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# Analýza vnútorného prostredia bytových domov pred a po komplexnej obnove

# Assessment of indoor environmental quality in residential buildings before and after renovation

**Ph.D. thesis**

**2016** **Ing. Veronika Földváry**

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Study programme: Theory and Environmental Technology of Buildings

Study field: 5.1.4. Building Construction

Training workplace: Department of Building Services

Supervisor: prof. Ing. Dušan Petráš, PhD.

Co-Supervisor: doc. Ing. Gabriel Bekö, PhD.

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**Slovenská technická univerzita v Bratislave** **Stavebná fakulta**
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# DECLARATION OF HONOUR

I declare that this thesis is my own work, and that all references to, or quotations from, the work of others are fully and correctly cited.

……………………………………………

Ing. Veronika Földváry

In Berkeley, USA, 28th May 2016

Author of the thesis

*“By recording your dreams and goals on paper,*
*you set in motion the process of becoming the person you most want to be.*
*Put your future in good hands — your own.”*

–Mark Victor Hansen-

*I would like to dedicate this work in memory of my beloved grandparents,*
*Terézia and Peter Pál Sárosfai and István Földváry,*
*who always inspired me to follow my dreams and be a good person.*

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# SUMMARY

The dissertation thesis investigates the impact of energy renovation on the indoor environmental quality of apartment buildings. Two case studies were carried out. The first field 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 second field study investigated one residential building before and after its renovation. Both objective measurements and subjective evaluation using questionnaire were used. Temperature, relative humidity and the concentration of $CO_2$, were measured in the bedrooms of the apartments in both studies. Moreover, in the second case study additional measurements of indoor air pollutants were carried out, such as nitrogen dioxide, formaldehyde and (total) volatile organic compounds. $CO_2$ concentration was significantly higher in the renovated dwellings that reflected lower air exchange rates in the apartments in winter. The higher $CO_2$ concentrations and lower air exchange indicated increase of formaldehyde concentrations in the apartments. Moreover, strong association was found between levels of formaldehyde and relative humidity. These observations were linked to insufficient airing out in the apartments and occupants´ lower satisfaction with perceived air quality after renovation. In a greater fraction of the apartments the occupants ventilated as frequently as before renovation and was inadequate to achieve better indoor air quality indoors. The 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. 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 indoor air quality in newly energy-renovated residential buildings.

# SÚHRN

Hlavným cieľom dizertačnej práce bola analýza vplyvu obnovy bytových domov na kvalitu vnútorného prostredia. Boli vykonané dve prípadové štúdiá. Prvá prípadová štúdia bola realizovaná v troch dvojiciach bytových domov. Dvojicu bytových domov tvorili domy postavené v rovnakej stavebnej sústave, stojace vedľa seba, s rovnakou orientáciou na svetové strany, pričom jeden z dvojice domov bol obnovený a druhý sa nachádzal v pôvodnom stave. V druhej štúdii bol vybraný jeden bytový dom, v ktorom sa uskutočnili experimentálne meranie pred a po jeho komplexnej rekonštrukcii. Analýza dát a hodnotenie výsledkov boli založené na objektívnych meraní a dotazníkovom prieskume. Vnútorná teplota, vlhkosť a koncentrácia oxidu uhličitého boli monitorované v oboch štúdiách. Okrem toho, v druhej prípadovej štúdii boli analyzované aj koncentrácie znečisťujúcich látok vyskytujúce sa vo vnútornom vzduchu, ako napr. koncentrácia oxidu dusičitého, prchavých organických látok a formaldehydu. Koncentrácia oxidu uhličitého bola vyššia v obnovených bytových domoch, čo viedlo k výraznému zníženiu intenzity výmeny vzduchu. Vyššie koncentrácie $CO_2$ a nižšie intenzity výmeny vzduchu mali za následok zvýšenie koncentrácie formaldehydu. Navyše, pozitívna korelácia bola nájdená pri hodnotení závislosti koncentrácie formaldehydu od relatívnej vlhkosti. Tieto výsledky boli značne ovplyvnené vetracími návykmi obyvateľov, čo prispelo aj k nižšej spokojnosti obyvateľov s pociťovanou kvalitou vzduchu v bytoch nachádzajúcich sa v obnovených domoch. Výsledky simulácií potvrdili, že ak nie sú prijaté opatrenie na zníženie koncentrácie $CO_2$ a zvýšeniu intenzity výmeny vzduchu , obnova bytových domov jednoznačne môže znížiť kvalitu vnútorného vzduchu. Inštalácia mechanických vetracích systémov alebo odsávania v kuchyni a hygienických miestnostiach môže výrazne prispieť k zlepšeniu kvality vzduchu v obnovených bytových domoch.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# NOMENCLATURE

## Abbreviations

| | |
|---|---|
| ACC | Acceptability |
| AER | Air exchange rate |
| AHU | Air handling unit |
| AM | Arithmetic mean |
| ANOVA | Analysis of variance |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| BPIE | Building Performance Institute Europe |
| CAV | Constant air volume |
| CI | Confidence interval |
| $CO_2$ | Carbon dioxide |
| CV (RMSE) | Coefficient of variation of root mean square error |
| DHW | Domestic hot water |
| DNPH | Dinitrophenylhydrazine |
| EU | European Union |
| GM | Geometric mean |
| HEALTHVENT | Health-Based Ventilation in Europe |
| HVAC | Heating, ventilation and air-conditioning |
| IAQ | Indoor air quality |
| IDA ICE | Indoor Climate and Energy Simulation Tool |
| IEQ | Indoor environmental quality |
| ISO | International Organization for Standardization |
| IVL | Swedish Environmental Research Institute |
| LOD | Limit of detection |
| N | Number of observations |
| NA | Not available |
| $NO_2$ | Nitrogen dioxide |
| NV | Natural ventilation |
| OR | Odd ratio |
| PAQ | Perceived air quality |
| PP | Polypropylene |

| | |
|---|---|
| PSP | Porous polyethylene |
| P-value | Determining value of probability in statistics |
| RH | Relative humidity |
| RMSE | Root mean square error |
| SBS | Sick building syndrome |
| SWEDAC | Swedish accreditation agency |
| T | Air temperature |
| TS | Thermal sensation |
| TVOC | Total volatile organic compound |
| U-value | Heat transfer coefficient |
| VAV | Variable air volume |
| VOC | Volatile organic compound |
| WHO | World Health Organization |

**Symbols**

| | | |
|---|---|---|
| $C_a$ | (ppm) | Outdoor concentration $CO_2$ |
| Ci(t) | (ppm) | $CO_2$ concentration (ppm(V)) at time t (h) |
| $C_O$ | (ppm) | $CO_2$ concentration in the beginning (at time t=0) |
| E | (l/h) | Estimated metabolic $CO_2$ generation rate per person in the zone |
| F | (m$^3$/s) | $CO_2$ emission rate |
| H | (m) | Height |
| ƛ | (h$^{-1}$) | Air change rate |
| M | (met) | Metabolic rate |
| n | | Number of examined hours |
| $\eta_{gn}$ | | Heat gain utilization factor |
| $Q_{em,Is}$ | (kWh) | Heat loss of the system via heat transfer |
| $Q_{gn}$ | (kWh) | Total heat gains during the heating season |
| $Q_H$ | (kWh) | Heat demand |
| $Q_{H,dis,Is,an}$ | (kWh) | Heat losses via distribution system |
| $Q_{HEAT}$ | (kWh) | Energy need for space heating |
| $Q_{ht}$ | (kWh) | Total energy losses during the heating season |
| $Q_{HW}$ | (kWh) | Energy need for DHW |
| $Q_W$ | (kWh) | Heat demand needed for DHW |

| | | |
|---|---|---|
| $Q_{W,d}$ | (kWh) | Heat losses via distributions system |
| r | | Correlation coefficient |
| $R^2$ | | Coefficient of determination |
| RQ | | Respiratory quotient |
| $t_i$ | (h) | Time |
| $V_R$ | ($m^3$) | Volume of the room |
| W | (kg) | Weight |
| $W_{H,dis, aux,am}$ | (kWh) | Annual actual energy consumption of circulation pumps |
| $W_{W,d,pump}$ | (kWh) | Energy needed for operation of circulating pumps |
| $X_{obs,i}$ | | Observed value in each particular hour of the calibration period |
| $\overline{X_{obs}}$ | | Average of the observed values in the whole calibration period |
| $X_{pred,i}$ | | Predicted value in each particular hour of the calibration period |

# 1. INTRODUCTION

The building sector is responsible for one third global energy consumption. The need to reduce energy consumption and greenhouse gas emissions became a national priority across the European Union member countries (1; 2; 3; 4). A large proportion of the European population resides in multi-family buildings (1). 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, with the highest intensity in housing construction reported over the period 1971 – 1980 (1). A significant fraction of these buildings (~70%) does not fulfil the current European requirements on energy efficiency (5). In order to fulfil the reduction criteria of energy consumption and promote environmental sustainability set out by the Energy Performance of Buildings Directive, building retrofit campaigns for existing multi-family buildings have been implemented (6; 7). However, the effect of these programs was not systematically assessed. Especially the assessment of effects of energy improvements of buildings on indoor air quality and occupants´ well-being is often neglected. Consequently, Slovakia, just as several other eastern and central European 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 reduce the energy consumption and may improve thermal comfort by decreasing drafts and reducing thermal radiation from cold walls and windows (3). However, tightening the building envelope without compensating measures, unfortunately a widespread practice, often results in reduced intake of outdoor air (infiltration rate) and may increase the concentration of indoor-generated air pollutants (8).

People spend about 80% of their time at home (9). Occupant exposure occurring in the residential environment can be substantial. Low ventilation rates, which can be caused by improved airtightness, and the resulting exposures have been associated with numerous long-term and acute health effects such as respiratory diseases, cancer, allergies, sensory irritations and sick building syndrome symptoms (10; 11; 12). Therefore, there is an urgent 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 present study was designed to shed new light on the aforementioned connections between residential multifamily building renovation, energy performance, indoor environmental quality and occupant health and comfort.

# 2. STATE OF THE ART

## 2.1 Current state of the residential stock

From the emotional to the architectural value, buildings occupy a key place in our lives and society as a whole. Their construction, design, operation and purpose of use not only influence productivity and well-being of people and their interactions with others, they also significantly contribute to energy-related sustainability challenges. The building characteristics also define how much energy is consumed by buildings as well as how much energy demand is needed for operation of systems of building services (heating, domestic hot water preparation, ventilation and cooling) to create a pleasant environment (1; 13).

### 2.1.1 European residential stock

The Building Performance Institute Europe (BPIE) recently screened all EU28 countries together with Switzerland and Norway with the aim of collecting existing data related to buildings and building policies. The exercise was undertaken using a team of experts in each Member State. The data collected were mainly extracted from official statistics and studies at Member State level supported by expert estimations (1).

#### 2.1.1.1 Building typology

Within the residential sector, different types of single family houses (e.g. detached, semi-detached and terraced houses) and apartment blocks are found. Apartment blocks may accommodate several households typically ranging from 2-15 units or in some cases holding more than 20-30 units (e.g. social housing units or high rise residential buildings). Analysis of data gathered by BPIE (1) indicates that, across the European Union member countries, 64% of the residential building floor area is associated with single family houses and 36% with apartments **(Figure 2.1)**.

According to national statistics (1; 2) Sweden, Finland, France, Austria and Czech Republic have approximately the same share of apartment blocks and single family houses **(Figure 2.2)**, both around 50% is the whole residential stock. United Kingdom and the Netherlands have a large number of single family houses, up to 80% in United Kingdom and 70% in the Netherlands. The percentage of family houses is the lowest in Germany and Switzerland (below 30%).

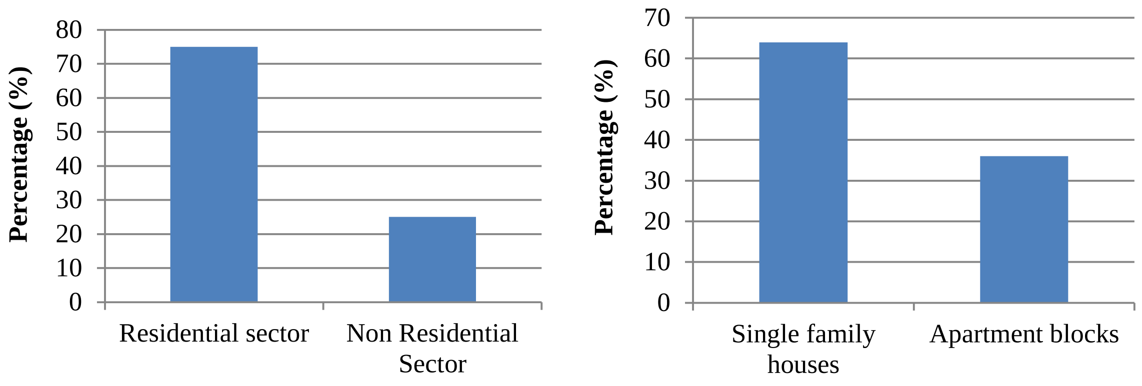


Figure 2.1 Floor space distribution by building type for all buildings (left) and for residential buildings (right) (1)

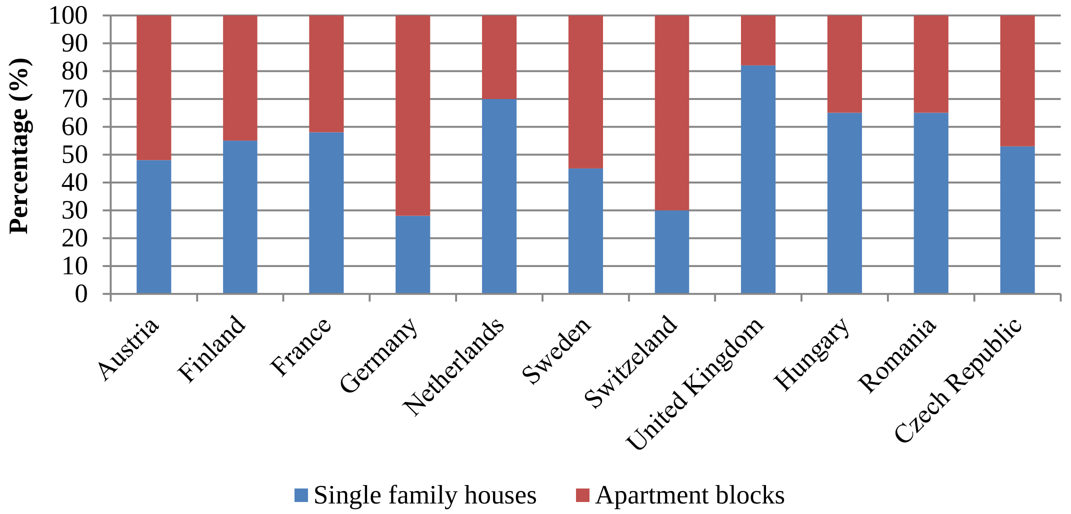


Figure 2.2 The breakdown of residential stock into single family houses and apartment blocks by selected European (1; 2)

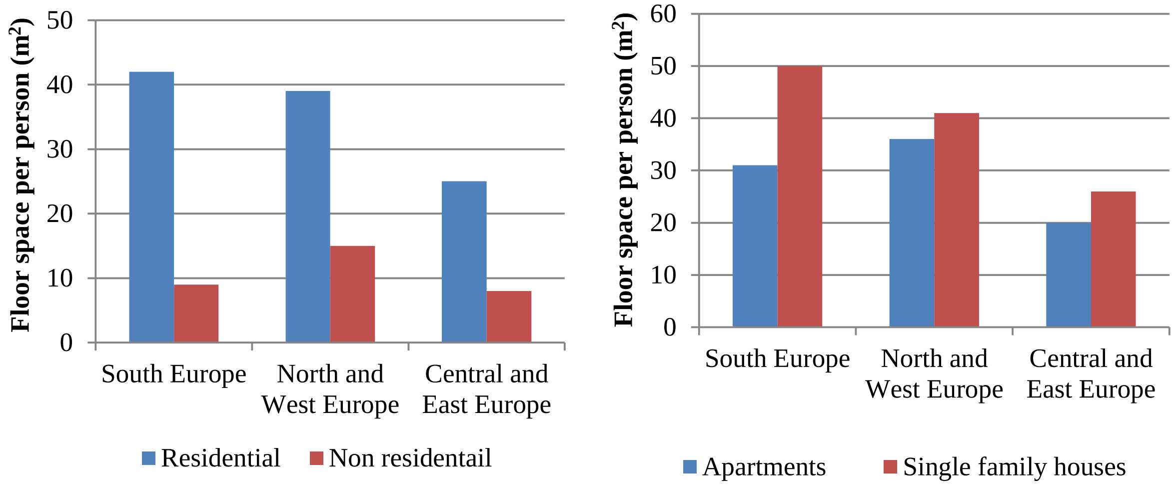


Figure 2.3 Floor space per person by building type for all buildings (left) and residential buildings sector (right) in regions of Europe (1)

According to the survey by BPIE (1), countries in the North and West region have higher total floor area per person than in the South and Central and East regions **(Figure 2.3)**. Upon closer examination, the countries of Central and Eastern Europe tend to have lower space standards in terms of dwellings with a floor space of around 25 $m^2$/person in comparison to the Northern and Southern European countries, which have space standards typically of around 40$m^2$/person. The different approaches taken for defining and measuring floor area within this sector also have an impact on these numbers. It is interesting to note that in all regions, the floor space standards in apartments are lower than in single family houses.

#### 2.1.1.2 Age profile of the residential stocks and ownership of apartments

Buildings across Europe are associated with different time periods dating even before the 1900s. Historical buildings certainly have a significant heritage value while construction techniques and building regulations such as building codes imposed at the design phase have a great influence on the energy performance of a building built in a specific period.

The age of the dwelling stock relates to its physical characteristics, including thermal performance. In fact, a substantial share of the residential stock in Europe is older than 50 years. Existing dwellings are representing the vast majority of the building stock exceeding the number of newly built dwellings with high performance levels in most of the European countries.

