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INDOOR AIR QUALITY OF RESIDENTIAL BUILDING BEFORE AND AFTER RENOVATION

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Abstract

This study investigates the impact of energy renovation on the indoor air quality of an apartment building during the heating season. The study was performed in one residential building before and after its renovation. An evaluation of the indoor air quality was performed using objective measurements and a subjective survey. The concentration of CO2 was measured in the bedrooms, and a sampling of the total volatile compounds (TVOC) was performed in the living rooms of the selected apartments. Higher concentrations of CO2 and TVOC were observed in the residential building after its renovation. The concentrations of CO2, and TVOC in some of the cases exceeded the recommended maximum limits, especially after implementing energy-saving measures on the building. The average air exchange rate was visibly higher before the renovation of the building. The current study indicates that large-scale renovations may reduce the quality of an indoor environment in many apartments, especially in the winter season.

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Key words

- Indoor environmental quality,
- Carbon dioxide concentration,
- Volatile organic compounds concentration.

1 INTRODUCTION

Most of the residential buildings in Slovakia that were built in the 20th century do not satisfy the current requirements for energy efficiency presented in the national building code. Nationwide remedial measures have been taken to improve the energy efficiency of these buildings and reduce their energy use (Földváry V., Bekö G., Petráš D., 2014). However, since the impact of these measures on indoor air quality is rarely considered, they often compromise indoor air quality due to the decreased ventilation and infiltration rate.

The highest development in the housing stock, as a result of economic changes and population growth, has been recognized as taking place during the second half of the 20th century (Jurelionis A., Seduikyte L., 2010). The majority of housing in Central and Eastern Europe was constructed from panel technology. The degradation of its quality, which has led to its renovation, has become one of the most important measures from an energy-saving point of view.

The aim of the study was to evaluate the impact of basic energy-saving measures on indoor air quality in a typical high-rise residential building built in the 1960s in Slovakia.

2 BUILDING DESCRIPTION

The residential building investigated (Figure 1.) is located in Šamorín, Slovakia. It was built in 1964 from lightweight concrete panels. The building was naturally ventilated. Exhaust ventilation was only used in sanitary rooms, such as the bathrooms and toilets. Renovation of the building was carried out in 2015 and included the following measures: insulation of the building envelope using polyethylene (80 mm), insulation of the roof using mineral wool (120 mm), and hydraulic balancing of the heating system. New plastic frame windows had already been installed in recent years in most of the apartments in the building.(Földváry V., Bekö G., Petráš D., 2015)

Fig. 1 *The evaluated dwelling before and after the refurbishment.*

3 METHODOLOGY OF THE MEASUREMENTS

The first round of the measurements was performed in January 2015 when the building was still in its original condition, and the second round was performed in January 2016 after energy saving-measures had been implemented. Twenty apartments were selected across the residential building; they were equally distributed on the lower, middle and highest storeys of the building. The same apartments were investigated in both winter seasons over a period of eight days (Földváry V., 2016); Bekö G., Földváry V., Langer S., Arrhenius K., 2016). The temperature, relative humidity, CO_2 concentration, and volatile organic compound concentration (TVOC) were measured in the bedrooms (the TVOC concentration in the living rooms) of the apartments. HOBO U12-012 data loggers and CARBOCAP CO_2 monitors (Figure 5) were used for recording the temperature and CO2 concentration data.

For the TVOC concentration Perkin-Elmer adsorption tubes (Figure 6) with 200 mg Tenax TA were used. The measurements were performed according to ISO 16017-2. All the devices were calibrated before the measurement campaign began. The data were recorded at 5-minute intervals for eight days in each apartment. The locations of the instruments were selected with respect to the limitations of the carbon dioxide method (Földváry V., Bekö G., Petráš D., 2015)

Fig.2 Hobo *data logger and Carbocap CO_2 monitor (Sánka I., Földváry V., Petráš D. (2016))*

Each unit was placed at a sufficient distance from the windows and beds to minimize the effect of the incoming fresh air or the effect of the sleeping occupants. The space between the furniture and the room corners was avoided. The CO_2 concentration was used to calculate the air exchange rate over eight nights in each bedroom. The occupants CO_2 emission rate was determined from their weight and height as set out in questionnaires (Földváry V., Bekö G., Petráš D., 2015); Földváry V., 2016).

