Evaluation of indoor environment and energy consumption in dwellings before and after their refurbishment

HANA BUKOVIANSKA PUSTAYOVÁ
Slovak University of Technology
in Bratislava
Faculty of Civil Engineering
Department of Building Services
hana.bukovianska@gmail.com

VERONIKA FÖLDVÁRY
Slovak University of Technology
in Bratislava
Faculty of Civil Engineering
Department of Building Services
veronika.foldvary@gmail.com

DUŠAN PETRÁŠ
Slovak University of Technology
in Bratislava
Faculty of Civil Engineering
Department of Building Services

The current study investigates the impact of building renovation on the energy consumption, thermal comfort, indoor air quality and occupants´ satisfaction. Two sets of experiments were carried out. Indoor air quality was investigated in three pairs of dwellings while energy evaluation and investigation of the thermal comfort were carried out in six pairs of residential buildings. Each pair of the dwellings consisted of two buildings with identical construction; however, the building pairs were mutually different. One of the buildings was recently renovated, while the other one was in its original condition. Both objective measurements and subjective evaluation using questionnaires have been used. Temperature, relative humidity and CO_2 concentration were measured in the apartments in winter and summer period. Energy performance and thermal comfort were investigated in the heating season. The study indicates that the large-scale renovations may reduce energy consumption of the building stock. However, without considering the impact of energy renovation on environmental quality, the implemented energy saving measures may reduce the quality of the indoor environment in many apartments, especially in the winter season.

Introduction

Buildings are at the pivotal centre of our lives. The characteristics of a building, its design, its appearance, feel, and its technical standards not only influence our productivity, our well-being, our moods and our interactions with others, but they also define the amount of energy consumed by a building [1].

Energy retrofitting of the existing European building stock provides both significant opportunities and challenges. It is an important topic not only in the field of energy conservation, but it may influence the quality of life as well. People spend more than 90% their time indoors, with a significant portion of this time spent at home [2], therefore the potential impact of energy saving measures on indoor environmental quality should not be neglected. This is especially the case in countries where the trend is to reduce air infiltration by tightening the building. Changes caused by renovation can be negative or positive, and some measures will not influence indoor environmental quality at all [3].

The parameters of the indoor environment that have an impact on the energy performance of buildings as well as input parameters for the building systems design and energy performance calculations are well specified by Standard EN 15 251(2007). It defines the global comfort as the sum of different aspects, i.e. thermal comfort, indoor air quality, visual comfort and acoustic comfort. The standard also recommends parameters of indoor temperatures, ventilation rates, illumination levels and acoustical criteria for the design, heating, cooling, ventilation and lighting systems. It is mainly applicable to moderate thermal environments, where the objective is to reach the satisfaction of the occupants [4]. The impact of energy retrofitting on the indoor air quality is rarely considered. The indoor air quality may be often compromised due to decreased ventilation and infiltration rate.

This study provides an insight in the energy performance of the Slovak residential buildings and investigates impact of building renovation on indoor environmental quality.

Indoor air quality and air exchange rate evaluation

Methodologies

The study was performed in three pairs of residential buildings. One of the buildings in each pair was renovated and the other was in its original state. The energy-retrofitting included thermal insulation of facade, replacement of windows with energy efficient ones and hydraulic balancing of the heating system. The non-renovated buildings were mostly in their original state. However, new plastic frame windows have been already installed over the last years in most of the apartments in these buildings. Natural ventilation was used in all buildings. Exhaust ventilation was present in bathrooms and toilets [5].

Experimental measurements were performed during the heating season in 2013/2014 and in summer 2014. Temperature, relative humidity and the concentration of CO_2 were measured in bedrooms of the apartments using a HOBO U12-012 data logger (Onset Computer Corp., USA) and CARBOCAP CO_2 monitors (GMW22, Vaisala, Finland). The data were recorded in 5 minute intervals for one week in each building [6]. The locations of the instruments were selected with respect to the limitations of the carbon dioxide method [7]. The measurements were conducted in 94 apartments in the winter (45 apartments in original buildings, 49 in renovated ones) and in 73 apartments in the summer season (35 apartments in original buildings, 38 in renovated ones). Data from night periods between 20:00 and 6:30 were used for calculation of air change rates. Occupancy and physical state of residents were also included into the process of calculation [8].

