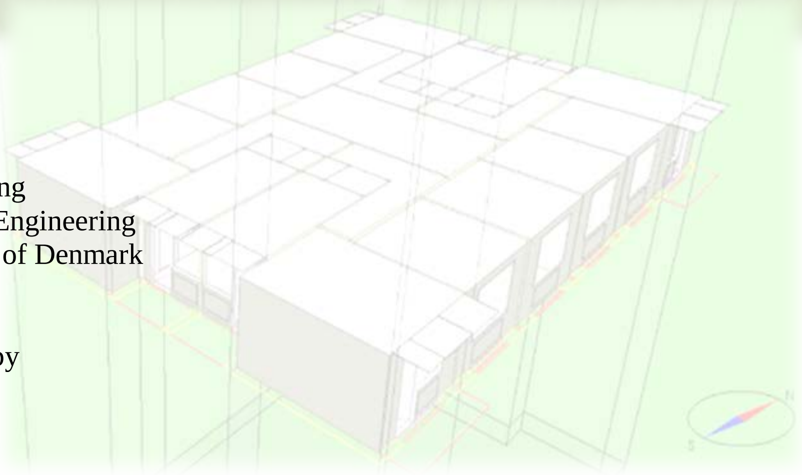
Impact of energy retrofitting on the indoor environmental quality of multifamily residential dwellings

Final report to the Bjarne Saxhofs Fond

Gabriel Bekö
Indoor Climate and Building Physics
DTU Civil Engineering
Building 402
Nils Koppels Alle, 2800 Kgs. Lyngby
E-mail: gab@byg.dtu.dk

Kgs. Lyngby, 20 December 2016



DTU Civil Engineering
Department of Civil Engineering
Technical University of Denmark

Building 118
DK-2800 Kgs. Lyngby
Denmark

www.byg.dtu.dk
Tel: (+45) 45 25 17 00
Fax: (+45) 45 88 32 82
Mail: byg@byg.dtu.dk

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1. Preface

The project "Impact of energy retrofitting on the indoor environmental quality of multifamily residential dwellings" was carried out at DTU Byg in the period form 1.12.2014 until 31.12.2016. The aim of the project was to conduct field measurements in multifamily residential buildings in Slovakia, which were either recently energy renovated or were in their original condition. The impact of the renovation on indoor air quality, occupant comfort and health as well as on their behaviour with regard to ventilation was studied. Additional simulations aimed to recommend solutions for improvement of indoor air quality in originally naturally ventilated retrofitted dwellings. The project comprised both field data collection regarding indoor environmental quality and occupant satisfaction, analyses of data obtained from the facility management and simulations using IDA ICE - Indoor Climate and Energy simulation tool.

This report summarizes the main findings. It is supplemented with conference and journal publications that emerged from the data. Additional information and detailed discussion of the results is provided in the PhD thesis that was completed on the basis of this project and is available upon request.

The project was financed by Bjarne Saxhof Foundation.

2. Introduction and objectives

Buildings are responsible for a substantial portion of global energy consumption. Residential buildings constitute the largest part of the building stock, with 75% by floor space within the European Union (BPIE, 2011). Energy standards for new homes are being strengthened and various programs are underway to retrofit existing homes. Much of the retrofit activity emphasize single-family homes. If the energy policy goals should be met, multi-unit housing must also be retrofitted. Relatively few studies have focused on apartment-level retrofits.

Energy retrofit measures can influence indoor environmental quality (IEQ), including thermal comfort, acoustic conditions and levels of indoor air pollutants that affect health (Jaggs and Palmer, 2000; Flourentzou and Roulet, 2002). Ma et al. (2012) present an overview of methodologies widely used for selecting energy retrofits. Adding insulation to exterior walls or replacing single pane windows with efficient ones reduce heating and cooling demands, drafts and thermal radiation to cold walls and windows. However, sealing leaks to outdoors without compensating measures, a widespread practice, reduces outdoor air ventilation and increases indoor air concentrations of air pollutants (Villi et al., 2013; Noris et al., 2013a). Insulation materials can emit volatile organic pollutants. Indoor environmental quality (IEQ) has not been a primary goal of most retrofit programs. Consequently, countries are not capitalizing on a potentially large opportunity to improve IEQ.

Few studies have investigated the potential for simultaneous energy and IEQ benefits when retrofits are implemented in apartments. A study from New Zealand reported improved comfort, indoor air quality and health symptoms resulting from upgrading insulation and replacing ineffective heating systems (Howden-Chapman, 2007). In the study by Noris et al. (2013b) sixteen apartments in three buildings were retrofit with the goal of simultaneously reducing energy consumption and improving indoor environmental quality (IEQ). Retrofit measures included envelope sealing, installation of mechanical ventilation, replacement of heating and cooling systems, and adding wall-mounted particle air cleaners. An overall improvement of IEQ, including lower concentrations of pollutants after the retrofits was observed. Langer et al. (2014) compared the indoor air quality in 22 newly built passive houses and 21 conventional buildings. The median air exchange rate was slightly higher in the passive houses than in conventional buildings. The concentrations of NO2 and formaldehyde were lower in passive houses than conventional buildings, while TVOC concentrations were higher in the passive houses.

Most European countries obtained a large housing stock since the 1950’s due to economic changes and growing population. Majority of these residential buildings, especially in Central Europe were built from prefabricated concrete blocks. They have a significant energy consumption. Due to poor maintenance, their renovation became one of the most important measures addressing energy conservation in these countries (Jurelionis et al., 2010). Their retrofits often only include adding additional insulation on the façade, replacing windows and hydraulic balancing of the heating system. It is largely unclear how such changes influence indoor environmental quality. Understanding the impact of these measures on the energy performance of buildings, their indoor environment and occupant behaviour is crucial in order to benefit from the opportunity of simultaneous energy and IEQ retrofits.

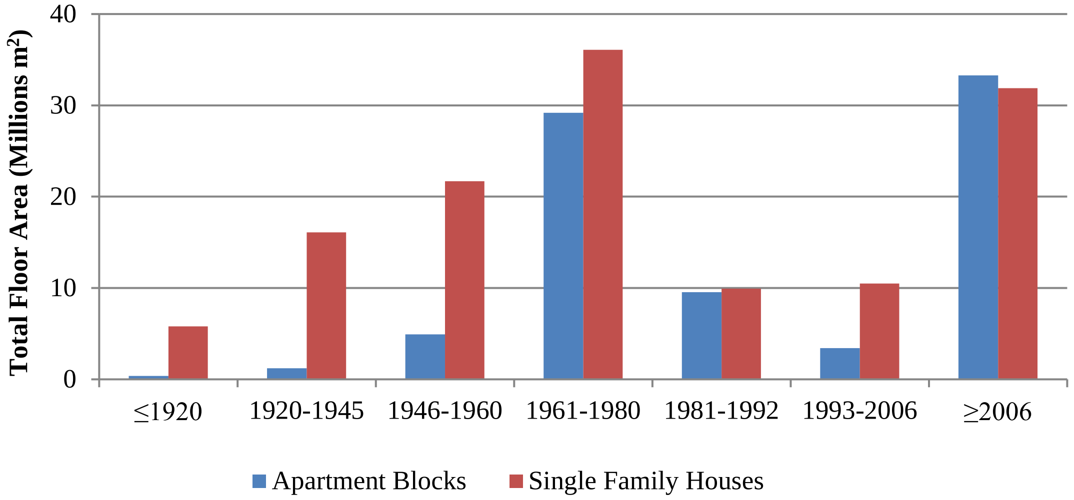

Figure 1. Breakdown of the building stock by age in Slovakia.

Slovakia well represents the building stock of Central Europe as well as a large fraction of the residential buildings in western and northern Europe. Most of the dwellings were built from 1948 to 1990, with the highest intensity in housing construction reported over the period 1971 – 1980 (Figure 1). Nationwide remedial measures are taken to improve the energy efficiency of these buildings. This study aimed to conduct a more profound investigation of the impact of energy renovation on IEQ in multifamily apartment buildings. The main objectives were:

- To evaluate the alterations in basic parameters of indoor environmental quality, such as indoor air temperature, relative humidity and CO_2 concentration, using objective measurements.
- To evaluate the alterations in air exchange rates and pollutant concentrations (NO_2, (T)VOC and formaldehyde) indoors, using objective measurements.
- To evaluate the alterations in perceived air quality, sick building syndrome symptoms and occupants´ behaviour using questionnaire survey.
- By means of simulation software, to assess indoor air quality of naturally ventilated residential building and to propose improved ventilation strategy.
- To provide recommendations for policy makers, engineers and the public based on outcomes of the field and simulation studies.

3. Methods

Case study I

Case Study I began before the initiation of the project funded by Bjarne Saxhof Fond. Since the data has been largely analysed as part of this project and the other activities in the project are directly related to Case Study I, it will be briefly summarized here.

Selected buildings

The study was performed in three pairs of naturally ventilated multi-storey residential buildings in the town of Samorin, in Slovakia, 25 km from the capital Bratislava. One of the buildings in each pair was renovated (Table 1). 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. Although these windows were replaced by the owners of the apartments themselves, there may not be big differences in construction and physical characteristics of the windows used. Usually windows with plastic frames and double glazing are used in residential buildings to replace non-energy efficient transparent constructions.

Table 1. Characteristics of the studied buildings (Source: Housing association institutes)

Building pair	I.		II.		III.	
	Original	Renovated	Original	Renovated	Original	Renovated
Building condition						
Construction year	1965	1970	1970	1972	1980	1983
Orientation of the entrance side	East		North West		North	
Height (m)	27.71		30.24		13.05	
Volume (m^3)	9 412	9 683	5 936	6 114	6333	6 523
Area (m^2)	3 408	3 449	1 875	1 913	2 174	2 217
Number of floors	10		9		4	
Number of apartm. on each floor	4		2		2	
Number of entrances	1		1		3	

Data collection

The data collection was performed in two phases. The winter monitoring of indoor environmental parameters and the questionnaire survey were carried out in 94 apartments, 45 apartments in the non-renovated and 49 in the renovated buildings. The measurements took place from the middle of November 2013 to the end of January 2014. Another set of measurements was performed the following year between the middle of July 2014 and the end of August 2014. The same apartments were planned to be investigated in summer season as during the winter measurements. However, some of the apartments were not available for summer measurements due to summer holidays. In summer 73 apartment were investigated in total, 35 in the original buildings and 38 in the retrofitted ones.

The physical measurements included continuous measurements of indoor air temperature, relative humidity and carbon dioxide (CO_2) concentration in bedrooms of the apartments using HOBO U12-012 data loggers and CARBOCAP CO_2 monitors. All devices were calibrated prior to the measurements. The data were recorded in 5 minutes intervals for about a week in each apartment. One unit was used in each apartment. The locations of the instruments were selected with respect to the limitations of the carbon dioxide method. Each unit was placed in sufficient distance from windows and beds to minimize the influence of the incoming fresh air or the influence of sleeping occupants. The space between furniture and room corners was avoided.

The objective of the questionnaire survey was to investigate the impact of building renovation on occupants´ every day habits related to heating settings and perceived indoor environmental quality in their apartments. The questionnaire was addressed to one person in each apartment in both winter and summer. It was filled by the occupants at the same time as the experimental measurements were performed. The questions were related to some building characteristics, occupant behaviour and habits, sick building syndrome symptoms and occupants' perception of indoor air quality and thermal environment. The same questionnaire was used in the original and the renovated buildings. However, the questionnaire used in the renovated buildings contained additional questions related to changes in occupants´ behaviour after building renovation.

Case study II

Selected buildings

The second case study was performed in one of the previously investigated residential buildings from Case study I, before and after its renovation (Figure 2). The selected building was a nine storey residential dwelling with forty apartments in total. The renovation of the dwelling included exactly the same energy saving measures as it was already defined in the previous chapter; envelope and roof insulation and hydraulic balancing of the heating systems.

Figure 2. The residential building in its original (left) and renovated (right) condition

Data collection

The questionnaire survey and the measurement campaign were carried out during two winter seasons. 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 were implemented. Twenty apartments were selected across the building, equally distributed on the lower, middle and highest storeys of the building. The same apartments were investigated in both winter seasons (Figure 3).

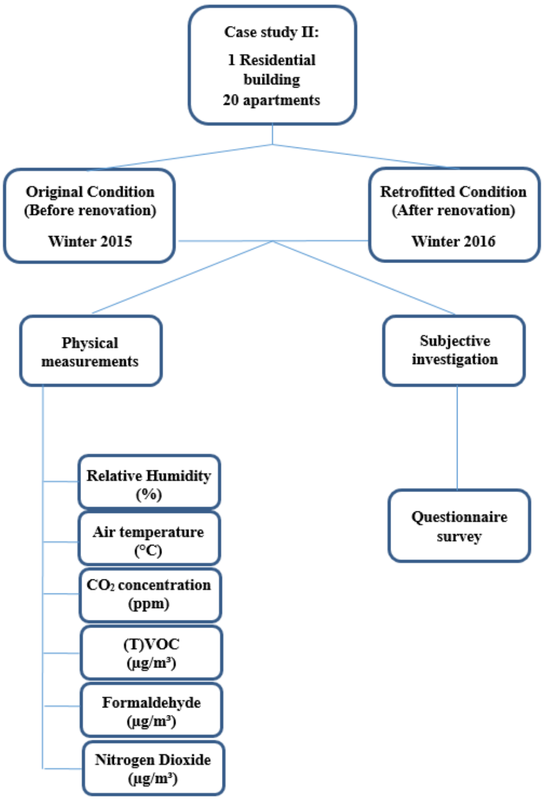

Figure 3. Data collection methodology for Case Study II.

During eight days air temperature, relative humidity, concentrations of carbon dioxide (CO_2) nitrogen dioxide (NO_2), formaldehyde and volatile organic compounds (VOCs) were measured. Temperature, relative humidity and CO_2 concentration were measured in bedrooms of the apartments using the same methodology as in the Case study I. HOBO U12-012 data loggers and CARBOCAP CO_2 monitors were used for data recording. All the devices were calibrated before the measurement campaign began. The data were recorded in 5 minutes intervals. A set of passive samplers for NO_2, formaldehyde and VOC were placed centrally in the living rooms of each investigated apartment. The samplers were always positioned at least 1.5 m above floor level. Locations near windows and radiators were avoided. One NO_2 passive sampler was also placed on one of the balconies to obtain outdoor data during the measurement week.

The questionnaire survey was carried out concurrently with the physical measurements before and after the renovation of the building. The questionnaire was nearly identical to that used in the first case study. Minor modifications were implemented in some of the questions.

Energy efficiency of the buildings

The detailed methodology of comparing energy efficiency of the original and renovated buildings followed in this work is shown in Figure 4. It consists of two parts. One of the methods was based on energy calculation using national standards and building code to classify buildings into energy classes. The second method used for energy performance assessment was based on the real energy consumption in the original and the renovated buildings. Slovakia has had a national database since 2010 and has taken significant steps in the direction of developing a functional database with open content. The Slovak National Building Code is determined by Executive Regulation of MTCRD SR 364/2012, based on European Parliament, Directive 2010/31/EU and the Codex of Laws No.

300/2012. It defines that new and renovated buildings constructed by 2016, have to meet minimum criteria, determined by upper limit of B class for total energy need. Energy efficiency of buildings is expressed by energy classification of buildings into energy classes according to the National Building Code. The process of energy classification is based on calculation of heat demand as well as on calculation of energy need for space heating and domestic hot water (DHW) preparation using standardised conditions for determination of building energy efficiency (Table 2). These parameters were calculated in accordance with the local technical standards.

Table 2. Energy classes of space heating, DHW, total and primary energy need for building category of residential buildings, in kWh/m^{2}year.

Category	Energy classes							
	A0	A	B	C	D	E	F	G
Space heating	-	≤ 42	43-86	87-129	130-172	173-215	216-258	> 258
DHW	-	≤ 12	13-24	25-36	37-48	49-60	61-72	> 72
Total energy demand	-	≤ 54	55-110	111-165	166-220	221-275	276-330	> 330
Primary energy	≤ 54	55-108	109-216	217-324	325-432	433-540	541-648	> 648

The input data used in the calculations as well as the measured data of the actual energy consumption for space heating were provided for this study by the housing association institutes. The obtained values represent the overall average energy consumption calculated from monthly monitored energy consumption for heating for each building from September until April next year. This eight-month period represents the heating season, when the buildings were supplied by heat. The data were provided for five years (2010-2014). However, some data were not available for some of the studied buildings due to personnel changes in the housing association companies and contract modifications between the residential buildings and the responsible housing management.

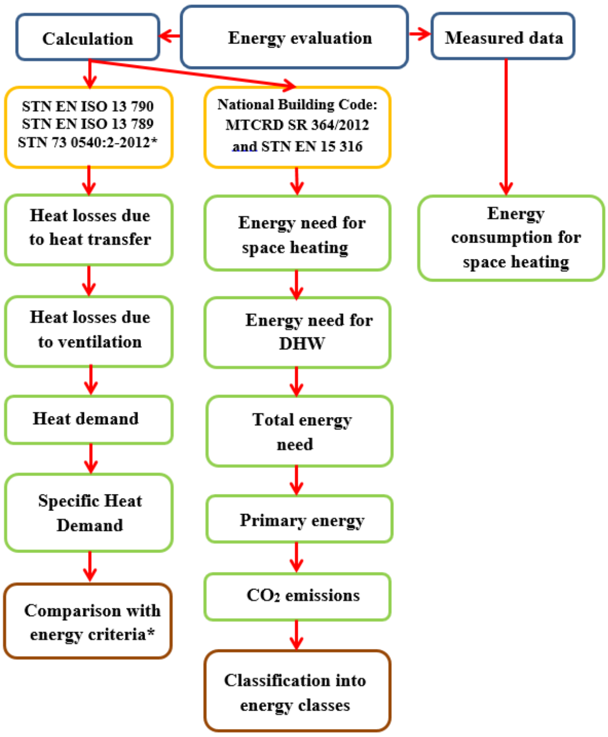

Figure 4. Conceptual outline of the energy investigation methodology

Simulations

One building was chosen to create a simulation model of its original and renovated state. Indoor environmental quality parameters with main focus on CO_2 concentration were simulated using different alternatives of ventilation systems. The aim of the simulations was to recommend solutions for improvement of indoor air quality in originally naturally ventilated retrofitted dwellings in Slovakia. Finally, the most efficient control principle of the ventilation system was chosen from three examined alternatives, taking into account the system´s energy performance and installation’s simplicity. IDA ICE - Indoor Climate and Energy simulation tool is a dynamic multi-zone simulation application for accurate study of the thermal environment and indoor climate of individual zones in relation to the energy consumption of buildings.

In order to validate the model by comparison to the measured data, the final model was created for one bedroom located in one of the selected apartments. The examined apartment was oriented to southeast and the bedroom had eastern orientation. The total area of the apartment was 68 m^2, and the bedroom had an area 13.5 m^2 (Figure 5). The simulation model was created for the period of the heating season when the measurements took place, between 10th and 18th December 2013. All necessary weather data for this period were retrieved from the Slovak Hydrometeorological Institute (SHMI).

