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# Effect of energy renovation on indoor air quality in multifamily residential buildings in Slovakia

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*Keywords: retrofitting, apartment buildings, natural ventilation, air exchange rate, occupant perception*

## Abstract

Buildings are responsible for a substantial portion of the global energy consumption. Most of the multifamily residential buildings built in the 20$^{th}$ century in Central and Eastern Europe do not satisfy the current requirements on energy efficiency. Nationwide measures are taken to improve the energy efficiency of these buildings. The impact of these measures on the indoor air quality (IAQ) is rarely considered. The objective of the present study was to evaluate the impact of simple energy renovation on IAQ, air exchange rates (AERs) and occupant satisfaction in multifamily residential buildings in Slovakia. Three pairs of identical naturally ventilated multifamily residential buildings were examined. One building in each pair was newly renovated, the other was in its original condition. Temperature, relative humidity (RH) and the concentration of carbon dioxide ($CO_2$) were measured in 94 apartments (57%) during one week in the winter. A questionnaire related to perceived air quality, sick building syndrome symptoms and airing habits was filled by the occupants. In a companion experiment, the IAQ was investigated in 20 apartments (50%)

of a single residential building before and after its renovation. In this experiment, concentrations of nitrogen dioxide ($NO_2$), formaldehyde and total and individual volatile organic compounds (TVOC, VOC) were also measured. $CO_2$ concentrations were significantly higher and air exchange rates were lower in the renovated buildings. Formaldehyde concentrations increased after renovation and were positively correlated with $CO_2$ and RH. Building energy renovation was associated with lower occupant satisfaction with the indoor climate. Simple energy retrofitting efforts should be complemented with improved ventilation in order to avoid adverse effects on the quality of the indoor environment.

# 1 Introduction

Buildings are responsible for one third of the global energy consumption [1]. Reduction of energy consumption and greenhouse gas emissions is a national priority in the European Union member countries [1, 2]. The residential sector represents a major target group for national programs supporting energy efficiency improvements of existing buildings. More than 50% of the European population resides in multifamily buildings [3].

The potential negative impact of building energy conservation measures on indoor air quality is a matter of concern. Minimizing air infiltration by tightening the building envelope is a common practice [4, 5, 6, 7, 8, 9]. When unaccompanied by improved ventilation, such energy saving measures can lead to insufficient ventilation rates [10] and increased exposure of building occupants to indoor pollutants [11, 12, 13]. Residential exposure is of particular concern, as more than half of the time spent indoors takes place in residences [14]. It is therefore important to understand how energy saving strategies influence indoor air quality and the comfort and health of occupants.

Studies on the impact of energy retrofits of dwellings on IAQ are relatively limited. Improved thermal conditions and health indicators were reported after installing standard insulation in New Zealand [15]. In California, comprehensive energy retrofits combined with improved mechanical ventilation systems and air cleaners resulted in improved indoor environmental conditions [16]. Positive effects of energy

retrofitting on indoor environmental quality and occupant satisfaction were also shown in mechanically ventilated residential buildings in Sweden [17]. Additionally, better indoor air quality in low-energy or passive houses compared to conventionally built houses has been reported in a number of studies [18, 19, 20, 21]. Satisfactory indoor air quality in these buildings was achieved by relatively high air exchange rates provided by mechanical ventilation.

Energy saving measures started to receive increased attention in Central and Eastern Europe since the 1990's, two decades later than in Western Europe. Indoor air quality however does not receive consideration to the same extent. Adoption of new building standards with primary focus on energy conservation is feared to compromise indoor air quality. This is especially the case in the almost exclusively naturally ventilated buildings built before 1990. Very few studies have been conducted in multifamily residential buildings in Central and Eastern Europe [21, 22, 23, 24]. Multifamily residential buildings in Slovakia were built between 1948 and 1990 and they well represent the residential building stock of Central and Eastern Europe. About 70% of these buildings do not fulfil the current European requirements for energy efficiency [25]. This has led to the implementation of numerous energy retrofit campaigns for existing multifamily buildings [3]. However, the effect of these programs on indoor air quality and occupant wellbeing is neglected.

The objectives of the present study were to evaluate in multifamily residential buildings in Slovakia the impact of energy renovation on i) temperature, relative humidity, $CO_2$ concentration, air exchange rates and concentrations of selected air pollutants using objective measurements, and on ii) perceived air quality and occupants' airing habits using questionnaire survey.

# 2 Materials and methods

## *2.1 Experiment I*

### *2.1.1 Selected buildings*

The first experiment included three pairs of multi-storey residential buildings made of prefabricated and pre-stressed concrete panels. Each pair consisted of a non-renovated and an identical renovated building

(Table 1). The energy-retrofitting measures included thermal insulation of the façade and the roof, and hydraulic balancing of the continuously operating heating system. The façade was insulated with expanded foam polystyrene of 80 mm thickness. Mineral wool insulation of 120 mm thickness was added to the roof. The ground floor apartments in each building were situated above an unheated basement. The basement ceiling was thermally insulated with 80 mm thick expanded foam polystyrene. No changes have been made to the windows, since new plastic frame windows have been already installed by the owners in most of the apartments before the study. All buildings were naturally ventilated. Exhaust fans operated by the light switch were present in the bathrooms and toilets. No modifications were made to the ventilation systems during the renovation. All buildings were located within 1 km from each other, in the rural city of Šamorín (13.000 inhabitants), 25 km from the capital of Slovakia, Bratislava.