The calculation of the air exchange rates was performed using the following mass balance (Persily A. K. (1997)):

$$Ci(t)=(C0-Ca)\ .\ e(-\lambda\ .\ ti)+Ca+E\ .\ 103\lambda\ .\ VR\ .(1-e-\lambda\ .\ ti)\ \text{(ppm)} \quad (1)$$

Ci(*t*) - concentration (ppm(V)) at time t (h)
*C*0 - concentration in the beginning (at time t=0)
Ca - outdoor concentration (ppm)
λ - air exchange rate (h-1)
E - estimated metabolic CO_2 generation rate per person in the zone (l/h)
VR - volume of the room (m3)
ti - time (h)

A questionnaire survey was used to determine the subjective evaluations of the quality of the indoor environments. The questionnaire survey was carried out along with the objective measurements. Two

Fig.3 Perkin-Elmer *adsorption tube*

types of documents were prepared (for the unrenovated and renovated building).

The questionnaire contained 6 main parts:

1. basic information about the occupants
2. the state of the building
3. the ventilation habits of the occupants
4. sick building syndrome symptoms
5. perceived air quality
6. thermal comfort

4 RESULTS

The results of the measured values of CO_2, AER, and the TVOC parameters along with the questionnaire survey are as follows:

A. Carbon-dioxide concentration and air exchange rate

The CO_2 concentrations before and after the renovation of the building are shown in Figure 9. Most of the CO_2 concentration data points were within the acceptable limit (blue line) before the renovation (red line), while significantly higher concentrations were measured after the renovation (green line). Table 4 and Figure 10 present the descriptive statistics of the day and night-time CO_2 concentrations before and after the renovation of the residential building. The grand average was 1205 ppm, and the median was 1190 ppm before the renovation.

After implementing the energy-saving measures, the CO_2 concentration visibly increased. The mean was 1570 ppm, and the median was 1510 ppm. Table 5 shows the percentages of the average day and night-time CO_2 concentrations above four cut-off values in the residential building before and after its renovation. A higher number of the apartments exceeded 1500 ppm and the upper concentrations during both the day and night-time after the renovation than before the renovation.

The lower CO_2 concentration before the renovation resulted in higher AERs in the apartments (average 0.61 h-1). After the renovation, the mean air exchange rate (0.44 h-1) dropped below the recommended minimum (0.5 h-1) (Table 6 and Figure 11).

Tab. 1 *Day and night-time CO_2 concentrations before and after the renovation of the residential building. (Sánka I., Földváry V., Petráš D., 2016); Sánka I., Földváry V., Petráš D., 2017)*

a) Before the renovation (N=20)

Time period	CO_2 (ppm)			
	Average	Minimum	Maximum	Median
Day	1040	595	1550	1030
Night	1400	740	2665	1300
Whole period	1205	660	2050	1190

b) After the renovation (N=20)

Time period	CO_2 (ppm)			
	Average	Minimum	Maximum	Median
Day	1320	790	2210	1265
Night	1925	865	3575	1825
Whole period	1570	870	2770	1510

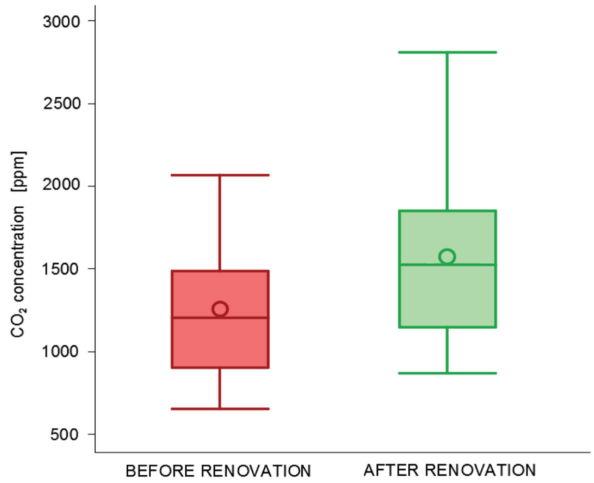

Fig. 5 *CO_2 concentration before and after renovation as a statistical output (Sánka I., Földváry V., Petráš D., 2016); Sánka I., Földváry V., Petráš D., 2017)*