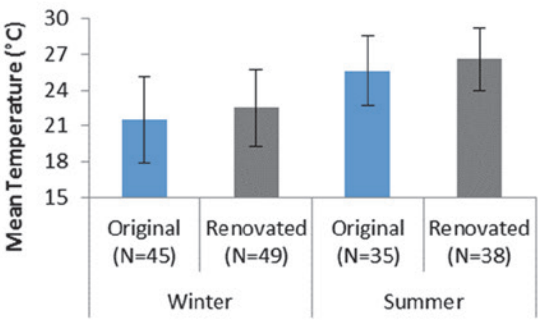
At each visit, the residents were asked to fill in a questionnaire regarding some building characteristics, occupant behaviour and habits, sick building syndrome symptoms and occupants' perception of indoor air quality and thermal environment. The occupants of the renovated buildings were also asked questions about altered habits after renovation [5].

The CO_2 concentration was used to calculate the air exchange rate during 5–8 nights in each bedroom. The occupants' CO_2 emission rate was determined from their weight and height available from the questionnaires [9].

Results and discussion

Indoor air quality

According to ISO 7730 and ASHRAE Standards, the recommended range of the indoor temperature during the winter conditions is between 20°C and 24°C [10, 11]. In the winter season the overall mean indoor air temperature was higher in the renovated buildings (22.5°C) compared to the original dwellings (21.5°C), (**Figure 1**). The indoor temperature in bedrooms was within the recommended range for most of the time in both the original (78%) and the renovated (91%) dwellings. Longer periods with average temperatures below 20°C were observed in the non-renovated buildings (18%) than in the renovated ones (2%).



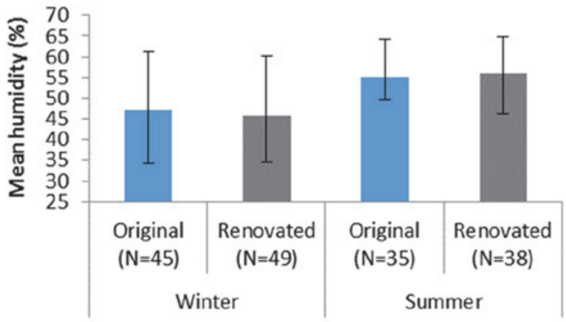


Figure 1. Average indoor temperature (left) and humidity (right) in the bedrooms of the investigated during the winter and summer season. Ends of the whiskers characterises the minimum and maximum values.

The recommended indoor temperature during summer conditions ranges between 23°C and 26°C [10, 11]. In summer the overall average temperature was 25.7°C in the original dwellings and 26.6°C in the renovated dwellings (**Figure 1**). According to the results obtained from the whole measurement period 49% of apartments in the original building and 71% of apartments in the renovated dwellings were out of the recommended range with higher indoor temperatures than 26°C. The rest of the apartments met the criteria of the guidelines.

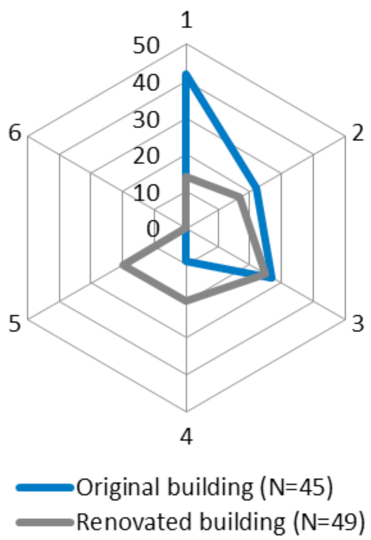
The recommended indoor relative humidity is between 30% and 60% [11]. The mean relative humidity across almost all the apartments met the prescribed range (**Figure 1**). In winter only two apartments in the original buildings and one apartment in the renovated dwellings reported higher average relative humidity than the recommended maximum. In summer except four apartments in the original buildings as well as in the renovated ones all the apartments met the criteria on the indoor relative humidity.