The BPIE survey (1) has classified buildings in different age bands (specific chronological periods) for each country. In order to allow some comparison between the age profiles of the residential building stock of different countries, data for each country were consolidated into three representative age bands:

- Old (typically representing buildings up to 1960)
- Modern (typically representing buildings from 1961 to 1990)
- Recent (typically representing buildings from 1991 to 2010).

More than 40% of European dwellings have been constructed before the 1960s when energy building regulations were very limited. A large boom in building construction was in 1961-1990 when the housing stock, with a few exceptions, more than doubles in this period **(Figure 2.4)**. The existing building stock will continue to dominate for the next 50 or more years. The lack of sufficient insulation of the building envelope in older buildings was also reflected through the historic U-value data which comes with no surprise as insulation standards in those construction years were limited. Due to poor maintenance and high energy consumption the energy performance of these buildings is in poor condition (1; 14; 15). With their potential to deliver high energy and $CO_2$ savings as well as many societal benefits, energy efficient buildings can have a pivotal role in a sustainable future (1; 16; 17; 18; 18; 19).

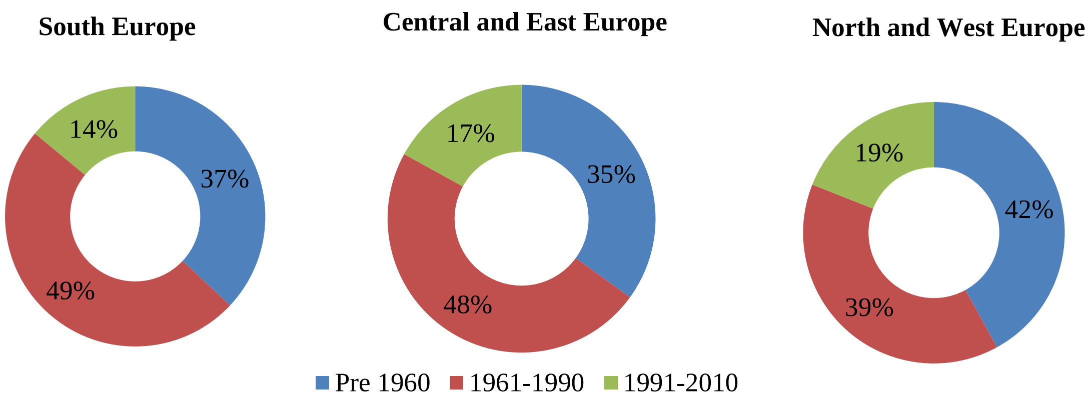


Figure 2.4Age categorisation of housing stock in Europe (1)

Significant country-by-country variations are also evident. The countries with the most recently constructed buildings (1990-2010) appear to be Austria and Finland, while countries with the highest rate of construction in the “modern” period (1961-1990) seem to be Germany, Hungary and Romania **(Figure 2.4)**.

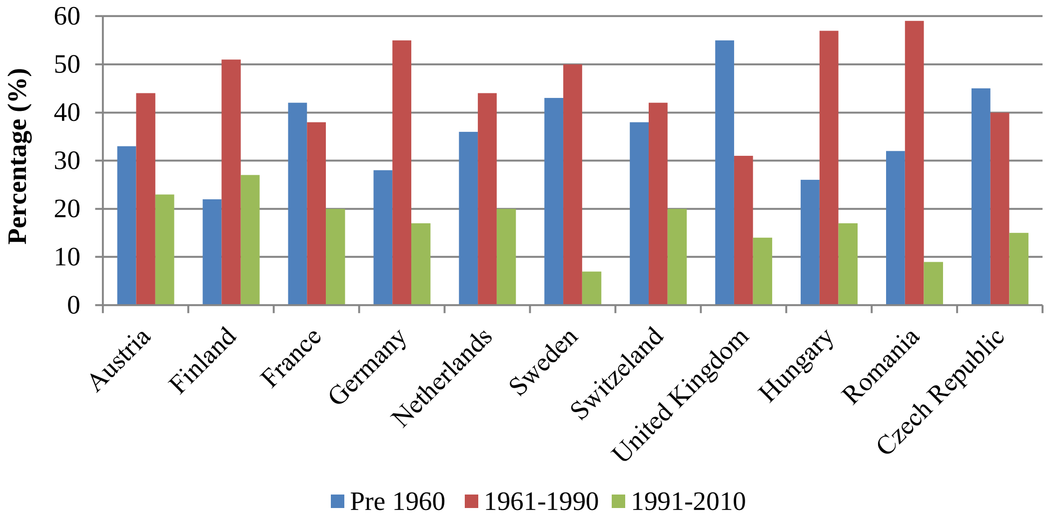


Figure 2.5 Age profile of the European residential stock (1)

BPIE survey and study by Meijer et al (1; 2) show that the largest share of the residential stock is held in private ownership, with the highest percentages in Romania (95%) and Hungary (87%). Countries with the biggest share of private tenants (someone who is renting home from a private landlord or housing association) are Switzerland, Sweden, Germany and Czech Republic and countries with significant portions of public rented (owned by government) dwellings are Austria, United Kingdom, and the Netherlands **(Figure 2.6)**.

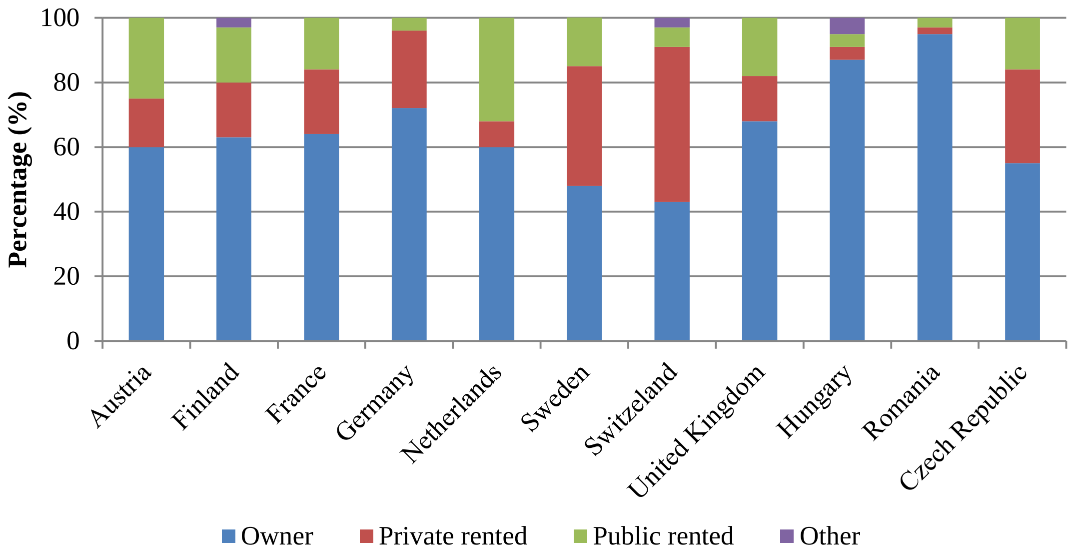


Figure 2.6 Tenure of residential buildings in Europe (1; 2)

#### 2.1.1.3 Energy performance

Buildings contribute to a large proportion of total energy use worldwide. The significance of the residential building sector in terms of energy consumption is well acknowledged (1; 2; 20; 21; 22; 23; 24). They comprise the biggest segment of the European building stock and are responsible for the majority of the sector's energy consumption. The European building sector is responsible for 40% of the overall energy consumption in Europe. According to data exacted from Eurostat (25), in 2010 European households were responsible for 68% of the total final energy use in buildings. Energy in households is mainly consumed by heating, cooling, hot water and appliances where the dominant energy use in homes is space heating.

The space heating is mainly determined by a heat transmission losses (proportional to the insulation degree), by ventilation and air infiltration losses (determined by the ventilation system, building fabric and build quality), and by the efficiency of the heating system (26). The strong correlation between heating degree days and fuel consumption emphasises the link between climatic conditions and use for heating as the year-to-year fluctuations in heating consumption largely depend on the climate of a particular year. The significant increase in use of appliances in households is also evident through the steady increase in electricity consumption (38% over the last 20 years) **(Figure 2.7)**; (2).

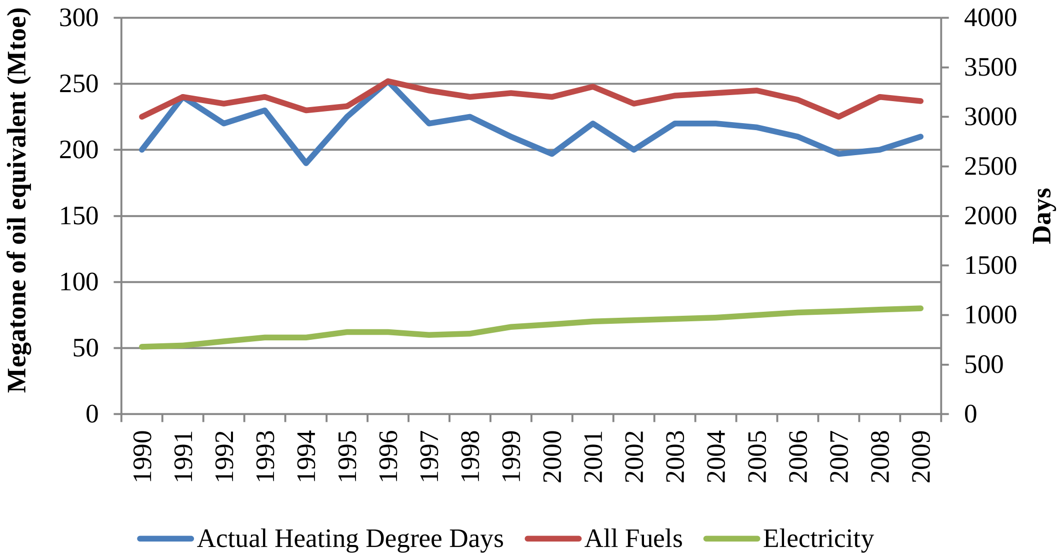


Figure 2.7 Historical final energy use in the residential sector in European Union (1)

The performance of households depends on a number of factors such as the performance of the installed heating system and building envelope, climatic conditions, behavioural characteristics (e.g. typical indoor temperatures) and social conditions (e.g. fuel poverty meaning that not all buildings are used at maximum capacity). Despite different improvements in, for instance, heating systems, there is still a large saving potential associated with residential buildings that has not been exploited. These technologies are easily implemented in new buildings, but the challenge is mostly linked to our existing stock which forms the vast majority of our buildings (1; 2). The European Union has enacted several actions dealing directly and indirectly with energy efficiency of existing buildings aiming to reduce the building energy. Retrofitting of existing residential buildings has been claimed as one crucial way to reduce energy consumption and greenhouse gas emissions. The theme is described in more details in sub-chapter 2.3.

### 2.1.1.4 $CO_2$ emissions

The levels of energy consumed in buildings place the sector among the most significant $CO_2$ emissions sources in Europe, depending on factors including urban morphology, architectural typology, buildings' performance and in particular the envelope performance, efficiency of the equipment and systems, and the inhabitants´ behaviour. The effect of these factors on energy and environmental performance of particular building stock might be various, from least efficient up to most efficient influences as shown in paper by Salat et al (14) . Awareness of the $CO_2$ reduction potential of the existing buildings is widespread among stakeholders. The European Union, national governments and housing associations including the building owners as well, have vested interests in trying to achieve a more sustainable existing building stock (27; 28).

In terms of $CO_2$ emissions, buildings are responsible for around 36% in Europe (1). The average specific $CO_2$ emission in Europe is 54 $kgCO_2/m^2$ where the national values of $kgCO_2$ per floor space vary in the range from 15-105 $kgCO_2/m^2$ as shown in **Figure 2.8**. The building performance is a key component in influencing of the level of $CO_2$ emission. In addition, $CO_2$ emissions are linked to the particular energy mix used in buildings in a given country. For example, the extent to which renewable energy is employed in the buildings, the use of district heating and co-generation, the sources of electricity production in each country affect the $CO_2$ emissions related to buildings. Variations in the energy supply mix highly influence the $CO_2$ performance of buildings where, for instance, Sweden and France are among the lowest in Europe due to their dependence on hydroelectricity and nuclear energy, respectively.

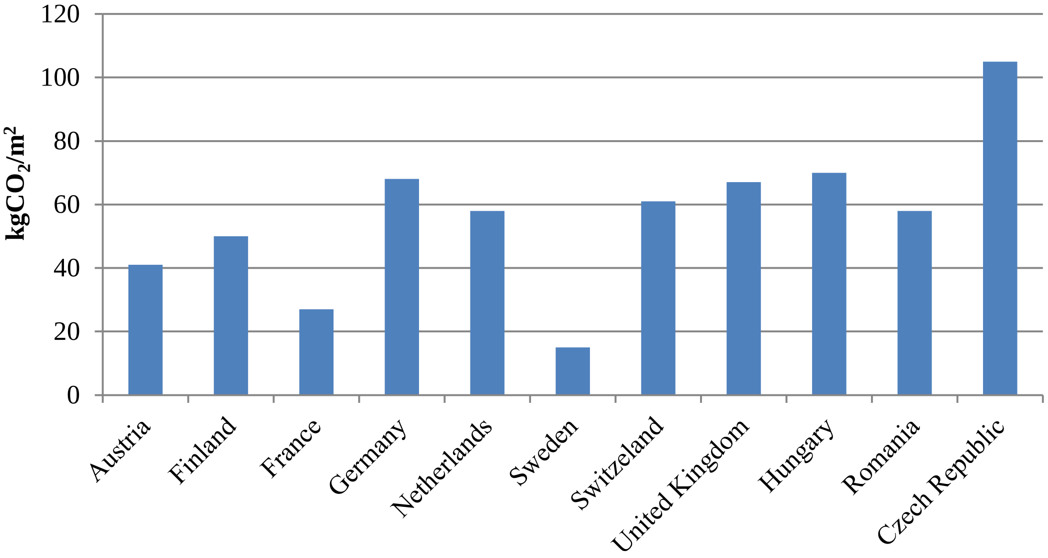


Figure 2.8 $CO_2$ emissions per useful floor area (1)

### 2.1.1.5 Ventilation system

Data gathered for the HEALTHVENT project (29) provides distribution of types of the ventilation systems used in European Union member countries. The distribution of ventilation systems in residential buildings clearly shows that natural ventilation and fan assisted natural ventilation account for more than 50% of total existing systems, except in Finland and the Netherlands, where mechanical ventilation is more dominant. It is interesting to observe that Austria and United Kingdom have natural ventilation in more than 85% of their apartments **(Figure 2.9)**.

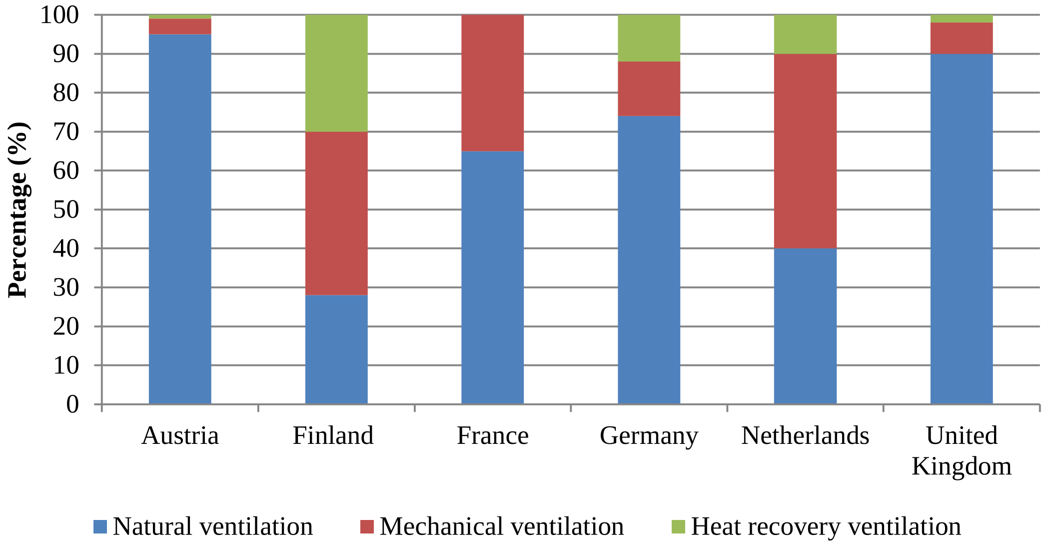


Figure 2.9 Summary of ventilation systems used in European residential stock (29)

### 2.1.2 Slovak residential stock

Slovakia well represents the Central European building stock as well as a large fraction of the residential buildings in Western and Northern Europe. According to statistical surveys (1; 25), Slovakia is represented by 341,000,000 m² of building floor area, out of which 89% (303,490,000 $m^2$) belong to residential buildings. The data indicates that across Slovakia 24% of the residential floor area is associated with apartment buildings and 65% with single family houses. The building stock is distributed across different building types as it is shown in **Figure 2.10**. It was also reported that 89% of existing apartments are held in private ownership out of which 75% is occupied by owner and 13% is private or public rented. 8% of the Slovak apartments have public owners and the status of the rest of the apartments (3%) has not been defined.

As in almost across all European countries, most of the apartment blocks and single family houses in Slovakia were built from 1945 to 1992, with the highest intensity in housing construction reported over the period 1961 –1980 **(Figure 2.11)**, (1; 30). This historical period of the Slovak architecture was characterised by various construction and structural systems, with a particular inclination to prefabricated concrete technology (large-panel system buildings). After 1992 atypical buildings started to be designed on an individual basis. The Ministry of Transport, Construction and Regional Development of Slovak republic classified the apartment buildings into five groups of construction systems which were influenced by requirements of building structures properties of various construction periods **(Table 2.1)**, (29; 30).