**Table 1.** Characteristics of the studied buildings

| **Building pair** | **I.** | | **II.** | | **III.** | |
|---|---|---|---|---|---|---|
| Building condition | Original | Renovated | Original | Renovated | Original | Renovated |
| Construction year | 1965 | 1970 | 1970 | 1972 | 1980 | 1983 |
| Major orientation | East | East | Northwest | Northwest | North | North |
| Height (m) | 27.7 | 27.7 | 30.2 | 30.2 | 13.1 | 13.1 |
| Number of floors | 10 | 10 | 9 | 9 | 4 | 4 |
| Number of apartments on each floor | 4 | 4 | 2 | 2 | 6 | 6 |
| Number of measured apartments | 20 | 20 | 11 | 15 | 14 | 14 |
| Volume of each apartment ($m^3$) | 210 | 210 | 258 | 258 | 194 | 194 |
| Area of each apartment ($m^2$) | 75 | 75 | 92 | 92 | 69 | 69 |
| Heating system/Heating device | District heating/Radiators with thermostatic valves | | | | | |

### *2.1.2 Physical measurements and questionnaire survey*

The experiment was carried out between the middle of November 2013 and the end of January 2014. Ninety-four apartments were investigated in total, 45 were in the three non-renovated and 49 in the three renovated buildings. The measurements in each apartment lasted one week.

Air temperature and relative humidity were measured in the bedrooms by HOBO U12-012 data loggers (Onset Computer Corp., USA). The concentrations of $CO_2$ were measured with 5-minute intervals by CARBOCAP $CO_2$ monitors (GMW22, Vaisala, Finland) connected to the HOBO data logger. All

instruments were newly calibrated prior to the measurements. The locations of the instruments were selected with respect to the limitations of the $CO_2$ method [26]. Each unit was placed at a sufficient distance from windows and beds to minimize the influence of the incoming fresh air or the influence of sleeping occupants.

$CO_2$ concentrations obtained between 20:30 and 6:30 during each measured night, room volume and the occupants' body weight and height were used to calculate the AER in the bedrooms. The methodology using a spreadsheet that employed the carbon dioxide mass balance equation has been described in detail earlier [27]. Briefly, the $CO_2$ concentration build-up period was used to estimate the AER for each respective night in the occupants' bedrooms [26, 27, 28, 29]. Air exchange rate in the room was estimated by fitting a non-linear curve to the measured pattern of the $CO_2$ concentration at a given $CO_2$ emission rate, room volume and outdoor $CO_2$ concentration. Occasionally $CO_2$ concentration decays were used, when $CO_2$ levels began to fall while the room was occupied in the evening, i.e. when the occupants indicated that they aired out. When the concentration build-up or decay could not be clearly defined, the air exchange rate was determined using a mass balance model applied on the estimated steady-state $CO_2$ concentration [26]. Only trustworthy fractions of the night periods with clear $CO_2$ concentration patterns were extracted and used for further analysis. AERs were determined separately for each night with known occupancy. The final air exchange rate for each bedroom was calculated as a time-weighted average of the air exchange rates obtained for each relevant time period.

One occupant in each apartment was asked to fill a questionnaire. The questions were related to some building characteristics, occupant behavior and habits (e.g. frequency and duration of airing), sick building syndrome symptoms and occupants' perception of the indoor air quality and thermal environment (e.g. acceptability of indoor air quality in the apartments using the continuous acceptability scale [30~~34~~]. The questionnaire used in the renovated buildings contained additional questions related to potential changes in the occupants' indoor climate related behavior after renovation (e.g. self-reported altered airing habits).

## *2.2 Experiment II*

### *2.2.1 Selected buildings*

The second experiment was performed in the original building of building pair I from Table 1. After a new set of winter measurements in 20 apartments (50%), the building was renovated in the fashion described in section 2.1.1. The measurements were then repeated in the same apartments during the following winter. The 20 apartments were equally distributed on the lower, middle and higher floors of the building. No major changes were made to the interior of the apartments between the two measurement campaigns, unless stated otherwise (replaced furniture or carpet in three apartments; see section "*3.3 Impact of renovation on $NO_2$, VOCs and formaldehyde*".

### *2.2.2 Physical measurements and questionnaire survey*

The week-long measurements in the second experiment were carried out simultaneously in all 20 apartments. The first round of measurements (non-renovated condition) was performed in January 2015. In order to have as similar outdoor conditions as possible during the two measurement campaigns, the follow-up measurements (renovated condition) were performed in January 2016.

Temperature, relative humidity and $CO_2$ concentrations were measured and AERs were calculated using the same methodology as in Experiment I (section 2.1.2). A set of passive samplers for $NO_2$, formaldehyde and VOCs were placed centrally in the living room of each investigated apartment (Figure S1) [18, 31]. The samplers were placed at least 1.5 m above the floor. Locations near windows and radiators were avoided. $NO_2$ was measured with IVL diffusive samplers [32]. This technique provides an average concentration of the target pollutants in the air during the measured time period. The samplers were analysed for $NO_2$ with a wet chemical technique using a spectrophotometric method. The analytical procedure is accredited by the Swedish accreditation agency SWEDAC. The measurement uncertainty was 10% at 95% confidence level. The limit of detection (LOD) was 0.5 $\mu g/m^3$. For outdoor measurement, one $NO_2$ sampler was placed on a balcony on the third floor of the building.

Formaldehyde was measured with DSD-DNPH UmeX-100 passive samplers (SKC Inc., Eighty Four, PA, USA). The sampling period and the analytical technique (solvent extraction and high performance liquid chromatography) followed the ISO 16000-4 standard [33]. The LOD was 0.03 μg/m$^3$. Adsorption tubes filled with 200 mg Tenax TA (Perkin-Elmer) were used for passive sampling of VOCs. Their analyses were carried out in compliance with ISO 16017-2 [34]. The desorption of the tubes was carried out on a Markes TD100 desorber, where the adsorbed substances were released by heating the sorbent tubes during 7 min at 275°C and then transferred to a cold trap for focusing. The trap was then rapidly heated up again, analytes were released and reached a gas chromatography (GC) column for separation. The column effluent was split into two streams for the detection of individual compounds, one stream passing through the flame ionization detector and the other stream through the mass spectrometer.

VOCs were analyzed on a gas chromatograph (Agilent technologies 6890N) equipped with a flame ionization detector and a mass spectrometer 5975C inert MSD in the so-called electron impact mode. The GC column was a non-polar capillary column (5% phenyl polysilphenylene-siloxane, BPX5, 50 m long, 0.32 mm internal diameter, 1 μm film thickness). The temperature was held at 60°C for 2 minutes, then increased to 100 °C at 4 °C/min, then increased to 280 °C at 6 °C/min, with hold time 15 minutes.

