pittsburgh Sleep Quality Index (PSQI), in bedrooms with substandard air quality. This observation indicates that the configuration of bedrooms with analogous characteristics may exert a significant influence on the satisfaction levels of their occupants with regard to air quality.

4. DISCUSSION OF RESULT

Table 2. *Comparison of air quality measures*

			PM2.5		**p-value**	**HUMIDITY**		**p-value**	**CO-2**		**p-value**
			Case-1	Case-2		Case-1	Case-2		Case-1	Case-2	
WINTER	Bedroom without bathroom use	**mean**	2.746688	16.47133	P<0.0001	25.69394	23.7493	P<0.0001	475.0708	718.7734	P<0.0001
		min	0	39		10	16.1		258	384	
		max	11	8		41.6	38.9		948	1547	
	Bedroom with bathroom use	**mean**	3.348288	11.68769	P<0.0001	27.77708	32.39609	P<0.0001	476.9613	664.9615	P<0.0001
		min	0	6		18.8	21.9		243	387	
		max	12.4	26		46	59.4		977	1252	
	Bathroom without bathroom use	**mean**	16.47133	2.746688	P<0.0001	23.7493	25.69394	P<0.0001	718.7734	475.0708	P<0.0001
		min	3.2	0		16.1	13.3		384	258	
		max	30.8	8.7		92.9	96.6		1547	1248	
	Bathroom with bathroom use	**mean**	11.68771	3.348288	P<0.0001	32.39607	27.77708	P<0.0001	664.9863	476.9613	P<0.0001
		min	1	6		20	19		498	315	
		max	21	26		92	97		2150	1877	
SUMMER	Bedroom without bathroom use	**mean**	2.62549	18.2877	P<0.0001	32.88053	39.26797	P<0.0001	495.3921	520.0909	P<0.0001
		min	1	16		17	29.1		253	383	
		max	4.1	21		44.9	50.3		1156	1415	
	Bedroom with bathroom use	**mean**	1.255303	19.43373	P<0.0001	30.24906	45.65278	P<0.0001	431.5101	590.4477	P<0.0001
		min	0.7	16.5		19.2	30.9		228	388	
		max	4.7	21.7		48.3	55.8		7885	1166	
	Bathroom without bathroom use	**mean**	22.42035	1.902853	P<0.0001	35.5591	49.32709	P<0.0001	573.1011	465.3675	P<0.0001
		min	19.1	0		23.1	36.1		396	233	
		max	25	3.7		46	79.6		1213	1007	
	Bathroom with bathroom use	**mean**	21.19084	1.069606	P<0.0001	36.92058	42.68536	P<0.0001	520.5415	391.8358	P<0.0001
		min	15	0		25.5	32.9		399	220	
		max	25	3.2		82.4	75.7		2069	1142	

The mean, range and t-test results of measurements are presented in Table 2. Concurrently, the findings of the Case-1 and Case-2 measurements indicated significant disparities among the air quality factors, including $PM_{2.5}$, humidity, and CO_2 ($P < 0.0001$). The graph comparing average humidity values is shown in Figure 11. Humidity levels are significantly higher in summer measurements than in winter. The use of the bathroom during winter months has been shown to result in an increase in average humidity levels across all measurements. However, the impact of bathroom usage on humidity levels is less pronounced during summer months, likely due to the enhanced ventilation during that season.