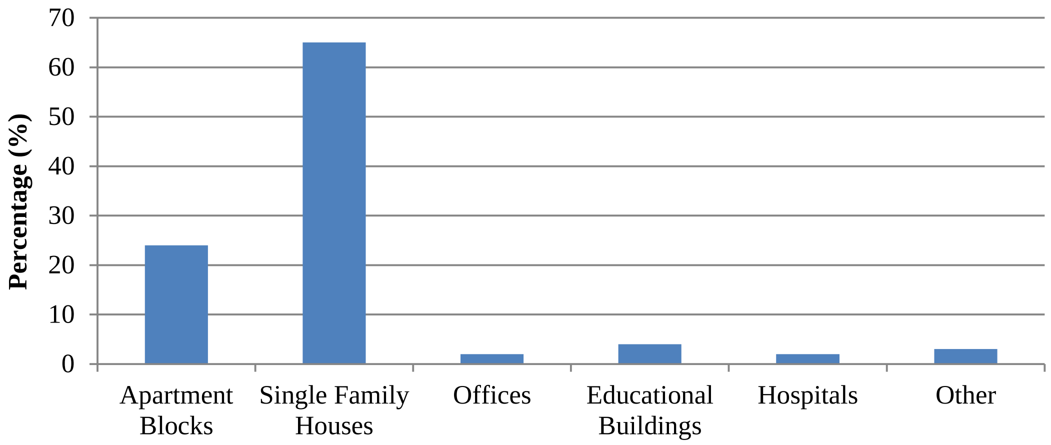


Figure 2.10 Percentage distribution of the Slovak building stock (1)

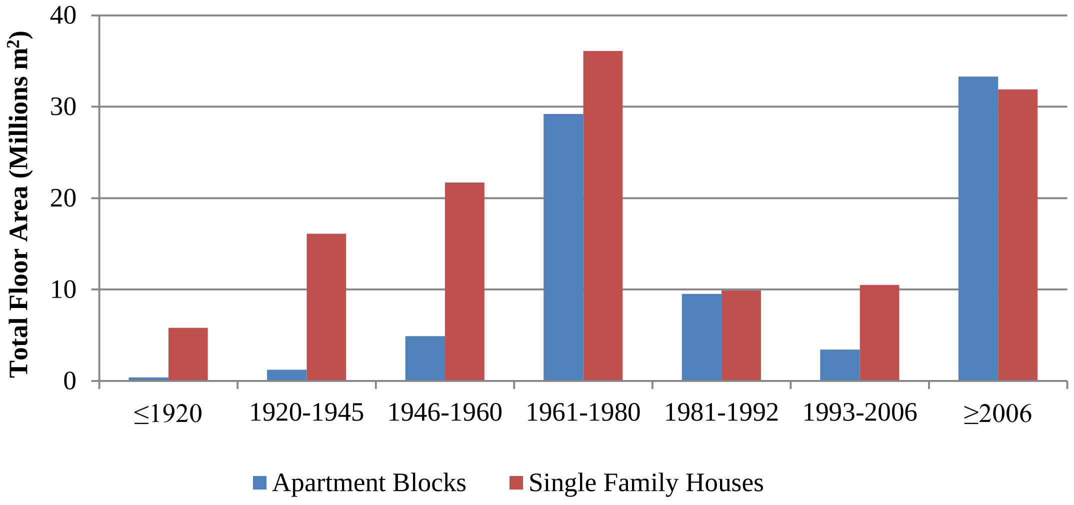


Figure 2.11 Breakdown of the building stock by age bands (1)

Table 2.1 Number and total floor area of apartment buildings characterised by type of construction systems (29; 30)

| **Type of construction system** | **Number of buildings** | **Total floor area ($m^2$)** |
|---|---|---|
| Brick and pre-assembled masonry panels | 6 761 | 10 733 966 |
| Single-layer large-panel system, built between 1955-1983 | 7 983 | 29 807 256 |
| Multi-layer large panel system, built between 1971-1983 | 2 131 | 8 234 737 |
| Large-panel system, built between 1983-1988 | 3 646 | 16 159 811 |
| Atypical buildings (unusual building shape) from 1992 | 65 | 58 776 |
| Other (Unspecified) | 1 137 | 427 121 |
| **Total** | **21 723** | **65 421 666** |

Changes in U-values (heat transfer coefficient) of pre-existing apartment buildings in Slovakia by different construction periods were also specified by BPIE (1). Substantially lower U-values were reported in buildings constructed after 2011 compared to apartment buildings built in the 20th century **(Figure 2.12)**. The differences between the highest (1946-1960) and lowest U-values (≥2011) were significant for all constructions. Although the U-value of the external walls and floor have shown improvement after 2011, the majority of them still does not meet the strictest criteria defined by the national standard (31).

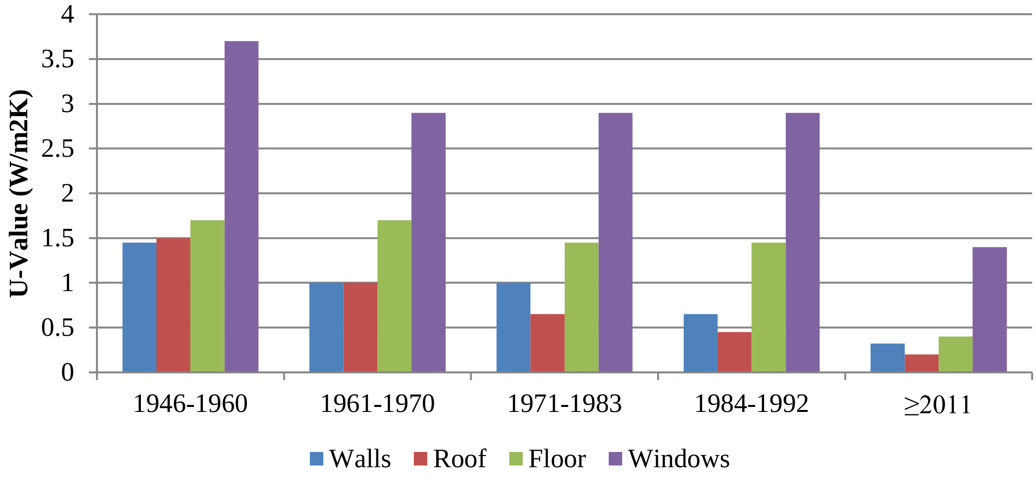


Figure 2.12 U-values of pre-existing apartment buildings in Slovakia (1)

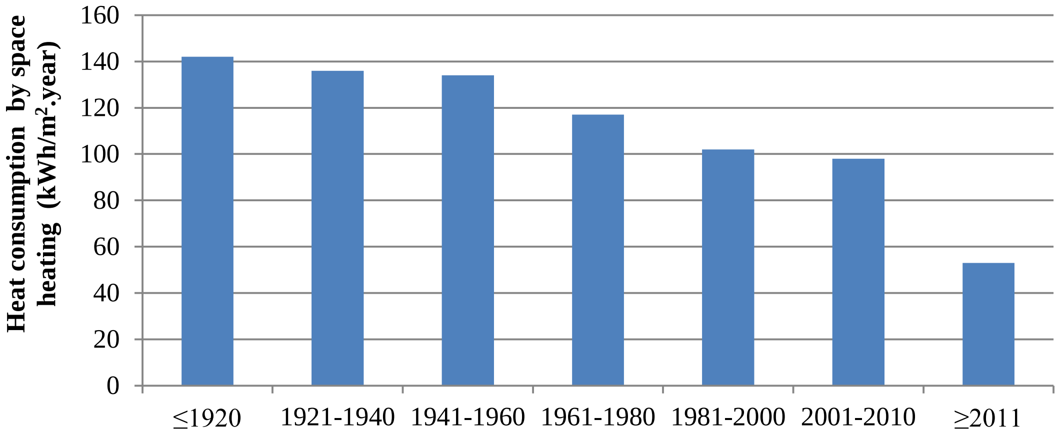


Figure 2.13 Consumption levels of space heating in Slovak residential sector by age of apartment buildings (1; 25)

According to BPIE and Eurostat inspections (1; 25) the heat consumption level of apartment buildings ranges between 53 and 142 kWh/m$^2$year depending on age bands of the residential buildings **(Figure 2.13)**. Apartment buildings built before 1980 were responsible for the highest heat consumption by space heating, especially in buildings built before 1920, with average heat consumption 142 kWh/m$^2$year. Obvious decrease in level of heat consumption started after 1981, largely influenced by climate condition changes and new trends used in building constructions and architecture improving energy efficiency conditions of buildings (30).

Majority of residential stock is connected to district heating systems. Natural gas is the most common fuel by 70% **(Figure 2.14)**. The use of coil is represented by 10% mostly used in regions of Northern Slovakia. The usage of renewable energy sources represents very low percentage from the total percentage of energy products, in total 1.5%. 16.5% of the used sources were not specified exactly (1). According to statistic surveys (1; 25) the $CO_2$ emissions by the residential building sector in Slovakia was fifteenth among the 28 European Union countries with almost 70 $kgCO_2$ emissions per $m^2$ useful floor area. This is higher than that of countries such as United Kingdom, Germany, Belgium, Hungary and Czech Republic.

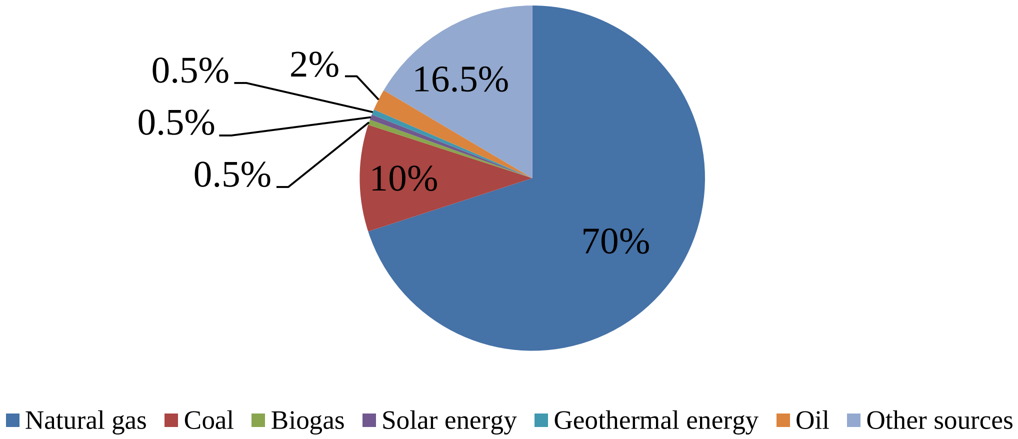


Figure 2.14 Percentage distribution of energy sources used for heating in Slovak apartment buildings (1)

## 2.2 Indoor air quality parameters

The major purpose of buildings is to provide a healthy and comfortable environment for occupants. In most parts of the world humans spend up to 80% of their lifetime indoors. More than half of the time spent indoors takes place in homes (9). It is therefore important to identify the parameters that influence indoor air quality and thus the comfort and health of inhabitants in their homes. Additionally, occupant behaviour may substantially influence the indoor environment.

### 2.2.1 Indoor air quality in residences

Many earlier studies investigated indoor air quality in different types of residences. Temperature, humidity, the concentrations of $CO_2$, $NO_2$ (nitrogen dioxide), formaldehyde and TVOC (total volatile organic compounds) as well as air exchange rates, were investigated in 157 single-family houses and 148 apartments in Sweden (32). The results of the physical measurements reported a relationship between concentrations of selected compounds and age, type and location of building and ventilation system. The air exchange rate, concentration of formaldehyde and TVOC were higher in the naturally ventilated dwellings than in buildings equipped with mechanical ventilation system. Investigation of indoor environment was carried out by questionnaire surveying in 550 residents located in Dalian, China (33). Measurements of formaldehyde and $CO_2$ concentrations were also performed. Visible correlation was found between formaldehyde concentrations and duration and frequency of ventilation. With increasing of indoor $CO_2$ concentrations occupants reported breathing difficulties, headache and stuffy air. In a study by Kotol et al (34) also $CO_2$ concentration was used as an indicator of indoor air quality in 79 Greenlandic dwellings built before 1970, between 1970 and 1990 and after 1990. Moreover, indoor temperature and humidity were recorded in bedrooms. Higher $CO_2$ concentrations and moisture were found in newer residential buildings than in dwellings built before 1990. The $CO_2$ concentration depends on lot of factors, i.e. number of occupants, the duration of ventilation, ventilation rate and room volume. The typical indoor air concentrations of $CO_2$ are between 500 and 1500 ppm (11; 35). $CO_2$ in those concentrations is not generally thought to be harmful. It is an indicator of concentrations of other pollutants in the air and of the ventilation rates per occupant. A laboratory study by Kajtár et al (36) and Satish et al (37) suggests that human well-being and capacity to concentrate attention are reduced when $CO_2$ concentration in the air increases up to 3000 ppm.

### 2.2.2 Effect of indoor air quality on health and sick building syndrome symptoms

Home environments can be important determinants of resident health. Because of the effects on health, indoor air quality is widely recognized as an important public health issue. The indoor air may be polluted by broad range of components originating from both indoor and outdoor sources (38). In multifamily housing, building characteristics can be shaped by construction and renovation practices, as well as by the actions of both professional staff involved in building operation and maintenance and building residents. In the home, determinants of environmental exposures include pollutant sources, product usage and resident activity patterns, presence and performance of ventilation systems, design and maintenance of building systems, and pest infestation levels (39).

#### 2.2.2.1 Importance of ventilation in residences and its effect on human health

Ventilation is necessary to remove indoor generated pollutants from indoor air or dilute their concentration to acceptable levels. Ventilation may have harmful effects on indoor air quality and climate if not properly designed, installed, maintained and operated as summarised by Seppänen et al (40; 11). It may bring harmful substances or deteriorate indoor environment. Ventilation interacts also with the building envelope and may deteriorate the structures of the building. Ventilation changes the pressure differences across the structures of building and may cause or prevent infiltration of pollutants from structures or adjacent spaces. Moreover, some conclusions on performance of ventilation in respect of human responses were defined. It was found that ventilation rate below 10 L/s per person are associated with a significantly worse prevalence of one or more health or perceived air quality outcomes. Low ventilation may lead to high indoor humidity and moisture accumulation in building structures or materials. That may lead to increased dust mites, and particularly high humidity can increase the risk of microbial growth, and subsequently to microbial contamination and other emissions in buildings. In epidemiological studies, moisture damage in building was associated with a number of health effects including respiratory symptoms and diseases (41).

The review by Dimitroulopoulou (42) showed that ventilation is increasingly becoming recognised as an important component of a healthy dwelling. Ventilation requirements receive major attention in building regulations, across Europe. However, ventilation measurements across Europe show that ventilation is often poor, resulting in reduced ventilation rates (lower than 0.5 $h^{-1}$, which is currently a standard in many European countries), increased concentrations of indoor pollutants and hence exposure to health risk. Studies in the Nordic countries (43; 44; 45) showed that at ventilation rates greater than 0.5 $h^{-1}$, there is no direct association between air change rates and asthma or allergy among children. However, at ventilation rates lower than 0.5 $h^{-1}$, allergic symptoms were reported as well as rhinitis and bronchial obstruction (8; 45). No association was found between ventilation rates and doctor-diagnosed asthma. Moreover, the findings in the review indicated that low ventilation can be considered as a risk factor for irritation. The ventilation measurements in the Nordic countries showed that a large percentage of the monitored dwellings did not fulfil the minimum requirement of 0.5 $h^{-1}$ (up to 60% in Denmark, about 50% in Finland, 30%–40% in Norway). In Sweden, different samples of dwellings showed contrary results, although the large national study reported 55% of multiple and 85% of single dwellings having ventilation rates lower than 0.5 $h^{-1}$. The Norwegian dwellings seem to be better ventilated than the other Scandinavian ones. Ventilation rates greater than 0.5 $h^{-1}$ were reported in the Netherlands as well as in Greece and Portugal, which had rates greater than 0.5 $h^{-1}$, and up to 1.5 $h^{-1}$ in Greece and 1.2 $h^{-1}$ in Portugal. Higher ventilation rates were measured in the mechanically ventilated dwellings compared to the naturally ventilated dwellings in a number of countries such in Netherlands, Portugal, Sweden. Surveys showed that although occupants generally think that ventilation is important, their understanding of the ventilation systems in their own houses is low, resulting to under-ventilated homes.

Under-ventilated homes may result in increase of pollutants indoors. Material emissions were recognised to have an influence on the total pollution load of buildings (46). The research and development activities in the area of material emissions started with formaldehyde emissions from particle boards about thirty years ago. Labelling schemes and quality control greatly reduced the problem with particle boards manufactured in Europe but not with those imported from some other countries. Research shows that almost all materials emit chemical pollutants. Much focus has been on paints, varnishes and flooring materials. Unfortunately the harmful emissions are not limited to the finishing materials, but include also furniture, partitions, etc. In some cases, also sealants and injection putties created problems due to high VOC (volatile organic compounds) emissions. Even though the emission rates of materials have been significantly reduced due to labelling schemes, ventilation is needed to dilute the VOC concentrations to acceptable levels, particularly in new and renovated buildings.

Brasche and Bischof (47) investigated the time spent indoors as a major importance in the evaluation of indoor exposure to formaldehyde. The overall mean time of 15.7 hours per day is in line with results from United States and Canada. The US Environmental Protection Agency (EPA) (48) indicated an inhalation rate of 0.63 $m^3/h$ and 10 hours per day for residential exposure. Stubenrauch et al (49) estimated inhalation rates of 0.8 $m^3/h$ for adults and 0.25$m^3/h$ for young children over 21 hours per day. The World Health Organisation (WHO) (50) calculated probabilistic estimates of 24 hours time-weighted average concentrations of formaldehyde in the air. The results indicated that one in two persons would be exposed to concentration of 24-29 $\mu g/m^3$, while 1 in 20 persons would be exposed to 80-94 $\mu g/m^3$. Acute, chronic (non-cancer), and potential carcinogenic effects on humans were reported for formaldehyde.