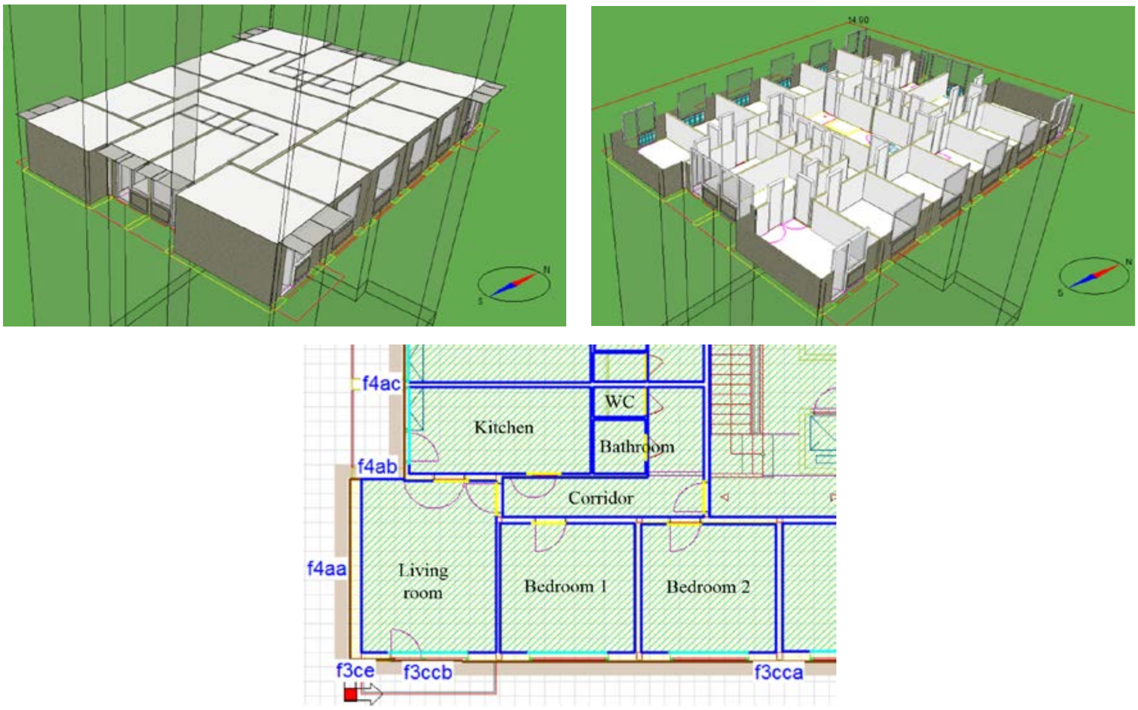

Figure 5. 3D model of the typical floor and the floorplan of the apartment selected for the simulation study

The simulated and the measured parameters were compared within the same time interval. The comparison was performed on hourly basis. In order to calculate the deviations between the simulated and measured data, two separate statistical indices were used; the Root Mean Square Error (RMSE) and variation of Root Mean Square Error (CV(RMSE)).

In total four separate iterations in the theoretical building model were needed to calibrate the model. One modification was related to temperature settings and three were related to CO_2 concentration. The iterative process of calibration was performed manually and the results of each iteration were used as input for the following iteration, until each examined parameter matched closely the measured data. The calibrated model was used for further modelling of three alternative ventilation strategies, presented for the renovated condition of the dwelling: natural ventilation, demand controlled ventilation and constant air volume system (Table 3).

Table 3. Description of the simulated additional ventilation systems.

Ventilation system	Description
1. Original state	Used in whole apartment, except bathroom and toilet, where exhaust system (CAV) was installed. The return air for CAV was 21.3 L/s (5.89 h^{-1}). The fans were operated only during the occupancy period (6:30-7:30 and 19:00-20:30).
2. Standard air handling unit (AHU) System type: a) VAV, CO_2 and T control b) VAV, CO_2 control	Used in whole apartment, except bathroom and toilet where exhaust system (CAV) was installed. The supply and the return air flow in the AHU was 15.4 L/s (1.66 h^{-1}). The return air for CAV was 21.3 L/s (5.89 h^{-1}) in the sanitary rooms. Operated 24 hours.
3. Modified Constant Air Volume (CAV)	Natural ventilation in the rooms. Exhaust system installed in the bathroom, toilet and kitchen. The return air for CAV was 21.3 L/s (5.89 h^{-1}) in the sanitary rooms and 16.95 L/s (4.96 h^{-1}) in the kitchen. The system was operated only during the occupancy period of the zones (Kitchen: 6:30-7:00; 17:00-18:30; Sanitary rooms: 6:30-7:00; 19:00-20:30). Internal doors were always open.

4. Results

Case study I

Temperature and relative humidity

The overall average temperature difference in the original and the renovated residential buildings showed to be statistically significant in both winter ($p<0.01$) and summer ($p=0.01$-0.05). The mean winter temperature in the original buildings was 21.5 °C and in the renovated dwellings 22.5°C. Higher average temperature was measured in the renovated buildings (26.6°C) compared to the non-renovated ones (25.5 °C) also in the summer. According to thermal comfort criteria, the optional range of the indoor temperature in winter is between 20-24°C. The overall mean temperature was within the recommended range in 78% of bedrooms in the original dwellings and in 91% of the bedrooms in the renovated buildings. Longer periods with overall average temperatures below 20 °C were observed in the non-renovated buildings (18%) than in the building after renovation (2%). Only very small percentage of apartments exceeded the maximum recommended value of 24 °C; 4% in the original and 6% in the renovated dwellings. Figure 6 on the right shows the cumulative frequency of overall average temperatures in the residential buildings.

The optimal summer range of indoor temperature is between 23°C and 26°C. 56% of the apartments in the original building exceeded the recommended range. 11% of bedrooms had temperatures below 23°C, and in 45% of the bedrooms the overall average temperature was above the recommended maximum. Indoor temperatures under 23°C occurred in apartments located in building type III. According to the measurement protocol and outdoor data provided by the Slovak Hydrometeorological Institute, during the given measurement week lower average outdoor temperatures (17 °C) were noticed compared to the other summer days (20°C). 69 % of apartments in the renovated dwellings had higher average temperature than 26°C. Lower percentage of bedrooms in the renovated dwellings (29%) was within the recommended temperature range compared to the percentage of bedrooms in the original buildings (51%).

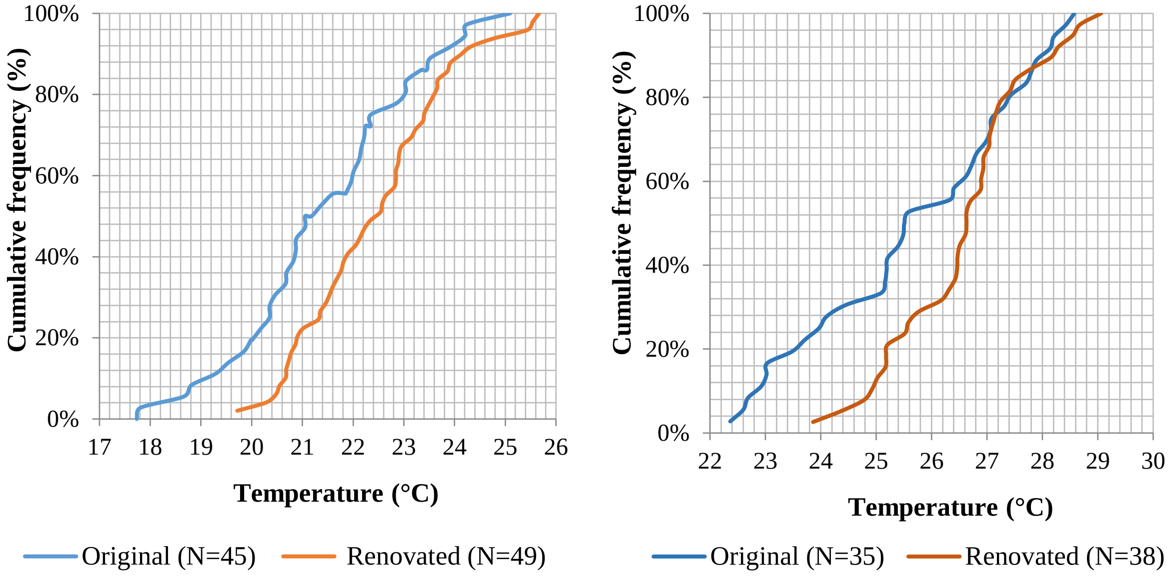

Figure 6. Cumulative percentage distribution of overall (day and night together) average indoor temperature in the bedrooms of the original and renovated residential buildings in winter (left) and summer (right).

The grand average RH indoors was 47% in the original and 46% in the renovated buildings in winter. In summer, these values increased to 55% in the original dwellings and 56% in the renovated residential buildings. The results did not show statistical significance between the original and the renovated residential buildings, neither in winter nor in summer ($p>0.1$).

CO_2 concentration and air exchange rate

The difference in average CO_2 concentrations between the renovated and the original dwellings was approaching statistical significance ($0.05<p<0.1$) in winter. The median was 1110 ppm and the grand mean was 1180 ppm in the non-renovated dwellings. In the retrofitted buildings both, the median (1290 ppm) and the overall mean (1380 ppm) were slightly higher than in the original buildings. In summer the difference between the two types of the buildings was not statistically significant ($p>0.1$). The original residential buildings were characterized by higher median (515 ppm) and overall mean

(850 ppm) CO_2 concentrations than the retrofitted buildings, where the median was 480 ppm and the overall mean was 815 ppm.

Since it was assumed that the occupants spent the majority of time in their rooms during the nights, cumulative percentage distribution of the average night CO_2 concentrations for each of the bedrooms was conducted to show the fractions of apartments where the average night-time CO_2 concentrations exceeded 1000, 2000 and 3000 ppm (Table 4).

Table 4. Percentage of average night-time CO_2 concentrations above three cut-off values in the investigated buildings

Cut-off values of CO_2 concentrations	**Winter**		**Summer**	
	Original (N=45)	**Renovated (N=49)**	**Original (N=35)**	**Renovated (N=38)**
CO_2 >1000 ppm (%)	71	80	43	40
CO_2 >2000 ppm (%)	16	31	0	3
CO_2 >3000 ppm (%)	3	6	0	0

The regression analyses and ANOVA tests indicated an association between CO_2 concentration and building renovation, occupancy of the apartments and bedrooms, and occupants' smoking habits. The coefficient of determination obtained from the regression model was $R^2 = 0.29$. ANOVA model resulted in $R^2 = 0.35$ (Figure 7).

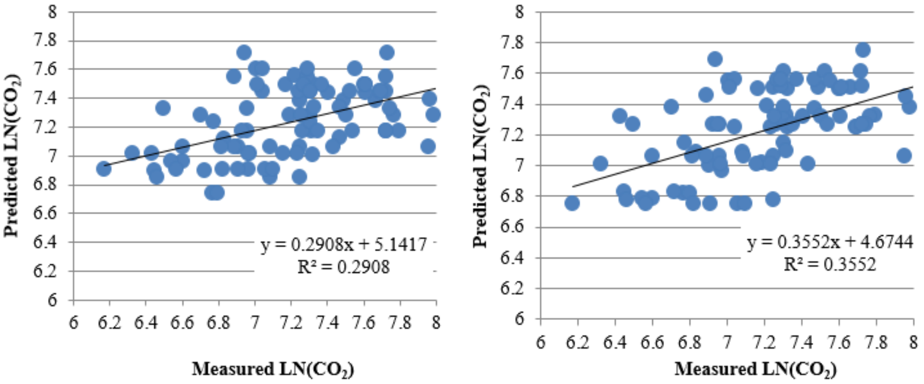

Figure 7. Logarithm of the measured CO_2 concentrations in winter plotted against the predicted values from regression (left) and ANOVA (right) models created after identifying predictor variables with inclusion criteria of $p < 0.2$.

The results indicate that the obtained air exchange rates in both building types were log-normally distributed in winter, but not in summer. The average air exchange rate across the apartments in the original buildings was significantly higher than in the renovated buildings in winter ($p<0.01$), but not in summer ($p>0.05$) (Figure 8). In winter the grand average air exchange rate was 0.79 h^{-1} in the original buildings. The AER ranged between 0.22 and 3.69 h^{-1}. In the renovated buildings the overall average AER (0.48 h^{-1}) was slightly lower than the recommended 0.5 h^{-1}. In these buildings the AER ranged between 0.06 and 1.33. In summer, the air exchange rate was similar in both, the original and the renovated buildings. In the non-retrofitted buildings the air exchange rate was 7.88 h^{-1} and in the renovated ones it was 8.80 h^{-1}.

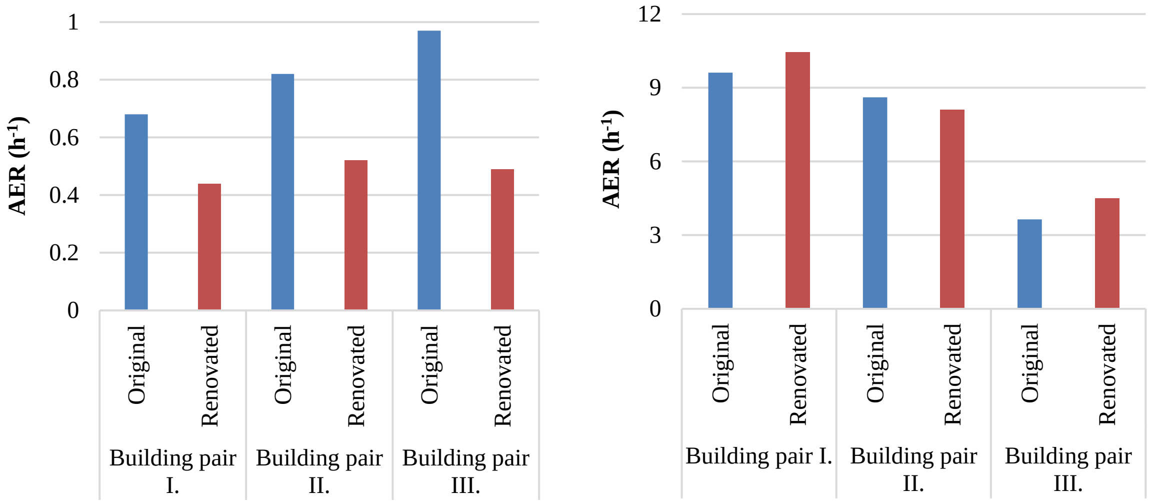

Figure 8. Average AERs presented in each of the investigated residential building in winter (left) and summer (right). Note the different scale of the y-axis.

Perceived air quality and occupant behavior

During the winter, a greater fraction of the occupants indicated poor air quality in the renovated buildings compared to the non-renovated buildings (Figure 9). In each of the original dwellings the majority of the occupants responded in the winter that the indoor air quality in the bedroom during night/in the morning is not unpleasant. The response was less positive in the renovated buildings, corresponding to the lower AER in these buildings. 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 and apartments.

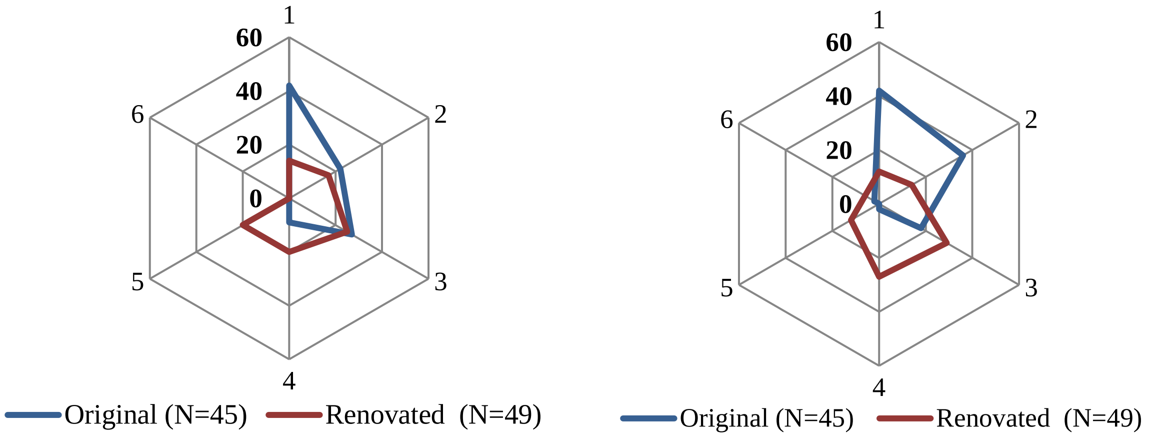

Figure 9. Summary of answers to the questions “How unpleasant do you think the IAQ is in your bedroom during night/in the morning?”(left), and “How unpleasant do you think the IAQ is in your apartment?”(right). The results shown for winter.

A large fraction of the occupants (78%) did not change their airing habits in winter after energy renovation took place. Only 22% of the residents indicated that they air out more often than before renovation. Decreased air exchange rate contributed to the higher occurrence of odors caused mainly by cooking and smoking. In summer, 47% of the residents changed their airing habits and indicated that they air out more than before renovation. However, reasons for more frequent airing in the summer were not reported by the occupants. Figure 10 summarizes the airing frequency as reported by the occupants for daytime and night, in summer and winter.

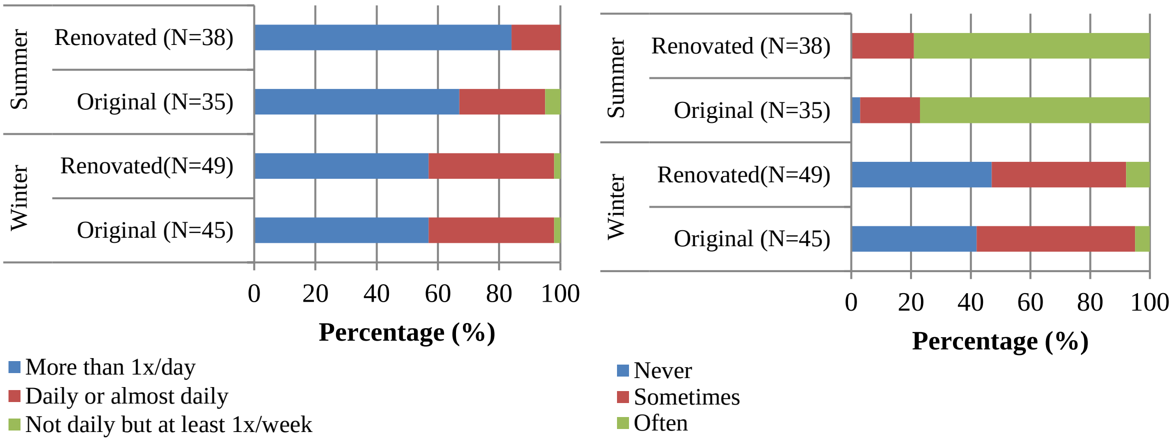

Figure 10. Frequency of airing in the bedrooms of the original and the renovated residential buildings during day-time (left) and at night (right), in winter and summer.

Sick building syndrome symptoms

The frequencies of sick building syndrome symptoms were obtained for headache, fatigue, itchy eyes, nausea and dry skin. Logistic regression was used to look for relationship between the prevalence of a symptom (not having vs. having the symptom while in the apartment (both sometimes and often)) and selected independent variables in winter. Multiple linear, stepwise forward and backward regression analyses were conducted to identify predictor variables with inclusion criteria of $p<0.2$. Although the gender and age category of the occupants was selected by the model ($p>0.2$), the two variables were kept in the model due to their known relationship with SBS symptoms. Dry skin and nausea were not significantly related to any of the characteristics of the investigated dwellings. Positive relationship with borderline significance was found between CO_2 concentration and itchy eyes (OR=2.94, p=0.07) (Figure 11). Positive ORs were found for CO_2 also for headache (OR=2.18, p=0.20) and fatigue (OR=2.00; p=0.19).

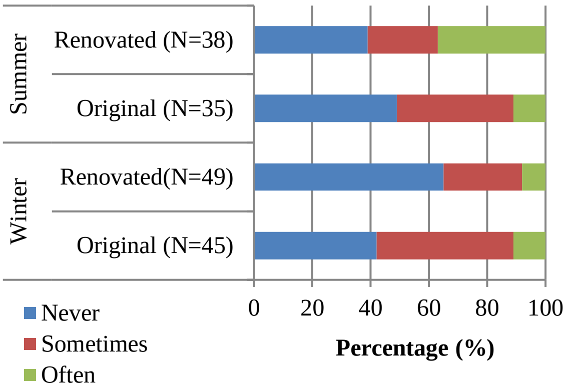

Figure 11. The frequency of reported itchy eyes in the two building types in summer and winter.

In spite of the fact that the relationship between SBS symptoms and age groups was not significant at p<0.05, the occurrence of itchy eyes was more frequent in age groups 41-50, 51-60 and people older than 70 years old. The odds ratio for headache and fatigue was highest and significant in the age group 41-50 years. More fatigue and headache was reported in all age categories compared to the reference group of 20-30 years. For all symptoms male gender was associated with more symptoms, although the relationship was not significant.