In the winter the average CO_2 concentration during the nights across all apartments was higher in the renovated buildings than in the original ones. In 83% of apartments located in the renovated buildings the average CO_2 concentration was higher than 1 000 ppm, while this was the case in 75% of apartments in the original buildings. The fractions of apartments where the 20-min running average CO_2 concentrations exceeded 1 000, 2 000 and 3 000 ppm are shown in **Table 1**. In the summer the average night-time CO_2 concentrations were similar in both types of buildings [5].

Table 1. Night-time CO_2 concentrations and fractions of apartments with average CO_2 above 1000 ppm and with at least one 20-minute period with CO_2 above three cut-off values in the investigated buildings.

	Winter		Summer	
	Original N=45	Renovated N=49	Original N=35	Renovated N=38
Mean CO_2 during night (ppm)	1425	1680	845	815
Average CO_2 >1 000 ppm (%)	71	80	43	40
20-min period CO_2 >1 000 ppm (%)	75	83	43	40
20-min period CO_2 >2 000 ppm (%)	17	32	0	5
20-min period CO_2 >3 000 ppm (%)	4	8	0	0

According to results obtained from questionnaire surveys the residents in the non-renovated buildings did not indicate severe problems with the perceived air quality. During the winter, a greater fraction of the occupants indicated poor air quality in the renovated buildings compared to the non-renovated buildings (**Figure 2**). In the summer, most of the subjects in the renovated buildings found the indoor air quality good while occupants in the original buildings indicated medium to good indoor air quality in the bedrooms [5].



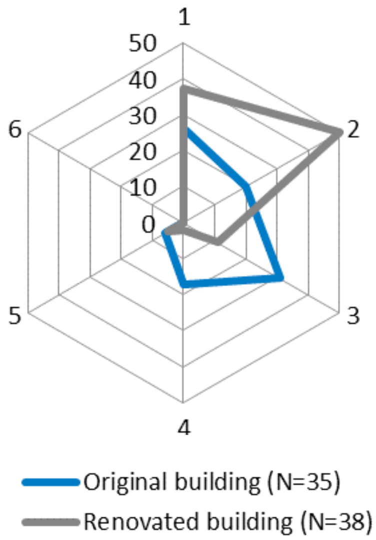


Figure 2. Summary of answers to the question "How unpleasant do you think the indoor air quality is in your bedroom during night/in the morning?". Answers were from 1 – perceived air quality was not a problem, to 6 – poor indoor air quality. One occupant in each apartment answered during winter (left) and summer (right) [1].

Air exchange rate

The average air exchange rate across the apartments in the original buildings (0.79 h^{-1}) was significantly higher than in the renovated buildings (0.48 h^{-1}) in winter. The average air exchange rates were above the minimum recommended value (0.5 h^{-1}) in 63% of apartments located in the original dwellings, unlike in the renovated ones (42%). In the summer the average air exchange rates were similar in both types of buildings [5]. The majority of the evaluated apartments in the non-renovated (97%) as well as in the renovated dwellings (94%) exceeded the minimum criteria for the air exchange rates (**Figure 3**).

Energy renovation may change the indoor environment in the dwellings. It may directly lead to lower ventilation rates and higher concentrations of indoor pollutants [12]. Ventilation rates are also influenced by the occupants´ ventilation habits. In the present study 22% of the occupants in the renovated buildings indicated that they ventilate more often during the winter than before renovation. This may indicate increased CO_2 concentrations and poorer indoor air quality associated with renovation works. The results from the summer further support this observation; 47% of residents indicated that they have changed their ventilation habits and ventilated more often than they did before renovation. People ventilate more often at higher ambient temperatures. This leads to higher ventilation rates in summer than in winter [13, 14]. The larger fraction of occupants in the renovated homes changed their ventilation habits in the summer compared to winter. This may partly explain the lower CO_2 concentrations and better perceived air quality in the renovated buildings than in the original buildings in the summer, as opposed to the winter [5].