Additionally, ventilation is commonly used also for temperature control. As in many countries the outdoor temperature is most of the year below indoor temperature, the ventilation can be used to reduce high room temperatures. High room temperature increases the prevalence of sick building syndrome symptoms, deteriorates the perceived air quality, increases the sensation of dry air in winter and affects the performance and productivity (40). The effect of air temperature on thermal comfort is well known, but its effect on indoor air quality is not so widely recognized. Studies have shown that warm and humid air is stuffy (51), and room air temperature in the winter causes a higher number of typical sick building syndrome symptoms than cooler air (46). Studies by Fang et al (52; 53) and Humphreys et al (54) suggest use of low room air temperature and low relative humidity in the winter from a standpoint of good indoor air quality and energy economy.

### 2.2.2.2 Residences and sick building syndromes

The SBS (sick building syndrome) is used to describe a situation in which the occupants of a building experience acute health- or comfort-related effects that seem to be linked directly to the time spent in the building. The complainants may be localized in a particular room or zone or may be widespread throughout the building. One important strand lies in sick building syndrome, which is a set of non-specific symptoms occurring in a particular building and not caused by specific illness such as allergy or infection. SBS is widely used to describe symptoms experienced inside a building, such as headaches, eye, nose, or throat irritations, itchy skin, and fatigue (55). These symptoms, while common in the general population, become more prominent the longer a person stays inside a building, but they tend to disappear when he or she goes out. There are few studies among adults and SBS in relation to domestic exposures related to the building construction, including ventilation systems as well.

SBS is closely related with indoor air quality. Subjective perceptions of indoor air quality, including odor perceptions and sensory irritations, provide useful information on indoor environment, especially in large-scale questionnaire survey among population. The Swedish studies from 1990s (56; 10) reported that medical symptoms compatible with the SBS symptoms were more common in newer buildings, in multi-family houses, and in publicly owned apartments. Those results showed that SBS symptoms were related to atopy, age, female gender, building age and ownership of the building. Moreover, in Stockholm, the most common reported odors were stuffy odors (25.9%) and musty odors (15.6%) (57). Sources of perceived odors and biological agents were building interior decoration, building materials, use of different customer products and mold contamination.

Sensation of air dryness is another important subjective evaluation on indoor air quality. It was found that the increased air pollution level is a more important factor related with the sensation of ‘‘dryness’’ than the low relative air humidity (58). Lin et al (59) found that the sensation of air dryness had the highest proportion within those people (57.4%) who were involved in the study in China. The findings were followed by perceived stuffy odor (40.6%), unpleasant odor (27%), tobacco smoke odor (25.5%) and sensation of humid air (17.9%).The prevalence of SBS symptoms in the same time period was 40.4% for general symptoms, 47.7% for mucosal symptoms and 9.5% for skin symptoms, respectively. Moreover, it was found that the dampness, the presence of cockroaches and mosquitoes, prenatal exposure to decoration and close traffic were all risk factors of SBS.

### 2.2.3 Effect of indoor air quality on comfort of occupants

Several studies investigated indoor environment conditions and occupant satisfaction in existing multi-family dwellings. Recently, Du et al. (60) assessed the indoor environmental quality in residential buildings in North-East Europe. Sixteen existing multi-family buildings in Finland and twenty in Lithuania were investigated prior to their renovation to assess the potential for improving indoor environmental quality along with energy efficiency. Indoor temperature, relative humidity, $CO_2$, CO (carbon monoxide), PM (particular matter), $NO_2$, formaldehyde, VOCs were measured. The results indicated that most of the measured parameters were within the recommended limits. Potential for improvements appeared to be the largest with respect to thermal conditions and ventilation adequacy. Occupant reported satisfaction with indoor air quality was compared with measured parameters. Indoor $PM_{2.5}$, $PM_{10}$, formaldehyde, relative humidity in Finland, and $PM_{2.5}$, $NO_2$, radon, fungi, and relative humidity in Lithuania were found slightly higher in the rather unsatisfied or unsatisfied group than in the satisfied or fairly satisfied group, but the differences were not statistically significant. The $CO_2$ concentrations in Lithuania were found significantly higher in the rather unsatisfied or unsatisfied group (1086 ± 230 ppm) than in the satisfied or fairly satisfied group (940 ± 360 ppm). In Poland airtightness of external walls and windows was reported as the main reason for poor indoor air quality (61; 62). The level of $CO_2$ concentration increased above 3000 ppm in the evaluated households. Poor perceived indoor air quality was reported by occupants living in those dwellings.

The study by Zalejska-Jonsson et al (63) investigated overall satisfaction and satisfaction with thermal comfort, air and sound quality in Swedish residential apartments. Questionnaire survey was carried out in period of May-June 2008. Generally the occupants were satisfied with the indoor environmental quality in their apartments. However, in those apartments where dissatisfaction was observed, the discomfort was mostly caused by draught, dust and low indoor temperature. Indoor air quality was found as the most important factor affecting the overall satisfaction of occupants. Respondents´ overall satisfaction, which depended on the construction year of the building was effected by different indoor environmental problems. Occupants of dwellings built before 1975 indicated sensitivity to thermal comfort problems (too low temperature) caused by poor insulation of the building envelope and low energy efficiency of windows. Problems with stuffy air and unpleasant smell were determined by occupants who lived in dwellings built between 1975 and 1995.

Assessment of indoor environment of Danish dwellings using questionnaires were carried out by Frontczak et al (64). The questionnaires focused on inhabitants´ behaviour, their knowledge regards building systems designed for controlling indoor environment and the ways in which they achieve comfort. The results showed that visual, acoustic and thermal conditions as well as air quality are considered by inhabitants to be the most important parameters determining comfort. Manual control of the indoor environment was indicated by the respondents as highly preferred. Most of the respondents who had a problem related to the indoor environment did not try to find information on how to solve it because they considered that is was not serious.

## 2.3 Energy retrofitting of buildings

Retrofitting of existing residential buildings has been claimed as one crucial way to reduce energy consumption and greenhouse gas emissions within Europe (14; 20; 21; 23). The European Union has enacted several actions dealing directly and indirectly with energy efficiency of buildings aiming to reduce the building energy use through two Energy Performance Building Directives: Directive 2002/91/EC (6) and Directive 2010/21/EU (7); (shortly EPBD and EPBD recasting). While the first directive was more focused on methodologies and new buildings, the second one is giving more importance to existing buildings not only when subject to major renovation but also when building technical elements and technical systems are retrofitted or replaced.

### 2.3.1 European residential stock

Meijer et al (2) reviewed and compared the current renovation activities across Europe. Expert interviews were carried out in eight European countries. The interviews showed the investments in renovation activities are equal to or lower than the money invested in new constructions in residential sector. Sweden, Germany and United Kingdom seem to be the exceptions to this rule. In Austria the estimated number of apartments undergoing refurbishment is around 100 000 every year compared to new apartments built annually (45 000). In Finland, residential buildings account for half of the renovation activities and their share is expected to increase as the stock built in 1960-1970 will soon come to an age requiring renovation. In Sweden, twice as many renovations occur compared with new constructions; 120 000 apartment were renovated whereas 61 300 new flats were built in 2000-2004. The number of Swiss building renovated each year, however, exceeds the number of newly built housing and the unit costs per renovation are lower than for newly built buildings. Although no statistical data are available for the ratio of newly built to renovated dwellings in the Netherlands, the authors´ estimation based on their experience is that each year twice as many dwellings are renovated than newly built. Data from heating systems replacement were also gathered for countries mentioned above. Each year heating systems are replaced in 4% of Austrian, 9% of French, 5% of German and 18% in Finish dwellings. As indicated in previous studies on sustainable building by Sunikka (18) and Klunder (65) the policy analysis and expert interviews in this study confirm that the main barriers to sustainable renovation identified in all eight countries are a lack of knowledge and the unconvincing cost-benefit relation whereby an investor does not always profit from improved performance.

Evaluation of Swedish retrofitted multi-family dwellings with improved energy performance was carried out in two studies by Liu et al (66; 4). In the first one (66), one non-retrofitted and one retrofitted building built in late 1970s were chosen from the same area as the main study objects. The results showed that the retrofitted building has potential to reach a 39% reduction of space heating demand, which is higher than the 2020 national goal. The second study (4) showed that the multifamily buildings in Sweden have great potential to reduce their energy use by 50% by 2050, by means of measures such as external wall insulation, window replacement, and heat recovery system installation and especially by adjusting heating systems and utilizing solar or photovoltaic panels adjusting heating system.

Many studies completed by various European organisations of multi-family buildings built from 1880 onwards (most buildings from around the 1960s) demonstrated that substantial energy savings up to 90% could be obtained with implementing of insulation to the exterior building façade, installing new windows and using renewable energy sources (67; 68; 69; 70; 71; 72). The study of Serbian residential housing by Matic et al (73) investigated the integrated design strategies, applied in refurbishment of the prefabricated residential housing, erected in 1970s in Belgrade, in order to achieve energy savings accompanied with reduction of $CO_2$ emissions and improvement of households´ health and comfort. Energy efficiency has been optimized implementing building performance simulations. Significant reduction of thermal and cooling loads with the reference to the building´s existing status was obtained. Renovation encompassed optimization of building envelope and ventilation system.

The effect of a major domestic energy efficiency refurbishment programme on domestic space heating fuel consumption was examined in England (74). Dwellings were monitored either before or after the introduction of energy efficiency retrofit measures such as cavity wall insulation, loft insulation, draught stripping and energy efficient heating system. Data were collected and half-hourly living room and main bedroom temperatures were monitored for 2–4 week period over two winters from a total of 1372 households selected from five major urban areas in England. The findings showed that cavity wall and loft insulation can reduce the space heating fuel consumption by 10% in centrally heated properties and 17% in non-centrally heated properties. However, the introduction of a gas central heating system, although theoretically more efficient, has no significant impact on reducing fuel consumption even after adjusting for increased internal temperature. In Greece, the breakdown of energy conservation for space heating showed that conservation from wall insulation ranges between 21 and 36% and between 25 and 42% for 3-5 cm insulation thickness, respectively, between 10 and 30% from thermostatic valves, about 18% from new boiler, 4–24% and 5–28% from floor insulation with 3-5-cm thickness, respectively (75).

### 2.3.2 Slovak residential stock

National strategies and project proposals by the Slovak Government give overview of ongoing retrofit strategies in Slovakia (5; 30). They also present the scope of residential buildings expected by 2020. Only little research investigating renovation of the Slovak residential stock has been carried out (76).

The construction of prefabricated multi-family buildings came to an end in 1993. All of these residential buildings, erected according to design documents with substantial levels of repetitiousness, were constructed up to 1992, i.e. they have been in use for over 20 years (1; 5; 30). A large proportion of these structures are approaching the end of their viable life. The need for renovation is also corroborated by changes in legislation and, in particular, technical regulations relating to the essential requirements of structural, fire and user safety, hygiene, health and the environment, as well as acoustic protection, energy savings and thermal protection. Data gathered from 2011 (30) show that 41% of multi-family buildings have been renovated, at least partially. The extent of residential buildings´ renovation is the following: 53% renovated in Northern Slovakia, followed by 50% in Western region (the region of the capital), while the Eastern regions (31%) and Central Slovakia (32%) languish at the other end of the scale.

According to the action plan of The Ministry of Transport, Construction and Regional Development (5) improvements in the energy performance of buildings will be linked to deep renovations. During deep renovations, attention needs to be paid to the major renovation of buildings’ technical systems, i.e. the space heating system and hot water system. Slovakia has a well-developed district heating system that covers more than 30 % of overall heat consumption (approximately 16 100 multi-family buildings). Most heat sources and heat distribution systems were built prior to 1990. The boilers used in district heating systems vary considerably in terms of their age, technical parameters and fuel type. Most of the boilers in operation are less than 15 years old. District heating systems tend to use warm water and hot water distribution systems. Most heat distribution systems are between 20 and 30 years old, and their technical condition reflects this. As the expected service life of these sources and distribution systems is between 20 and 25 years, the major renovation of technical equipment also encompasses heat and hot water production and distribution. Projections indicate that such renovation should continue at an annual rate of 29 000 dwellings in multi-family buildings. The renovation of such a number of dwellings should have covered, in 2020, 72.38 % of multi-family buildings.

Pustayová (76) investigated the impact of renovation on energy performance of residential buildings located in the capital of Slovakia. The study was performed in typical Central European apartment blocks built in 1970´s, constructed from prefabricated concrete blocks. The selected residential buildings were inspected in their original and renovated conditions. Energy saving measures included insulation of the building envelope, replacement of old windows for new energy efficient ones and balancing of the heating system. The energy investigation of the buildings was carried out by energy auditing (77), including inspection, evaluation and analysis of the existing condition of the selected buildings. The energy saving potential was higher than 30% across all investigated structural systems in the study. According to energy classification, the energy retrofitted dwellings were classified into higher energy classes than the original ones. Energy monitoring was based on periodic (weekly) recording of the energy consumption data and measurements of the corresponding mean outdoor temperature. The ET (energy-temperature) curve for each building was created, in order 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 results indicated to clear difference between the original and renovated buildings. The outcome showed roughly 30-40% difference in energy consumption between actual energy consumption in original buildings and the optimised data in renovated dwellings. As the previous studies from Europe, the Slovak example also confirms that energy retrofitting can contribute significantly to reduce energy consumption of buildings.

### 2.3.3 Energy retrofit tools and protocols

A variety of protocols, tools, and standards are available from energy utilities and state, federal and private energy organizations as well as from research projects to guide the selection and implementation of energy retrofits for homes (78; 79; 80; 81; 82; 20). These protocols, tools, and standards seek to maximize energy savings per unit expenditure, and often employ energy modelling, cost-benefit estimation, and engineering judgment.

Ma et al (82) presented a systematic methodology for appropriate retrofits of existing buildings for energy efficiency and sustainability. The study concluded that the whole-of-building retrofit with comprehensive energy simulation, economic analysis and risk assessment is an effective approach to identifying the best retrofit solutions. Appropriate selection criteria and weighting factor assignments are essential in the formulation of multi-objective optimisation problems to select the most cost effective retrofit strategies. Major concerns of building owners in regard to retrofits should be carefully considered during the development of the optimisation problem. Therefore the study recommended to perform further research on facilitate cost effective building retrofits, low energy adaptive strategies for building applications, human factors on building retrofits and on risk assessment of building retrofits

The European collaborative effort (TABULA) (80; 81) focused on the creation and applicability of European building typologies with emphasis on the residential sector, enabling an understanding of the structure and the modernization processes of the building sector in different European countries. By “building typology” they mean classification of building according to some specific characteristics, which in this case are related to energy performance. The energy consumption in building depends on number of factors including the envelope construction, in accordance to the national building standards in force at that time and, in particular, the use of thermal insulation and materials used for the building envelope or even the type of electromechanical installations. Based on the TABULA harmonised structure, a total of 13 national building typologies were created, each representing the corresponding residential building stock. Each national typology consists of different building types with energy related characteristics that are representative of the corresponding country, classified on the basis of two critical parameters, i. e. age and size. These classification results in a group of building categories corresponding to distinct, nationally defined construction periods and up to four general building sizes in the national residential building stock, namely: single family house, terraced house, multi-family house and apartment block. Each typology is supplemented by two sub-typologies describing the most common building construction types and system installations in the participating countries. The first one includes descriptions of building construction types (walls, roofs and windows) and their respective heat loss coefficients before and after refurbishment and g-values for glazing. The second one includes description of heat generation, storage and distribution system types for space heating and domestic hot water production. The proposed approach focuses on the energy consumption for space heating and domestic hot water production, which constitute the main energy consuming end-uses.

Some protocols specify diagnostic measures and associated procedures for maintaining or improving indoor environmental quality during home energy retrofits (78; 20) and raise occupants ‘satisfaction (7). However, indoor environmental quality improvement has not been a primary goal of most retrofit programs. Jaggs et al (78) developed a European diagnosis and decision making method for building refurbishment to assist apartment owners who are considering refurbishment or upgrading their buildings. The methodology identifies the most appropriate refurbishment actions, together with an initial cost estimate, taking into account energy and indoor environmental quality issues. The method starts with the distribution of questionnaires to residents of the apartment buildings in order to gather data on indoor environmental quality issues. After collecting the data areas for further investigation during the energy performance and indoor environment retrofit (EPIQR) are highlighted. The EPIQR condition site survey assesses the apartment building on 50 elements. Each element is graded on a four-point scale from good to poor condition. The energy performance of the building is addressed by information gathered by the means of a walk through energy audit during the site visit together with information from historical data such as fuel bills. Following the condition survey the programme suggests suitable refurbishment and upgrading actions for each element. The program shows which measure will have the most impact on the general improvement of the building, the energy consumption and the indoor environmental quality issues while also giving an initial cost estimate for the work required.

The objective of the study by Noris et al (3) was to develop methods for selecting packages of retrofits that simultaneously save energy and improve indoor environment quality conditions in apartments with independent space conditioning systems (heating and air conditioning, if present). The project also sought to evaluate and demonstrate the energy savings and indoor environment quality improvements realized through application of the protocol and implementation of the retrofits.  Examples of retrofits selected via this protocol include air sealing coupled with application of energy efficient ventilation equipment, replacement of gas ranges with pilot lights, addition of thermal insulation, upgrading of filtration systems, and replacement of single pane windows with more efficient windows. The projected energy savings for the buildings ranged from 17 to 27%, with simultaneous substantial predicted improvements in thermal comfort and indoor air pollutant levels. Relative to current practices, the protocol described in this document has the potential to better maximize the total societal benefits of building retrofits, consequently, the protocol should be of interest to building owners, retrofit contractors, utilities, and governmental organizations involved with building retrofits.

Asadi et al (83) presents a multi-objective optimization model to assist stakeholders in the definition of intervention measures aimed at minimizing the energy use in the building in a cost effective manner, while satisfying the occupant needs and requirements. An existing house needing refurbishment is taken as a case study to demonstrate the feasibility of the proposed multi-objective model in a real-world situation. One of the key steps in building retrofit is the selection of retrofit actions among a large number of possibilities. The problem is in fact a multi-objective optimization problem, characterized by the existence of multiple and competing objectives, a set of feasible solutions that are not predefined but are implicitly defined by a set of parameters and a set of constraints that should be taken into account to reach the best possible solution. However, the problem is usually approached through simulation that focuses on particular aspects of the problem rather than a global confrontation. The target was to develop a multi-objective mathematical model to provide decision support in the evaluation of technology choices for the building retrofit strategies. The model allows explicitly for the simultaneous consideration of all available combinations of alternative retrofit actions. It also allows for the consideration of logical, physical and technical constraints.