Case study II

Physical measurements

The difference in CO_2 concentration between the pre-retrofit and post-retrofit condition was statistically significant. The median of the average night-time concentrations was 1300 ppm before renovation and 1870 ppm after renovation. During night-time, increase of CO_2 concentration was observed in each of the investigated apartments. The ratios of the CO_2 concentrations after and before renovation were between 1.03 and 3.6 (average ratio after-to-before was 1.49).

The AER across the investigated apartments were log-normally distributed, and showed significant difference between the values obtained before and after renovation ($p<0.5$). Lower CO_2 concentration before renovation resulted in higher AERs in the apartments (average 0.61 h^{-1}). After renovation the mean AER (0.44 h^{-1}) dropped below the recommended minimum (0.5 h^{-1}) (Figure 12).

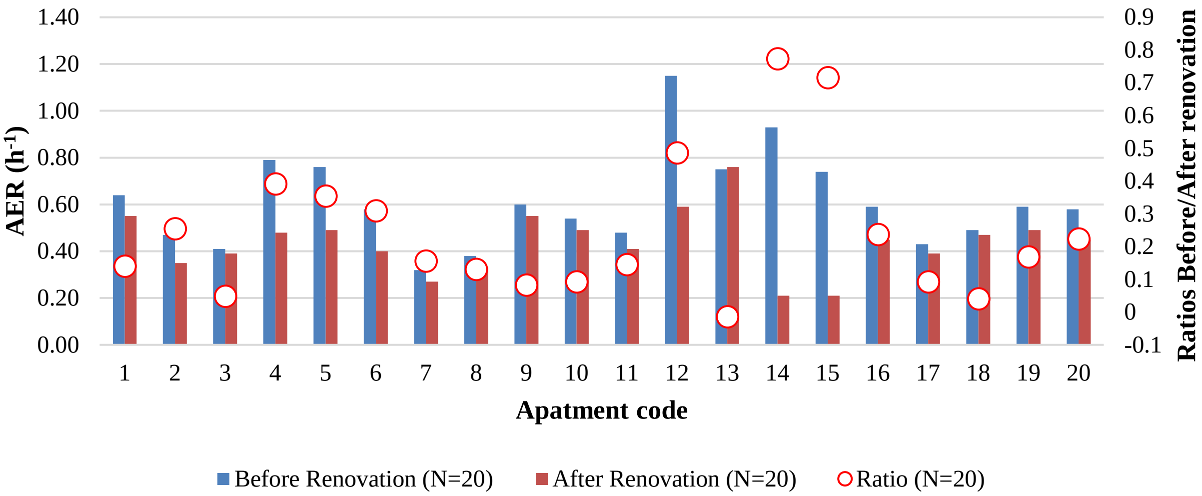

Figure 12. Average AERs in each of the apartments before and after renovation of the residential building.

According to the WHO Guidelines for Indoor Air Quality the recommended maximum value of NO_2 concentrations indoors is 40 µg/m³. The average concentrations across all apartments were lower than the recommended maximum limit in both conditions of the dwelling. The recommended maximum limit of NO_2 concentration was exceeded in only one apartment, where the NO_2 was slightly above the maximum recommended value (42.1 µg/m³) before renovation. Lower average NO_2 concentration was observed in the apartments before renovation. However, the difference between the two conditions was not statistically significant ($p>0.1$). In half of the apartments an increase of NO_2 after renovation was observed. The ratios of after-to-before concentrations were between 1.03 and 4.36 (average ratio was 2.08). In the rest of the apartments a decrease was seen (ratio from 0.35 to 0.85; average 0.66).

The difference between results of formaldehyde before and after renovation were statistically significant ($p<0.05$). The concentrations ranged between 15 and 54 µg/m³ before renovation and between 23 and 67 µg/m³ after renovation. The World Health Organisation recommends a maximum formaldehyde concentration of 100 µg/m³. Although the concentrations of formaldehyde were below this limit in all apartments, an increase in the formaldehyde concentration was observed in 75% of the apartments after renovation. Among these apartments, the ratio of formaldehyde concentrations after and before renovation was between 1.09 and 2.5 (average range was 1.62). In the rest of the apartments only slight decrease was observed in formaldehyde concentrations (ratio between 0.82 to 0.94; average 0.89) (Figure 13).

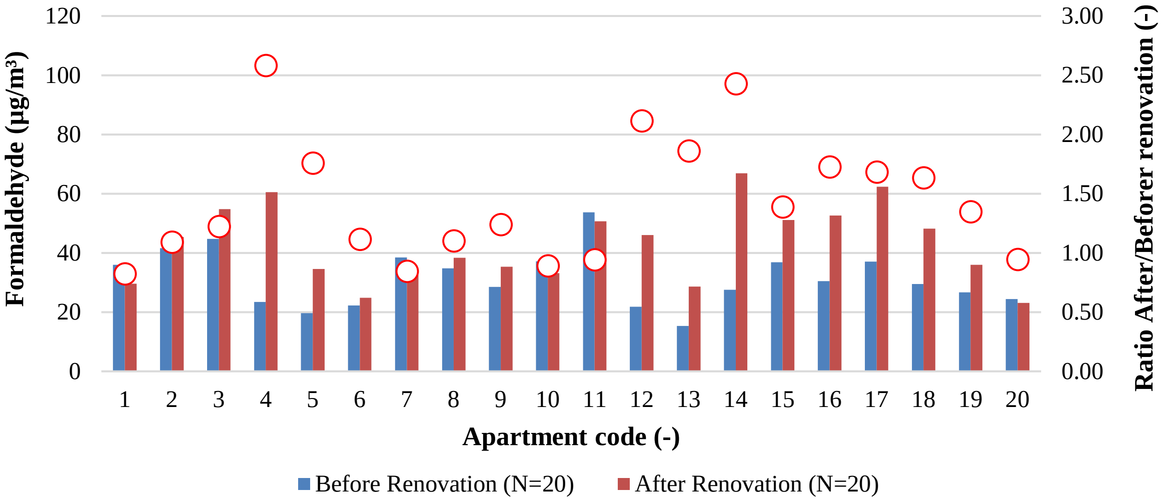

Figure 13. Formaldehyde concentration in each of the apartments before and after renovation of the residential building. The circles present the ratio between the obtained concentrations (after/before renovation).

The pre- and post-retrofit data of the TVOC were log-normally distributed. Although the difference between the two conditions were not statistically significant ($p>0.1$), the overall mean of TVOC was higher after renovation (772 µg/m³) than before (569 µg/m³). Over 80% of apartments had a TVOC concentration above the limit recommended by the WHO (300 µg/m³) (Table 5). The TVOC concentration exceeded 1000 µg/m³ in one apartment before renovation and in five apartments after renovation. After renovation, in three apartments a slight increase of TVOC concentration was observed. The ratios were 1.00, 1.01 and 1.3. In another seven apartments a more substantial increase was seen, with ratios from 1.4 to 8.4. Out of these seven apartments, three apartments were characterized by extremely high ratios. The TVOC was 6.2, 7.6 and 8.4 times higher after then before renovation in those particular apartments. This was caused by new carpets and a new sofa reported to be obtained in these apartments.

Table 5. Number of apartments with TVOC concentrations above four cut-off values in the investigated building before and after its renovation.

Cut-off values of TVOC concentrations	Before Renovation (N=20)	After Renovation (N=20)
TVOC > 300 µg/m³	16 (80%)	17 (85%)
TVOC > 500 µg/m³	10 (50%)	12 (60%)
TVOC > 1000 µg/m³	1 (5%)	5 (25%)
TVOC > 2000 µg/m³	0	1 (5%)

In total fifty individual VOCs were identified in the investigated residential building before and after renovation. The majority occurred very rarely. Significant difference was observed between heptane, limonene, benzene, hexanoic acid, haxanal and isobutanol before and after renovation of the building. The average concentration of benzene decreased after renovation. The rest of the individual VOCs were higher in the building after renovation.

Questionnaire survey

Most of the occupants did not indicate any problems with the indoor air quality before renovation, while after renovation their satisfaction decreased (Figure 14). Acceptability of indoor air quality was assessed using the continuous acceptability scale, ranging from “clearly unacceptable” (coded as -1) to “clearly acceptable” (coded as 1). Higher acceptability with the perceived air quality (PAQ) was observed before renovation of the building ($p<0.01$). The average acceptability with indoor air quality was similar in the living rooms (0.64) and the bedrooms (0.60) before renovation. After renovation the average acceptability in the two rooms was again similar. However, it decreased to 0.38 in the living rooms and 0.37 in the bedrooms.

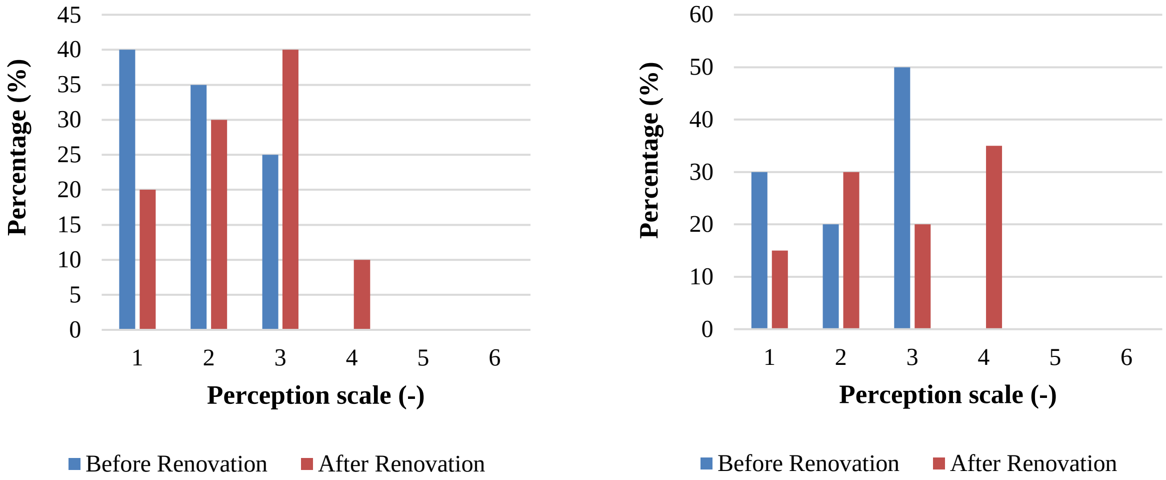

Figure 14. Summary of answers to the questions “How unpleasant do you think the indoor air quality is in your living room” (left), and “How unpleasant do you think the indoor air quality is in your bedroom?” (right). Possible answers were from 1 (PAQ not a problem) to 6 (unpleasant indoor air quality).

The percentage of occupants who indicated to ventilate more than once per day in their bedrooms before renovation (40%) slightly dropped after renovation (30%). This indicates a slightly lower frequency of airing out in the bedroom after renovation. Additionally, the duration of daily airing, as reported by the occupants, somewhat decreased after renovation. While 30% of the occupants aired out for about 20 minutes and 35% aired out for about 30 minutes per day before renovation, after renovation 40% aired out for 20 minutes but only 25% for 30 minutes. The results indicate that longer airing resulted in higher AERs across the apartments. Although some residents indicated poor indoor air quality along with longer airing, the overall trend shows an increase in the occupants´ satisfaction with indoor air quality with longer airing (Figure 15).

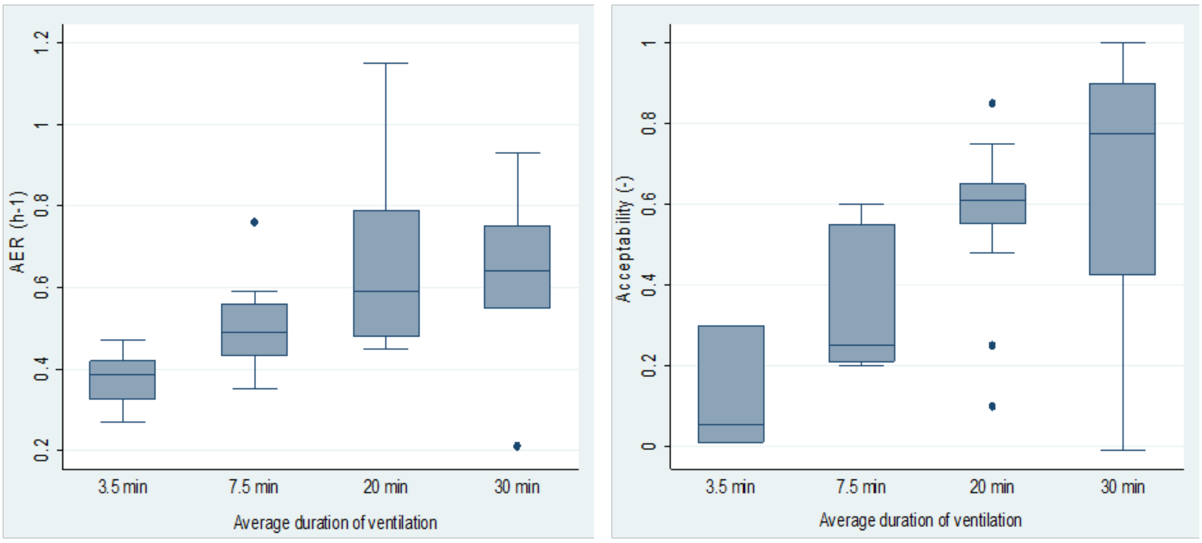

Figure 15. Relationship between AER (left) and occupants' acceptability of indoor air quality (right) and the reported average duration of daily airing in bedrooms. The figures are based on data before and after renovation together (N=40).

The frequency of selected symptoms occurring among the occupants before and after the renovation is shown in Figure 16. Multivariate logistic, stepwise forward and backward regression analyses were conducted to identify predictor variables with inclusion criteria of $p<0.2$ and look for associations between symptoms and selected variables. Each of the symptoms were investigated by statistical analyses. However the results are presented only for itchy eyes and headache. The evaluation of the rest of symptoms did not show any significance among the selected variables. Renovation may have impact on occurrence of itchy eyes (OR=7.12, $p=0.05$). Higher risk of headache was found after renovation (OR=1.38, $p=0.19$).

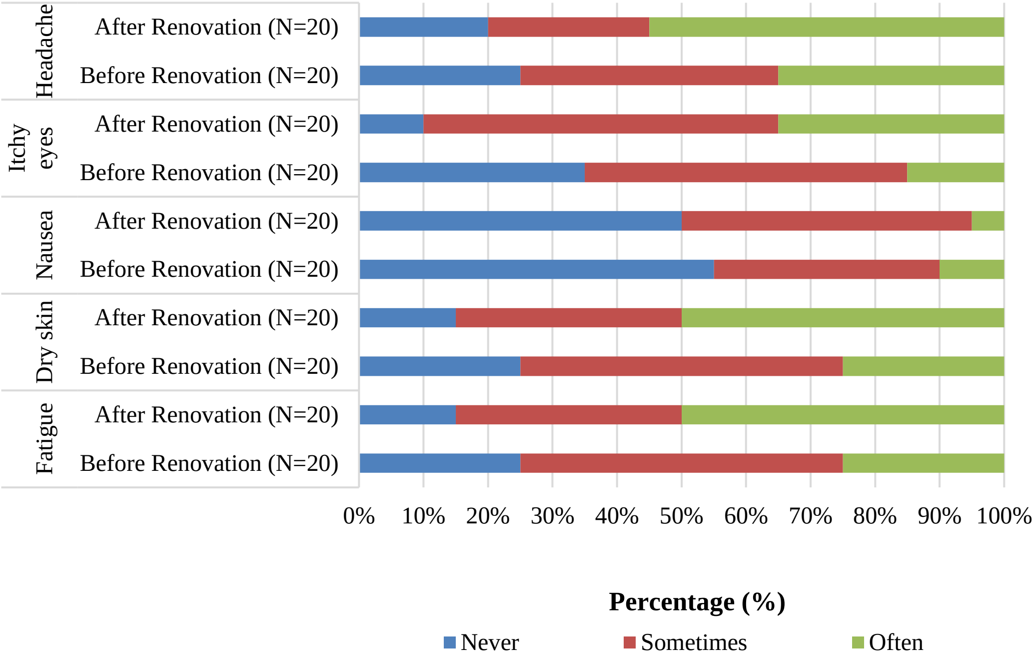

Figure 16. Frequency of sick building syndrome symptoms before and after renovation. The results are based on answers to the question: "Do you feel fatigue (headache, nausea, itchy eyes and dry skin) during your stay in your apartment?"

Relationship between the investigated variables

No correlation was observed between NO_2 concentrations and the measured air quality parameters and pollutants. However, significant correlation was found between formaldehyde and AER, CO_2 concentration, and relative humidity (Table 6). The results indicate that at higher CO_2 concentration ($r=0.57$, $p<0.01$); and lower AERs ($r=-0.59$, $p<0.01$) the formaldehyde levels increase. Higher relative humidity also led to higher formaldehyde concentration ($r=0.48$, $p<0.01$). Formaldehyde concentrations seemed to be slightly higher at higher temperatures, but the correlation was weak ($r=0.14$, $p>0.1$). TVOC was higher at higher formaldehyde concentrations ($r=0.27$, $0.05<p<0.1$) and slightly higher at lower AER, but the correlation was weak and not statistically significant ($r=-0.21$, $p>0.01$). Positive correlation was observed between AERs and acceptability of air quality ($r=0.79$, $p<0.01$), and negative between formaldehyde concentrations and acceptability ($r=-0.53$, $p<0.01$).

Table 6. Correlation coefficients between the measured parameters and concentrations of pollutants.

Parameter	NO_2	Formaldehyde	TVOC	CO_2	T	RH	AER
NO_2	-	-	-	-	-	-	-
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^{*}	0.56^{*}	-	-
AER	-0.19	-0.59^{*}	-0.21	-0.87^{*}	-0.16	-0.51^{*}	-

$^{*}p<0.01$, $^{**}p<0.05$, $^{***}p<0.1$

The association of formaldehyde with AER, temperature and relative humidity was confirmed by regression analysis. It indicated significant association between formaldehyde and AER ($p<0.05$) and relative humidity ($p<0.05$). The association between formaldehyde and indoor air temperature was borderline significant ($0.05<p<0.1$). The model´s coefficient of determination was $R^2=0.48$.

Energy efficiency of the buildings

Annual heat demand for space heating

The heat loss due to heat transfer via building constructions and ventilation for building pair I are shown in Figure 17. 10 kWh/m^2.year heat gains were produced by solar gains and 24 kWh/m^2.year generated by internal heat sources, in both the original and renovated building. However, the difference between heat losses due to heat transfer via building facade was still clear. 64 kWh/m^2.year was transmitted thru the building envelope of the original building compared to 15 kWh/m^2.year in the renovated building. Heat losses due to ventilation and transparent constructions were defined as the second more dominant factor influencing the total annual heat demand.