Calibration was done by application of microliter amounts of solution of toluene in diethyl ether on the tubes. The concentration of TVOC and the the individual VOCs were quantified in toluene equivalents. The limit of detection for the individual VOCs was 0.2 μg/m$^3$ based on 3 times the signal-to-noise ratio. All values below LOD were replaced with ½ LOD.

The questionnaire survey was carried out concurrently with the physical measurements before and after the renovation of the building, as described for Experiment I.

### *2.3 Data analysis*

Statistical analyses were performed in STATA software, release 12.0 (StataCorp LP, College Station, Texas, USA). In the first experiment, differences in the measured parameters between renovated and non-renovated buildings were tested with parametric and non-parametric two-sample tests (student´s t-test and Wilcoxon rank sum test) as the measured parameters were not always normally distributed. Corresponding tests for paired samples were used on data from the second experiment. Pearson's correlation coefficient was used to identify correlations between variables. Multivariate linear regression was used to examine the associations between $CO_2$ concentration (log-normally distributed and logarithmically transformed) and indicators of building characteristics and occupant behavior. The associations between $NO_2$, TVOC and formaldehyde (log-normally distributed and logarithmically transformed) and the other indoor air quality parameters measured in this study (temperature, RH, $CO_2$) were also tested with linear regression. Stepwise forward and backward regression analyses were used to identify predictor variables with inclusion criteria of $p<0.2$.

## 3. Results and discussion

### *3.1 Impact of renovation on temperature and relative humidity*

Table 2 presents the descriptive statistics of the measured parameters. The indoor air temperature was significantly lower in the original buildings than in the renovated ones in both experiments ($p<0.01$) (Figure 1). The relative humidity was similar in the renovated and the non-renovated buildings.

In Experiment I, the average temperature in 18% of the apartments in the non-renovated buildings did not fulfil the recommended optimal range (20-24 °C) [35]. After renovation, only one apartment was under-heated. However, energy renovation can lead to increased periods of overheating [36]. Overheating occurred in three apartments (7%) in the non-renovated buildings and in six apartments (12%) in the renovated ones. In both the renovated and the non-renovated buildings, the average relative humidity slightly exceeded the recommended 60% in two of the apartments.

In Experiment II, 25% of the apartments before renovation had the average indoor temperature below 20 °C. No under-heating or overheating occurred after renovation. The average relative humidity slightly exceeded the recommended 60% in only one apartment before renovation.

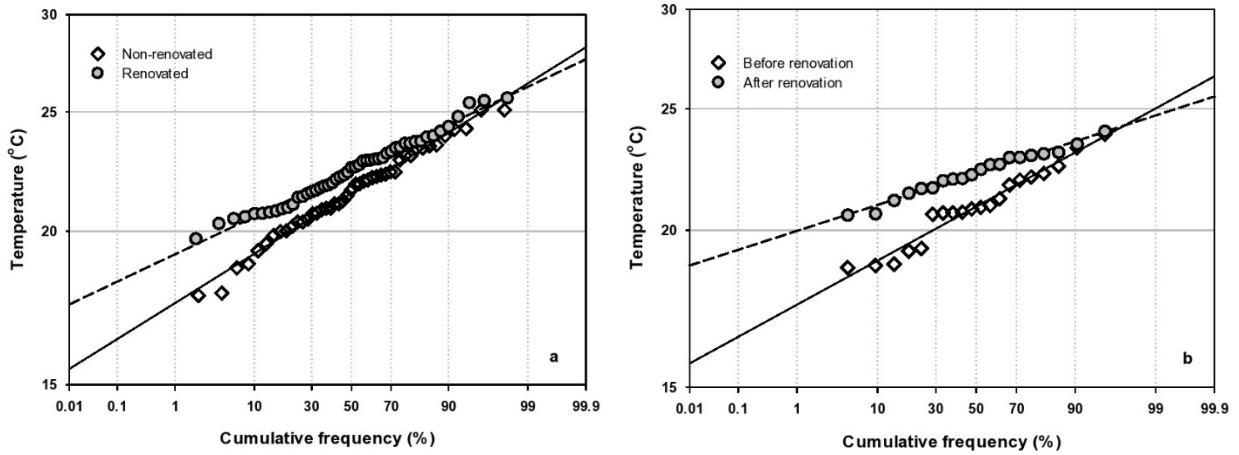


**Figure 1.** Cumulative frequency distribution of the average indoor temperatures in Experiment I (a) and Experiment II (b).

Kotol et al. [37] reported under-heating in 17% of the investigated Greenlandic households built in the second half of the 20$^{th}$ century. Temperatures lower than 20 °C were found in 30-40% of Estonian [38] and Lithuanian [22] dwellings. It has been suggested that the occupants may maintain low temperatures in order to minimize heating costs [39]. However, uninsulated dwellings built in the 20$^{th}$ century may have significantly lower indoor operative temperatures during the winter due to colder internal surfaces. Howden-Chapman et al. [15], Liu et al. [40] and Pustayova [41] found that adding thermal insulation in older dwellings increases the indoor air temperature in winter, which has positive implications for thermal comfort and energy savings. In a Swedish study the indoor temperature ranged between 21-25 °C in the retrofitted dwellings and between 19.7-21.8 °C in the non-retrofitted ones [40]. In an earlier Slovak study [41], the average indoor temperature in non-renovated multifamily buildings was lower (18.3-23.6 °C) than in renovated ones (22.2-25.3 °C). In New Zealand households [15] the indoor temperature increased by 0.6 °C and the relative humidity decreased by 1.4-3.8% after adding insulation on building envelope.