## 2.4 Impact of energy retrofitting on indoor environmental quality

Energy retrofitting and its impact on indoor environmental quality is a challenging task. Finding appropriate technical solutions to the problems is often difficult. The home environment changed considerably during the past decades because of the rapid advancements in building technology. In Central and Eastern European countries the impact of energy saving measures on ventilation rates started in the 1990’s with the energy crisis leading to increased costs for energy, and thus for the heating of buildings. Residences have become more tightly sealed as amended residential building standards have been adopted and energy conservation measures have been implemented. The potentially negative impact on indoor air quality from some of these measures is a matter of concern, especially in those countries, where efforts were put into minimizing air infiltration losses by means of building envelope insulation, better insulated windows, and sealing of the building structure (20; 84; 85; 86; 87; 88). The implementation of these energy saving measures are usually not followed by enhanced mechanical ventilation and this leads to lower effective ventilation rates in residences (8). By reducing ventilation rates caused by envelope tightening, indoor pollutant concentrations may increase and result in increased exposure of occupants (89; 90; 91). It is important, therefore, to achieve a balance between energy conservation and comfortable and healthy indoor environment (92). To reduce levels of indoor air pollutants caused by energy conservation measures, improvements in construction practice should aim toward elimination of the sources, application of mitigation techniques and adequate ventilation (93; 94).

Few home retrofit studies demonstrated improvements of indoor environmental in Lithuania (95), New Zealand (96) and California (97). They reported improvement in thermal comfort, indoor air quality and health symptoms resulting from upgrading insulation and replacing ineffective heating systems or heating systems that vent combustion gases indoors. Investigation of impact of energy retrofitting of Swedish residential buildings on indoor environmental quality also showed positive effect on indoor environment (66). During retrofit, 15-30 cm polystyrene insulation for external wall was added. Moreover, all the facades, which were brick before the retrofit, were changed to rendered facades. Double-glazed windows ($U=2.9W/(m^2K)$) were replaced by triple-glazed windows ($U=1.2W/(m^2K)$). 50 cm cellulose insulation was added on the roof in order to reduce heat losses through the roof. The ventilation system was upgraded from mechanical exhaust ventilation system before the retrofit to mechanical ventilation system with heat recovery after the retrofit. The occupants in the retrofitted building reported that they were generally more pleased with their indoor climate. In the non-retrofitted building the indoor environment during winter was considered as "good" but "unacceptable" during summer unlike in the retrofitted building where the level of acceptance with indoor environmental quality was "best" in winter and "good" in summer. The simulations also showed that the indoor environment improved both during winter and summer.

Moreover, recently published articles reported more acceptable indoor environmental quality in low-energy and passive houses than in the conventionally built new houses. The quality of the indoor environment in the newly built passive dwellings was comparable to or better than in the conventionally built new houses and the Swedish housing stock (98). Formaldehyde concentrations were significantly lower in the passive houses than in the conventional ones and in the housing stock. TVOC concentrations were significantly higher than in the conventional houses, but were not significantly different from the housing stock. The good indoor air quality in the investigated new buildings was explained by the relatively high air exchange rates achieved by mechanical ventilation, which was used in all of the buildings. Derbez et al (99; 100) and Holopainen et al (101) studied the indoor environmental quality and occupant satisfaction in French and Finish energy efficient (low-energy) houses. According to measurements and interviews the results show that indoor environmental quality is generally acceptable over time despite some specific problems. Occupants suffered less from high room temperature, insufficient ventilation and dim light in the recently built low-energy houses than occupants in the older conventional houses. The differences between the perceived environment quality of the new energy efficient and existing building stock were higher in the winter than in the summer.

In contrast to the above mentioned studies, there is still an increasing concern regarding the impact of energy renovation and retrofits on the indoor environment and occupants' well-being. The scientific literature in this field is scarce, especially considering the number of parameters that may locally influence this relationship (e.g. building characteristics, climate, social aspects, etc.).

# 3. OBJECTIVES OF THE STUDY

The study seeks to evaluate the impact of basic energy retrofits of multifamily dwellings on indoor environmental quality and energy savings. In relation to building retrofit measures, 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.

The first case study is presented in Chapter 4. The outcomes of the second field study (Case study II.) are shown in Chapter 5. The energy consumption of the selected residential buildings is investigated in Chapter 6. The modelling of indoor air quality using various type of ventilation systems and further discussion of possible recommendations for achieving better indoor air quality in residential buildings currently using natural ventilation are presented Chapter 7.

# 4. INDOOR ENVIRONMENTAL QUALITY (CASE STUDY I)

## 4.1 Materials and methods

### 4.1.1 Studied buildings

Selection criteria included multi-story residential buildings built in representative Slovak construction technologies using prefabricated and pre-stressed concrete panels typical for the construction period of the second half of the 20th century; pairs of buildings built in identical construction systems, where one of the dwellings was in its original condition and the other one was renovated; location in same neighbourhood; using natural ventilation and same type of heating system. When suitable residential buildings were found, the housing association companies provided technical data, building information and blueprints of the selected residential buildings. The detailed methodology of the building selection process is presented below, in **Figure 4.1**.

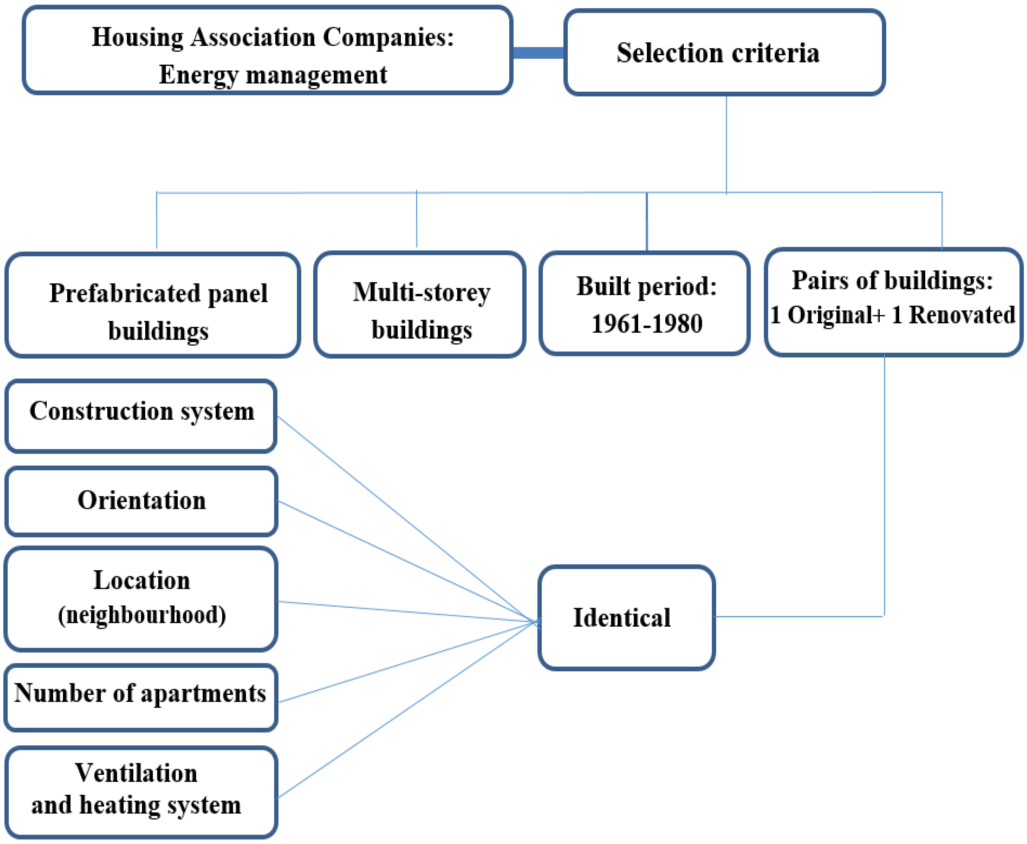


Figure 4.1 Building selection criteria

The residential buildings examined in this study were located in the urban area of Šamorín; situated in south-western Slovakia, about 20km from the capital of Bratislava (**Figure 4.2**).

Figure 4.2 The town of Šamorín (Source: www.wikimedia.org)

The study was performed in three pairs of naturally ventilated multi-storey residential buildings (**Table 4.1**). One of the buildings in each pair was renovated. 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 4.1 Characteristics of the studied buildings (Source: Housing association institutes)

| 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 | | 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 | |

## A) ORIGINAL BUILDINGS:

The selected buildings were constructed mainly using prefabricated concrete technologies. External walls were constructed from prefabricated concrete blocks of a thickness 150 and 300 mm, consisting from three main layers, e.g. inner concrete membrane, keramzite concrete and outer cover layer. The ceiling constructions were made from reinforced concrete of a thickness 150 mm. The width of vertical joints between the panels was 24 mm. Joints with vertical contact were opened with a groove, used mostly for water drainage. Horizontal contacts were characterized with a width of 20 mm of joints. The joints within the panels were filled by permanently elastic sealant. The roof of the buildings was constructed as a single casing flat roof. Thermal insulation material was not used during the building process.

The building inspection showed that the external construction was in poor condition and there was not paid sufficient attention to their maintenance. Typical malfunctions included crack of joints between the panels causing the construction to leak, degradation of concrete and surface treatment of peripheral structures, detachment of concrete and materials used for surface treatment (**Figure 4.3** Malfunctions of the building envelope (Source: Author)). The thermal performance of the main building constructions does not fulfill the current requirements on energy efficiency (Chapter 6); (31).

Figure 4.3 Malfunctions of the building envelope (Source: Author)

**B) RENOVATED BUILDINGS:**

The energy-retrofitting of building constructions included thermal insulation of façade (**Figure 4.4**) and roof and replacement of transparent constructions in common areas of the buildings (entrance, basement and corridors). For the thermal insulation of the façade expanded foam polystyrene of 80 mm thickness was used. 120 mm of mineral wool insulation was added on the roof. Single-glazed windows with U-value of 2.9 W/m$^2$K were replaced by double-glazed plastic windows with U-value of 1.2 W/m$^2$K. In each investigated building ground floor apartments were located above the unheated basement. Thermal insulation of the basement ceilings was performed. As a thermal insulation, expanded foam polystyrene in thickness of 80 mm was added. The detailed heat transfer coefficient characteristics of the original and the renovated buildings´ constructions are presented in **Chapter 6**.

Figure 4.4 Building envelope after thermal insulation implementation (Source: Author)

## C) BUILDING SERVICES:

### i. Heating and domestic hot water (DHW)

Each of the investigated buildings was supplied by using the same district heating system and DHW supplies. The maintenance of the pipelines of the heating and DHW system was neglected for many years in the original buildings. To minimise heat losses via pipes, the pipes were insulated using foaming polyethylene in each of the retrofitted buildings. The main control valves were also replaced with new ones (**Figure 4.5**).

Figure 4.5 Condition of the heating system piping in the original (left) and the renovated (right) buildings (Source: Author)

As a part of the renovation process hydraulic balancing of the heating system was carried out, i.e. optimisation of the water distribution in the heating systems of the residential buildings with purpose to provide the intended thermal condition at optimum energy efficiency and minimal operating costs. The majority of the apartments, in both types of the buildings, was equipped with new thermostatic radiator valves providing easy self-regulation control of the indoor temperature in the rooms.

ii. Ventilation

Only naturally ventilated buildings were investigated in this study. Exhaust ventilation was present in bathrooms and toilets only (**Figure 4.6**). The renovation process did not involve the existing exhaust ventilation system nor the provision of any new means of ventilation.

Figure 4.6 Exhaust ventilation in sanitary rooms (Source: Author)

### 4.1.2 Data collection

The data collection was performed in two phases (**Figure 4.7**). 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 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.

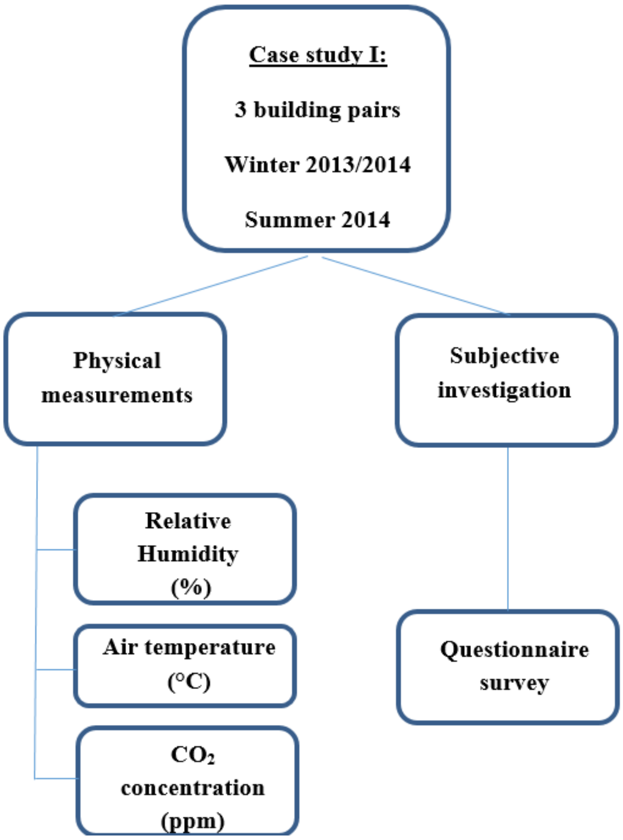


Figure 4.7 Data collection methodology for case study I.

#### 4.1.2.1 Physical measurements

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 (Onset Computer Corp.,USA; temperature range -20 °C to 70 °C ± 0.35 °C; relative humidity range 5% - 95% ± 2.5%) and CARBOCAP $CO_2$ monitors (GMW22, Vaisala, Finland; measuring range 0-5000 ppm; accuracy ± 2% of range ± 2% of reading); (**Figure 4.8**). The $CO_2$ monitor was connected to a Hobo data logger via an external cable. All the 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 (102). 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.

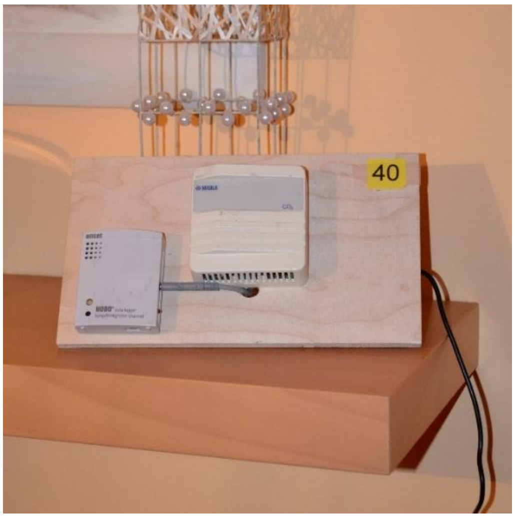


Figure 4.8 HOBO U12-012 and CARBOCAP CO2 monitors (Source: Author)

#### 4.1.2.2 Air exchange rate calculation

The $CO_2$ concentration data obtained in period between 20:30 and 6:30 each measurement night were used for air exchange rate calculation in order to avoid noise in data from unknown activities (102; 103; 104; 105). It was assumed that during the period over which the data were analysed occupants spent majority of the time in their rooms and the $CO_2$ generation rate was constant.

Three different approaches in the obtained $CO_2$ concentrations were used to determine the air exchange rate in the room for the respective night (103):

i. <u>BUILD-UP:</u> Firstly, the clear $CO_2$ concentration build-up periods (102) were used to estimate the air exchange rates for each respective night in the occupants´ bedrooms. The calculation of air exchange rates was performed using an Excel-based software in the rooms by fitting a non-linear curve to the measured pattern of the $CO_2$ concentration at a given $CO_2$ emission rate (**Equation 4.1**), room volume and outdoor $CO_2$ concentration (103). As an outdoor $CO_2$ concentration, constant 390 ppm was considered in the calculation process. The spreadsheet employed the carbon dioxide mass balance equation (**Equation 4.2**).

   The $CO_2$ emission rate depends on the height, weight, level of activity and respiratory quotient (102) and it is given by the following equation:

$$F = RQ \,.\, (0.00056028 \,.\, H^{0.725} \,.\, W^{0.425} \,.\, M) / (0.23 \,.\, RQ \,.\!+ 0.77) \qquad (m^3/s) \qquad (4.1)$$

Where:

| | |
|---|---|
| RQ | is respiratory quotient (0.83) |
| H | is height (m) |

| | |
|---|---|
| W | is weight (kg) |
| M | is metabolic rate (met; 1 met). |

Respiratory quotient is above 1.00 for heavy physical activity, about 5 met. In our case value of 0.83 was considered as a respiratory quotient (**Figure 4.9**). It characterises an adult of average size engaged in light or sedentary activities (1 met). The height and the weight of the occupants as well as the volume and occupancy of bedrooms were available from questionnaires for each of the nights. Based on the obtained information, the emission rates were calculated for each of the occupants located in the bedrooms during night-time periods. Sum of the emission rates obtained for each occupant present in the room was used for air exchange rate calculation.