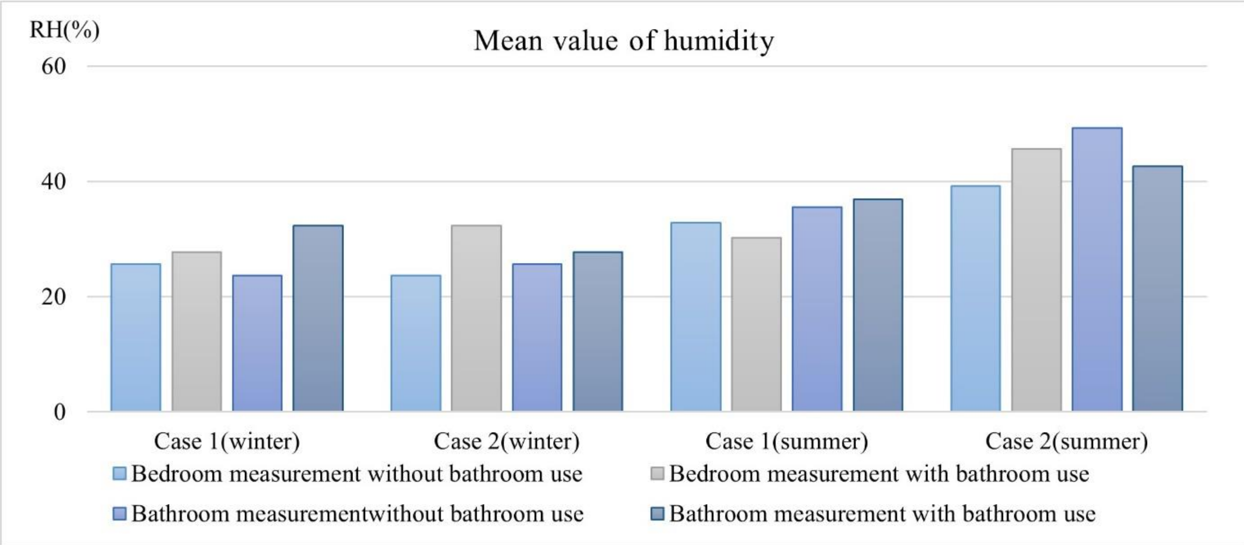

Figure 11. *Comparison of humidity means value in measurements*

$PM_{2.5}$, one of the important indicators of air quality, refers to particles found in the air, including dust, soot, dirt, smoke, and liquid droplets. Figure 12 provides a comparative analysis of the mean $PM_{2.5}$ values across both summer and winter periods. $PM_{2.5}$ levels in bedroom are significantly higher in Case-2 than Case-1 and conversely, the $PM_{2.5}$ measurements conducted in the bathroom typically exhibit higher concentrations in Case-1. The measurements of $PM_{2.5}$ obtained from bathrooms consistently exhibited higher concentrations compared to those collected in bedrooms.