1

**Table 2.** Descriptive statistics of the measured parameters. Values are based on average values obtained for each apartment over the monitoring period.

| | | | T (°C) | RH (%) | $CO_2$ whole period (ppm) | $CO_2$ night-time (ppm) | AER ($h^{-1}$) [c] | $NO_2$ ($\mu g/m^3$) | TVOC ($\mu g/m^3$) | Formaldehyde ($\mu g/m^3$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Experiment I [a] | Non-renovated (N=45) | Mean (Min.-Max.) | 21.5 (17.6-25.1) | 46 (34-65) | 1180 (430-3380) | 1425 (480-3380) | 0.79 (0.22-3.69) | - | - | - |
| | | Geom. Mean | 21.5 | 47 | 1100 | 1260 | 0.64 | - | - | - |
| | | Median | 21.7 | 48 | 1100 | 1360 | 0.66 | - | - | - |
| | | Std. Dev. | 1.8 | 7 | 495 | 675 | 0.69 | - | - | - |
| | Renovated (N=49) | Mean (Min.-Max.) | 22.5 (19.2-25.8) | 46 (31-61) | 1380 (510-3570) | 1680 (630-3570) | 0.48 (0.06-1.33) | - | - | - |
| | | Geom. Mean | 22.4 | 45 | 1295 | 1530 | 0.38 | - | - | - |
| | | Median | 22.5 | 46 | 1290 | 1510 | 0.43 | - | - | - |
| | | Std. Dev. | 1.5 | 1.3 | 590 | 745 | 0.31 | - | - | - |
| Experiment II [b] | Before renovation (N=20) | Mean (Min.-Max.) | 20.9 (18.7-23.9) | 46 (34-61) | 1205 (595-2665) | 1410 (595-1550) | 0.61 (0.32-1.15) | 15.4 (6.1-42.1) | 569 (179-1805) | 32 (15-54) |
| | | Geom. Mean | 20.8 | 46 | 1165 | 1325 | 0.58 | 13.4 | 489 | 30 |
| | | Median | 20.8 | 45 | 1190 | 1300 | 0.59 | 13.5 | 500 | 30 |
| | | Std. Dev. | 1.5 | 8 | 400 | 515 | 0.2 | 8.9 | 357 | 9.4 |
| | After renovation (N=20) | Mean (Min.-Max.) | 22.2 (20.6-24.0) | 48 (39-59) | 1570 (790-3575) | 1925 (865-3575) | 0.44 (0.21-0.76) | 16.5 (4.5-36.2) | 773 (185-2362) | 43 (23-67) |
| | | Geom. Mean | 22.2 | 48 | 1545 | 1825 | 0.42 | 14.5 | 623 | 41 |
| | | Median | 22.3 | 48 | 1510 | 1870 | 0.45 | 16.3 | 575 | 42 |
| | | Std. Dev. | 0.9 | 6 | 500 | 660 | 0.13 | 8.3 | 568 | 13 |

a) Three pairs of residential buildings; one in each pair was in its original condition and the other was renovated.

b) Single residential building investigated before and after its renovation.

c) In Experiment I, n=43 in the non-renovated buildings and n=44 in the renovated building, due to missing data.

### *3.2 Impact of renovation on $CO_2$ concentrations and air exchange rates*

In Experiment I, the median of the average $CO_2$ concentrations obtained for each apartment for the whole measurement period was higher in the renovated than in the non-renovated buildings (1290 ppm vs. 1100 ppm; $p>0.05$). Similar trend was observed for the $CO_2$ concentrations in the night-time, when the occupants were presumably in the bedroom. The cumulative frequency distribution of the average night-time $CO_2$ concentrations is shown in Figure 2. In the non-renovated buildings, the median night-time $CO_2$ concentration was 1360 ppm, in the renovated dwellings it was 1510 ppm. On average, the $CO_2$ concentration was above 1000 ppm during 58% of the measured night periods in the non-renovated buildings and during 72% in the renovated buildings. The highest 20-min running average of $CO_2$ concentrations exceeded 1000 ppm, 2000 ppm and even 3000 ppm in a number of apartments; this was more frequent in the renovated buildings (Table S1).

The stepwise multivariate regression analysis (Figure S2, Table S2) confirmed the association between elevated $CO_2$ concentrations and building renovation. Additional variables retained in the model were occupancy in the apartment and in the bedrooms (positive association) and the occupants' smoking habits (negative association). Lower $CO_2$ concentrations in the smokers' apartments were presumably caused by different airing habits. Sixty percent of smokers indicated that they air out over a longer period (20-30 minutes on average), while 63% of non-smokers aired out on average for 7.5 minutes or less. The $CO_2$ concentrations were higher in the renovated apartments despite the fact that more smokers lived in the renovated buildings (38%) than in the non-renovated buildings (27%).

The regression model explained 29% of the variation in the $CO_2$ concentration. A stronger model could be obtained by including additional parameters, such as indoor-outdoor temperature difference, wind conditions and variables related to building characteristics and occupant behavior [10, 42]. Especially predictor variables related to occupant behavior are suspected to be of importance, as the climate and building related variables were similar for all investigated apartments.

In Experiment II, the median of the average $CO_2$ concentrations obtained for each apartment for the whole measurement period was higher after renovation than before (1510 vs. 1190 ppm). The difference was statistically significant ($p<0.05$). The median night-time $CO_2$ concentration before renovation was 1300 ppm, while after renovation it was 1870 ppm ($p<0.05$). The average time fraction when the night-time $CO_2$ concentration exceeded 1000 ppm was 69% before renovation and 80% after renovation. The average night-time $CO_2$ concentration increased with renovation in every apartment (by 3-360%). According to the questionnaire, the usual bedroom occupancy did not change between the two measurement campaigns, which were a year apart.