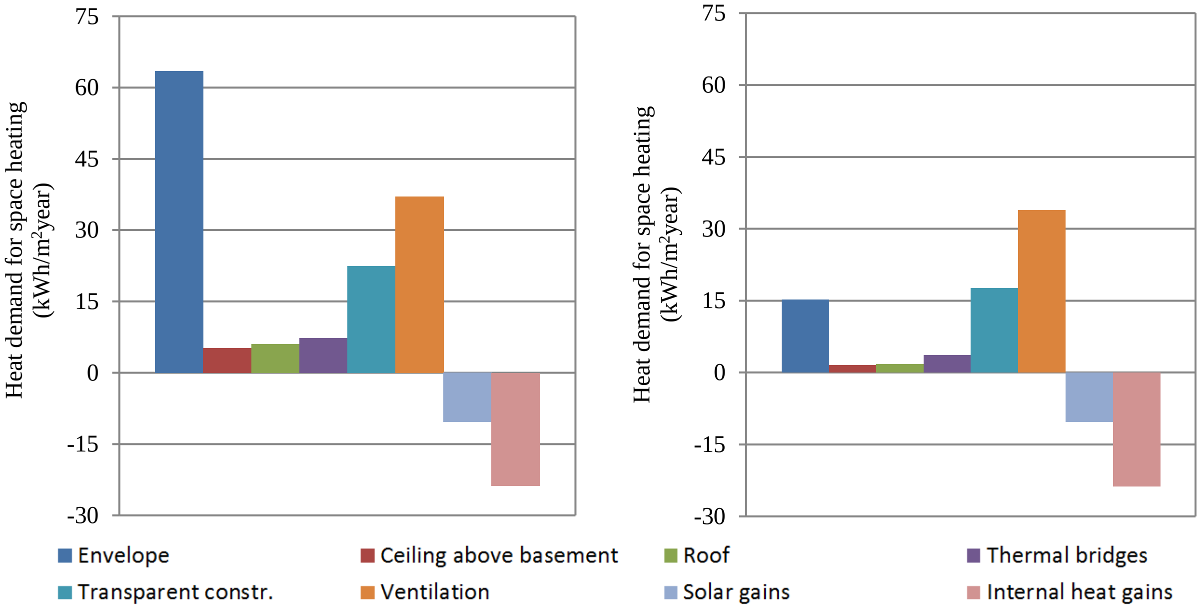

Figure 17. Calculated annual values of heat losses due to heat transfer via building constructions and ventilation as well as of produced heat gains for building pair I: the original building (left), the renovated building (right).

Table 7 presents the calculated annual heat demand for all the investigated buildings. The original buildings are compared to the retrofitted ones. The results well illustrate the impact of the energy saving measures on the heat demand. The differences between the original and renovated buildings were higher than 40% in each case of the building pairs. The calculated specific heat demands were compared to energy criteria specified by STN 73 0540:2-2012. The heat demand in the renovated buildings met the criteria of the normalized values, but did not fulfil the conditions given by requested values. The standard considers the requested values stricter than the normalized. However, the specific heat demand in the original buildings did not fulfil the normalized criteria.

Table 7. Calculated annual (specific) heat demand for the investigated residential buildings compared to the standardized values.

		Heat demand (Q_H)			Specific heat demand		
Building pairs	Building condition	kWh/year	GJ/year	Difference (%)	Calculated kWh/m^2.year	Normalized kWh/m^2.year	Requested kWh/m^2.year
I	Original	366 385	1 319	63	108	56	27
	Renovated	136 543	492		40		
II	Original	182 293	656	49	97	50	25
	Renovated	94 836	341		49		
III	Original	254 582	916	60	117	53	26
	Renovated	99 660	359		45		

Energy demand and classification into energy classes

Table 8 shows the calculated annual energy demand for space heating and DHW preparation as well as the final total energy need, per unit of floor area. Based on these results the energy classification of the investigated building was carried out. The final values were used for energy classification according to the criteria presented in the Slovak Nation Building Code. The total energy demand is defined as a sum of annual energy demand for space heating and DHW per unit of floor area. According to the required maximum total energy demands for the various categories, the original buildings were classified into energy class D, and the renovated dwellings were categorized into energy classes C (building pair II) and B (building pair I and III). The energy demand for space heating was visibly lower in the renovated buildings due to implementing energy saving measures on building constructions and systems of building services. The higher total energy demand was followed by higher annual primary energy (Figure 18) and CO_2 emissions (Figure 19) in the original buildings compared to the renovated dwellings.

Table 8. Classification of the residential buildings into energy classes based on their annual energy demand for space heating and DHW preparation and total energy demand

		Energy demand for space heating			Energy demand for DHW			Total energy demand	
Build. pair	Building condition	kWh/year	kWh/m^2.year	Energy class	kWh/year	kWh/m^2.year	Energy class	kWh/m^2.year	Energy class
I	Original	462 585	136	D	119 280	35	C	171	D
	Renovated	198 543	58	B	62 083	18	B	76	B
II	Original	271 875	145	D	69 376	37	D	182	D
	Renovated	168750	90	C	42 088	22	B	112	C
III	Original	301 556	139	D	69 571	32	C	171	D
	Renovated	156 678	71	B	44 341	20	B	91	B

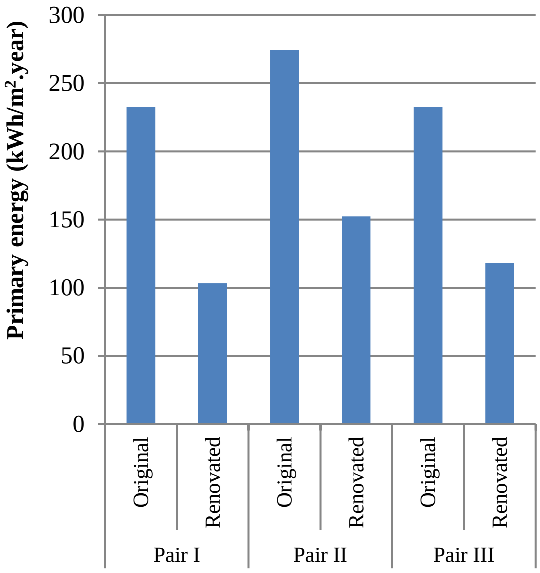

Figure 18. Calculated annual primary energy need per floor area in the original and renovated residential buildings

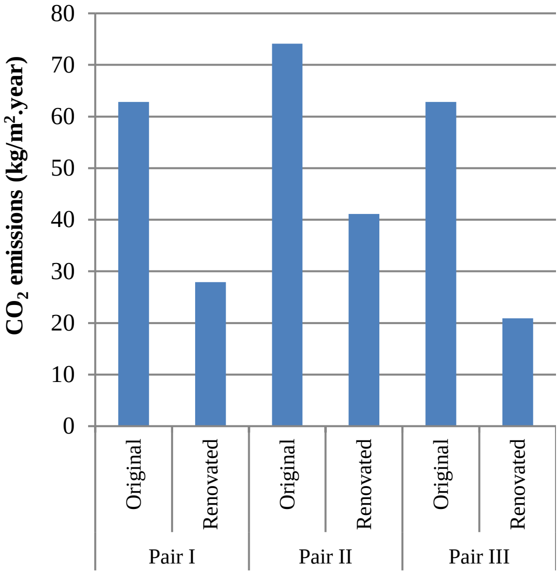

Figure 19. Calculated annual CO_2 emissions per floor area in the original and renovated apartment buildings.

Measured energy consumption for space heating

The data of the real heat consumption used for space heating are shown in Table 9. Reduction of the heat consumption was achieved in the reconstructed buildings compared to the values before the building renovation as well as to the values representing the corresponding original buildings. Lower heat consumptions were measured in 2014 compared to the previous years in all cases of the residential buildings. This decrease might be explained by the outdoor weather conditions during the winter season. According to the Slovak Hydro-meteorological Institution, during the last heating season higher average outdoor temperature was measured (4.5°C) than during the previous winters, when the average outdoor temperature ranged between -0.8 and 2 °C.

Table 9. Heat consumption for space heating for heating seasons 2010-2014; (Source: Housing association companies).

Building pair	Building condition	Heat consumption kWh/year				
		2010	2011	2012	2013	2014
I	Original	NA	322 140	322 780	328 170	174 100
	Renovated	NA	NA	NA	151 590	115 210
II	Original	NA	NA	NA	194 310	146 470
	Renovated	200 220	177 310	145 195	101 130	NA
III	Original	NA	NA	NA	218 840	165 140
	Renovated	NA	196 148	197 962	136 449	106 960

The numbers in the purple boxes are the heat consumption in the renovated building before the energy saving measures were implemented. The numbers in the red boxes represent the energy consumption of the renovated building after retrofitting.

Figure 20 presents the annual measured energy consumption compared to the calculated energy need for space heating. The results show that the real energy consumption was always lower than the calculated values.

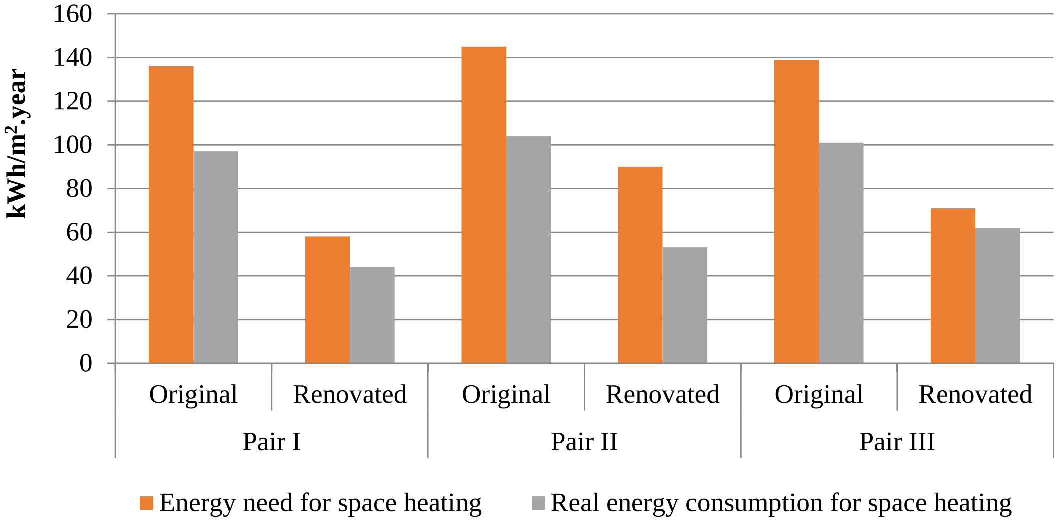

Figure 20. Comparison of the measured heat consumption (2013) and the calculated energy need and heat demand for space heating in the investigated residential buildings

Simulations

When natural ventilation was used, the CO_2 concentration was higher than 1000 ppm during the majority of the day time in the simulated (70%) and the actual building model (87.5%) as well. During occupied periods, especially overnight, the CO_2 concentration was above 2000 ppm (Figure 21). Using demand controlled ventilation or constant air volume ventilation led to significantly lower CO_2 levels during the occupied periods. The CO_2 concentration with demand controlled ventilation ranged between 510 and 855 ppm during the occupancy period. When the room was not occupied, the CO_2 level dropped even lower, in some periods reaching the outdoor level (~400 ppm). Using a CAV exhaust system in the sanitary rooms and the kitchen and at the same time keeping the internal doors opened resulted in CO_2 concentrations between 770 and 1130 ppm during the occupancy period. In the unoccupied period the CO_2 level dropped to 500 ppm.

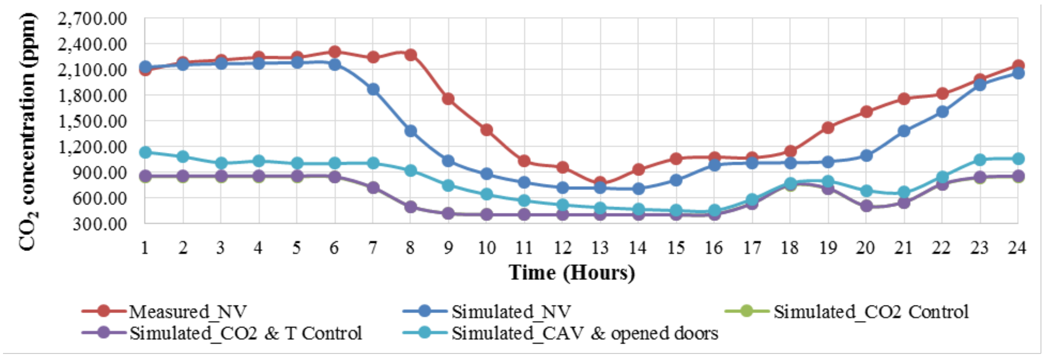

Figure 21. Hourly simulated versus measured values of CO_2 concentration in the bedroom located in the renovated residential building. Data for "Simulated_CO_2 Control" is invisible due to overlap with "Simulated_CO_2 and T control".

The energy consumption of the investigated ventilation strategies was assessed. The use of an air handling unit requires more energy than the operation of exhaust fans. The monthly energy consumption of the demand controlled systems was similar in both cases of the selected systems. The annual energy consumption of the air handling unit with "CO_2 and temperature control" was 27 kWh/m^2. The energy consumption of the AHU using "CO_2 control" was 29 kWh/m^2. The annual energy consumption for the operation of the exhaust fans (CAV system) was 3.2 kWh/m^2.

5. Conclusions and recommendations

Conclusions

This study presented experimental investigation of the impact of building renovation on IAQ and occupant comfort in residential buildings in Slovakia. The link between building energy-renovation and the quality of the built environment was examined in relation to physical parameters such as indoor air temperature, relative humidity, CO_2 concentration, air exchange rate, indoor air pollutant concentrations (NO_2, TVOC, individual VOCs and formaldehyde), and subjective parameters such as occupant satisfaction, airing habits and SBS symptoms. The main findings of the are summarized below.

Thermal comfort:

- Under-heating and lower average indoor temperature was observed in the original buildings. Yet, higher percentage of occupants in the original building than in the renovated ones indicated the thermal environment to be acceptable.
- The average indoor temperature in the summer was higher in the renovated dwellings. Yet, significantly higher thermal acceptability was observed in the renovated buildings.

- No significant differences were found in relative humidity between the original and renovated residential buildings.

Indoor air quality:

- Significantly higher CO_2 concentrations and lower AERs were observed in the renovated residential buildings. A larger fraction of apartments in the renovated buildings had lower AERs in winter than the recommended minimum limit ($0.5\ h^{-1}$).
- Low AERs resulted in increase of formaldehyde concentration. At higher values of relative humidity higher formaldehyde concentrations were observed. Formaldehyde concentrations seemed to be slightly higher at higher temperatures, but the correlation was weak.
- Indoor-to-outdoor ratios of NO_2 varied among the apartments in both original and renovated buildings, without obvious pattern. Ratios above one in a number of apartments indicate the presence of indoor combustion sources.
- The TVOC concentrations exceeded 300 $\mu g/m^3$ in a 80% of the apartments before renovation already. Even higher average concentrations were observed after renovation. The presence of new furniture seemed to cause significantly elevated levels of TVOCs in some of the apartments where furniture replacement was reported during the year of renovation.
- The occupants indicated to be more satisfied with the IAQ before renovation. Higher acceptability with IAQ was obtained at higher AERs and lower formaldehyde concentrations.
- In the first case study only 22% of the occupants changed their airing habits after renovation, while in the second case study no significant changes were observed in residents´ airing habits before and after renovation. This could result in lower AERs, higher concentrations of pollutants and poorer IAQ.
- Building renovation resulted in higher prevalence of some of the SBS symptoms, such as itchy eyes, headache and fatigue.
- Computer simulations indicated that using exhaust systems in kitchens and sanitary rooms while keeping doors of the rooms open may be one of the low-cost ventilation strategies able to provide improved indoor air quality in energy-retrofitted buildings with minimal additional energy penalty.
- When old, leaky residential buildings are upgraded into more airtight and energy efficient ones, the retrofitting effort should consider aspects of ventilation in order to ensure sufficient air exchange rates and acceptable and healthy IAQ.

Recommendations

The goal of the implementation of energy renovation strategy is to achieve better energy efficiency of buildings. However, the effect of these programs has not been systematically assessed. The effects on IAQ and occupant well-being is often neglected. There is an urgent need to assess the impact of the currently applied building renovation practices on the residential IAQ on a nationwide scale. The following recommendations can be drawn:

- When planning refurbishments, requirements for a healthy and comfortable indoor environment should be included. Such requirements are recommended to be reflected in national renovation strategies.
- In national legislation, stricter energy performance requirements should be complemented with appropriate requirements and recommendations to secure a comfortable and healthy IAQ for the occupants. Such requirements should cover factors such as for example minimum ventilation rates, thermal environment and emission from building materials.

- Potentials for further energy savings, while improving IAQ, should be exploited in energy-retrofitting programs. Demand-controlled ventilation and heat recovery through mechanical ventilation systems should be optimized in order to achieve the highest possible energy savings while providing improved IAQ.
- IAQ indicators are recommended to be integrated in energy certification programs.

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Appendix 1 – Conference paper: “Seasonal variation in indoor environmental quality in non-renovated and renovated multifamily dwellings in Slovakia”

Földváry, V., Bekö, G., Petráš, D. 2015. Seasonal variation in indoor environmental quality in non-renovated and renovated multifamily dwellings in Slovakia. Proceedings of Healthy Buildings 2015, Eindhoven, Netherlands, Paper No. ID474.

D: Energy and sustainability
D.1 Energy and IEQ

SEASONAL VARIATION IN INDOOR ENVIRONMENTAL QUALITY IN NON-RENOVATED AND RENOVATED MULTIFAMILY DWELLINGS IN SLOVAKIA

Veronika Földváry[1,2*], Gabriel Bekö[1], and Dušan Petráš[2]

[1]International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark
[2]Department of Building Services, Faculty of Civil Engineering, Slovak University of Technology in Bratislava

*Corresponding email: veronika.foldvary@gmail.com

Keywords: residential building, energy retrofitting, carbon dioxide, occupant behaviour

SUMMARY

This study investigates the impact of energy renovation on the indoor environmental quality of apartment buildings during summer and winter months. The study was performed in three pairs of residential buildings. One of the buildings in each pair has been renovated and the other was in its original state. Both objective measurements and subjective evaluation using questionnaire have been used. Temperature, relative humidity and the concentration of CO_2, were measured in the bedrooms of the apartments. In winter, the average CO_2 concentration during night was higher in the renovated buildings. In summer, the average night-time CO_2 concentrations were similar in both types of buildings. The average air change rate in the original buildings was significantly higher than in the renovated buildings in winter, but not in summer. The larger fraction of occupants in the renovated homes that changed their ventilation habits in the summer compared to winter 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. The current study indicates that large-scale of renovations may reduce the quality of the indoor environment in many apartments, especially in the winter season.

INTRODUCTION

Due to poor maintenance and high energy consumption, the energy efficiency and sustainability of many of the multifamily dwellings in Europe built since the 1950s are becoming a serious concern (Salat, 2009; Carvalho, 2012). Renovation of the existing building stock, with its main focus on energy conservation, became an important goal in many European countries. Multifamily residential buildings in Slovakia well represent the residential building stock of Central Europe. A significant fraction of these buildings is relatively old and does not fulfil current requirements on energy efficiency. Most of them are in great need of renovation. The potential impact of energy saving measures on indoor environmental quality should not be neglected. This study investigates the impact of energy renovation on the indoor environmental quality of apartment buildings during summer and winter months.

METHODOLOGIES

The study was performed in three pairs of residential buildings. One of the buildings in each pair has been 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.

Temperature, relative humidity and the concentration of CO_2 were measured in the bedrooms of the apartments using HOBO U12-012 data loggers (Onset Computer Corp.,USA) and CARBOCAP CO_2 monitors (GMW22, Vaisala, Finland). The data were recorded in 5 minutes intervals for about a week in each apartment between November 2013 and January 2014 (winter) and between July and August 2014 (summer). Data from night periods between 20:00 and 6:30 were used in order to avoid noise in the data from unknown activities and occupancy in the room.

The measurements were conducted in 94 apartments during winter and in 73 apartments during summer. At each visit, the residents were asked to fill in a questionnaire regarding some building characteristics, occupant behavior and habits, sick building syndrome symptoms and occupants' perception of indoor air quality and thermal environment. The occupants were asked to assess the acceptability of the thermal environment on the continuous acceptability scale with codes from -1 (clearly unacceptable) to -0.01 (just unacceptable) and from 0.01 (just acceptable) to 1 (clearly acceptable) (Iwashita et al, 1990). The occupants of the renovated buildings were also asked questions about altered habits after renovation (Földváry et al, 2014).

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. The calculation of AER from occupant-generated CO_2 has been described in detail by Bekö et al. (2010). Statistical analyses were performed in STATA, release 11.0 for windows (StataCorp LP, College Station, Texas, USA). Differences between the two building types were tested with parametric student's two-sample t-test.