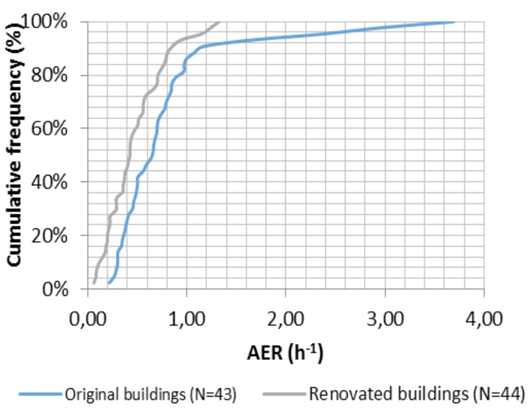
Thermal comfort and energy evaluation

Methodologies

This part of the study was performed in six pairs of residential buildings. In each pair of the buildings was renovated and the other was in its original state. Each pair of the dwellings contained from identical apartment buildings in term of construction systems. The following Slovak structural systems were chosen: TA 06 BA, BA NKS, ZTB, BA NKS P.1.15, P.1.14, P.1.15. Building refurbishment included three energy efficiency strategies: thermal insulation of facade and roof, replacement of windows in common premises, hydraulic balancing of the heating system. The non-renovated buildings were mostly in their original state. However, in the residential part of the buildings, approximately 90% of the windows have been already replaced with energy efficient (plastic) ones [15].

Energy audit was carried out to investigate the energy performance of the residential buildings. It included inspection, evaluation and analysis of existing situation of the selected buildings. Energy need for heating was calculated for each investigated dwelling according to EN ISO 13790. Also the real data of energy consumptions were collected from the housing associations maintaining the selected buildings. The detailed steps of energy auditing are shown in publication by Dahlsveen et al [16].

The data collected from energy monitoring were processed in ENSI EAB software. Energy-Temperature diagram (ET-diagram) performed by this software was used for data analyses. It presents ET-curves tailored for quick calculations of the energy performance in original and new buildings.



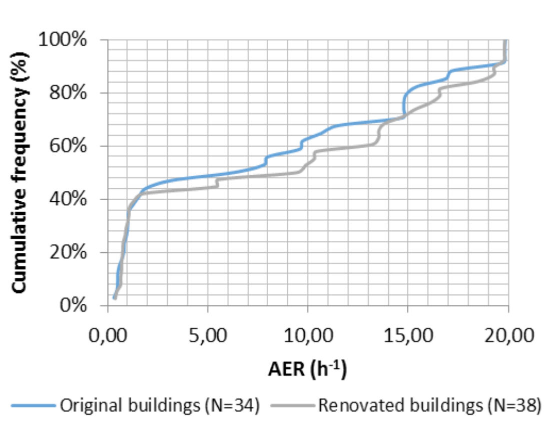


Figure 3. Cumulative percentage of air exchange rates in the original and the renovated buildings during winter (left) and summer (right).

For the purpose of the subjective evaluation two types of questionnaires were created (questionnaires used in the original and the renovated buildings). The questionnaires contained questions about basic information on the inhabitants, building characteristics, thermal comfort and local discomfort as well as about occupants´ ventilation habits. The occupants of the renovated buildings were also asked questions about altered heating and ventilation habits after renovation [15].

The evaluation of thermal environment was performed using PMV (predicted mean vote) and PPD (percentage of dissatisfied) indices. The survey asked subjects about their thermal sensation on the ASHARE seven-point scale from cold (–3) to hot (+3). Fanger's equations were used to calculate the PMV of a large group of occupants (N=244 in original; N=236 in renovated dwellings). It also took into account the occupants' physical activity (metabolic rate), the thermal resistance of their clothing, air temperature, mean radiant temperature, air velocity, and partial water vapour pressure [10].

The field measurements of indoor temperature and relative humidity were performed in the living rooms of selected apartments (N=8 in original; N=12 in renovated buildings), in period of the heating season from October 2011 to April 2012. The data were recorded in 15 minute intervals by using HOBO U12 loggers.