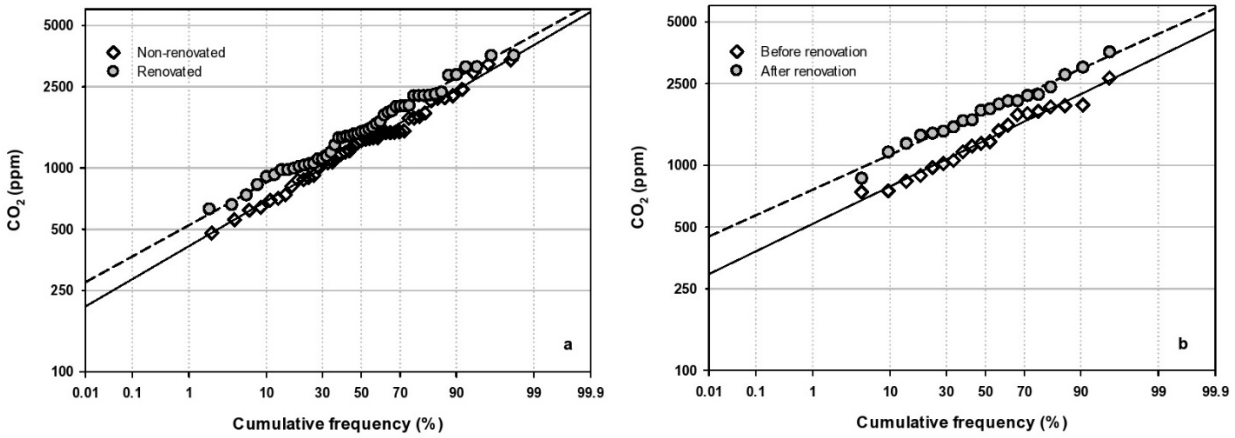


**Figure 2.** Cumulative frequency distribution of the average night-time $CO_2$ concentrations in Experiment I (a) and Experiment II (b).

The air exchange rates were significantly lower in the renovated buildings than in the non-renovated ones in both Experiments ($p<0.05$). The median air exchange rates in both experiments were above the recommended minimum of 0.5 $h^{-1}$ before renovation (Table 2). After renovation they decreased below this value. Figure 3 shows the cumulative frequency distribution of air exchange rates. In Experiment I, 37% of the apartments in the non-renovated buildings and 58% in the renovated buildings had an average air exchange rate below 0.5 $h^{-1}$. In Experiment II, the air average exchange rate was below 0.5 $h^{-1}$ in 40% of the apartments before renovation and in 85% after renovation. In 19 out of the 20 apartments the average air exchange rates decreased with renovation to 5-75% of their corresponding value from a year earlier.

New and renovated buildings are tighter than older buildings due to improved construction techniques and stricter regulations. In our study, air exchange rates decreased despite the fact that windows were not replaced during the renovation process. This indicates that adding insulation on the building envelope can substantially increase air tightness and decrease infiltration, presumably through decreased air leakage area (e.g. cracks, seals and joints between concrete panels, joints between walls and windows, other building components). Without the implementation of ventilation systems, air exchange rates in such naturally ventilated buildings can be low [27, 31, 42, 43, 44].

Du et al. [22] compared the indoor environmental quality in 40-year old non-renovated multifamily buildings in Lithuania and Finland. Mechanical ventilation was present in 80% of the Finnish apartments, in none of the Lithuanian ones. Significantly higher concentrations of $CO_2$ and a number of air pollutants were measured in the Lithuanian apartments. The authors concluded that the differences might also be partly attributable to different occupant behaviour in the two countries. Although occupant behaviour can change with building renovation (see section "*3.4 Airing habits and perceived air quality*"), it is unlikely to fully explain the lower AER in the renovated buildings in our study, especially in Experiment II, where the same apartments with the same occupants were investigated both before and after renovation.

With the increase in energy prices in the 1970s in Western and Northern Europe, ventilation rates decreased until new building codes in the 1980s started to require higher ventilation rates [10, 27, 31]. In Central and Eastern Europe energy prices increased in the 1990s. As minimum ventilation recommendations continue to be rarely addressed in energy renovation programs, decreased air exchange rates in renovated buildings may lead to increased exposure of occupants to indoor generated air pollutants.

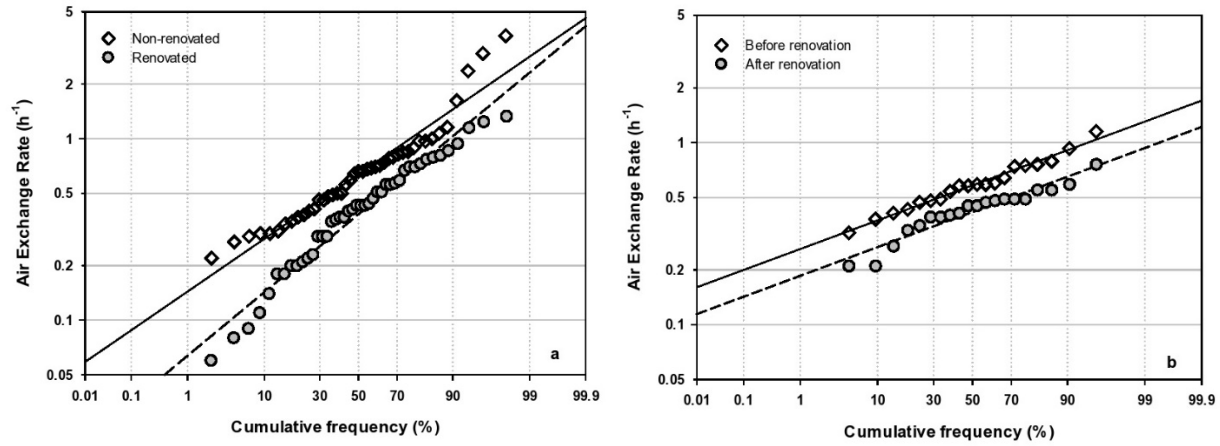


**Figure 3.** Cumulative frequency distribution of the average air exchange rates in Experiment I (a) and Experiment II (b).

### *3.3 Impact of renovation on $NO_2$, VOCs and formaldehyde*

The median concentration of $NO_2$ across all apartments in Experiment II was lower than the recommended annual maximum of 40 µg/m³ [45], both before and after renovation. The recommended limit value was exceeded in one apartment before renovation. Lower median $NO_2$ concentration was observed before renovation (15.4 µg/m³) than after renovation (16.5 µg/m³) (Figure 4a, Figure S3). The difference was not statistically significant ($p>0.1$). The observed concentrations were similar to those reported in Northern Europe [30] and Lithuania [22]. Higher $NO_2$ concentrations were observed in Czech Republic (37.7 µg/m³) and Switzerland (23.8 µg/m³) [46].