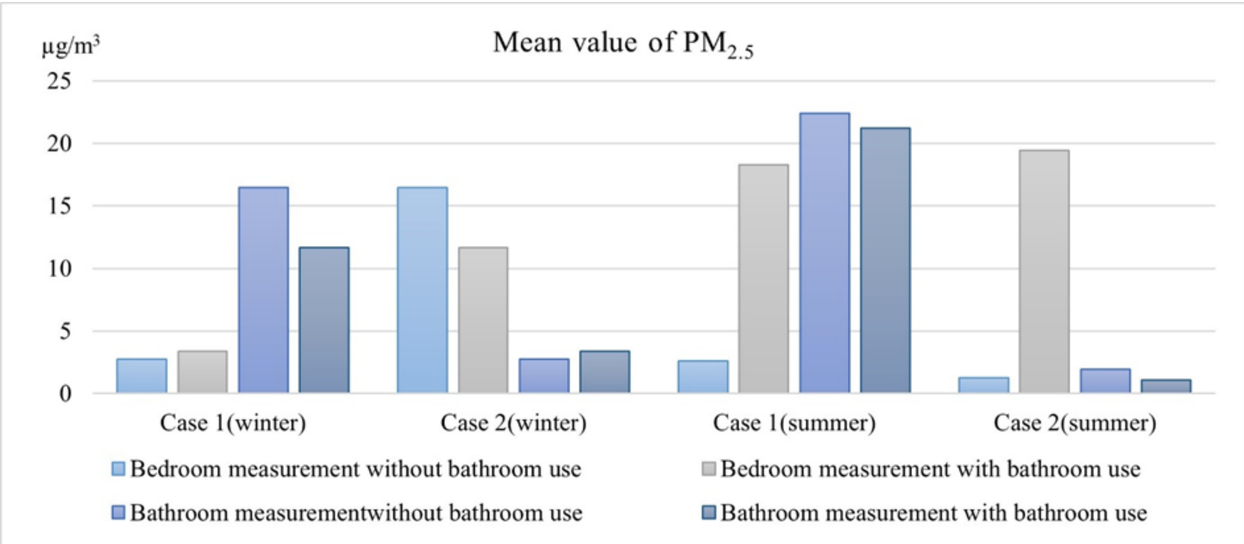

Figure 12. *Comparison of $PM_{2.5}$ means value in measurements*

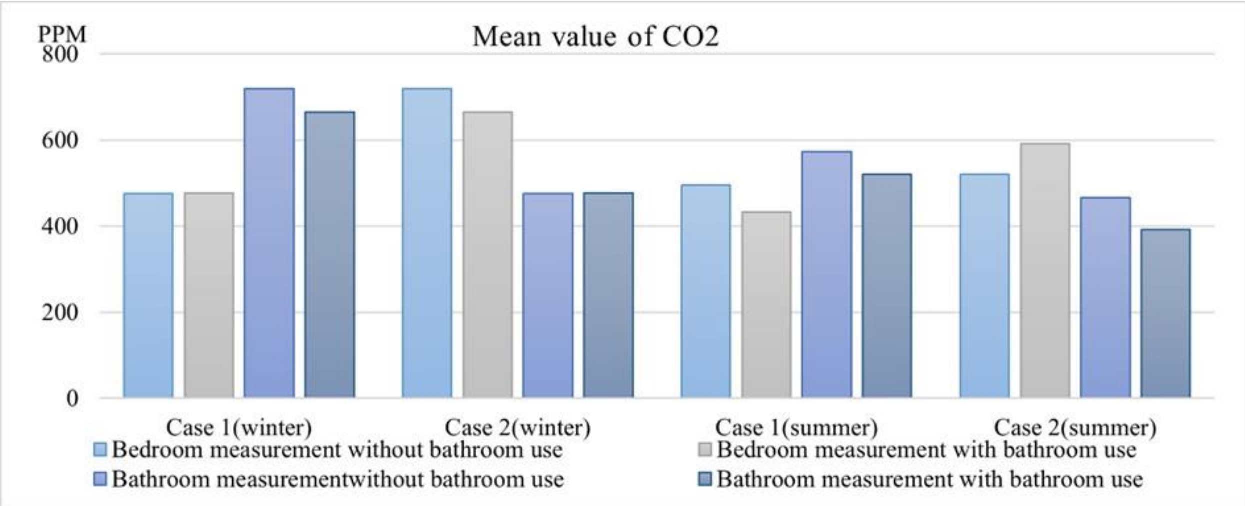

Figure 13. *Comparison of CO_2 means value in measurements*

CO_2 has been identified as a significant indoor air pollutant, and its control is strongly recommended for the purpose of enhancing indoor air quality. The mean CO_2 values obtained from these measurements are presented in Figure 13. The mean CO_2 rates for all areas in Case-2 are higher than those in Case-1, both in summer and winter measurements. A general observation indicates a decrease in CO_2 values during summer measurements.

The results obtained in this study, which were conducted to take long-term measurements and create preliminary findings, were considered cautious due to the small size of the sample. Notwithstanding, the findings suggest a correlation between sleep quality and air quality with the configuration of bedrooms. It has been demonstrated that employing diverse plan typologies may yield more precise outcomes. While it is challenging to obtain measurements over an extended period, advancements in simulation technologies may facilitate the incorporation of different scenarios in CFD analyses. A contemporary study [7] in literature, utilizing a modest sample size, has examined the impact of environmental factors in the bedroom on sleep quality and physiological parameters. This investigation revealed that elevated CO_2 and temperature levels can adversely affect sleep efficiency and quality. This study lends further support to this hypothesis by demonstrating the efficacy of planning in shaping the built environment. The article on this subject highlights the potential benefits of bedroom design in promoting sleep quality and overall health, particularly during heatwaves, and suggests a focus on creating environments that could help mitigate the effects of heat to enhance resilience and well-being in a warming climate [34]. Another study's [35] findings indicated that attaining CO_2 concentrations of 1,000 ppm or higher resulted in a substantial deterioration in sleep quality, a decline in sleep efficiency, an increase in awakenings, a decrease in deep sleep, and a negative impact on the following day's cognitive performance, in comparison to a CO_2 concentration of 750 ppm. The interviews in this study also reveal that air quality has an impact on sleep quality. A recent study [36] emphasizes the critical role of proper ventilation in sleeping environments to maintain indoor air quality, particularly by keeping CO_2 levels below 750 ppm and 1,000 ppm, as many conventional sleeping spaces quickly exceed these limits. This indicates that CO_2 levels should be regulated at lower thresholds, as they constitute a significant factor influencing indoor air quality. The findings, based on measurements collected during both summer and winter in the same locations, indicate that effective ventilation during summer months and the presence of a favorable outdoor environment with optimal air quality have a substantial impact on the quality of indoor air. A study characterized the indoor air quality in naturally ventilated bedrooms in cold climates [22] revealed the relationships between ventilation, indoor thermal environment, and air quality factors, such as CO_2 and TVOC concentrations. Similarly, the findings of the present study demonstrate that bedrooms experience increased ventilation during the summer months, which has a positive effect on air quality. Conversely, it has been observed that bedrooms receive less ventilation during the winter months, and this decrease in ventilation is accompanied by a proportional change in air quality.