Results and discussion

Energy consumption and monitoring

a) Energy evaluation

The energy need for heating was calculated for each pair of the residential buildings [15]. **Table 2** shows a detailed summary of the real energy consumptions, energy needs for heating and the classification of the investigated buildings into energy classes according to the Slovak regulations. The energy saving potential was higher than 30% across all investigated structural systems with the highest percentage of difference in energy need for heating (52%) in case of T06 BA residential buildings. The real data of energy consumption were alike the results from calculation except for two structural systems, ZTB and BA NKS-S P.1.15. Noticeable difference between calculated and real values might be caused by standardized climatic conditions for Bratislava which were used in the calculation method. The real conditions are usually different from the standardized ones. In our study the real outdoor temperature was changing day to day during the heating season. As it was expected, the energy retrofitted dwellings were classified into higher energy classes than the original ones.

b) Energy monitoring

Energy monitoring was based on periodic (weekly) recording of the energy consumption data and meas-

Table 2. Summary of real energy consumption, energy calculation and energy classification of the residential buildings.

Structural system	State of building	Real energy consumption (kWh)	Difference	Energy need for heating (kWh)	Difference	Floor area (m²)	Energy class for heating
T06 BA	Original	307433	55%	352148	52%	3723	D
	Renovated	138889		169846			B
BA NKS	Original	388956	39%	368329	34%	3980	D
	Renovated	238703		241607			C
ZTB	Original	722910	15%	843437	51%	9094	D
	Renovated	611930		409814			B
BA NKS S P.1.15	Original	476440	28%	530000	40%	6110	D
	Renovated	341469		319871			B
P.1.14	Original	367970	43%	360571	38%	4680	C
	Renovated	209278		224244			B
P.1.15	Original	239192	51%	343533	51%	3421	D
	Renovated	117890		181263			B

urements of the corresponding mean outdoor temperature. The ET-curve for each pair of the buildings was created to compare the results between the actual state of energy consumption in the original buildings and the optimal energy consumption in the retrofitted ones. The ET-curve was created for each investigated building type. **Figure 4** shows an example of ET-curves for the structural systems T06 BA and P.1.14.

The solid line represents buildings in the original condition and the dot line characterises the retrofitted buildings. The curve consists of two parts. The sloping line presents energy consumption of the heating system and the horizontal one shows energy consumption of the domestic hot water (DHW). The energy of the delivered DHW was not inquired into detail. It was calculated based directly on floor area. This method is characterised by the assumption that there is a linear relationship between the DHW demand and the floor area of the building [17].

Thermal comfort

The greater fraction of occupants indicated slightly warm and warm thermal sensation in both types of buildings, with higher percentages of "warm (+2)" thermal environment in the renovated dwellings (50%) compared to the original ones (30%). Regarding the thermal preferences of occupants´, higher percentage of respondents preferred warmer thermal environment in the non-renovated dwellings (31%) compared to the responses from occupants in the retrofitted buildings (8%). The majority of occupants were satisfied with