In the absence of indoor combustion sources, the major source of $NO_2$ indoors is outdoor air. The outdoor concentration of $NO_2$ was 12.4 µg/m³ and 12.0 µg/m³ during the measurements before and after renovation, respectively. The indoor-to-outdoor (I/O) concentration ratios indicated the presence of indoor combustion sources in a number of apartments (Figure S4). The weak negative correlation between AER and $NO_2$ (Table 3) further supports the presence of indoor sources. None of the apartments had a gas stove or a gas burner. Candle burning and smoking may have been responsible for the high I/O ratios. Smokers lived in 40% of the apartments. We did not collect detailed information on the frequency of candle burning and on

the location, where smoking occurred. In order to better understand the impact of energy renovation on indoor $NO_2$ concentrations, continuous measurements, a longer measurement period and better identification of the indoor sources of $NO_2$ are warranted.

**Table 3.** Pearson correlation coefficients between the measured parameters (both measurement campaigns combined, N=40).

| Parameter | $NO_2$ | Formaldehyde | TVOC | $CO_2$ | T | RH | AER |
|---|---|---|---|---|---|---|---|
| **Formaldehyde** | -0.09 | - | - | - | - | - | - |
| **TVOC** | -0.09 | 0.27 | - | - | - | - | - |
| **$CO_2$** | 0.2 | 0.57* | 0.16 | - | - | - | - |
| **T** | -0.12 | 0.14 | 0.09 | 0.06 | - | - | - |
| **RH** | -0.05 | 0.48* | 0.3** | 0.57* | -0.37 | - | - |
| **AER** | -0.19 | -0.59* | -0.21 | -0.87* | -0.16 | -0.51* | - |

*p<0.01, **p<0.05

The median TVOC concentration was higher after renovation (575 µg/m³) than before (500 µg/m³), but the difference was not significant (Figure 4b). The average TVOC concentrations in 80% of apartments before renovation and in 85% after renovation substantially exceeded the putative upper limit (300 µg/m³) recognized by the German Federal Environment Agency as a hygienically safe level [47]. The TVOC concentration exceeded 1000 µg/m³ in one apartment before renovation and in five apartments after renovation (Figure S5).

TVOC concentrations in this study were substantially higher than those reported in other studies [18, 31]. An increase in the average TVOC concentration was observed in 12 apartments (60%) after renovation. Among these apartments, the ratio of TVOC concentration after and before renovation was between 1.01 and 8.41. Three apartments experienced more than 6-fold increase in TVOC levels. In these apartments, the occupants replaced old furniture or a carpet with new ones. This is in line with earlier studies where new materials, furniture and interior renovation were indicated to cause increased concentrations of volatile organic compounds [48, 49, 50]. We cannot therefore conclude that the performed energy renovation was solely responsible for the increased TVOC concentrations. However, the decreased air exchange rates likely contributed to the increase in TVOC levels in the apartments after renovation.

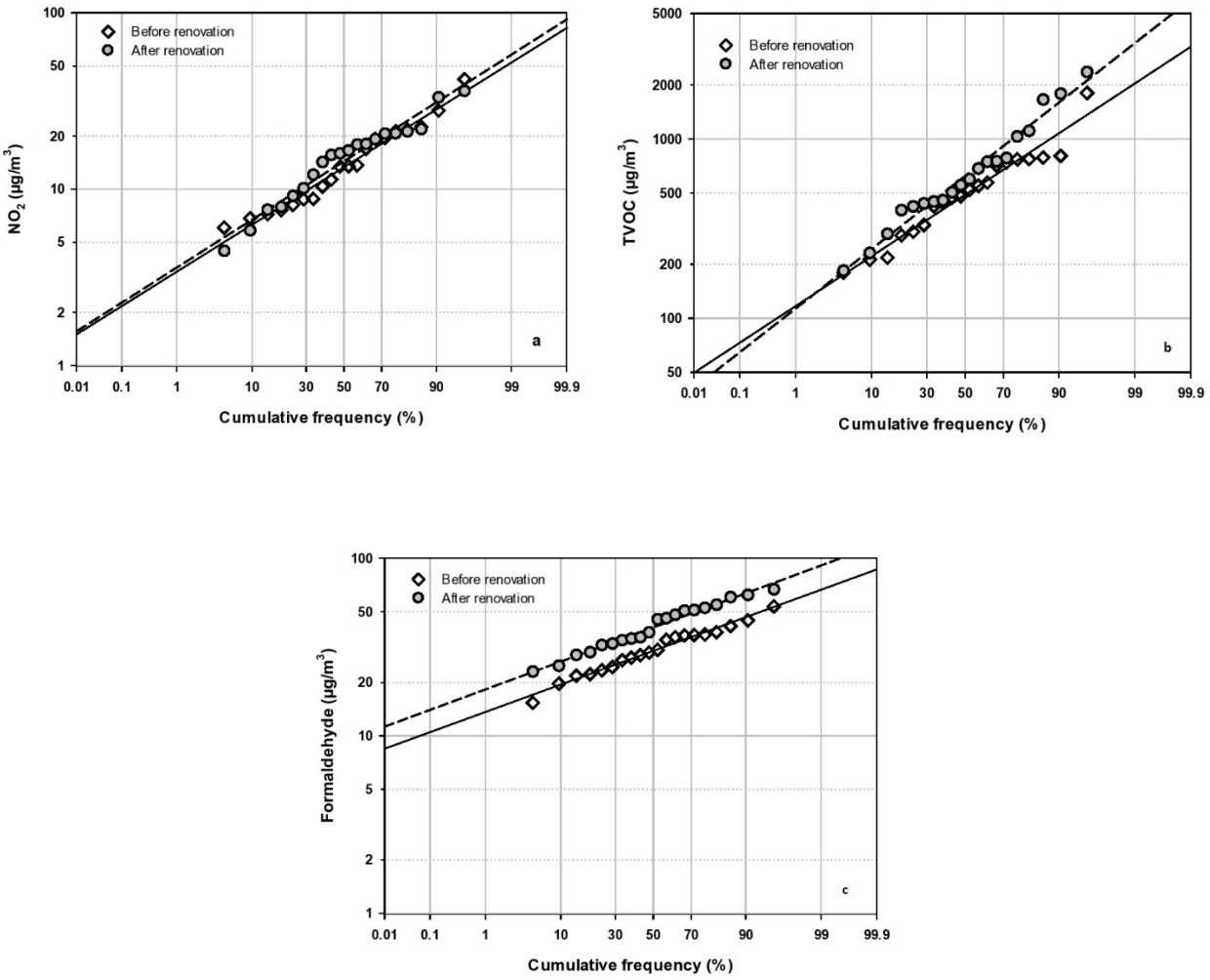


**Figure 4.** Cumulative frequency distribution of the $NO_2$ (a), TVOC (b) and formaldehyde (c) concentrations in Experiment II.