RESULTS AND DISCUSSION

In winter the average CO_2 concentration during night across all apartments was higher in the renovated buildings, although without statistical significance ($p=0.08$). In 80% of apartments located in the renovated buildings the average CO_2 concentration was higher than 1000 ppm, while this was the case in 71% of apartments in the original buildings. The fractions of apartments where the 20-min running average CO_2 concentrations exceeded 1000, 2000 and 3000 ppm are shown in Table 1. In the summer the average night-time CO_2 concentrations were similar in both types of buildings ($p=0.7$).

Table 1: Temperature, relative humidity, 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 CO2 above three cut-off values in the investigated buildings.

	Winter		Summer	
	Original n=45	Renovated n=49	Original n=35	Renovated n=38
Mean temperature (°C)	21.6[a]	23.0[a]	25.7	26.6
Mean humidity (%)	47	45	56	56
Mean CO_2 during night* (ppm)	1425	1680	845	815
Average CO_2 >1000 ppm (%)	71	80	43	40
20-min period CO_2 >1000 ppm (%)	75	83	43	40
20-min period CO_2 >2000 ppm (%)	17	32	0	5
20-min period CO_2 >3000 ppm (%)	9	8	0	0

*based on averages obtained for each apartment, [a] $p<0.05$ (original compared to renovated)

The average air exchange rate across apartments in the original buildings was significantly higher than in the renovated buildings in winter ($p<0.05$), but not in summer ($p>0.05$) (Table 2).

Table 2: Average air exchange rates in the original and renovated buildings

	Winter		Summer	
	Original n=43	Renovated n=44	Original n=34	Renovated n=38
Average AER (h^{-1})	0.79	0.48	7.88	8.80
P - value	0.007		0.607	

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 1). 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.

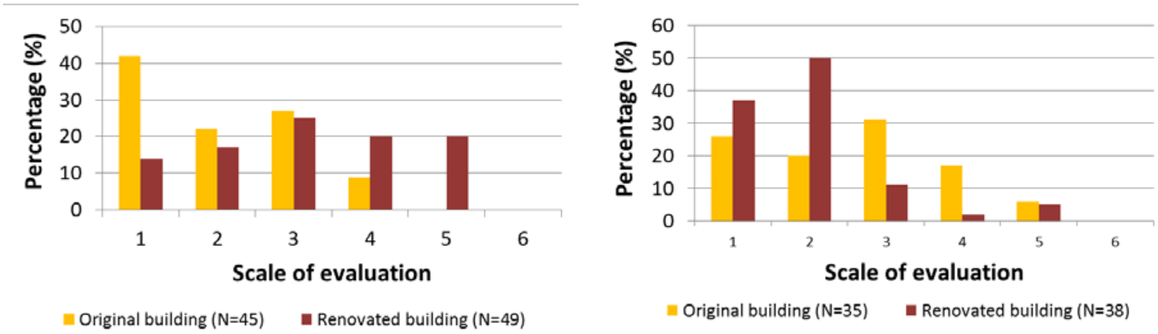

Figure 1. Summary of answers to the question “How unpleasant do you think the indoor air quality is in your bedroom during night/in the morning?”. Answers were from 1 - perceived air quality was not a problem, to 6 - poor indoor air quality. One occupant in each apartment answered during winter (left)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

The average acceptability (ACC) of the thermal environment in the original buildings (ACC=0.42) and the renovated buildings (ACC=0.31) was similar ($p > 0.05$) during the winter season. In the summer the occupants in the renovated buildings were more satisfied with their thermal comfort (ACC=0.53) than the residents of the original buildings (ACC=0.27; $p < 0.05$).

Energy renovation may change the indoor environment in the dwellings. It may directly lead to lower ventilation rates and higher concentrations of indoor pollutants (Noris et al, 2013). 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 related to renovation. The results from the summer further support this observation; 47% of residents indicated that they have changed their ventilation habits and ventilate 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 (Wallace et al, 2002; Dubrul, 1988; Howard-Reed et al, 2002). The larger fraction of occupants in the renovated homes that changed their ventilation habits in the summer (47%) compared to winter (22%) 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.

CONCLUSIONS

Renovation of apartment buildings in Slovakia 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 reconstruction.

ACKNOWLEDGEMENT

This work was supported by the Slovak Competence Center for SMART Technologies for Electronics and Informatics Systems and Services, project no. ITMS 26240220072 and by the Bjarne Saxhof Foundation, Denmark. Thanks are also due to Balassi Institute Budapest for co-founding of the research (Soós Kálmán Scholarship).

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Appendix 2 – Conference paper: “Effect of building renovation on energy use and indoor environment: Comparison of simulations and measurements in six apartment buildings”

Földvary, V., Kolarik, J., Bekö, G., Petras, D. 2016. Effect of building renovation on energy use and indoor environment: Comparison of simulations and measurements in six apartment buildings. Proceedings of Indoor Air 2016, Ghent, Belgium. Abstract No. 654.

Effect of building renovation on energy use and indoor environment: Comparison of simulations and measurements in six apartment buildings

Veronika Földváry[1,2*], Jakub Kolarik[2], Gabriel Bekö[2], Dušan Petráš[1]

[1] Slovak University of Technology in Bratislava, Bratislava, Slovakia
[2] Technical University of Denmark, Kongens Lyngby, Denmark
[*] *Corresponding email: veronika.foldvary@gmail.com*

SUMMARY

Energy performance and the indoor environmental quality (IEQ) in three naturally ventilated original and three identical but renovated residential buildings were compared using actual measurements. Although the implemented energy saving measures had the potential to improve energy performance of the dwellings, they led to poorer indoor air quality (IAQ). Additional simulations revealed that a simple intervention, such as using exhaust systems in kitchens and bathrooms and at the same time keeping doors of rooms open, may improve the IAQ in retrofitted multifamily buildings.

PRACTICAL IMPLICATIONS

The results advocate the need for measures to improve indoor air quality as a part of residential energy renovation projects.

KEYWORDS

Retrofitting, Residential Building, Energy Performance, Indoor Air Quality, Ventilation model

1 INTRODUCTION

Most of the apartment buildings in Slovakia were built from 1945 to 1992. Many of these buildings do not fulfil current requirements on energy efficiency. Energy saving measures, such as envelope insulation and tighter windows are implemented (Panayiotou et al., 2010). The impact of such energy renovation on IEQ is rarely considered. The objective of the present study was to investigate the actual measured energy use of naturally ventilated residential buildings and its relationship with IEQ.

2 MATERIALS/METHODS

Three pairs of buildings were investigated. One building in each pair was renovated and the other one was in its original state. Energy use for heating was monitored in all six buildings during the entire heating season and the specific heat demand was calculated according to the National Building Code (2012). IEQ parameters (see Table 1) were measured during the winter in 50% of all apartments within each building. Evening and night-time data are presented to represent occupied periods. Occupants´ satisfaction with IEQ in their apartments was investigated by using questionnaire survey. Additionally, dynamic building performance simulations were carried out using IDA-Indoor Climate and Energy software (EQUA Simulation AB, Sweden). CO_2 concentrations were simulated for one of the buildings before and after renovation using different alternatives of ventilation systems (no mechanical ventilation, constant volume and demand controlled ventilation).

3 RESULTS AND DISCUSSION

Table 1 compares the calculated specific heat demand, the measured energy performance and the measured IEQ in the original and the renovated buildings. Implementation of energy saving measures reduced energy use for space heating by more than 30%. Although the energy performance of the buildings improved after renovation, higher CO_2 concentrations ($p \geq 0.05$), lower air exchange rates (AER; $p < 0.05$) and lower acceptability of air quality (ACC) ($p < 0.05$) were observed in the renovated dwellings compared to the original buildings in winter.

For one of the buildings we created simulation models of its original and renovated state. Results of the simulations confirmed that energy renovation without considering additional ventilation, which is often the common practice, may increase CO_2 concentrations in the apartments (Table 2). Adding standard air handling units in bedrooms, or, at the minimum, exhaust systems in kitchens and bathrooms while at the same time keeping internal doors open, may significantly improve IAQ in newly energy renovated residential buildings.

Table 1. Summary of the energy performance and night-time (20:30-6:30) averages of IEQ parameters in the original and the renovated residential buildings

Building pairs	Building condition	Energy performance					Indoor Environmental Quality*						
		Specific heat demand			Actual energy use for space heating		RH	T	CO_2	AER**	ACC	Thermal Sens.	Thermal Accept.
		kWh/m^2.year	Energy class	Diff. (%)	kWh/m^2.year	Diff. (%)	(%)	(°C)	(ppm)	(h^{-1})	(-)	(-)	(-)
I	Original	136	D	57	96	53	49	21.4	1740	0.68	0.50	0	0.35
	Renovated	58	B		44		45	23.2	1930	0.44	0.06	2	0.30
II	Original	145	D	38	104	49	48	22.4	1320	0.82	0.49	1	0.67
	Renovated	90	C		53		47	23.1	1580	0.52	-0.02	2	0.38
III	Original	139	D	48	101	39	48	21.7	1060	0.97	0.71	1	0.58
	Renovated	71	B		62		47	21.8	1520	0.49	-0.04	2	0.17

*Each value is the grand mean obtained for all investigated apartments within the given building.
**The recommended minimum ventilation rate is 0.5 h^{-1}.

Table 2. Simulated night-time (20:30-6:30) averages of IEQ parameters in building pair I, and for the renovated building using various alternatives of ventilation systems

Building condition	Alternatives of ventilation system				Indoor Environmental Quality			
	Ventilation	System type	Location	Mech. air supply per year	CO_2	T_{op}	T_{air}	RH
					(ppm)	(°C)	(°C)	(%)
Original	Natural vent	Opened windows in period 7:00-7:30 and 19:00-19:30.	Bedroom	0 kWh	1190	17.8	17.9	37
Renovated	Natural vent	Opened windows in period 7:00-7:30 and 19:00-19:30.	Bedroom	0 kWh	1520	20.3	20.4	33
Renovated	Air Handling Unit	Temperature and CO_2 control	Bedroom	635 kWh	800	20.1	20.1	25
Renovated	Air Handling Unit	CO_2 control	Bedroom	624 kWh	795	19.9	19.9	25
Renovated	Air Handling Unit	CAV Exhaust only; opened doors of room	Kitchen, bathroom	0 kWh	755	19.0	18.8	27

5 CONCLUSIONS

Envelope insulation and window replacement can decrease the energy use for heating by over 40% in multifamily dwellings in Central Europe, built mainly of concrete panels. Such basic energy renovation may however deteriorate the indoor air quality, unless at least simple measures are taken to achieve increased air exchange rates in the apartments.

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ACKNOWLEDGEMENT: The study was supported by the Bjarne Saxhof Foundation, Denmark.

Appendix 3 – Conference paper: “Indoor air quality in a multifamily apartment building before and after energy renovation”

Bekö, G., Földvary, V., Langer, S., Arrhenius, K. 2016. Indoor air quality in a multifamily apartment building before and after energy renovation. Proceedings of the 5th International Conference on Human–Environment System, 29 October – 2 November, Nagoya, Japan. Paper No. 20103.

The Fifth International Conference on Human-Environment System
ICHES2016 Nagoya, October 29 - November 2, 2016

INDOOR AIR QUALITY IN A MULTIFAMILY APARTMENT BUILDING BEFORE AND AFTER ENERGY RENOVATION

Gabriel Bekö[1)], Veronika Földváry[1,2)], Sarka Langer[3)], Karine Arrhenius[4)]
1) International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, 2800 Lyngby, Denmark
2) Department of Building Services, Faculty of Civil Engineering, Slovak University of Technology in Bratislava, 81005 Bratislava, Slovakia
3) IVL Swedish Environmental Research Institute, 40014 Göteborg, Sweden
4) SP Technical Research Institute of Sweden, Department of Chemistry, 50115 Borås, Sweden

ABSTRACT

Buildings are responsible for a substantial portion of global energy consumption. Most of the multifamily residential buildings in central Europe built in the 20th century do not satisfy the current requirements on energy efficiency. Nationwide remedial measures are taken to improve the energy efficiency of these buildings and reduce their energy consumption. Since the impact of these measures on the indoor air quality is rarely considered, they often compromise indoor air quality due to decreased ventilation and infiltration rate. We compared the indoor air quality in a multifamily apartment building in Slovakia before and after energy renovation, during two subsequent winters. Measurements of temperature, relative humidity, concentrations of CO_2, formaldehyde, NO_2, and volatile organic compounds were performed during one week in January 2015 in 20 apartments in one multifamily building in Slovakia. Subjective evaluation of the indoor environment and occupant satisfaction using questionnaire has been also performed. The measurements were repeated in January 2016, after the building was energy-renovated. The renovation included thermal insulation of the façade. Natural ventilation was used in the building. Exhaust ventilation was present in bathrooms and toilets. No changes to the ventilation were done during renovation. After renovation, the ventilation rates in the apartments were significantly lower than before. Concentrations of formaldehyde, TVOC and certain individual VOCs were higher. The occupants indicated more dissatisfaction and a higher prevalence of some sick building syndrome symptoms after renovation. When residential buildings in central Europe are upgraded to more energy efficient ones, the retrofitting effort should include improved ventilation in order to ensure sufficient air exchange rates and acceptable and healthy IAQ. Without these considerations, energy reconstruction can adversely affect the quality of the indoor environment.

Keywords: Residential building; Energy retrofitting; Formaldehyde; VOC; Air change rate

1. INTRODUCTION

The building sector is responsible for one third of global energy consumption. The need to reduce energy consumption and greenhouse gas emissions became a national priority across the European Union member countries (BPIE, 2011; Meijer et al., 2009). A large proportion of the European population resides in multi-family buildings. Therefore, the residential sector represents a major potential target group for national programs supporting energy efficiency improvements of existing buildings and climate change mitigation. Multi-family residential buildings in Slovakia well represent the residential building stock of Eastern and Central Europe. Most of these buildings were built from 1948 to 1990. About 70% of these buildings do not fulfil the current European requirements for energy efficiency. Building retrofit campaigns for existing multi-family buildings have been implemented (EU, 2010). However, the effect of these programs on indoor air quality and occupant well-being is often neglected. Consequently, the countries fail to capitalize on the opportunity to improve indoor environmental quality on a nationwide scale.

Adding insulation to the building envelope or replacing inefficient single glaze windows with more efficient ones may lead to tighter buildings, resulting in reduced intake of outdoor air (infiltration rate). This may increase the concentration of indoor-generated air pollutants (Øie et al., 1998). Occupant exposure occurring in the residential environment can be substantial. These exposures may be associated with numerous long-term and acute health effects (Seppänen and Fisk. 2004). Therefore, there is a need to assess the impact of the currently applied building renovation practices, with the primary focus on energy conservation, on the residential indoor environmental quality, and provide recommendations for policy makers, engineers and the public. The objective of this study was to compare the indoor air quality in a multifamily apartment building before and after energy renovation, during two subsequent winters.

2. METHODS

The study was performed in a nine floor residential dwelling with forty apartments located in the building. Twenty apartments were selected across the residential building, equally distributed on the lower, middle and highest floors of the building. A questionnaire survey and measurements were carried out during two winter seasons, in January 2015 when the building was still in its original condition, and in January 2016 after energy saving measures have been implemented. The same apartments were investigated in both winter seasons during a period of eight days. The renovation of the dwelling included envelope and roof insulation, replacement of old windows for energy efficient ones and hydraulic balancing of the heating systems. Natural ventilation was used in the building. Exhaust ventilation was present in bathrooms and toilets. No changes to the ventilation were done during renovation.

Temperature, relative humidity and CO_2 concentration were measured in bedrooms of the apartments using HOBO U12-012 data loggers and Vaisala CARBOCAP CO_2 monitors. All devices were calibrated before the measurement campaign began. The data were recorded in 5 minutes intervals for eight days in each apartment. A set of passive samplers for NO_2, formaldehyde and VOC were placed centrally in living rooms of each investigated apartment. The samplers were always positioned at least 1.5 m above floor level. Sampling of NO_2 was carried out using IVL´s (Swedish Environmental Research Institute) diffusive samplers (Ferm, 2001). The gas molecules diffused into the sampler where they were quantitatively collected, which gave a concentration value integrated over time. NO_2 was analyzed by wet chemical techniques using a spectrophotometric method. The limit of detection for NO_2 was 0.5 $\mu g/m^3$ for the sampling period of one week. Formaldehyde was sampled using DSD-DNPH UmeX-100 (SKC Inc., Eighty Four, PA, USA). The limit of detection was 0.03 $\mu g/m^3$ for formaldehyde. High performance liquid chromatography analyses of the samplers were carried out. Perkin-Elmer adsorption tubes filled with 200 mg Tenax TA, were used for passive sampling of VOC. They were thermally desorbed at 275 °C for 7 minutes and calibrated by application of microliter amounts of solution of toluene in diethyl ether on Tenax tubes, before their shipping to Slovakia. The tubes were wrapped in aluminium folia and stored at room temperature until the measurement started. Gas chromatography/mass spectrometry analysis of the tubes was carried out in the laboratory. The limit of detection for the individual VOC was 0.2 µg/m^3. All parameters were also measured outdoors, on one of the balconies located on the third floor of the building.

Air exchange rates (AER) were calculated in the occupants' bedrooms from the occupant generated CO_2 concentrations for each night. CO_2 concentrations between 20:30 and 6:30 were used together with the occupants' body weight, height and room volume. A questionnaire regarding the occupants' comfort and wellbeing was administered to one occupant in each apartment during the measurement week, both before and after renovation. Stata statistical package release 12.1 (StataCorp LP, College Station, Texas, USA) was used for data analyses. Pearson's correlation coefficient was used to look for correlations between variables. Paired t-test and Wilcoxon signed rank test, where applicable based on normality of distribution, were used to compare the obtained results from the investigated apartments before and after renovation.

3. RESULTS

The overall average air temperature was significantly higher in the dwellings after renovation (22.2 °C) than before (20.9 °C), ($p<0.01$). The average temperatures in 25% of the apartments before renovation did not fulfil the criterion of the optional range (20-24 °C). Under-heating occurred in these particular apartments, where the mean temperature ranged between 18.3 °C and 19.7 °C. After renovation all 20 apartments met the required range of the thermal comfort criteria. The mean relative humidity was slightly lower before renovation (46%) than after renovation (48%), but the difference was not statistically significant ($p>0.1$).

The difference in CO_2 concentration between the pre-retrofit and post-retrofit condition was statistically significant. The median of the average night-time concentrations was 1300 ppm before renovation and 1870 ppm after renovation. During night-time, increase of CO_2 concentration was observed in each of the investigated apartments. The ratios of the CO_2 concentrations after and before renovation were between 1.03 and 3.6 (average ratio after-to-before was 1.49). The frequency distribution of the average CO_2 concentrations is shown in Figure 1.

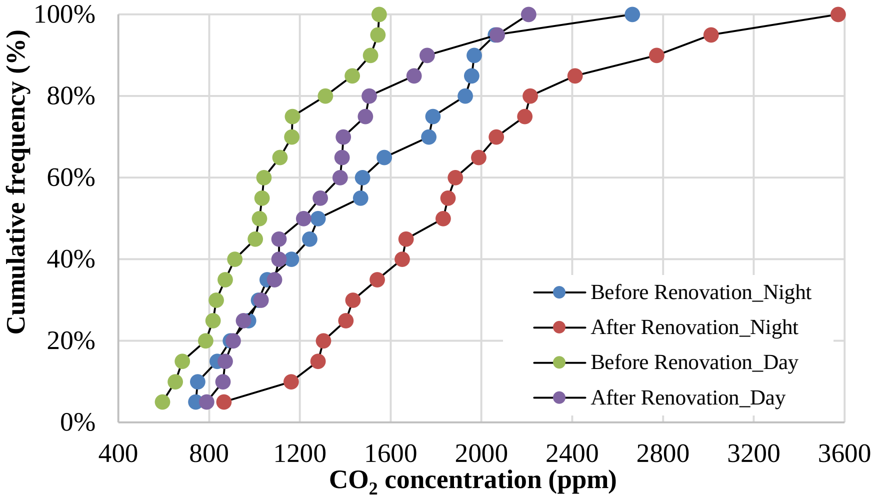

Figure 1. Cumulative frequency distribution of the average CO_2 concentration in the bedrooms during the day and night before and after renovation of the residential building.