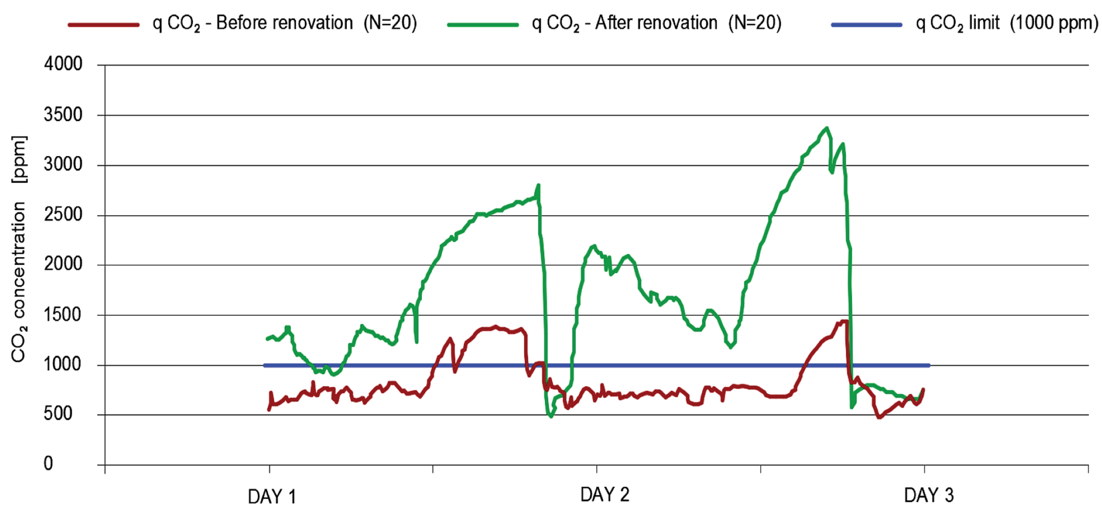

Fig. 4 *Example of CO2 concentration in one selected apartment during two days out of the whole measurement period before and after the renovation. (Sánka I., Földváry V., Petráš D., 2016); Sánka I., Földváry V., Petráš D., 2017)*

Tab. 2 *The percentages of the apartments where the average CO2 concentration exceeded 1000, 1500, 2000 and 2500 ppm during the day and night-time. (Sánka I., Földváry V., Petráš D., 2016); Sánka I., Földváry V., Petráš D., 2017)*

a) Before renovation (N=20)

Time period	Cut-off values [%]			
	CO_2>1000 (ppm)	CO_2>1500 (ppm)	CO_2>2000 (ppm)	CO_2>2500 (ppm)
Day	60	10	0	0
Night	75	40	10	5

b) After renovation (N=20)

Time period	Cut-off values [%]			
	CO_2>1000 (ppm)	CO_2>1500 (ppm)	CO_2>2000 (ppm)	CO_2>2500 (ppm)
Day	75	30	10	0
Night	95	70	40	15

Tab. 3 *AER before and after the renovation (Sánka I., Földváry V., Petráš D., 2016); Sánka I., Földváry V., Petráš D., 2017)*

AER	Average	Minimum	Maximum	Median
Before renovation (N=20)	0.61	0.32	1.15	0.59
After renovation (N=20)	0.44	0.21	0.76	0.45

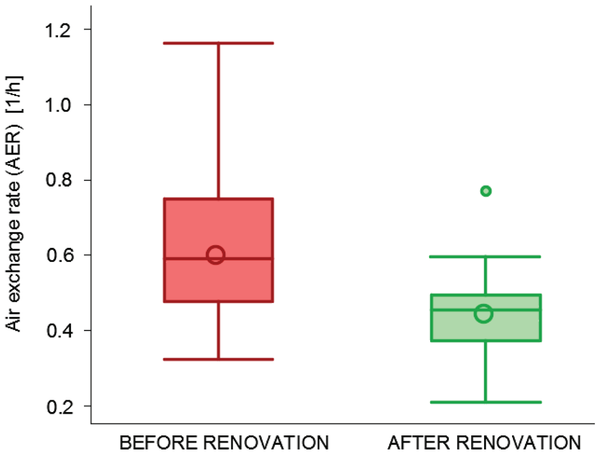

Fig. 6 *Air exchange rate before and after renovation as a statistical output (Sánka I., Földváry V., Petráš D., 2016); Sánka I., Földváry V., Petráš D., 2017)*

B. Concentration of volatile organic compounds

In both cases (before and after the renovation) the volatile organic compound (TVOC) concentrations were above the maximum limit value (300 mg/m^3) Even higher concentrations were measured in the apartments after refurbishment (Table 7). In some cases concentrations of TVOC were measured as very high (>1000 mg/m^3), which are illustrated by the green dots on Figure 12. Table 8 contains the percentages of the measured values exceeding the threshold values.