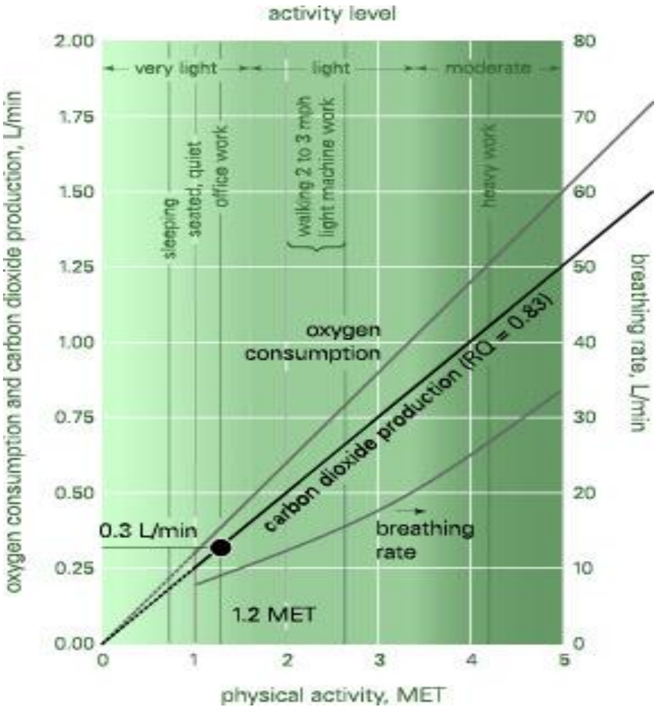


Figure 4.9 $CO_2$ concentration and oxygen consumption as a function of physical activity (102)

The mass balance formula is given as follows:

$$C_i(t) = (C_0 - C_a) .\ e^{(-\lambda .\ t_i)} + C_a + \frac{E .\ 10^3}{\lambda .\ V_R} . (1 - e^{-\lambda .\ t_i}) \qquad \text{(ppm)} \qquad (4.2)$$

Where:

| | |
|---|---|
| Ci(t) | is the concentration (ppm(V)) at time *t* (h) |
| $C_O$ | is the concentration in the beginning (at time *t=0*) |
| $C_a$ | is the outdoor concentration (ppm) |
| $\lambda$ | is the air change rate ($h^{-1}$) |
| E | is the is the estimated metabolic $CO_2$ generation rate per person in the zone (l/h) |

$V_R$ is the volume of the room ($m^3$)

$t_i$ is the time (h).

ii. DECAY: Decays of the $CO_2$ concentration were only used when the $CO_2$ level began to fall towards the background level in the air. It occurred rarely, when some of the occupants after occupying the bedroom indicated to ventilate before sleeping. The spreadsheet described above was used for the calculation.

iii. STEADY-STATE: Sometimes, the build-up or decay was not clearly defined within the selected data. In such a situation the air exchange rate was determined using a mass balance model applied on the estimated steady-state $CO_2$ concentration.

Only the most reliable fractions of the 10-hour night measurement period extracted for each night were used for further data processing. The air exchange rates were determined separately for each night with known occupancy. Data from night-time when the occupants were not present in the room were excluded. **Figure 4.10** shows an example of two subsequent nights of $CO_2$ concentration monitoring in one of the bedrooms. This example presents the selected final build-up curves and the air exchange rates corresponding to each curve.

The final air exchange rate for each room was calculated as a time-weighted average of the air exchange rates obtained for each relevant time period (night). From the means of all nights obtained for each of the apartments the whole building mean was calculated.

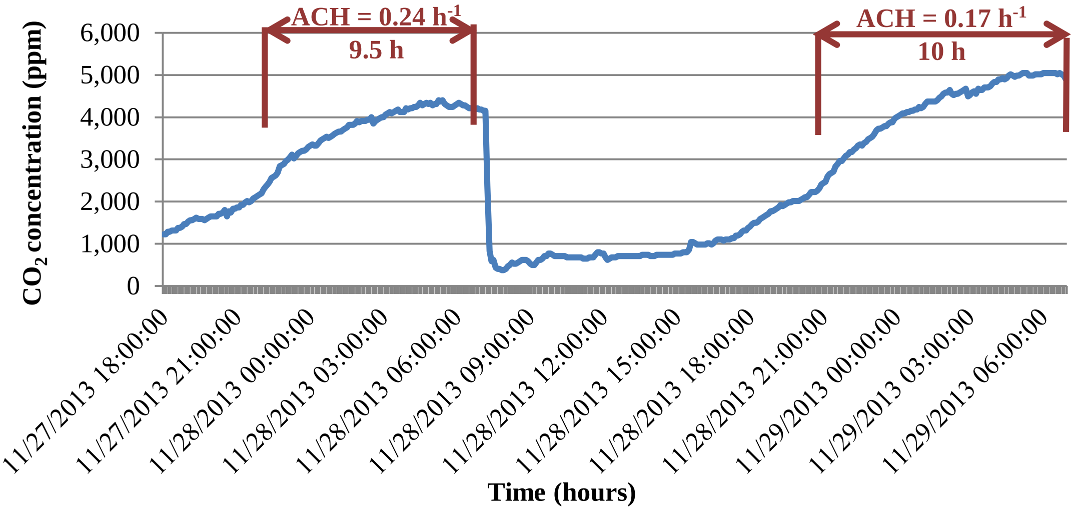


Figure 4.10 Example of air exchange rate determination corresponding to the build-up curve of CO2 concentration within two nights in one of the rooms

#### 4.1.2.3 Questionnaire survey

The objective of the questionnaire survey was to investigate the impact of building renovation on occupants´ every day habits related to energy efficiency settings and perceived indoor environmental quality in their apartments. The questionnaire was addressed to one person in each apartment in both, winter and summer season. 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. The example of questionnaires are presented in Appendix A.

The questionnaire survey was composed of seven main parts, as follows:

i. Basic information about the occupants (socio-demographic questions regarding age, gender, educational level of respondents, occupancy of apartment)
ii. Characteristics of the building construction (windows, flooring materials)
iii. Behaviour of the occupants (smoking, cooking, cleaning habits, pets and plants in the apartments)
iv. Sick building syndromes (fatigue, headache, nausea, itchy eyes and dry skin)
v. Characteristics of the room where the measurements took place (size, occupancy during nights, weight and height of the occupants, perceived indoor air quality in the mornings)
vi. Indoor air quality and ventilation habits of occupants (general perceived indoor air quality in the apartments, frequency and duration of ventilation during days and nights, changes in occupants´ ventilation habits after renovation)
vii. Thermal comfort and temperature settings (thermal sensation, acceptability of the thermal environment, indoor temperature preferences, possibilities in temperature settings and frequency of temperature control).

The majority of the questions were multiple choice questions. The rest used one of the following scales:

i. CONTINUOUS SCALE: Acceptability of indoor environmental parameters (indoor air quality and thermal comfort) was assessed using continuous scales (**Figure 4.11**), ranging from “clearly acceptable” (coded as 1 in the questionnaire) to “clearly unacceptable” (coded as -1), (106; 107; 108).

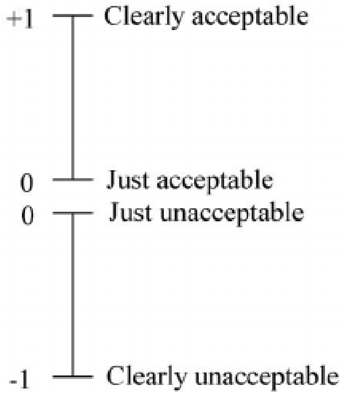


Figure 4.11Continuous acceptability scale

ii. POINT SCALE: Energy saving characteristics of the building and perceived air quality was evaluated using point scale, where the possible answers were from 1 to 6. When the question was related to building energy efficiency, number 1 characterised “very energy efficient” and number 6 “not energy efficient at all”. Regarding the perceived air quality investigation, number 1 represented “perceived air quality was not a problem” and number 6 presented “poor indoor air quality”. The questions were formulated as follows:

*“How unpleasant do you think the indoor air quality is in your bedroom during night/in the morning?”*

*“How unpleasant do you think the indoor air quality is in your apartment?”*

iii. SEVEN POINT SCALE: Thermal sensation was assessed by ASHRAE thermal sensation scale given by codes as follows: +3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), +1 (slightly warm), +2 (warm), and +3 (hot) (109). The questions were formulated as:

*“How do you assess the thermal sensation in your apartment?”*

*“What thermal sensation would you prefer to have in your apartment?”*

#### 4.1.2.4 Data analysis

Statistical analyses of the obtained data were performed in STATA general-purpose statistical software for Windows (StataCorp LP, College Station, Texas, USA), release 12.0.

The final results were visually presented for better understanding using:

i. DESCRIPTIVE STATISTICS used to describe the basic features of the data in the study:

We calculated mean, median, standard deviation, standard error, confident intervals and percentiles. In the boxplots throughout the results, the bottom and the top of the boxes represent the 25th and 75th percentiles and the line near the middle of the box is the median. The ends of the whiskers indicate the 10th and 90th percentiles. The full circles show the values below the 10th and above the 90th percentiles.

Frequency distribution and cumulative frequency were used for showing distribution of the data. Frequency distributions are depicted for all of the data as well as data grouped into categories (i.e. original and renovated buildings).

iv. STUDENT´S T-TEST was used to compare means of same variable between two groups (between the original and the renovated buildings) when the test statistic followed a normal distribution. In this study independent (unpaired) test was used to compare two sets of quantitative data when samples were collected independently of one another. P-value below 0.1 was considered borderline significant. P-value below 0.05 was considered significant.

v. WILCOXON TEST was used when the variables between the two related samples were not normally distributed.

vi. LOGISTIC REGRESSION was used to analyse the relationship between sick building syndrome symptoms and a variety of variables. The dependent variable was binary (1- having a symptom, 0 - not having a symptom). Having a symptom both “sometimes” and “often” were considered a positive answer (coded 1). Air exchange rates, building type (original/renovated), building code, age and gender of the occupants and the flooring material were included as independent variables.

vii. LINEAR REGRESSION was used to estimate the relationship between $CO_2$ concentration (log-normally distributed and logarithmically transformed) and indicators of building characteristics and occupant behaviour. Multiple linear, stepwise forward and backward regression analyses were conducted to identify predictor variables with inclusion criteria of $p<0.2$. The final model included building type (original/renovated), apartment location (floor), bedroom and apartment occupancy, position of bedroom door during night, frequency and duration of ventilation, and occupants´ smoking habits.

viii. To investigate the relationship between the $CO_2$ concentration and the six dwellings respectively was not possible in the regression model. Due to collinearity, the statistical test did not allow to include both the “building type” and the “building code” in the regression analyses. Therefore, ANALYSES OF VARIANCE (ANOVA) was used where the building code could be nested in the building type. Two factors are usually nested when the levels of one factor are similar but not identical, and each occurs in combination with different levels of another factor. $CO_2$ concentration (log-normally distributed and logarithmically transformed) was used as dependent variable. The input variables were as follows: building code, building type (original/renovated), apartment location (floor), bedroom and apartment occupancy, situation of doors, frequency and duration of ventilation, and occupants´ smoking habits. The building code characterised each of the investigated dwellings separately using coding of buildings from “1” to “6”.

## 4.2 RESULTS

### 4.2.1 Thermal comfort

#### 4.2.1.1 Indoor temperature

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 ($p=0.01$-$0.05$) **(Figure 4.12**). 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.

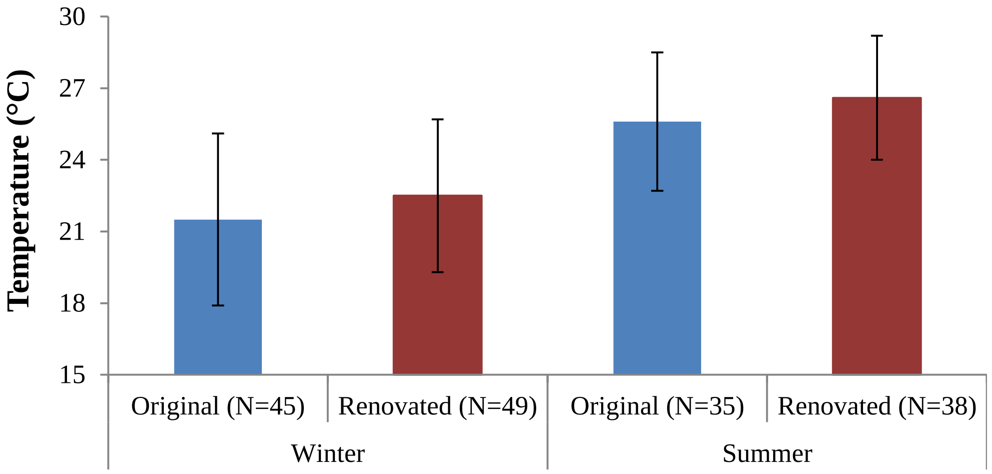


Figure 4.12 Grand average of indoor temperature in the original and the renovated residential buildings in winter and summer season. The whiskers represent the minimum and maximum average values.

The detailed outputs of the descriptive statistics are summarised in **Table 4.2**, for both day and night period, respectively. Both the day and night values show statistically significant differences between the original and the renovated dwellings in both winter and summer season.

Table 4.2 Descriptive statistics of the indoor air temperature.

a) Winter

| Descriptive statistics | Original (N=45) | | Renovated (N=49) | |
|---|---|---|---|---|
| | **Day** | **Night** | **Day** | **Night** |
| Grand Mean<br>(Min.-Max.) | 21.4<br>(17.6-25.1) | 21.7<br>(17.9-25.1) | 22.2<br>(19.2-25.6) | 22.7<br>(20.4-25.8) |
| Geometric mean | 21.3 | 21.7 | 22.1 | 22.7 |
| Median | 21.7 | 21.7 | 22.3 | 22.8 |
| Std. Dev. | 1.9 | 1.7 | 1.5 | 1.4 |
| Std. Err. | 0.28 | 0.25 | 0.21 | 0.20 |
| 95% CI | 20.8-21.9 | 21.3-22.3 | 21.7-22.6 | 22.3-23.1 |

**$0.05<p<0.1$**

**$p<0.01$**

b) Summer

| Descriptive statistics | Original (N=35) | | Renovated (N=38) | |
|---|---|---|---|---|
| | **Day** | **Night** | **Day** | **Night** |
| Grand Mean<br>(Min.-Max.) | 25.7<br>(22.4-28.7) | 25.8<br>(22.4-28.5) | 26.7<br>(23.9-29.6) | 26.6<br>(23.8-28.6) |
| Geometric mean | 25.6 | 25.7 | 26.7 | 26.4 |
| Median | 25.6 | 25.8 | 26.7 | 26.5 |
| Std. Dev. | 1.9 | 1.9 | 1.3 | 1.2 |
| Std. Err. | 0.31 | 0.31 | 0.20 | 0.19 |
| 95% CI | 25.0-26.3 | 25.2-26.4 | 26.3-27.1 | 26.0-26.8 |

**$p<0.01$**

**$0.05<p<0.1$**

**Figure 4.13** shows the cumulative percentage distribution of the overall (day and night time together) average temperature in the bedrooms of the investigated dwellings in winter and summer period. The figure on left presents the winter results. According to thermal comfort criteria (110), 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 on the right shows the cumulative frequency of overall average temperatures in the residential buildings in the summer. 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%).

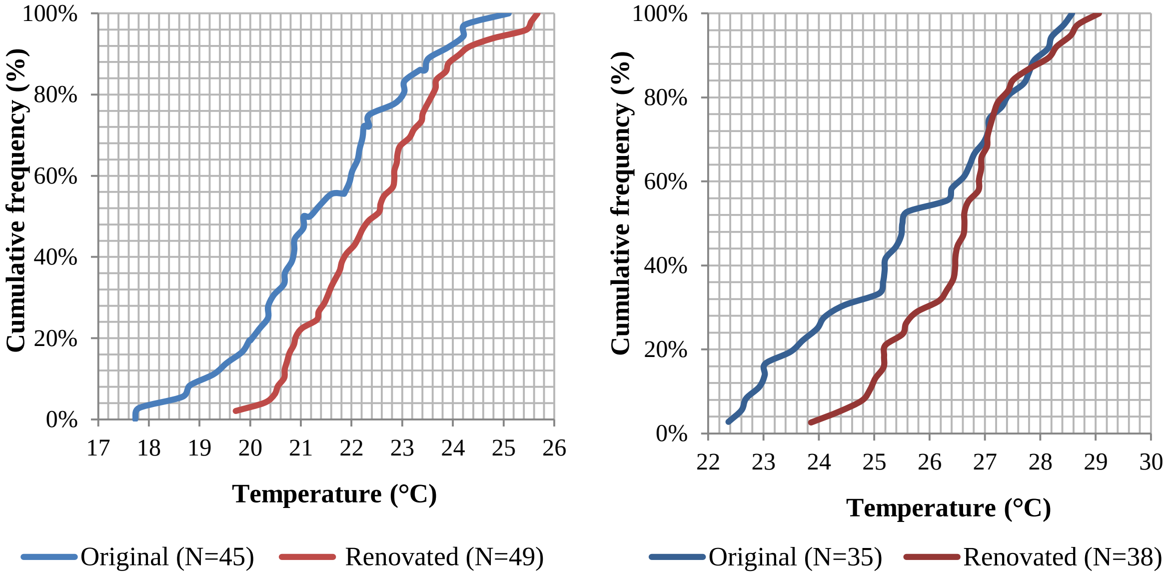


Figure 4.13 Cumulative percentage distribution of overall (day and night together) average indoor temperature in the bedrooms of the original and renovated residential buildings in winter (left) and summer (right).

### 4.2.1.2 Relative humidity

**Figure 4.14** presents the relative humidity obtained in both types of the investigated dwellings. The grand average 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).

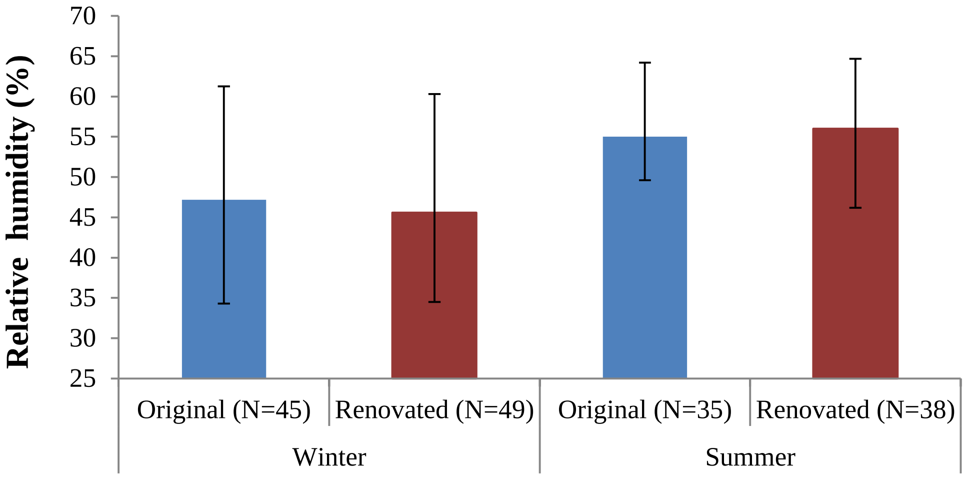


Figure 4.14 Grand average of relative humidity in the original and the renovated residential buildings in winter and summer season. The whiskers represent the minimum and maximum average values.