**Table 4.** Concentrations of the most abundant individual VOCs (µg/m³ as toluene equivalent).

| Compound | Before Renovation (N=20) | | | | After Renovation (N=20) | | | |
|---|---|---|---|---|---|---|---|---|
| | N>LOD | Mean (Std. Dev.) | Geom. Mean | Median | N>LOD | Mean (Std. Dev.) | Geom. Mean | Median |
| Heptane | 20 | 3.2 (2.8) | 2.5 | 2.6 | 18 | 12.4 (29.8) | 6.8 | 5.5 |
| Limonene** | 20 | 29.6 (28.1) | 19.8 | 19.2 | 20 | 162.9 (214.5) | 85.2 | 88.9 |
| a-pinene | 20 | 4.2 (4.4) | 2.5 | 2.4 | 20 | 7.2 (11.7) | 3.7 | 2.6 |
| 3-carene | 15 | 1.8 (2.1) | 3.8 | 1.0 | 19 | 5.2 (11) | 2.6 | 1.7 |
| Benzene* | 20 | 3.9 (2.8) | 3.1 | 3.1 | 19 | 2.0 (0.7) | 2.1 | 2.0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ethyl Benzene | 20 | 3.9 (3) | 3.2 | 3.1 | 20 | 6.4 (8) | 4.4 | 4.5 |
| Mp-Xylene | 20 | 6.9 (5.8) | 5.2 | 5.3 | 20 | 9.3 (10.2) | 6.9 | 6.3 |
| Toluene | 20 | 16.2 (13.9) | 12.1 | 11.1 | 20 | 14.6 (11.6) | 11.9 | 11.6 |
| Hexanal | 18 | 7.5 (8.8) | 5.6 | 4.5 | 20 | 10.0 (6.5) | 8.5 | 8.6 |
| Nonanal | 19 | 6.7 (11.3) | 6.4 | 6.1 | 20 | 4.7 (3.2) | 3.7 | 3.9 |
| 1-Butanol | 20 | 12.0 (5.8) | 10.5 | 11.5 | 20 | 12.7 (6.4) | 11.0 | 11.7 |
| Isobutanol** | 20 | 2.0 (1.5) | 1.6 | 1.5 | 18 | 3.5 (2.7) | 3.1 | 2.8 |
| 1-Pentanol | 17 | 1.6 (1.5) | 1.2 | 1.3 | 20 | 1.8 (1.6) | 1.4 | 1.2 |
| Hexanoic acid* | 20 | 5.0 (4) | 3.9 | 4.2 | 16 | 0.8 (0.5) | 0.9 | 0.8 |

*$p<0.01$, **$p<0.05$

In total 50 individual VOCs were identified. Table 4 summarizes the concentrations of the most abundant individual VOCs. Significant difference between the two conditions of the building was observed in the concentrations of limonene, benzene, isobutanol and hexanoic acid. The average concentration of benzene, nonanal and hexanoic acid decreased after the renovation, while the concentrations of the other VOCs increased. The presence of new sources and lower ventilation rates could have caused the increased concentrations of indoor generated VOCs. However, different occupant activities during the two 1-week measurement periods and consequently different indoor chemistry (e.g. terpene-ozone reactions) may have also contributed to the observed differences. The levels measured in this study are comparable to those obtained in Swedish apartments [30] and lower than reported for new buildings, as summarized by Derbez et al. [19].

The concentrations of formaldehyde were significantly higher after renovation than before ($p<0.05$) (Figure 4c). The concentrations increased in 75% of the apartments after renovation, on average by 60% (Figure S6). In the rest of the apartments they decreased only by about 10%. Decreased AER after renovation of the building may have significantly contributed to the increased formaldehyde concentrations in the apartments. It is noteworthy, however, that insulation materials, including foam board insulation such as the one used in the renovation process in the current study, could be major sources of formaldehyde [51]. Formaldehyde levels were in all apartments, both before and after renovation, below the 30-min average

exposure limit of 100 mg/m$^3$ recommended by the World Health Organization [45]. However, they were above the chronic reference exposure level of 9 µg/m$^3$, suggested by the California Office of Environmental Health Hazards Assessment [52]. Our median concentrations were comparable to those observed in other Western European countries [19, 49, 53, 54, 55, 56, 57] as well as Lithuania [22].

The significant negative correlation between AER and formaldehyde concentration (Table 3) reflects the ability of ventilation to remove formaldehyde emitted indoors. Similar results were reported in a number of earlier studies [31, 48, 51, 58]. Furthermore, significant positive correlation was found between relative humidity and both TVOC and formaldehyde, which is consistent with earlier findings [51, 59]. Formaldehyde concentrations were positively correlated with temperatures, but the correlation was weak. This may be explained by the relatively narrow range of indoor temperatures in the winter. In the stepwise regression analysis AER, temperature and relative humidity were retained in the model as predictors of formaldehyde concentration. These three variables explained 48% of the variation in the formaldehyde concentrations (Table S3). AER and RH remained significant in the final model.