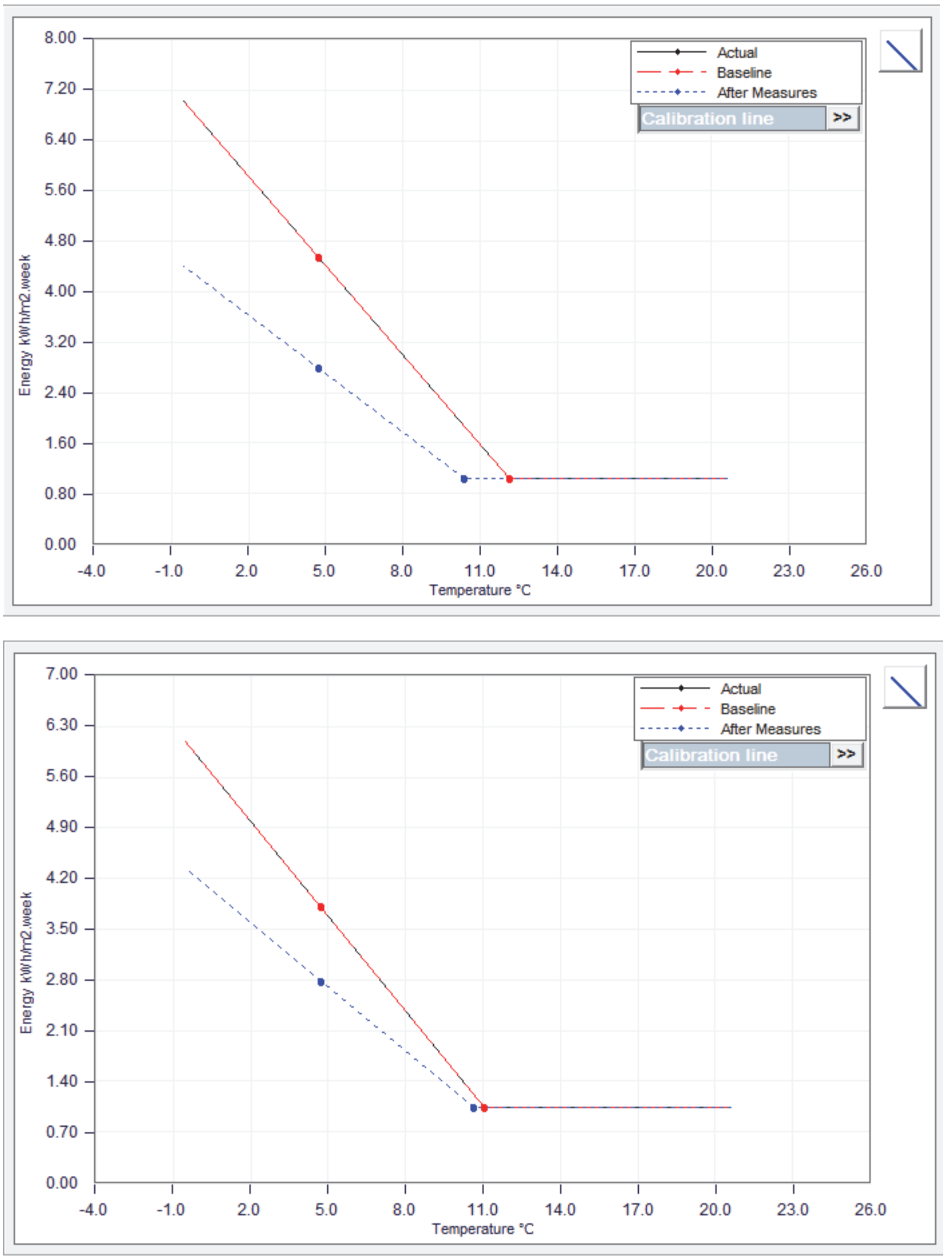


Figure 4. ET-curve for the the structural systems T06 BA (top) and P.1.14 (bottom).

the ordinary state of the air temperature in both types of the dwellings (**Table 3**), [15].

Indoor air temperature and relative humidity were classified by categories according to EN 15 251 (**Figures 5 and 6**). The overall mean air temperature was lower in the original dwellings (22.8°C) compared to the renovated ones (23.7°C). In case of the non-renovated buildings the air temperature was fluctuating between Category I and Category III, with mainly presented temperature range from 22°C to 24°C. In buildings after renovation the temperature was ranging from 23°C to 25°C. The measured relative humidity corresponded to Category II. Visible decrease of the relative humidity occurred from 1.2 2012 to 15.2 2012 when the outdoor temperature was ranging between −5°C and −10°C. The relative humidity was between 30% and 50% in the retrofitted buildings and it was mostly corresponding to Category III. The percentage of the time when the measured data were out of the limit are negligible in both types of the buildings [18, 19].

Table 3. Thermal sensation (left) and the thermal preferences (right) in the investigated residential buildings.

Thermal sensation	Original buildings (N=244)	Renovated buildings (N=236)
Mean	0.8	1.4
SD	1.1	0.9
Hot (+3)	2%	5%
Warm (+2)	30%	50%
Slightly warm (+1)	34%	28%
Neutral (0)	23%	15%
Slightly cool (−1)	9%	2%
Cool (−2)	2%	1%
Cold (−3)	1%	0%

Thermal preference	Original buildings (N=244)	Renovated buildings (N=236)
Mean	0.2	0
SD	0.6	0.4
Want warmer (1)	31%	8%
No change (0)	61%	85%
Want cooler (−1)	8%	7%