**Table 4.3** presents the outputs of descriptive statistics. The outcomes are shown for both day and night time in both, winter and summer season. The grand means ranged between 45 and 48 % in winter, and within 55 and 56 % in summer. No statistical significance (p>0.1**)** was found between the non-retrofitted and the retrofitted dwellings.

Table 4.3 Descriptive statistics of the indoor relative humidity.

a) Winter

| **Descriptive statistics** | **Original (N=45)** | | **Renovated (N=49)** | |
|---|---|---|---|---|
| | **Day** | **Night** | **Day** | **Night** |
| Grand Mean (Min.-Max.) | 46 (34-60) | 48 (35-65) | 45 (31-60) | 47 (33-61) |
| Geometric mean | 46 | 48 | 44 | 46 |
| Median | 47 | 48 | 45 | 47 |
| Std. Dev. | 6 | 7 | 7 | 7 |
| Std. Err. | 0.94 | 1.6 | 1.2 | 1.4 |
| 95% CI | 44-48 | 46-51 | 43-47 | 45-49 |

b) Summer

| **Descriptive statistics** | **Original (N=35)** | | **Renovated (N=38)** | |
|---|---|---|---|---|
| | **Day** | **Night** | **Day** | **Night** |
| Grand Mean (Min.-Max.) | 55 (49-64) | 56 (51-67) | 56 (46-64) | 56 (46-65) |
| Geometric mean | 54 | 54 | 55 | 55 |
| Median | 55 | 56 | 57 | 57 |
| Std. Dev. | 3 | 3 | 4 | 4 |
| Std. Err. | 0.58 | 0.57 | 0.68 | 0.70 |
| 95% CI | 54-56 | 55-58 | 54-57 | 55-58 |

**Figure 4.15** (left) presents the cumulative frequency distribution of the average relative humidity in the winter. According to ISO 7730 (110) the relative humidity indoors should be between 30 and 60% in both, winter and summer season. The average RH in the winter ranged between 34 and 61% in the original buildings. Only two apartments had an RH exceeding 60%. In the renovated dwellings all the apartments met the criterion of the recommended limit. The means ranged within 34 and 60%.

**Figure 4.15** (right) presents the cumulative frequency distribution for the summer season. The mean relative humidity met the recommended comfort range (110) in 91% of the apartments in the original buildings, and in 89% of apartments in the renovated dwellings. In the rest of the apartments the mean relative humidity ranged between 61 and 64%.

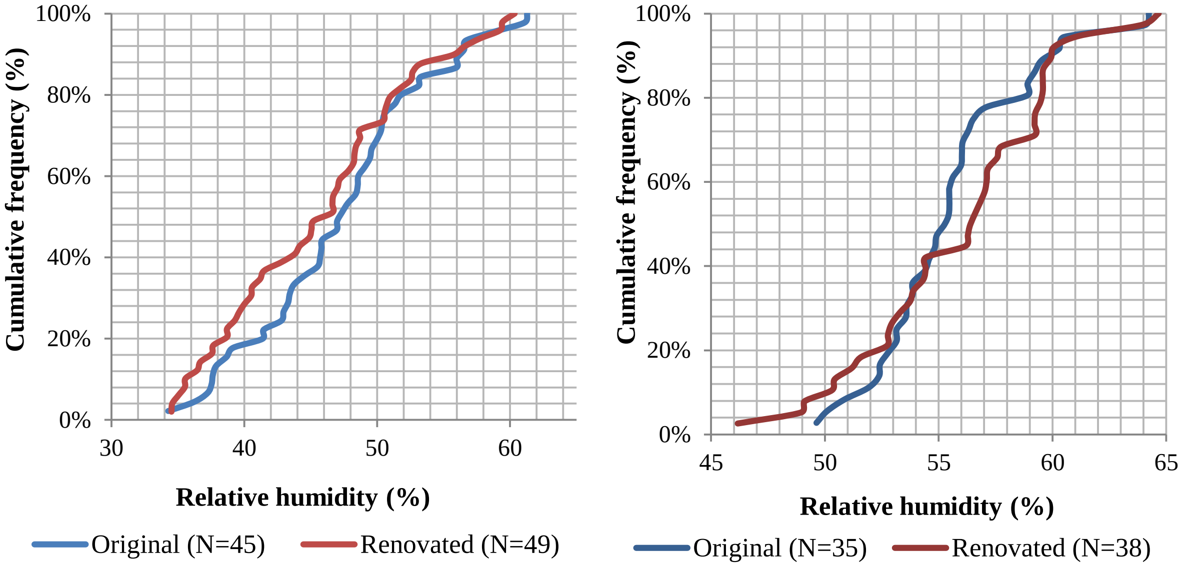


Figure 4.15 Cumulative frequency distribution of overall average relative humidity in the bedrooms of the original and the renovated residential buildings in winter (left) and summer (right).

### 4.2.1.3 Thermal sensation and acceptability of thermal comfort

**Figure 4.16** shows the boxplots of the thermal sensation votes. In winter, the average thermal sensation vote (TS) in the original buildings was between neutral and slightly warm (TS=0.5), while in the renovated dwellings the occupants indicated that they were slightly warm and warm (TS=1.7); ($p<0.05$). Although the thermal sensation was different in the two types of buildings, the average thermal acceptability (ACC) (**Figure 4.17**) was moderate in both, the original (ACC=0.42) and the renovated (ACC=0.31) dwellings ($p>0.05$). It should however be noted, that larger fraction of the occupants in the renovated buildings reported the thermal environment to be unacceptable, compared to the original buildings. In the original buildings 5% of the occupants reported unacceptable thermal environment (acceptability below zero), while in the renovated dwellings more than half of the occupants (57%) reported negative acceptability.

In summer, the thermal sensation increased up to between slightly warm and warm in the non-renovated dwellings (TS=1.7). In the renovated buildings the residents had similar average thermal sensation (TS=1.6; $p>0.1$), although the occurrence of feeling neutral or hot was more frequent. With increased thermal sensation in the original buildings from winter to summer, the occupants´ thermal acceptability decreased (ACC=0.27). On the contrary, it slightly increased in the renovated dwellings (ACC=0.53; $p<0.05$ between building types), despite the thermal sensation not having changed between the seasons and despite the slightly higher average temperature compared to the original buildings.

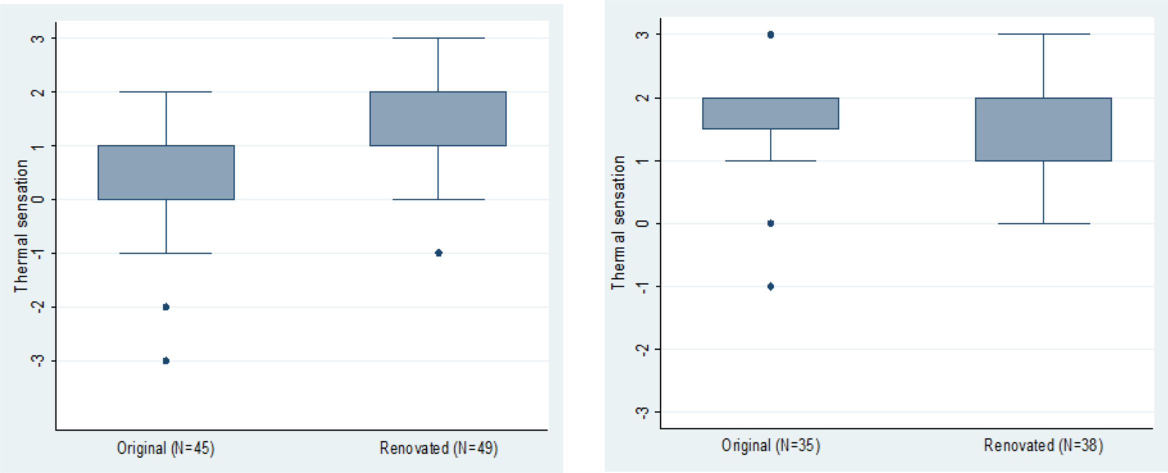


Figure 4.16 Boxplots showing the thermal sensation in the original and the renovated residential buildings in winter (left) and summer (right).

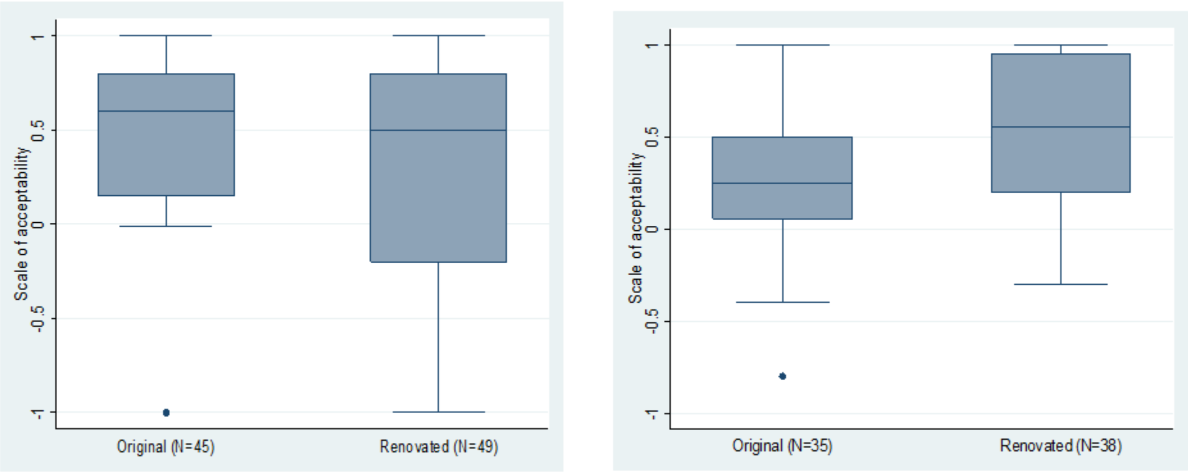


Figure 4.17 Boxplots showing acceptability of the thermal environment in the original and the renovated residential buildings in winter (left) and summer (right).

## 4.2.2 Indoor air quality

### 4.2.2.1 $CO_2$ concentration

**Figure 4.18** presents boxplots of the indoor $CO_2$ concentration in the original and the renovated buildings. The obtained grand averages are presented by empty circles in middle of the boxes. The difference in average CO2 concentrations between the renovated and the original dwellings was approaching statistical significance ($0.05<p<0.1$) in winter (left figure). 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 ($p>0.1$), (right figure). The original residential buildings were characterised by faintly higher median (515 ppm) and overall mean (850 ppm) of $CO_2$ concentrations than the retrofitted buildings, where the median was 480 ppm and the overall mean was 815 ppm.

The day and night time division of the data (**Table 4.4**) also showed similar significance between the building types as the obtained overall averages described above. Borderline significant difference could be observed between the non-renovated and the renovated residential buildings in winter ($p<0.1$) but not in summer ($p>0.1$).

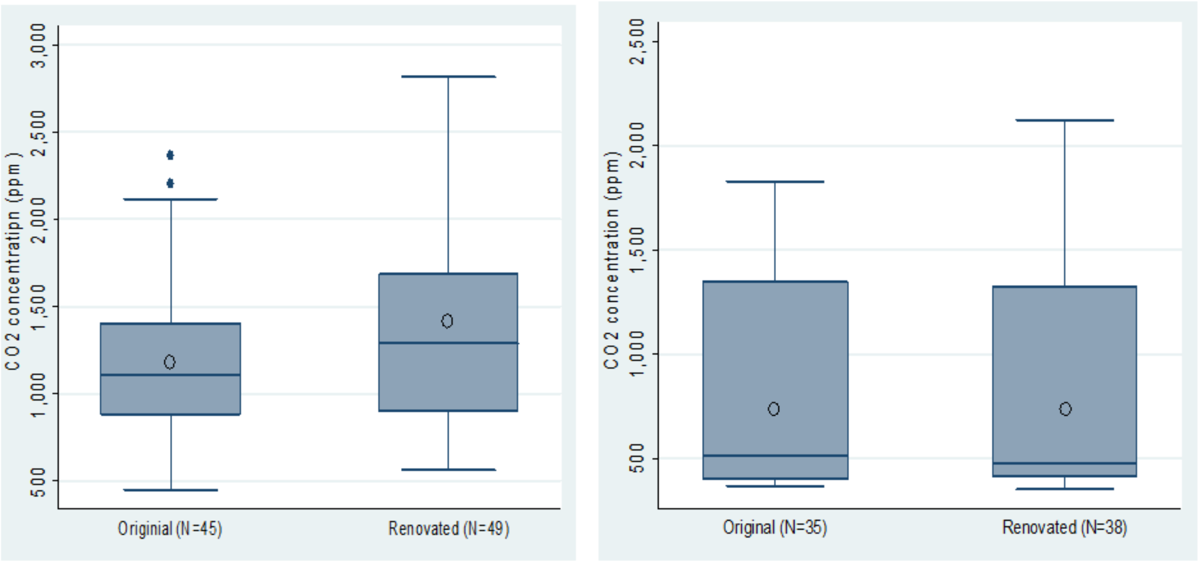


Figure 4.18 Boxplots showing the CO2 concentration in the original and the renovated residential buildings in winter (left) and summer (right). Circles indicate grand average.

Table 4.4 Descriptive statistics of the $CO_2$ concentrations

a) Winter

| Descriptive statistics | Original (N=45) | | Renovated (N=49) | |
|---|---|---|---|---|
| | **Day** | **Night** | **Day** | **Night** |
| Mean (Min.-Max.) | 985<br>(430-1860) | 1425<br>(480-3380) | 1135<br>(510-2210) | 1680<br>(630-3570) |
| Geometric mean | 935 | 1260 | 1060 | 1530 |
| Median | 945 | 1360 | 980 | 1510 |
| Std. Dev. | 320 | 675 | 430 | 745 |
| Std. Err. | 47.76 | 100.76 | 61.90 | 106.46 |
| 95% CI | 890-1180 | 1220-1630 | 1010-1260 | 1465-1890 |

**$0.05<p<0.1$**

**$0.05<p<0.1$**

b) Summer

| Descriptive statistics | Original (N=35) | | Renovated (N=38) | |
|---|---|---|---|---|
| | **Day** | **Night** | **Day** | **Night** |
| Mean<br>(Min.-Max.) | 820<br>(350-1920) | 875<br>(385-2045) | 770<br>(350-1920) | 870<br>(360-2370) |
| Geometric mean | 685 | 740 | 645 | 725 |
| Median | 490 | 585 | 465 | 510 |
| Std. Dev. | 480 | 510 | 480 | 555 |
| Std. Err. | 82.81 | 84.88 | 77.77 | 89.63 |
| 95% CI | 655-990 | 705-1050 | 615-930 | 690-1050 |

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 (**Figure 4.19**) was conducted to show the fractions of apartments where the average night-time $CO_2$ concentrations exceeded 1000, 2000 and 3000 ppm (**Table 4.5**). In the winter the average $CO_2$ concentration during at the night across all apartments was higher in the renovated buildings than in the original ones. In the summer the average night-time $CO_2$ concentrations were similar in both types of buildings. The percentage distribution of the summer average night-time $CO_2$ concentrations shows unusual shape of the curves compared to the winter distribution. 60% of the apartments, mostly occupied by one person, had an average night time $CO_2$ concentration around 600 ppm and the rest, where the rooms were occupied by two people, was above 1300 ppm (**Figure 4.19**, right). 6% of the apartments had an average between 1600 and 2400 ppm.

The regression analyses (**Table 4.7**) and ANOVA (**Table 4.6**) 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 $R^2 = 0.29$. The ANOVA model resulted in $R^2 = 0.35$ (**Figure 4.20**).

Table 4.5 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 |

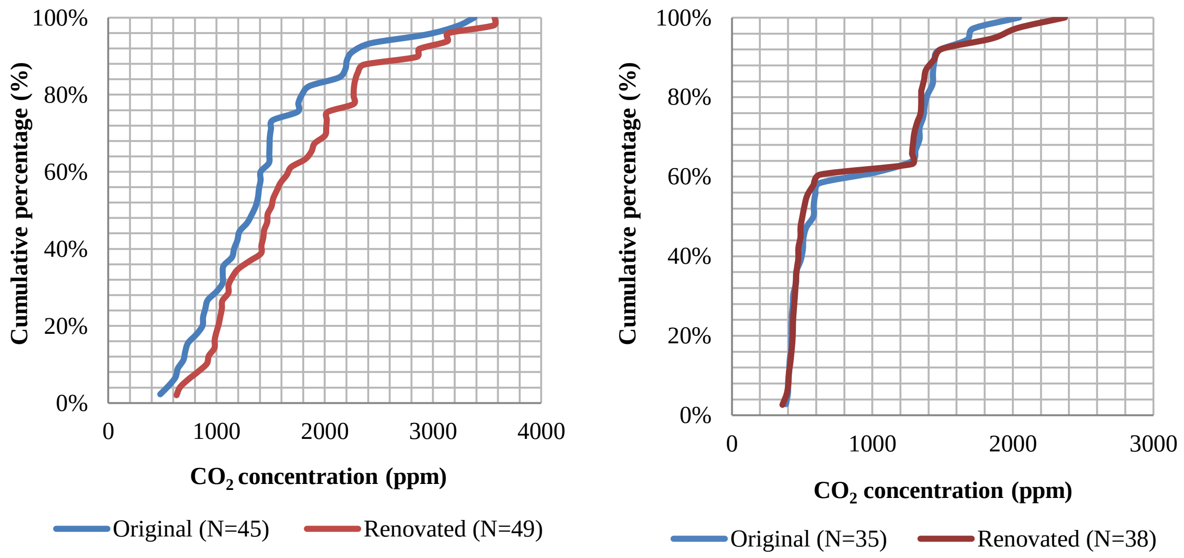


Figure 4.19 Cumulative percentage distribution of the average $CO_2$ concentration in the bedrooms of the original and the renovated residential buildings in winter (left) and summer (right).