5. CONCLUSION

This study analyzed how bedroom design affects air quality by comparing it to the measure. Within the scope of the study, one-month CO_2, $PM_{2.5}$, temperature, and humidity values for the summer and winter months of the residences with two different bedroom plans were measured, and the users were interviewed about air and sleep quality. After the study, it was determined that the air quality in the bathroom, which opens directly to the bedroom, is worse than in the other case, especially in winter, and the users complain about this. In the summer months, it is observed that there is a significant improvement in indoor air quality, particularly with night ventilation, with a positive effect on outdoor air quality. Especially in the winter months when underfloor heating is used, it is observed that the use of the bathroom has a positive impact on the relative humidity in the bedroom to reach the specified limit values. In addition, it was determined that CO_2 and $PM_{2.5}$ values, which are important pollution parameters, exceeded the maximum limit levels set by the standards when the bathroom was used.

These findings suggest that the volume of the bathroom, which provides an indirect connection to the bedroom, rather than opening the bedroom directly, will positively affect the air quality. In addition, it is observed that in multi-story housing planning, especially in the ventilation of wet areas, only natural chimneys are insufficient and must be supported by mechanical ventilation, or they have to be designed to increase natural ventilation. While such measures are considered in areas such as hotels, they are not as widely applied in residential design. Especially to overcome the odor problem, the relationship between the problematic spaces and the bedroom should be reduced as much as possible. Buffer zones, such as dressing rooms or intermediate halls, will prevent the odor problem from reaching the sleeping areas.

To improve the air quality in the sleeping areas, the passive ventilation options should be increased and then the hybrid options with mechanical support should be offered. In passive systems, priority should be given to placing openings in the direction of the prevailing wind and creating cross-ventilation opportunities. The layout should be designed to allow cross ventilation by ensuring that windows or vents in the bedroom and bathroom can be opened to facilitate air flow between the two areas, thus helping to remove moisture and contaminants. Installing windows that are operable and strategically placed to catch prevailing breezes can significantly enhance natural ventilation. Larger windows or those that open fully can facilitate better airflow. In addition, thermal chimneys can be used to remove bad air from the roof level. Adding ventilation grilles or passive vents to the bathroom door can help promote airflow without sacrificing privacy. To improve air quality, it is also important to reduce the carpet use in the bedrooms and to establish a regular cleaning routine according to the use of the room. Mechanical systems should be considered as a support to passive systems in apartments, especially in climates where thermal comfort conditions cannot be achieved by natural ventilation. Air quality monitoring systems should be installed in flats to increase user awareness of air quality. In addition, HEPA filters should be in place, and where there are air conditioning systems, ensure that this is being maintained and serviced.

As mentioned before, the long duration of the study, the limited number of measuring instruments, and the problems associated with obtaining permission from the houses where the measurements were to be taken prevent this study from being carried out in many buildings and from providing more general information. The research can be extended by increasing the number of samples and monitoring rooms of different sizes and dimensions. This study can be also continued with different master bedrooms created in different climates. Climatic variations can be considered when planning, especially in more humid regions where more attention needs to be paid to planning bathrooms together with bedrooms. With this study, the direct connection of the bathroom in the planning of the bedroom is open to discussion and at this point, different options can be tried to create a buffer zone between the spaces. However, it is important to consider this as preliminary research and to form a basis for further studies. In addition, further studies will evaluate how natural ventilation strategies can be applied here by measuring the effects of ventilation control systems and modeling air flows.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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