### *3.4 Airing habits and perceived air quality*

The frequency of airing out in the bedroom was almost identical in the non-renovated and renovated buildings in Experiment I. During daytime, the majority of occupants aired out “more than once a day” (57%) or “daily or almost daily” (41%). The rest of the occupants aired out “at least once a week” (2%). During the night, about 45% never aired out. The usual duration of airing during the day was similar in the two building types (~70% aired out less than 20 min. at a time). The residents in the non-renovated buildings indicated that during the night they air out over longer periods (~60% longer than 45 min.) compared to the occupants in the renovated dwellings (~30% longer than 45 min.). These results are somewhat surprising, given the fact that temperature was higher and indoor air quality poorer after renovation. However, 22% of the occupants in the renovated buildings reported that they aired out more often since renovation than they did before. No meaningful differences were observed in the self-reported airing habits before and after

renovation in Experiment II. As expected, longer duration of airing out resulted in higher air exchange rates and more acceptable indoor air quality (Figure S7).

The occupants found the indoor air quality in the bedroom and generally in the apartment more unpleasant in the renovated buildings (Figure S8). They indicated lower acceptability of the indoor air quality in these buildings ($p<0.01$) (Figure 5). Jurelionis and Seduikyte [23] found complaints about stuffy air and dry air in Lithuanian multifamily dwellings more prevalent after renovation than before (64% vs. 18% for stuffy air, 69% and 29% for dry air, respectively). The refurbishment included envelope insulation and new windows; no changes were made to the ventilation.

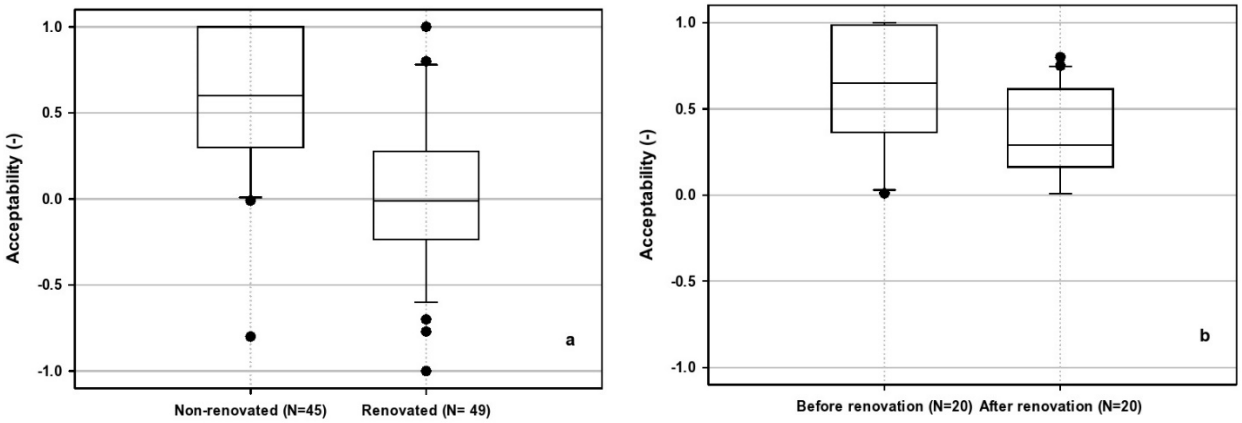


**Figure 5.** Acceptability of the indoor air in the apartments in Experiment I (a) and Experiment II (b). The bottom and the top of the boxes represent 25$^{th}$ and 75$^{th}$ percentiles and the band near the middle of the box is the median. The ends of the whiskers indicate 10$^{th}$ and 90$^{th}$ percentiles. The circles show the values below the 10$^{th}$ and above the 90$^{th}$ percentiles.

We observed a positive correlation between air exchange rate and acceptability of air quality ($r=0.79$, $p<0.01$), and a negative correlation between formaldehyde concentrations and acceptability ($r=-0.53$, $p<0.01$). The acceptability of indoor air quality was higher at lower TVOC concentrations, but the correlation was weak ($r=-0.22$, $p>0.05$). Increased levels of VOCs caused by low ventilation rate may adversely affect perceived air quality. Wolkoff [60] reported that hexanal (linseed oil in building materials and human debris, e.g. skin oils), hexanoic acid (an oxidative degradation product from linseed oil and skin

oils) and limonene (a common fragrance used in numerous consumer products) may be some of the most important compounds influencing perceived air quality. Higher concentrations of hexanal and limonene were observed after renovation (Experiment II).

Self-reported headache, itchy eyes, dry skin and fatigue were more prevalent after renovation than before (Figure S9). In multivariate stepwise logistic regression analyses, building renovation was a significant predictor of itchy eyes, along with sex and age of the occupants. However, the number of observations in these analyses was too low to obtain conclusive results.

Numerous studies have reported reduced indoor exposures, fewer SBS symptoms and lower risk of respiratory symptoms in new and renovated green buildings [16, 61, 62, 63]. These studies provide lessons to be learned regarding the simultaneous improvement of indoor environmental quality, when planning energy retrofitting of existing buildings. Protocols for selecting retrofits based on initial building conditions, predicted energy use, indoor environmental quality changes and cost have the potential to improve building performance and at the same time capitalize on the possible co-benefits of building retrofits [64]. The development of such protocols, which would reflect regional needs and conditions, are warranted.

# 4. Conclusions

This study investigated the impact of relatively simple energy renovation measures on indoor air quality and occupant comfort in multifamily residential buildings in Slovakia. Tightening the building envelope by adding thermal insulation reduced infiltration through air leakage and thus the air exchange rates in the apartments. Consequently, increased levels of formaldehyde and other volatile organic compounds were observed. Relatively high concentrations of total volatile organic compounds (TVOC) were measured in a large fraction of the apartments already before renovation. They were further elevated after renovation of the building. The occupants perceived the indoor air quality as better before renovation. Building renovation also resulted in slightly higher prevalence of some of the sick building syndrome symptoms. Energy renovation without considering its potential impact on the indoor environment can adversely affect the

indoor air quality. When old multifamily residential buildings in Central and Eastern Europe are upgraded to be more airtight and energy efficient, the retrofitting effort should include measures to improve ventilation in order to ensure acceptable and healthy indoor air quality. Installation of controlled natural ventilation or mechanical ventilation systems is recommended. At the minimum, building occupants should be encouraged to air out more often. These recommendations should be reflected in national building renovation strategies and energy certification programs.

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