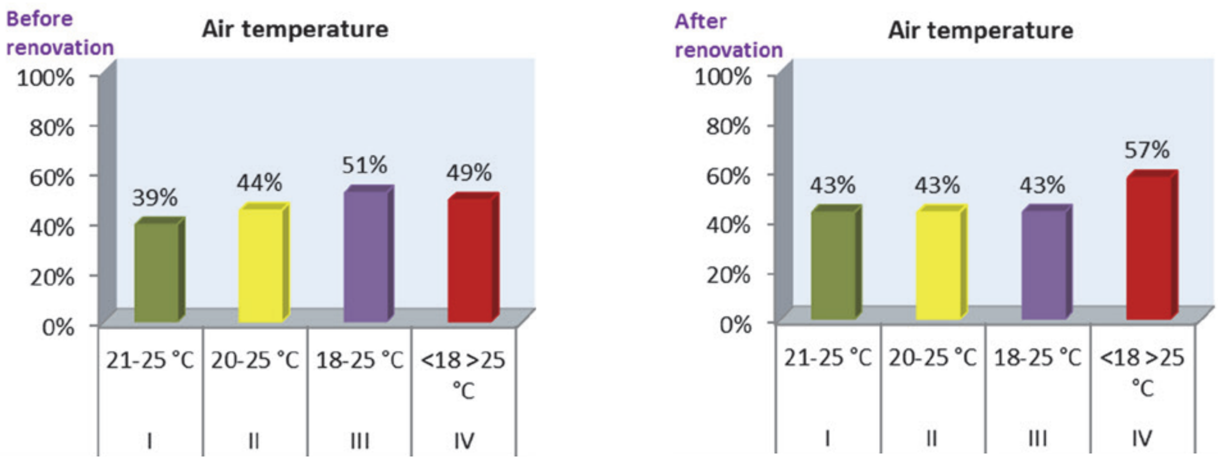


Figure 5. Classification of the air temperatures according to EN 15 251 in the original (left) and retrofitted (right) residential buildings.

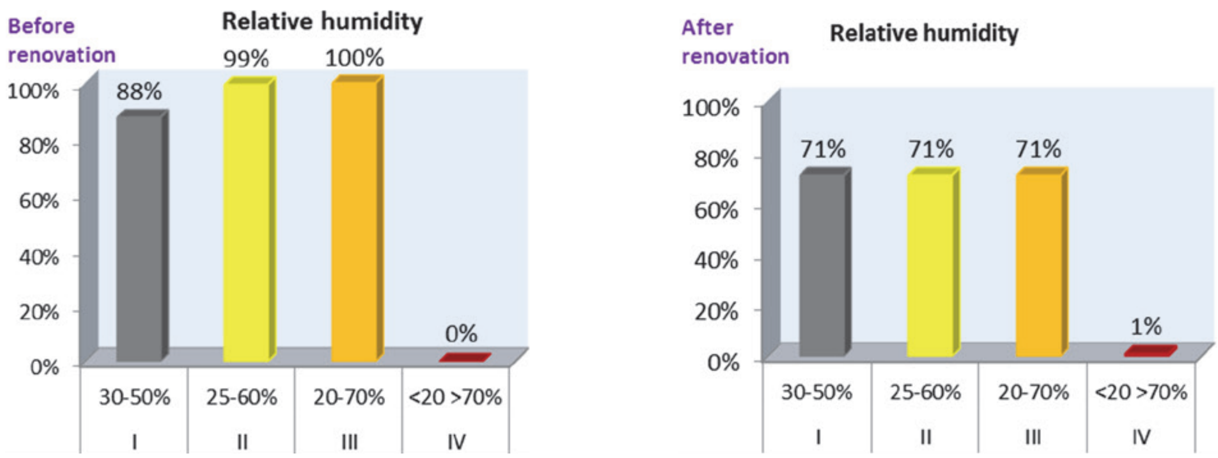


Figure 6. Classification of the relative humidity according to EN 15 251 in the original (left) and retrofitted (right) residential buildings.

Conclusion

Energy retrofitting can contribute significantly to reduce energy consumption of buildings. On the other hand, without consideration of its effects on indoor environmental quality and people as well as without properly made renovation plan it may reduce the quality of the indoor environment in the apartments, especially in the winter season. Unless measures are taken against decreasing ventilation rates during the reconstruction process (e.g. installing exhaust ventilation or mechanical ventilation), the occupants need to ventilate more in order to improve the indoor air quality to the level it was before the reconstruction. ■

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