The AER showed significant difference between the values obtained before and after renovation. Before renovation the average AERs was 0.61 h^{-1}. After renovation (0.44 h^{-1}) it dropped below the recommended minimum (0.5 h^{-1}) (Figure 2).

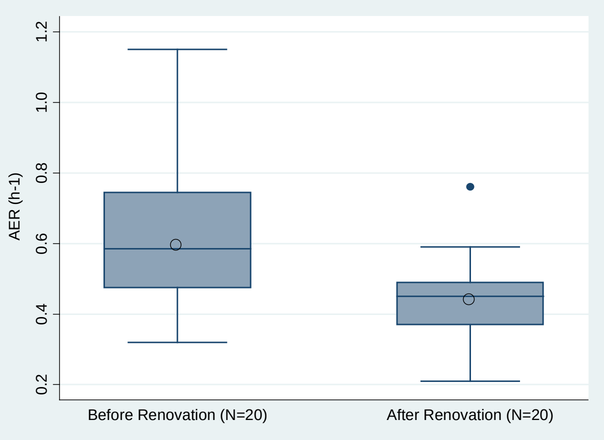

Figure 2. Boxplots of the AER before and after renovation of the residential building

The AER was lower than 0.5 h^{-1} in 40% of the apartments before renovation (ranged from 0.32 to 0.49 h^{-1}). The rest of the apartments met the criterion (ranged from 0.54 to 1.15 h^{-1}). After renovation, 85% of the apartments had a lower AER than 0.5 h^{-1}.

The NO_2 concentration was characterized by log-normal distribution. According to the WHO Guidelines for Indoor Air Quality the recommended annual average value for NO_2 concentration indoors is 40 µg/m³ (WHO, 2010). This limit was exceeded during the measurement week only in one apartment, where the NO_2 was 42.1 µg/m³ before renovation. Lower average NO_2 concentration was observed in the apartments before renovation (Figure 3). However, the difference between the two conditions was not statistically significant. In half of the apartments an increase of NO_2 after renovation was observed. The ratios between the indoor and outdoor concentration showed that in several apartments the indoor NO_2 was higher than the outdoor concentration indicating the presence of indoor sources.

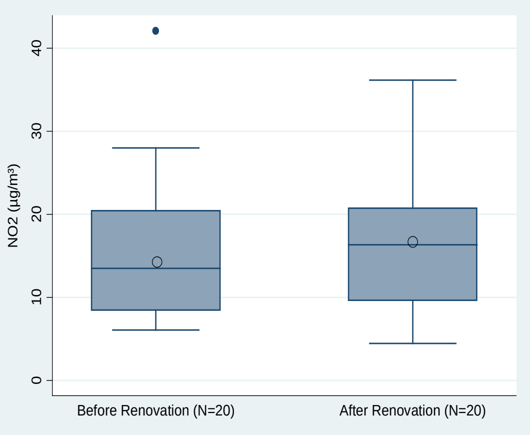

Figure 3. Boxplots of the NO_2 concentrations before and after the renovation of the residential building

Figure 4 shows boxplot of the formaldehyde concentrations before and after renovation of the building. The difference between the two conditions was statistically significant. The World Health Organization recommends a 30-minute average formaldehyde concentration of 100 µg/m³ (WHO, 2010). Although the concentrations of formaldehyde were below this limit in all apartments, an increase in the formaldehyde concentration was observed in 75% of the apartments after renovation. Among these apartments, the ratio of formaldehyde concentrations after and before renovation was between 1.09 and 2.5 (average 1.62). In the rest of the apartments only slight decrease was observed (average ratio 0.89).

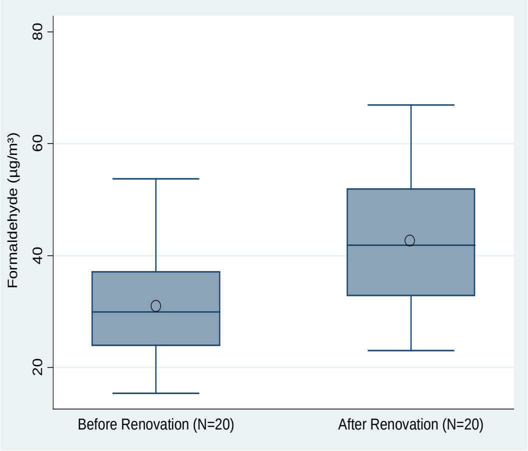

Figure 4. Boxplots of the formaldehyde concentrations before and after the renovation of the residential building.

Individual VOCs were also identified. The concentration of heptane, limonene, haxanal and isobutanol was significantly higher after renovation than before. The concentration of benzene and hexanoic acid was significantly higher before than after renovation. The difference in TVOC concentration was not significant, although the overall mean TVOC across all apartments was higher after renovation (772 µg/m³) than before (569 µg/m³) (Figure 5). Over 80% of apartments had a weekly average TVOC concentration above the limit of 300 µg/m³ recommended by Seifert (1990). A substantial increase was seen in seven apartments after renovation, with ratios from 1.4 to 8.4.

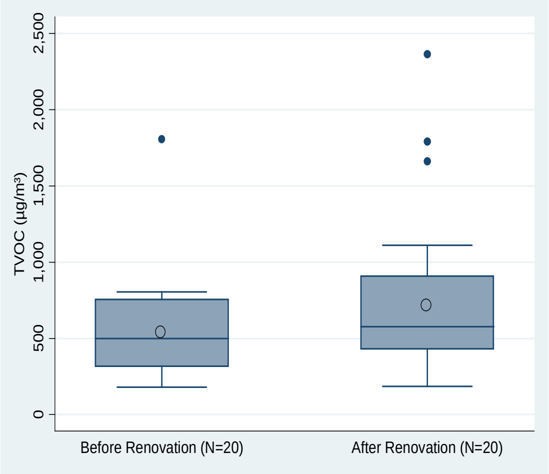

Figure 5. Boxplots of TVOC concentrations before and after the renovation of the residential building.

Most of the occupants did not indicate any problems with the indoor air quality before renovation, while after renovation their satisfaction decreased. Higher acceptability of the perceived air quality was observed before renovation. The prevalence of selected sick building syndrome (SBS) symptoms among occupants (those filling the questionnaire) is shown in Figure 6.

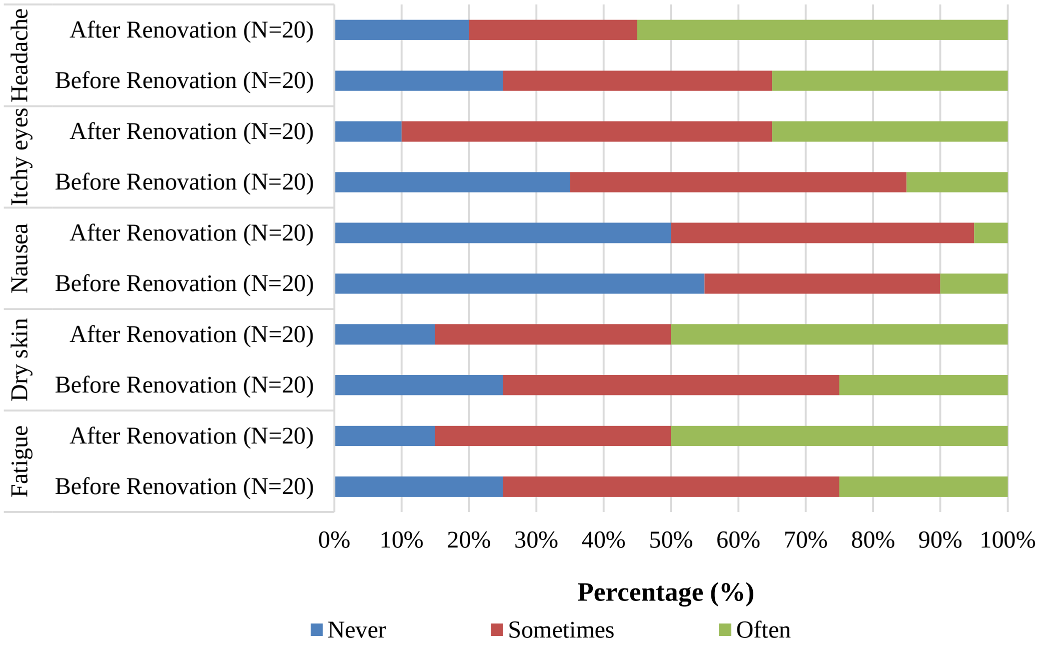

Figure 6. Prevalence of sick building syndrome symptoms before and after renovation.

Significant positive and relatively strong correlation was found between formaldehyde and CO_2 concentration, and relative humidity, negative correlation with AER (Table 1). Significant positive correlation was observed between AER and acceptability of air quality (r=0.79) and negative correlation between formaldehyde concentrations and acceptability (r=-0.53).

Table 1. Correlation coefficients between the measured parameters and concentrations of pollutants.

	NO_2	Formald.	TVOC	CO_2	T	RH
NO_2						
Formald.	-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***	**0.56***	
AER	-0.19	**-0.59***	-0.21	**-0.87***	-0.16	**-0.51***

$^*p<0.05$

4. DISCUSSION

Indoor air in residencies is a dominant contributor to personal exposure, because people spend a substantial fraction of the day at home. The results of this study further support the fact that energy renovation without considering the indoor environment can lead to deterioration of indoor air quality.

There was no clear pattern in the change of NO_2 concentrations, nor in the change of indoor/outdoor ratios from before renovation to after renovation. The ratios indicated the presence of indoor combustion sources in some of the apartments. However, none of the apartments in the present study had gas stoves and other combustion devices. Candle burning is however common during the winter seasons, especially during Christmas holiday period (Langer et al., 2015). Measurements of longer duration and detailed identification of the sources of NO_2 would validate the current results.

An earlier review of formaldehyde in indoor environment reported that insulation material could be one of the major sources of formaldehyde (Salthammer et al., 1995). Foam board materials, which were also used for envelope insulation in the current study, may cause high emissions. Moreover, fitting of the residential building with this insulation resulted in a tighter building construction and decreased ventilation in the apartments after renovation. The significant negative correlation between AER and formaldehyde concentration reflects that decreased ventilation may have contributed to increased formaldehyde concentrations. Furthermore, significant positive correlation was found between relative humidity and formaldehyde, which is in line with expectations (Parthasarathy et al., 2011).

The TVOC concentrations exceeded 300 $\mu g/m^3$ in a large fraction of the apartments already before renovation. More than 100% increase of TVOC was observed in three apartments. In these apartments furniture replacement (carpet/sofa) was reported after the first round of measurements. These activities could have caused an increase in TVOC levels. This is in agreement with similar observations in studies where new materials, furniture, paints may have led to increased TVOC concentrations (Park and Ikeda, 2006).

The occupants indicated to be more satisfied with the IAQ before renovation. Positive correlation was found between AERs and acceptability of the indoor air quality and negative correlation was observed between formaldehyde concentrations and acceptability of IAQ. Similar results were reported by Maddalena et al. (2015); lower perceived air quality was observed when the concentration of pollutants increased, which was the case at lower ventilation rates. Wolkoff (2013) reported that with specific focus on poorly perceived IAQ, hexanal (linseed oil in building materials and human debris, e.g. skin oils), hexanoic acid (an oxidative degradation product from linseed oil, skin oils and cooking) and limonene (a common fragrance used in numerous consumer products) may be some of the most important compounds. These three individual VOCs were among the most abundant ones in our study. Higher concentration of hexanal and limonene was observed after renovation, while the concentration hexanoic acid was higher while the building was in its original state.

We found higher prevalence of SBS symptoms after renovation of the apartment building. Both concentrations of pollutants and occupants’ perception and well-being may be affected by decreased AERs. However, multivariate regression models did not produce significant p-values for the associations between SBS symptoms and AER. No significant associations were observed between SBS symptoms and the concentrations of the measured indoor air pollutants. However, chemical substances emitted from building materials, including formaldehyde and other organic compounds may be associated with SBS symptoms (Salthammer et al., 2010). The lack of such association in our study may be partly due to the low number of investigated apartments. Further studies on the relationship between SBS symptoms and AER in larger number of dwellings before and after renovation are warranted.

Numerous studies have reported decreased prevalence of SBS symptoms and improvement of occupant health after moving into green buildings, where lower levels of several key pollutants, such as particles, NO_2, VOCs and allergens were measured (Colton et al., 2014; 2015). These studies could provide some lessons to be learned regarding the potential to improve indoor air quality, when energy retrofitting of existing buildings is performed.

5. CONCLUSION

The current study indicates that energy renovation of apartment buildings by simply adding thermal insulation may tighten the building, leading to reduced ventilation rates and poorer indoor air quality. Significantly higher CO_2 concentrations and lower AERs were observed in the building after its renovation. Lower AERs resulted in increased levels of formaldehyde. The TVOC concentrations exceeded 300 µg/m³ in a large fraction of the apartments before renovation, but even higher concentrations were measured after renovation. The occupants indicated to be more satisfied with the indoor air quality before renovation. Higher satisfaction with IAQ was indicated at higher AERs and lower formaldehyde concentrations. Building renovation also resulted in higher prevalence of some of the sick building syndrome symptoms, such as itchy eyes, headache and fatigue. When old, leaky residential buildings in central Europe are upgraded to more airtight and energy efficient ones, the retrofitting effort should include improved ventilation in order to ensure sufficient air exchange rates and acceptable and healthy IAQ. Energy reconstruction without considering its impact on the indoor environment can adversely affect the quality of the indoor environment in the apartments.

6. ACKNOWLEDGMENTS

The study was supported by the Bjarne Saxhof Foundation, Denmark. We thank the participating families for their cooperation.

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Appendix 4 – Journal paper: “Effect of energy renovation on indoor air quality in multifamily residential buildings in Slovakia”

Földváry, V., Bekö, G., Langer, S., Arrhenius, K., Petrás, D. 2017. Effect of energy renovation on indoor air quality in multifamily residential buildings in Slovakia, manuscript draft, to be submitted to Building and Environment in January 2017 (manuscript currently incomplete).

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

Authors: Veronika Földváry[1,*], Gabriel Bekö[2], Sarka Langer[3], Karine Arrhenius[4], Dušan Petráš[1]

[1]Faculty of Civil Engineering, Slovak University of Technology, Bratislava, Slovakia

[2]International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark

[3]IVL Swedish Environmental Research Institute, Göteborg, Sweden

[4]SP Technical Research Institute of Sweden, Department of Chemistry, Borås, Sweden

[*]*Corresponding email: veronika.foldvary@gmail.com*

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

Abstract

Buildings are responsible for a substantial portion of global energy consumption. Most of the multifamily residential buildings in central and eastern Europe built in the 20th century do not satisfy the current requirements on energy efficiency. Nationwide remedial 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. We examined the IAQ in three pairs of identical naturally ventilated multifamily residential buildings. One building in each pair was newly renovated, while the other was in its original state. Temperature, relative humidity (RH) and the concentration of carbon dioxide (CO_2) were measured in 50% of the apartments 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. 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. A large proportion of the European population resides in multifamily buildings [1].

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 [3, 4, 5, 6, 7, 8]. When unaccompanied by improved ventilation, such energy saving measures can lead to insufficient ventilation rates [9] and increased exposure of building occupants to indoor pollutants [10, 11, 12]. Residential exposure is of particular concern, as more than half of the time spent indoors takes place in residences [13]. It is therefore important to understand how energy mitigation 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 [14]. In California, comprehensive energy retrofit combined with improved mechanical ventilation systems and air cleaners resulted in improved indoor environmental conditions [15]. Positive effects of energy retrofitting on indoor environmental quality and occupant satisfaction were also shown in mechanically ventilated residential buildings in Sweden [16]. Additionally, better indoor air quality in low-energy or passive houses compared to conventionally built houses have been reported in a number of studies [17] [18, 19] [20]. 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 measures 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, 67, 36, Kauneliene et al., 2016). 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 [23]. This has led to the implementation of numerous energy retrofit campaigns for existing multifamily buildings [1]. However, the effect of these programs on indoor air quality and occupant wellbeing is entirely neglected. The present study aims to provide better understanding of the relationships between building renovation, energy performance, indoor environmental quality and occupant comfort in multifamily residential buildings in Slovakia. The objectives of the study were to evaluate 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 Selected buildings

Two experiments were performed. 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, replacement of single pane windows with energy efficient double pane plastic frame windows and hydraulic balancing of the 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 were present in bathrooms and toilets. No modifications were made to the ventilation systems during renovation. All buildings were located with 1 km from each other, in the rural city of Samorin (13.000 inhabitants), 25 km from the capital of Slovakia, Bratislava. 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 above. 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.

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
Orientation of the entrance side	East		Northwest		North	
Height (m)	27.7		30.2		13.1	
Volume (m^3)	9412	9683	5936	6114	6333	6523
Area (m^2)	3408	3449	1875	1913	2174	2217
Number of floors	10		9		4	
Number of apartments on each floor	4		2		2	

2.2 Physical measurements

The first 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. 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.

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 [24]. 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 were used for further analyses. The CO_2 concentrations, room volume and the occupants' body weight and height were used to calculate air exchange rates (AER) in the bedrooms [25]. The CO_2 concentration build-up period was used to estimate the AER for each respective night in the occupants' bedrooms [24, 25, 26, 27]. 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 to ventilate before sleeping. 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 [24]. 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.

In the second experiment, the concentrations of nitrogen dioxide (NO_2), formaldehyde, total volatile organic compounds (TVOC) and individual volatile organic compounds (VOCs) were also measured. A set of passive samplers for NO_2, formaldehyde and VOCs were placed centrally in the living room of each investigated apartment [17, 28]. 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 (29). 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 1 µg/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 [31]. 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 [32]. They were thermally desorbed at 275 °C for 7 minutes and analyzed by gas chromatography/mass spectrometry. The gas chromatograph oven temperature program was started at 60 °C, held for 2 minutes then increased to 100 °C at 4 ^{o}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 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.

2.3 Questionnaire survey

In both experiments one occupant in each apartment was asked to fill a questionnaire. The questionnaire used in the renovated buildings contained additional questions related to potential changes in the occupants' indoor-climate related behavior and habits after renovation (e.g. airing habits).

2.4 Data analysis

Statistical analyses were performed in STATA software, release 12.0 (StataCorp LP, College Station, Texas, USA). 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) in the first experiment. 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 formaldehyde (log-normally distributed and logarithmically transformed) and the other indoor air quality parameters measured in this study were also tested with linear regression. Stepwise forward and backward regression analyses were used to identify predictor variables with inclusion criteria of $p<0.2$. Regression analysis was not done for NO_2 and TVOC, as the correlations between their concentrations and the other measured parameters were weak.

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 ($p<0.01$) (Fig. 1). In the first experiment, the average temperature in 18% of the apartments before renovation did not fulfil the recommended optimal range (20-24°C) [33]. In the second experiment 25% percent of the apartments before renovation had the average indoor temperature below 20°C. After renovation, only one apartment was under-heated in the first experiment. However, energy renovation can lead to increased periods of overheating (Psomas et al., 2016). In this study, overheating occurred in three apartments (7%) in the non-renovated buildings and in six apartments (12%) in the renovated ones.