Tab. 4 *TVOC concentration before and after renovation*

TVOC concentration [μg/m3]	Average	Minimum	Maximum
Before renovation (N=20)	569	179	1805
After renovation (N=20)	773	185	2362

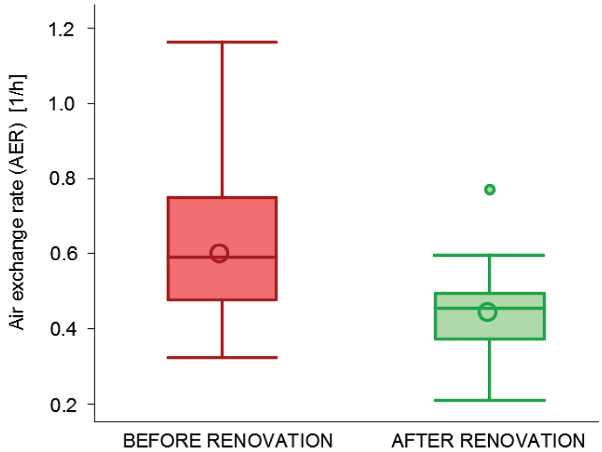

Fig. 7 *TVOC concentration before and after renovation as a statistical output (Sánka I., Földváry V., 2017)*

Tab. 5 *TVOC concentration before and after renovation (Sánka I., Földváry V., (2017))*

Limit values of TVOC concentration	Before renovation (N=20)	After renovation (N=20)
TVOC > 300 μg/m³ (%)	80	85
TVOC > 500 μg/m³ (%)	50	60
TVOC > 1000 μg/m³ (%)	5	25
TVOC > 2000 μg/m³ (%)	0	5

C. Results of the subjective measurements

The results of the questionnaire survey are based on the responses of the occupants of the evaluated residential building. The results below characterize the ventilation habits of the occupants, the perceived air quality, and the acceptability of the indoor air quality.

The residents labelled the acceptability of the indoor air on a scale from -1 to +1. The following figure shows the acceptability of the indoor air quality in the bedrooms and living rooms of the unrenovated and renovated building. The boxplot value of -1 represents poor air quality, and the value 1 represents good air quality.

The changes in the ventilation habits of the inhabitants before and after the renovation are presented in Table 9. The first part of the table shows the percentage characterizing the frequency, while the second part contains the duration of the ventilation.

The results indicate that the inhabitants did not change their ventilation habits after the renovation. Most of them ventilated the living room once a day, and the ventilation time was 7.5 min. The occupants ventilated bedrooms daily or almost daily but not every day. After the renovation, the ventilation time slightly increased but not significantly.

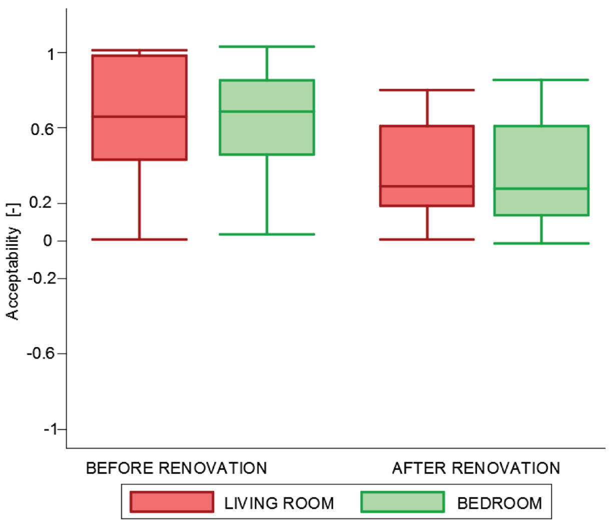

Fig. 8 *Acceptability of the indoor air as a statistical output*

Tab. 6 *Ventilation habits of the inhabitants*

Ventilation	Before renovation (N=20)		After renovation (N=20)	
	Whole apartment	Bedroom	Living room	Bed-room
Frequency of ventilation [%]				
More than once a day	70	40	60	30
Daily or almost daily	30	60	40	70
The average duration of ventilation [%]				
3.5 min	25	15	15	15
7.5 min	35	20	40	20
20 min	15	30	20	40
30 min	25	35	25	25