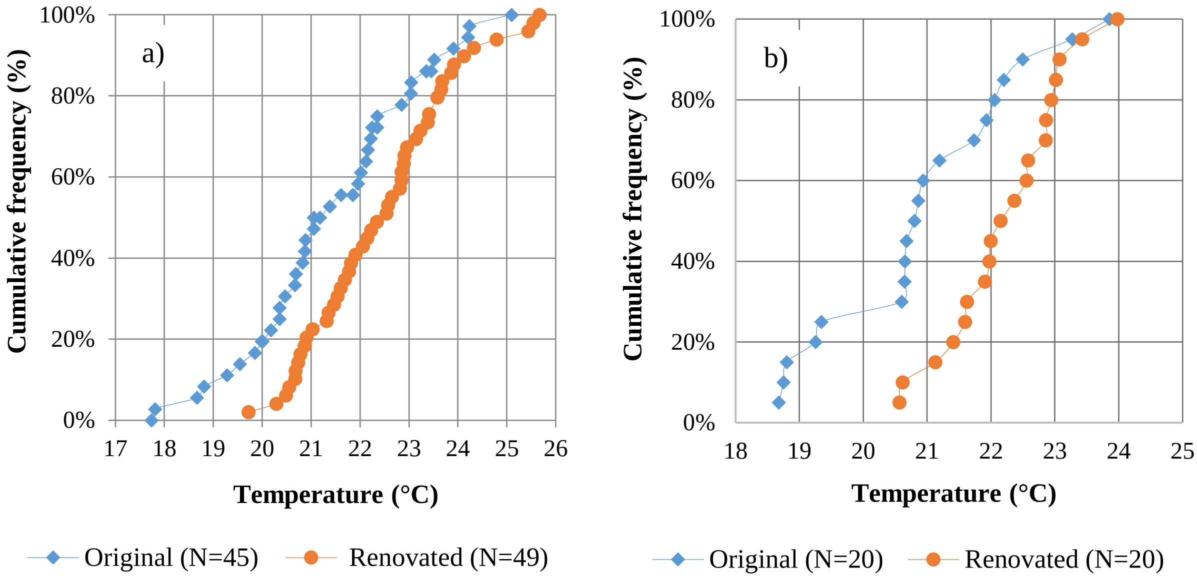

Fig. 1 Cumulative percentage distribution of the average indoor temperatures in Experiment I (a) and Experiment II (b).

Kotol et al. [34] reported under-heating in 17% of the investigated Greenlandic households built in the second half of the 20th century. Temperatures lower than 20°C were found in 30-40% of Estonian [35] and Lithuanian [36] dwellings. It has been suggested that the occupants may maintain low temperatures in order to minimize heating costs [37]. Uninsulated dwellings built in the 20th century may have significantly lower indoor operative temperatures during the winter due to colder internal surfaces. Howden-Chapman et al. [14], Liu et al. [38] and Pustayova [39] concluded that adding thermal insulation on older dwellings leads to increased indoor air temperatures and higher level of comfort in winter. In the 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 [38]. In an earlier Slovak study [39], the average indoor temperature in non-renovated multifamily buildings was lower (18.3-23.6°C) than in renovated ones (22.2°C-25.3°C). In New Zealand households [14] the indoor temperature increased by 0.6 °C and the relative humidity decreased by 1.4-3.8% after adding insulation on building envelope. In the current study, the relative humidity was similar in the renovated and non-renovated buildings. In the non-renovated buildings, the average relative humidity slightly exceeded the recommended 60% in two of the apartments in Experiment I and in one apartment in Experiment II. In the renovated buildings all apartments had the average RH within the recommended comfort range.

Table 2. Descriptive statistics of the measured parameters. Values of temperature and relative humidity are based on average values obtained for each apartment over the whole monitoring period.

			T (°C)	RH (%)	CO_2 whole period (ppm)	CO_2 night-time (ppm)	AER (h^{-1})	NO_2 (µg/m^3)	TVOC (µg/m^3)	Formaldehyde (µg/m^3)
Experiment I [a)]	Non-renovated (N=45)	Mean (Min.-Max.)	21.5 (17.6-5.1)	46 (34-65)	1180 (430-3380)		0.79 (0.22-3.69)	-	-	-
		Geom. Mean	21.5	47	1100		0.64	-	-	-
		Median	21.7	48	1100		0.66	-	-	-
		Std. Dev.	1.8	7	495		0.69	-	-	-
	Renovated (N=49)	Mean (Min.-Max.)	22.5 (19.2-5.8)	46 (31-61)	1380 (510-3570)		0.48 (0.06-1.33)	-	-	-
		Geom. Mean	22.4	45	1295		0.38	-	-	-
		Median	22.5	46	1290		0.43	-	-	-
		Std. Dev.	1.5	1.3	590		0.31	-	-	-
Experiment II [b)]	Before renovation (N=20)	Mean (Min.-Max.)	20.9 (18.7-3.9)	46 (34-61)	1205 (595-2665)		0.61 (0.32-1.15)	15.4 (6.1-42.1)	569 (179-1805)	32 (15-54)
		Geom. Mean	20.8	46	1165		0.58	13.4	489	30
		Median	20.8	45	1190		0.59	13.5	500	30
		Std. Dev.	1.5	8	400		0.2	8.9	357	9.4
	After renovation (N=20)	Mean (Min.-Max.)	22.2 (20.6-4.0)	48 (39-59)	1570 (790-3575)		0.44 (0.21-0.76)	16.5 (4.5-36.2)	773 (185-2362)	43 (23-67)
		Geom. Mean	22.2	48	1545		0.42	14.5	623	41
		Median	22.3	48	1510		0.45	16.3	575	42
		Std. Dev.	0.9	6	500		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.

3.2 Impact of renovation on CO_2 concentrations and air exchange rates

In both experiments the median CO_2 concentrations during the whole measurement period were higher in the renovated dwellings than in the non-renovated buildings (1290 ppm vs. 1100 ppm in Experiment I; 1510 vs. 1190ppm in Experiment II). The difference was statistically significant in Experiment II ($p<0.05$). 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 average night-time CO_2 concentration was 1425 ppm in Experiment I and 1410 ppm Experiment II. In the renovated dwellings these values were higher, 1680 ppm in Experiment I and 1925 ppm Experiment II. In Experiment I, 71% of the apartments in the non-renovated buildings and 80% in the renovated buildings had an average night-time CO_2 concentration above 1000 ppm. In Experiment II, it was 75% and 95%, respectively. The average night-time CO_2 concentration exceeded 2000 ppm and even 3000 ppm in a number of apartments; this was again more frequent in the renovated buildings. The average night-time CO_2 concentration increased with renovation in every apartment in Experiment II (by 3-360%). According to the questionnaire, regular bedroom occupancy did not change between the two measurement campaigns, which were a year apart.

The stepwise multivariate regression analyses (Fig. 3, Table 4) confirmed the association between increasing 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). According to the questionnaire, larger fraction of the occupants were smokers in the renovated buildings (38%) compared to the non-renovated buildings (27%). The 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 [9, 40]. Especially predictor variables related to occupant behavior are suspected to be of importance, as the climate and building related variables were similar for the investigated apartments.

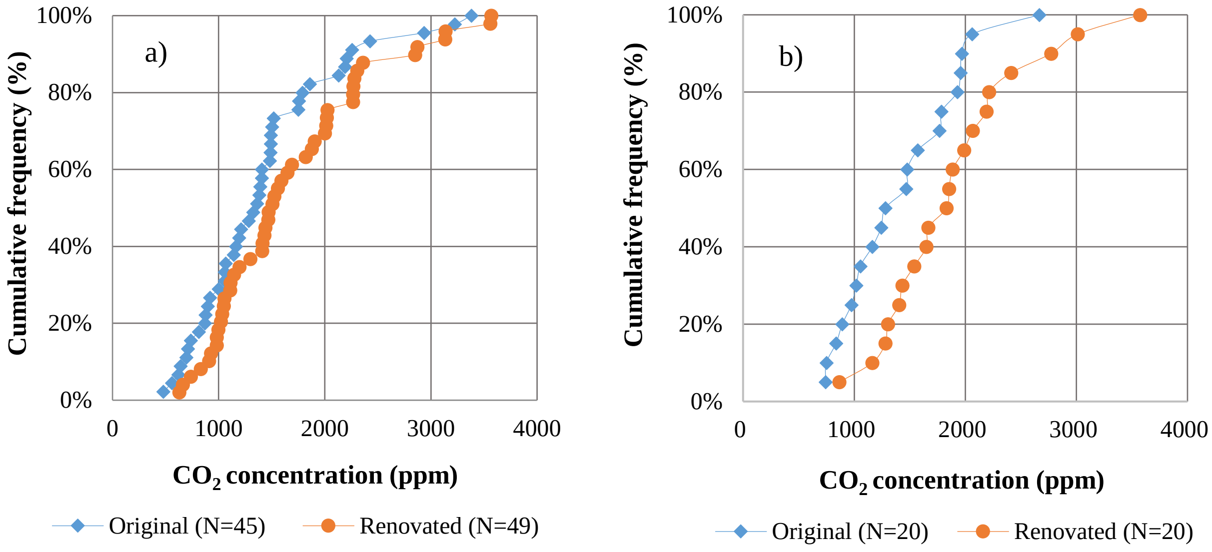

Fig. 2 Cumulative percentage distribution of the average night-time CO_2 concentrations in Experiment I (a) and Experiment II (b).

Table 4

Linear regression of logarithmically transformed CO_2 concentrations in the bedrooms in winter (Experiment I), $R^2 = 0.29$, n=94.

Parameter	**Parameter Estimate (Factor)**	**Std. Error**	**95% Confidence Interval**		**P-value**
Building type					
Reference: Original					
Reconstructed	0.15	0.08	-0.01	0.32	0.07
Occupancy of bedroom					
Reference: 1					
2	0.3	0.09	0.11	0.50	0.00
Occupancy of apartment					
Reference: 1					
2	0.22	0.12	-0.023	0.46	0.08
3	0.24	0.14	-0.03	0.52	0.08
4	0.38	0.16	0.07	0.70	0.02
Smoking habits					
Reference: Non-smoker					
Smoker	-0.16	0.09	-0.34	0.01	0.07
Constant	6.86	0.10	6.66	7.07	0.00

Factor – value of factors corresponding to the level of the categorical variable.

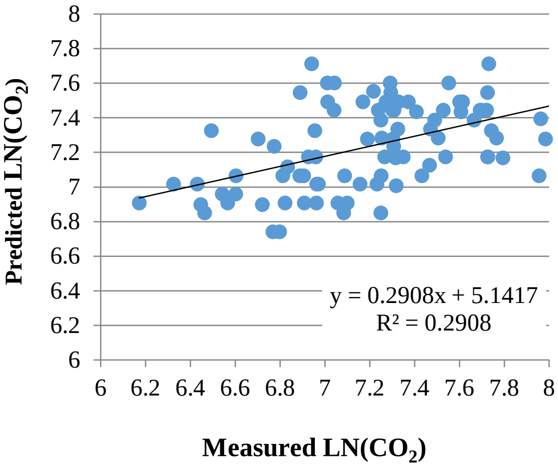

Fig. 3 Logarithm of the measured CO_2 concentrations in winter plotted against the predicted values from the regression model.

The air exchange rates were significantly lower in the renovated buildings than the non-renovated ones in both Experiments ($p<0.05$). The median air exchange rates were above the recommended minimum of 0.5 h^{-1} before renovation (Table 2). After renovation it decreased below this value. Figure 4 shows the cumulative frequency distribution of air exchange rates. In Experiment I, 37% of the apartments in the non-renovated buildings had an air exchange rate below 0.5 h^{-1}. It was 58% in the renovated buildings. In Experiment II, the air exchange rate was below 0.5 h^{-1} in 40% of the apartments before renovation and in 85% after renovation. In 19 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. Without the implementation of a ventilation system, air exchange rates in such naturally ventilated buildings can be low [25, 28, 40, 41, 42]. Du et al. [36] 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. Increasing airtightness would further exacerbate this pattern. The authors concluded that the differences may 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 and occupants participated both before and after renovation.

With the increase of 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 [9, 25, 28]. In central and eastern Europe energy prices increased in the 1990s. As minimum ventilation recommendations continue to be rarely addressed in energy renovation programs, decreasing air exchange rates in renovated buildings will lead to increasing exposure of occupants to indoor generated air pollutants.

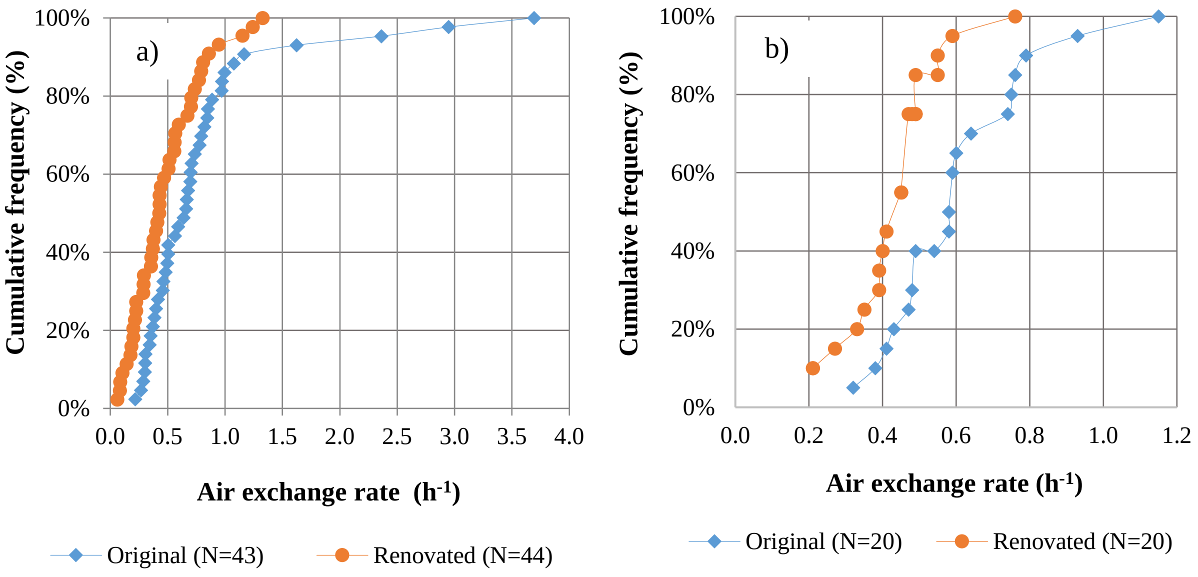

Fig. 4 Cumulative frequency distribution of the average air exchange rates in Experiment I (a) and Experiment II (b).

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 [43], both before and after renovation. The recommended limit value was exceeded in one apartment before renovation. Lower median NO_2 concentration was observed in the apartments before renovation (15.4 µg/m³) than after renovation (16.5 µg/m³) (Figure 5). The difference was not statistically significant (p>0.1). The observed concentrations were similar to those reported in northern Europe (see Table 7 in Langer and Bekö [28] for summary) and Lithuania [36]. Higher NO_2 concentrations were observed in Czech Republic (37.7 µg/m³) and Switzerland (23.8 µg/m³) [44].

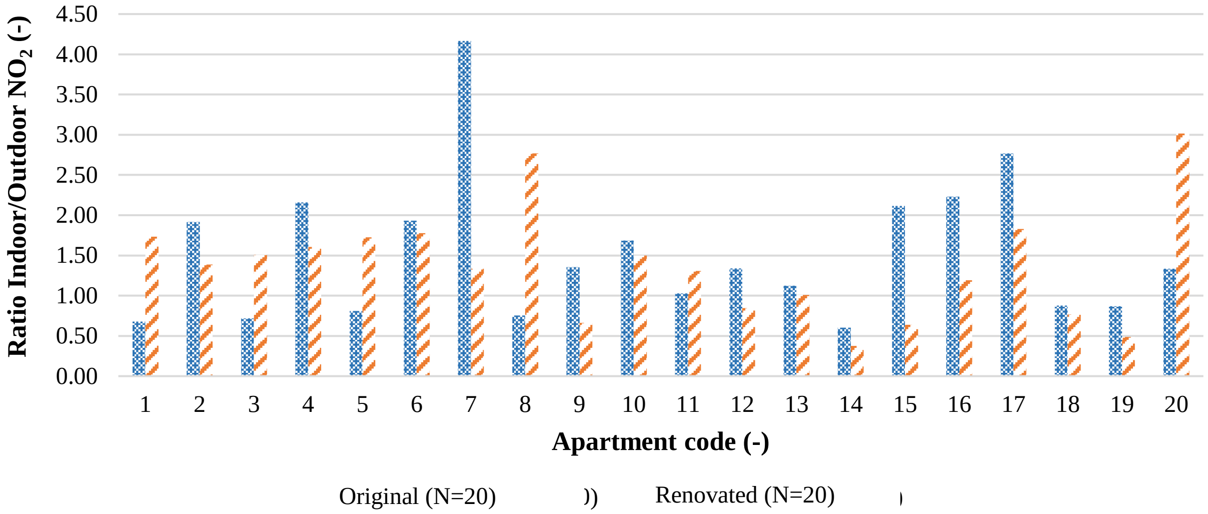

Fig. 5 Indoor/outdoor ratios of weekly average NO_2 concentrations in 20 apartments before and after renovation of the building

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. Only three out of 20 apartments had an I/O ratio below 1 both before and after renovation. The weak negative correlation between AER and NO_2 (Table 7) further supports the presence of indoor sources in the apartments. None of the apartments had a gas stove or gas burner. Candle burning and smoking may be responsible for the high I/O ratios. In order to better understand the impact of energy renovation on indoor NO_2 concentrations, continuous measurements, longer measurement period and better identification of the indoor sources of NO_2 are warranted.

The median TVOC concentration was higher after renovation (575 µg/m³) than before (500 µg/m³), but the difference was not significant. 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 (New Ref. 44 but needs renumbering). The TVOC concentration exceeded 1000 µg/m³ in one apartment before renovation and in five apartments after renovation. TVOC concentrations in this study were substantially higher than those reported in other studies (Langer and Bekö 2013 and references therein). An increase in the average TVOC concentration was observed in 11 apartments (55%) after renovation (between… and … % << after-to-before ratio - gb>>). TVOC concentration slightly decreased in the rest of the apartments. Three apartments experienced an 8-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 [Järnström et al. 2006; Brown et al., 2002] [50]. We cannot therefore conclude that the performed energy renovation was solely responsible for the increased TVOC concentrations.

Table 6

Concentrations of the most abundant individual VOCs ($\mu g/m^3$).

Compound	**Before Renovation (N=20)**				**After Renovation (N=20)**			
	N>LOD	Mean (Min-Max)	Geom. Mean	Median	N>LOD	Mean (Min-Max)	Geom. Mean	Median
Heptane	20	3.2 (0.9-9.1)	2.5	2.6	18	12.4 (0-137.8)	6.8	5.5
Limonene**	20	29.6 (4.6-90.7)	19.8	19.2	20	162.9 (10.9-810.3)	85.2	88.9
a-pinene	20	4.2 (0.4-14.1)	2.5	2.4	20	7.2 (1.0-51.4)	3.7	2.6
3-carene	15	1.8 (0-8.3)	3.8	0.9	19	5.2 (0-48.9)	2.6	1.7
Benzene*	20	3.9 (0.4-11.4)	3.1	3.1	19	2.0 (0-3.3)	2.1	2.0
Ethyl Benzene	20	3.9 (1.2-13.5)	3.2	3.1	20	6.4 (1.4-38.2)	4.4	4.5
Mp-Xylene	20	6.9 (1.9-24.9)	5.2	5.3	20	9.3 (2.5-48.2)	6.9	6.3
Toluene	20	16.2 (4.2-57.5)	12.1	11.1	20	14.6 (4.1-53.8)	11.9	11.6
Hexanal	18	7.5 (0-31.9)	5.6	4.5	20	10.0 (2.3-28.1)	8.5	8.6
Nonanal	19	6.7 (0-50.8)	6.4	6.1	20	4.7 (0.4-13.7)	3.7	3.9
1-Butanol	20	12.0 (3.3-24.8)	10.5	11.5	20	12.7 (2.7-25.4)	11.0	11.7
Isobutanol**	20	2.0 (0.4-7.4)	1.6	1.5	18	3.5 (0-11.1)	3.1	2.8
1-Pentanol	17	1.6 (0-5.5)	1.2	1.3	20	1.8 (0.7-6.7)	1.4	1.2
Hexanoic acid*	20	5.0 (1.4-15.7)	3.9	4.2	16	0.8 (0-2.3)	0.9	0.8

$^{*}p<0.001$, $^{**}p<0.05$,

In total 50 individual VOCs were identified. Table 6 summarizes the concentrations of the most abundant individual VOCs. Significant difference was observed between the two conditions of the building in concentrations of limonene, benzene, isobutanol and hexanoic acid. The average concentration of benzene, nonanal and hexanoic acid decreased after renovation. The concentrations of the other VOCs increased after the intervention. The presence of new sources and lower ventilation rates could cause increased concentrations of indoor generated VOCs. However, different occupant activities during the two 1-week measurement periods and different indoor chemistry (e.g. terpene-ozone reactions) may be responsible for the observed differences. The levels measured in this study are comparable to those obtained in Swedish apartments (28) and lower than reported for new buildings, as summarized by Derbez et al. (18).

The concentrations of formaldehyde were significantly higher after renovation than before ($p<0.05$). Formaldehyde levels were in all apartments below the 30-min average exposure limit of 100 mg/m^3 recommended by the World Health Organization [43] both before and after renovation. However, they were above the chronic reference exposure level of 9 µg/m^3, suggested by the California Office of Environmental Health Hazards Assessment (REF Nr.). Our median concentrations were comparable to those observed in other western European countries (Jurvelin et al., 2001; Raw et al., 2004; Gustafsson et al., 2005; Järnström et al., 2006; Marchand et al., 2008; Kolarik et al., 2012; Derbez et al., 2014 (18)) as well as Lithuania (36). The concentrations increased in 75% of the apartments after renovation, on average by 60%. In the rest of the apartments they decreased only by about 10%.

Table 7

Pearson correlation coefficients between the measured parameters.

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*	0.56*	-	-
AER	-0.19	-0.59*	-0.21	-0.87*	-0.16	-0.51*	-

$^*p<0.01$, $^{**}p<0.05$

The significant negative correlation between AER and formaldehyde concentration reflects the ability of ventilation to remove formaldehyde in indoor air, which originates primarily from indoor sources. Similar results were reported in a number of earlier studies (28; 50; 52; 53). Furthermore, significant positive correlation was found between relative humidity and both TVOC and formaldehyde, which is consistent with earlier findings [51], (52). 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.

Table 8

Linear regression of logarithmically transformed formaldehyde concentrations. $R^2 = 0.48$.

Parameter	Factor	95% Confidence Interval		P-value
AER	-0.32	-0.630	-0.004	0.04
Temperature	1.44	-0.140	3.027	0.07
Relative humidity	1.07	0.246	1.895	0.01
Constant	-5.21	-12.25	1.82	0.14

In the stepwise regression analyses AER, temperature and relative humidity were retained in the model as significant predictors of formaldehyde concentrations. These three variables explained 48% of the variation in the formaldehyde concentrations. 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 (52).

3.4 Airing habits and perceived air quality

According to the questionnaire survey, 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 for longer periods (~60% longer than 45 min.) compared to the occupants in the renovated dwellings (~30% longer than 45 min.). 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.

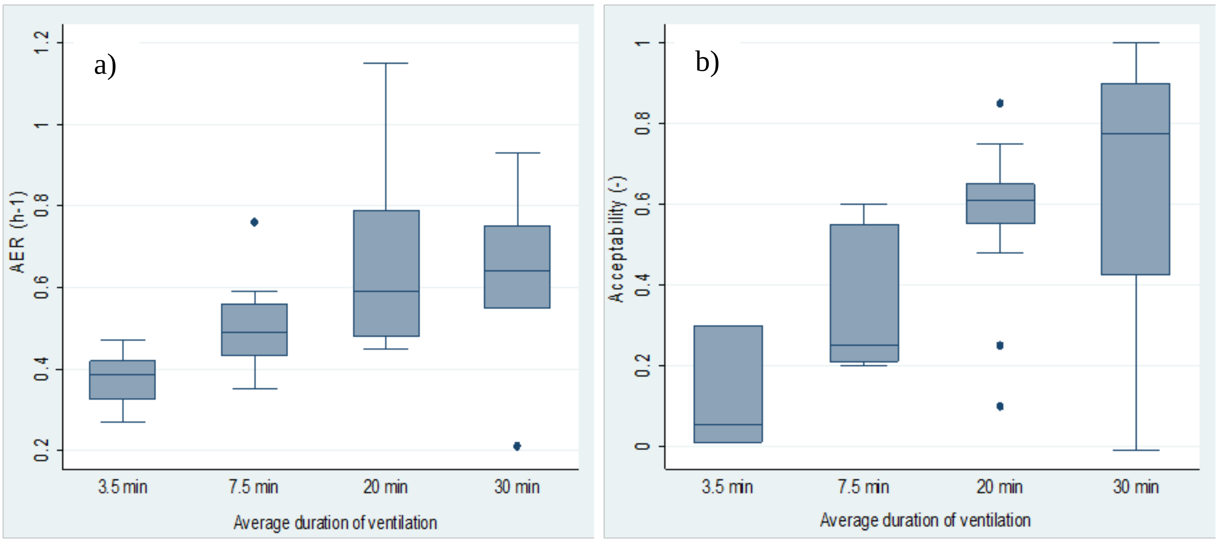

Fig. 6 Relationship between self-reported average duration of airing in bedrooms and air exchange rate (a) and occupants' acceptability of the indoor air quality (b). The figures are based on data from both before and after renovation in Experiment II (N=40).

The occupants found the indoor air quality in the bedroom and generally in the apartment more unpleasant in the renovated buildings. They indicated lower acceptability of the indoor air quality in these buildings ($p<0.01$). Jurelionis and Seduikyte [67] 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). Similar to our study, the refurbishment included envelope insulation and new windows; no changes were made to the ventilation.

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 ($r=-0.53$, $p<0.01$). Increased levels of VOCs caused by low ventilation rate may adversely affect perceived air quality. Wolkoff [66] 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 in Experiment II. Additionally, self-reported headache, itchy eyes, dry skin and fatigue were more prevalent after renovation than before. 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 (15; 69; Colton et al., 2014; Breysse et al., 2011). These studies can provide lessons to be learned on the simultaneous improvement of indoor environmental quality, when planning energy retrofitting of existing buildings. Protocols for selecting retrofits based on predicted energy use, indoor environmental quality changes, cost and initial apartment conditions have the potential to improve apartment performance and better capitalize on the benefits of building retrofits (Noris et al., Energy and Building 2013). The development of such protocols, which would reflect the 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 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 in 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 Europe are upgraded to more airtight and energy efficient ones, the retrofitting effort should include measures to improve ventilation in order to ensure acceptable and healthy indoor air quality. These recommendations should be reflected in national building renovation strategies and energy certification programs.

5. Acknowledgements

The study was supported by the Bjarne Saxhof Foundation, Denmark. We thank the participating families for their cooperation. The authors also thank Bárdos Gábor and Imre Sánka for their assistance with the measurements, Jakub Kolařík for technical advice and Dušan Ličina for his constructive comments on the manuscript.

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Appendix 5 – Journal paper: “Evaluation of indoor environment and energy consumption in dwellings before and after their refurbishment”

Földváry, V., Bukovianska, H., Petrás, D. 2016. Evaluation of indoor environment and energy consumption in dwellings before and after their refurbishment. REHVA European HVAC Journal. 53, 2, p.13-20.

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%).

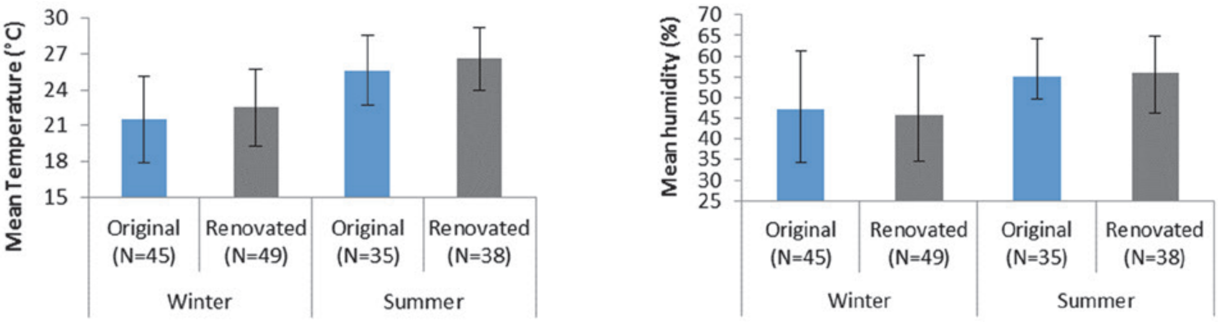

Figure 1. Average indoor temperature (left) and humidity (right) in the bedrooms of the investigated during the winter and summer season. Ends of the whiskers characterises the minimum and maximum values.

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].

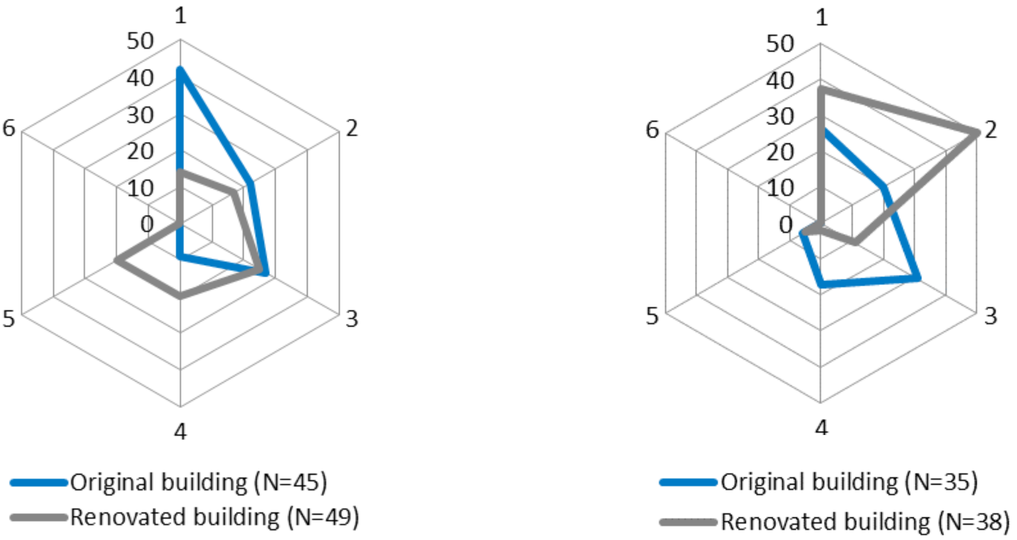

Figure 2. Summary of answers to the question "How unpleasant do you think the indoor air quality is in your bedroom during night/in the morning?". Answers were from 1 – perceived air quality was not a problem, to 6 – poor indoor air quality. One occupant in each apartment answered during winter (left)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

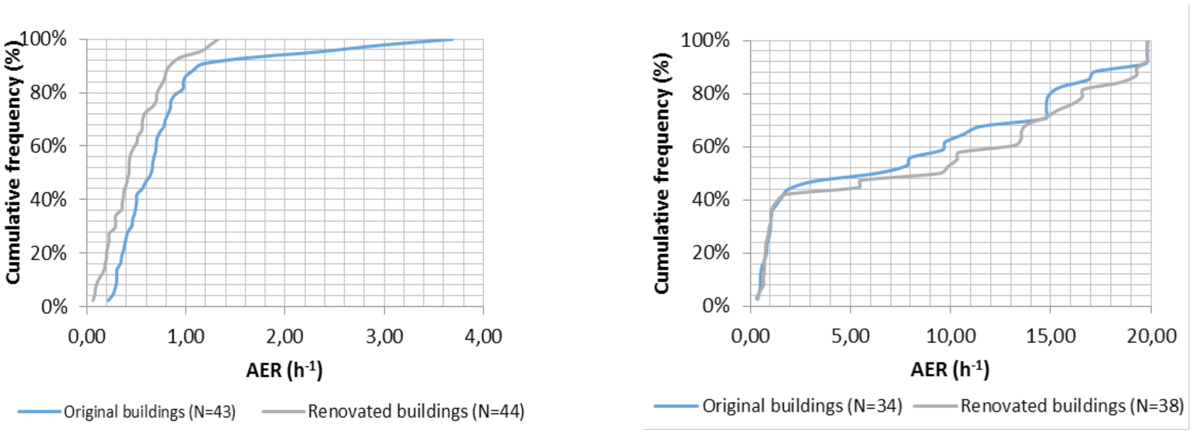

Figure 3. Cumulative percentage of air exchange rates in the original and the renovated buildings during winter (left) and summer (right).

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 (m^2)	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

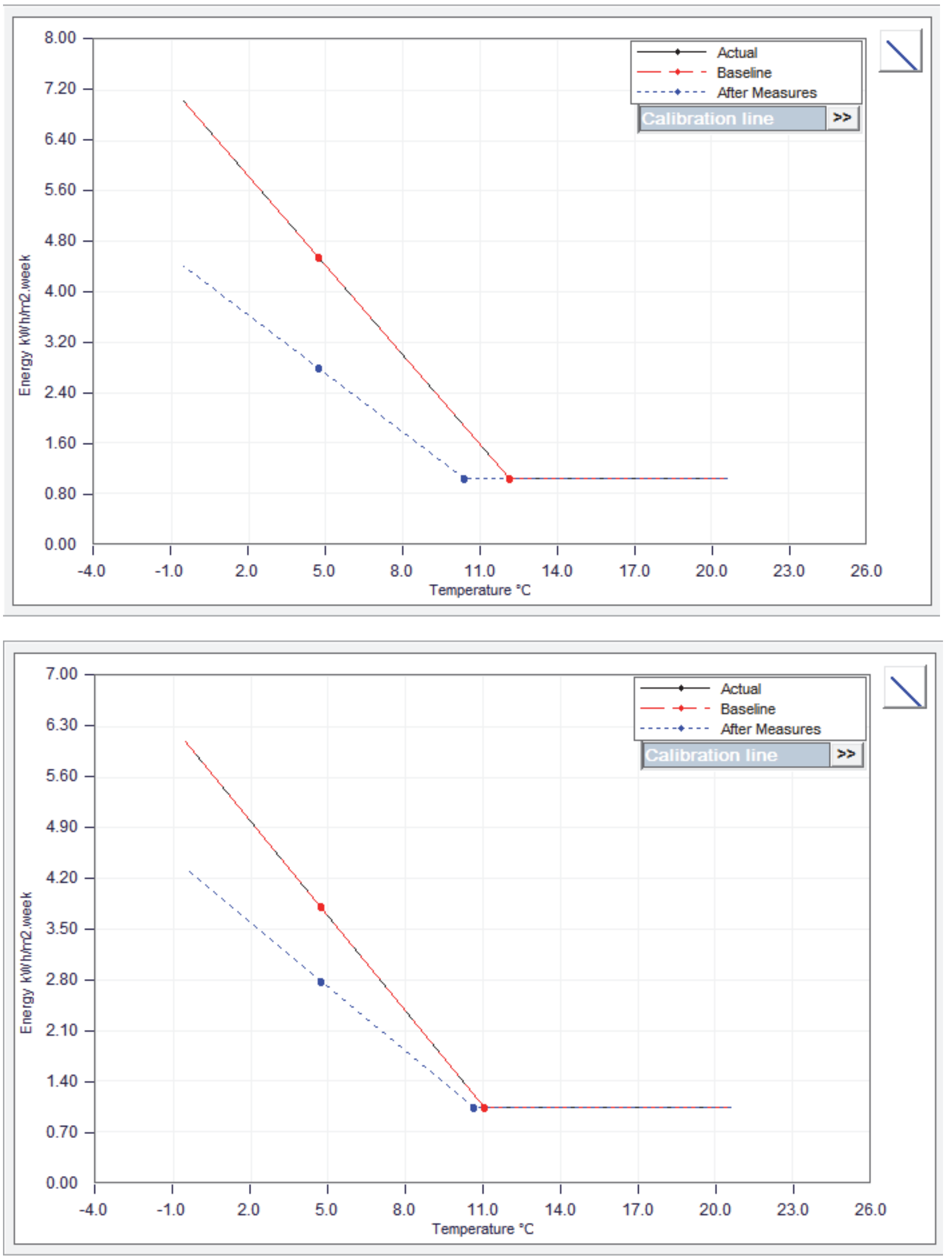

Figure 4. ET-curve for the the structural systems T06 BA (top) and P.1.14 (bottom).

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%

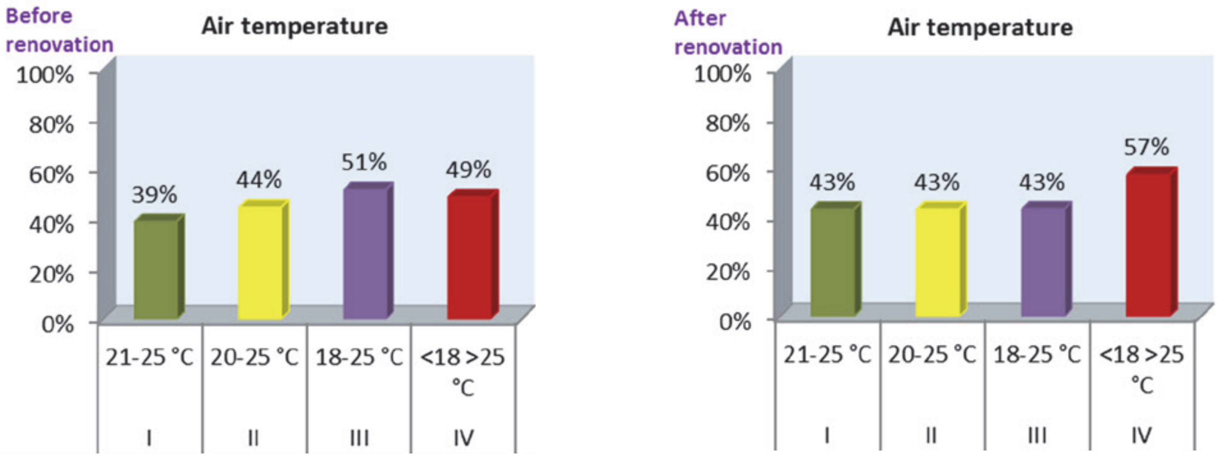

Figure 5. Classification of the air temperatures according to EN 15 251 in the original (left) and retrofitted (right) residential buildings.

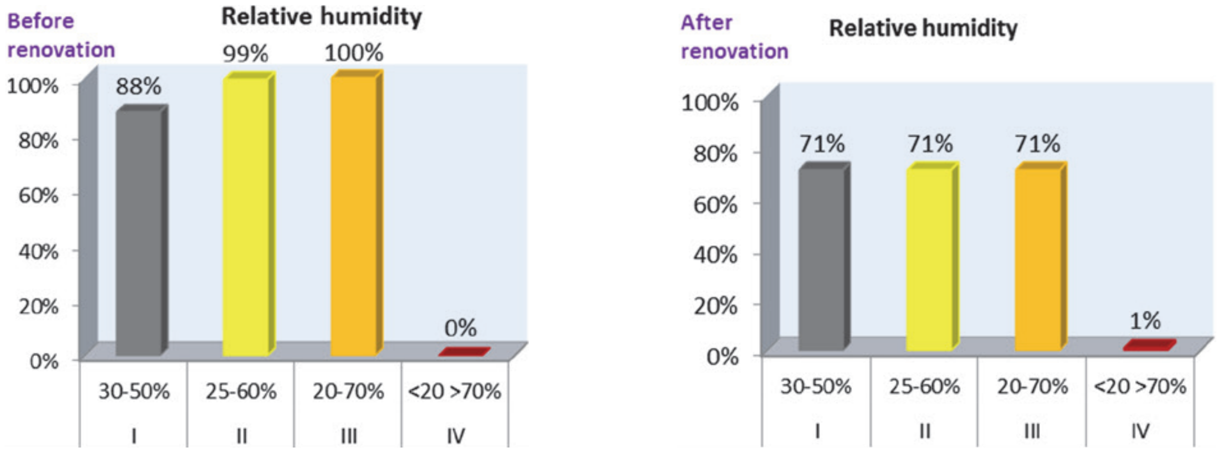

Figure 6. Classification of the relative humidity according to EN 15 251 in the original (left) and retrofitted (right) residential buildings.

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. ■

Acknowledgements

The authors want to thank Bjarne W. Olesen and Gabriel Bekö from the Technical University of Denmark for co-supervising of the projects.

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