The boxplots in Figure 14 shows the relationship between the duration of the ventilation and the air exchange rate, as well as the relationship between the duration of the ventilation and the acceptability of the indoor air.

The results clearly shows a linear relationship between the duration of the ventilation (AER) and the acceptability of the indoor air.

5 DISCUSSION

Indoor air quality is a dominant contributor to total personal exposure because most people spend a majority of their time indoors (N. Klepeis, W. C. Nelson, W. R. Ott el al., 2001). The findings presented in this measurement campaign further support the conclusions of previous studies in Slovakia (Földváry V., Bekö G., Petráš D., 2014) that deterioration of indoor air quality follows energy renovations. In this study the implementation of the energy-saving measures was not combined with measures to improve the indoor environmental quality, which explains the lower AERs and higher CO_2 and TVOC concentrations in the renovated buildings in the winter.

Many international studies have also attributed this phenomenon to the fact that older buildings are leakier and newer ones are more air-tight as a result of improved construction techniques and stricter regulations (Kotol M., Rode C., Clausen G., Nielsen T. R., 2014); Bekö G., Toftum J., Clausen G., 2011). The limitation of the study is its small sample size. The validation of the results on a larger sample size is warranted. The study is ongoing, and additional results will be available in the near future.

6 CONCLUSION

A key goal of the implementation of an energy renovation strategy is to achieve the improved energy efficiency of buildings. However, the effect of these programs has not been systematically assessed. The effects on indoor air quality and well-being of the occupants is often ignored. There is an urgent need to assess the impact of the currently applied building renovation practices on the residential indoor air quality on a nationwide scale.

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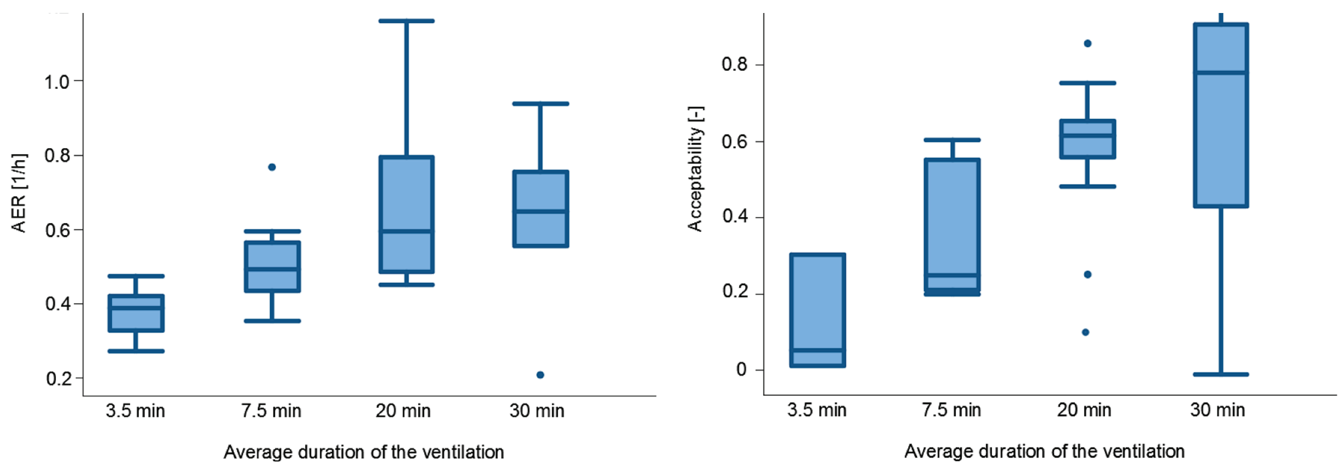

Fig. 9 *Relation between the AER and acceptability of the indoor air quality*

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