Table 4.6 ANOVA test of logarithmically transformed $CO_2$ concentrations (ppm) in bedrooms in winter. Model created after identifying predictor variables with inclusion criteria of $p < 0.2$, $R^2 = 0.35$

| **Source** | **Degrees of freedom** | **Mean square** | **F ratio** | **P-value** |
|---|---|---|---|---|
| Model | 10 | 0.68 | 4.57 | 0 |
| Building code \| Building type | 5 | 0.32 | 2.11 | 0.07 |
| Occupancy of apartment | 3 | 0.35 | 2.35 | 0.08 |
| Occupancy of bedrooms | 1 | 0.83 | 5.55 | 0.02 |
| Smoking habits | 1 | 0.94 | 6.28 | 0.01 |

Table 4.7 Linear regression of logarithmically transformed $CO_2$ concentrations (ppm) in bedrooms in winter. Model created after identifying predictor variables with inclusion criteria of $p < 0.2$, $R^2 = 0.29$

| **Parameter** | **Factor** | **Std. Error** | **95% CI** | | **P-value** |
|---|---|---|---|---|---|
| Building type<br>Reference: Original<br>Reconstructed | 0.15 | 0.08 | -0.014 | 0.315 | 0.07 |
| Occupancy of bedroom<br>Reference: 1<br>2 | 0.3 | 0.09 | 0.106 | 0.497 | 0.003 |
| Occupancy of apartment<br>Reference: 1 | | | | | |
| 2 | 0.22 | 0.12 | -0.027 | 0.461 | 0.08 |
| 3 | 0.24 | 0.14 | -0.031 | 0.523 | 0.08 |
| 4 | 0.38 | 0.16 | 0.067 | 0.704 | 0.02 |
| Smoking habits<br>Reference: Non-smoker<br>Smoker | -0.16 | 0.09 | -0.344 | 0.012 | 0.07 |
| Constant | 6.86 | 0.10 | 6.659 | 7.068 | 0.000 |

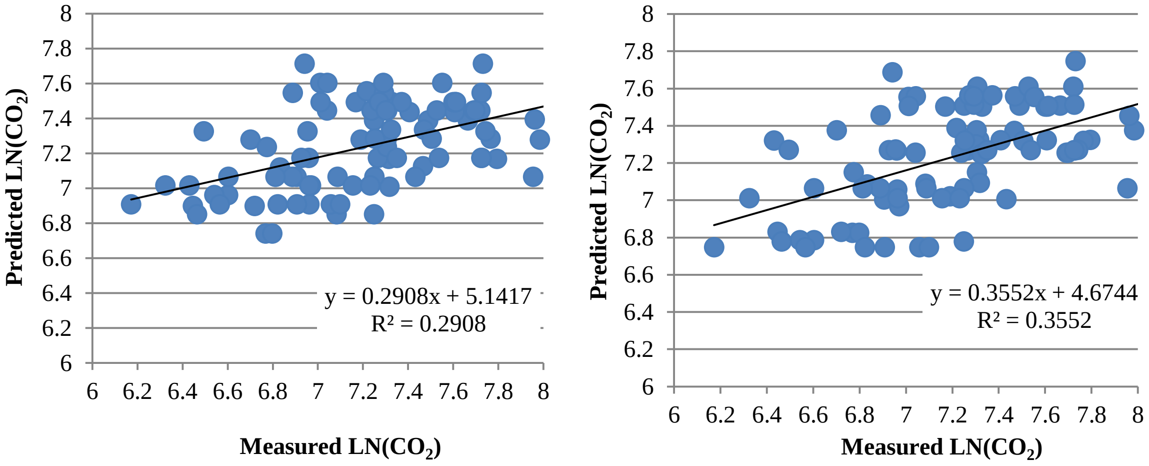


Figure 4.20 Logarithm of the measured $CO_2$ concentrations in winter plotted against the predicted values from regression (left) and ANOVA (right) models created after identifying predictor variables with inclusion criteria of $p < 0.2$.

### 4.2.2.2 Air exchange rate (AER)

**Figure 4.21** presents the distribution of air exchange rates. 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 ($p>0.05$). In winter the grand average air exchange rate was 0.79 $h^{-1}$ in the original buildings (**Table 4.8**). 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$^{-1}$. The highest average AER reached 19 h$^{-1}$ in some of the bedrooms.

**Figure 4.22** shows the average AER obtained for each of the six investigated buildings separately. The results show that in each of the original buildings the AER was higher compared to the retrofitted counterpart in winter ($p<0.01$). The AERs in the renovated building were around the minimum recommended value. In summer each of the buildings met the minimum criterion, with higher AER in building pairs I and II (AER=8.11-10.45 h$^{-1}$) compared to the building pair III (AER=3.64 and 4.5 h$^{-1}$). While there were some differences between building pairs, no differences were observed between the two buildings within each pair.

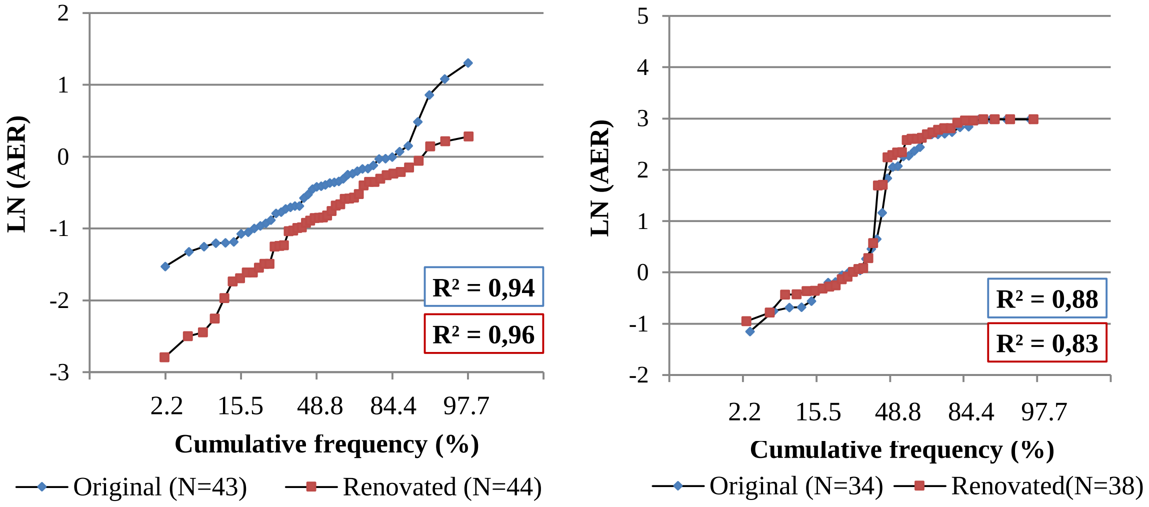


Figure 4.21 Distribution of the air exchange rates measured in the bedrooms of the original and the renovated residential buildings in winter (left) and summer (right).

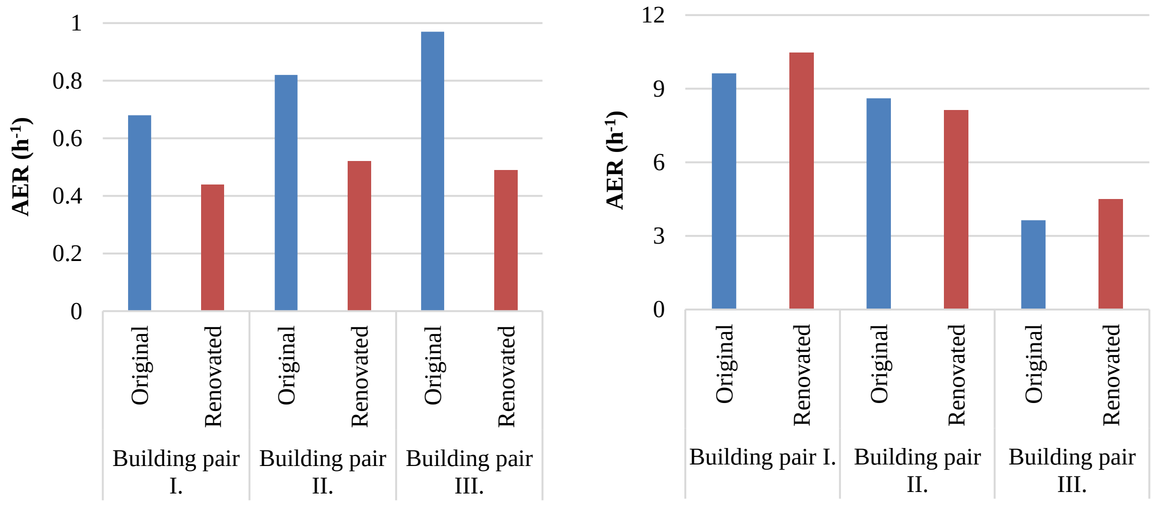


Figure 4.22 Average AERs presented in each of the investigated residential building in winter (left) and summer (right). Note the different scale of the y-axis.

Table 4.8 Descriptive statistics of the AERs.

| Descriptive statistics | Winter | | Summer | |
|---|---|---|---|---|
| | Original (N=43) | Renovated (N=44) | Original (N=34) | Renovated (N=38) |
| Mean<br>(Min.-Max.) | 0.79<br>(0.22-3.69) | 0.48<br>(0.06-1.33) | 7.88<br>(0.32-19.84) | 8.80<br>(0.39-19.82) |
| Geometric mean | 0.64 | 0.38 | 3.70 | 4.16 |
| Median | 0.66 | 0.43 | 7.05 | 9.66 |
| Std. Dev. | 0.69 | 0.31 | 7.32 | 7.67 |
| Std. Err. | 0.11 | 0.05 | 1.26 | 1.24 |
| 95% CI | 0.58-1.01 | 0.39-0.58 | 5.33-10.44 | 6.28-11.32 |
| p-value | 0.007 | | 0.607 | |

**Figure 4.23** shows the cumulative percentage distribution of AERs obtained from the original and renovated dwellings in winter and summer. **Figure 4.24** presents the percentage of the obtained air exchange rates classified into bins of air exchange rates. 63% of the air exchange rates in the original buildings met the criterion of 0.5 $h^{-1}$ in winter. In the renovated buildings 58% of apartments had an AER below 0.5 $h^{-1}$. These AERs were mostly between 0.2 and 0.5 $h^{-1}$. In the summer, more than 90% of the bedrooms in both building types had air exchange rates higher than 0.5 $h^{-1}$; 97% in the original buildings and 94% in the renovated dwellings.

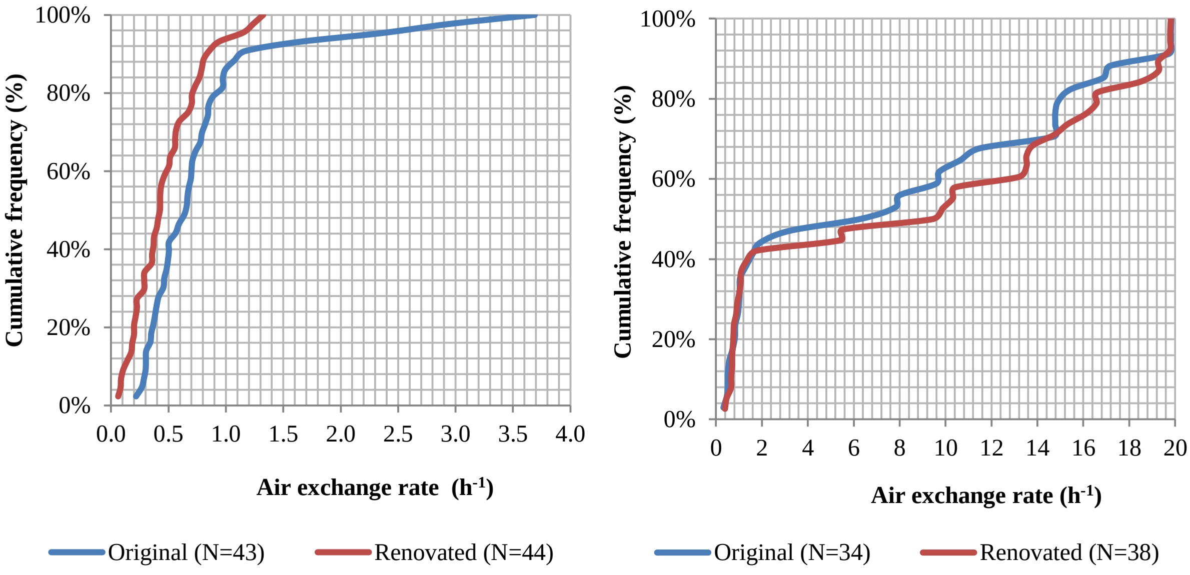


Figure 4.23 Cumulative frequency distribution of the average air exchange rates in the bedrooms of the original and the renovated residential buildings in winter (left) and summer (right).

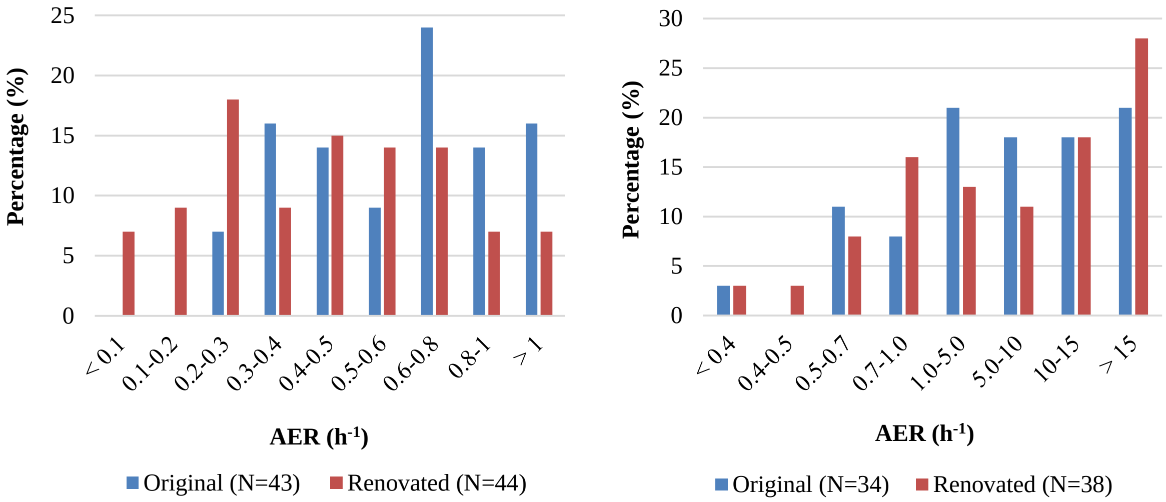


Figure 4.24 Frequency distribution of air exchange rates stratified into bins for both winter (left) and summer (right).

### 4.2.2.3 Perceived air quality (PAQ)

**Figure 4.25** and **Figure 4.26** present the occupants´ perception of indoor air quality in their bedrooms during night and in their apartments generally. During the winter, a greater fraction of the occupants indicated poor air quality in the renovated buildings compared to the non-renovated buildings. 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 (response "1","2" and "3"*;* **Figure 4.27**). The response was less positive in the renovated buildings, corresponding to the lower AER in these buildings. In the original building of type III, 64% of the occupants marked the least unpleasant indoor air quality. The highest average AER (0.97 $h^{-1}$) was also found in this building. 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. However occupants in each of the original buildings mostly indicated moderately good indoor air quality (options on the point scale between "2" and "4"). In the renovated dwellings occupants evaluated the PAQ to be somewhat better (between "1" and "3" with the highest fraction obtained for "2"). This is somewhat surprising, since no significant difference was found in the AER between the buildings in each pair. Similar trend was obtained for the acceptability of the indoor air quality (**Figure 4.28**). The difference between the original and the renovated buildings was statistically significant in both winter and summer ($p<0.01$),

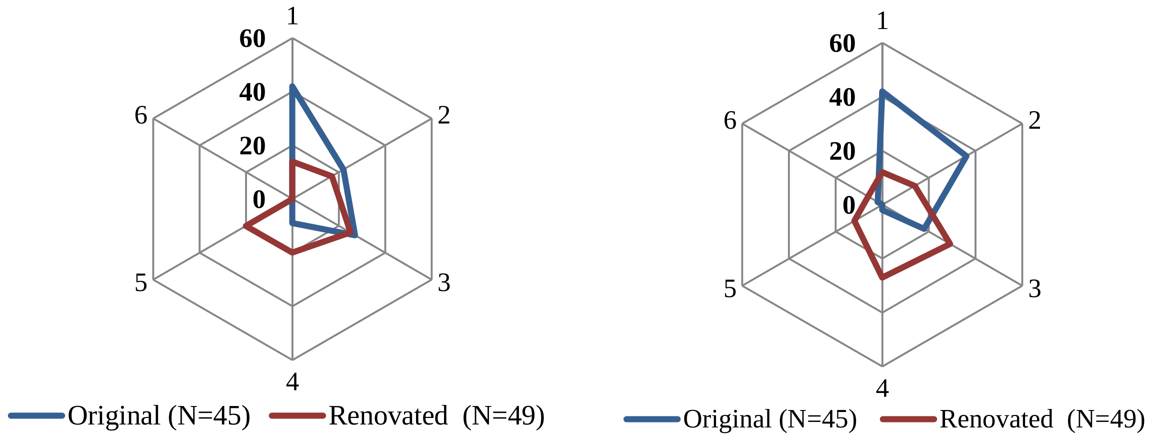


Figure 4.25 Summary of answers to the questions “How unpleasant do you think the IAQ is in your bedroom during night/in the morning?”(left), and “How unpleasant do you think the IAQ is in your apartment?”(right). The results show winter season.

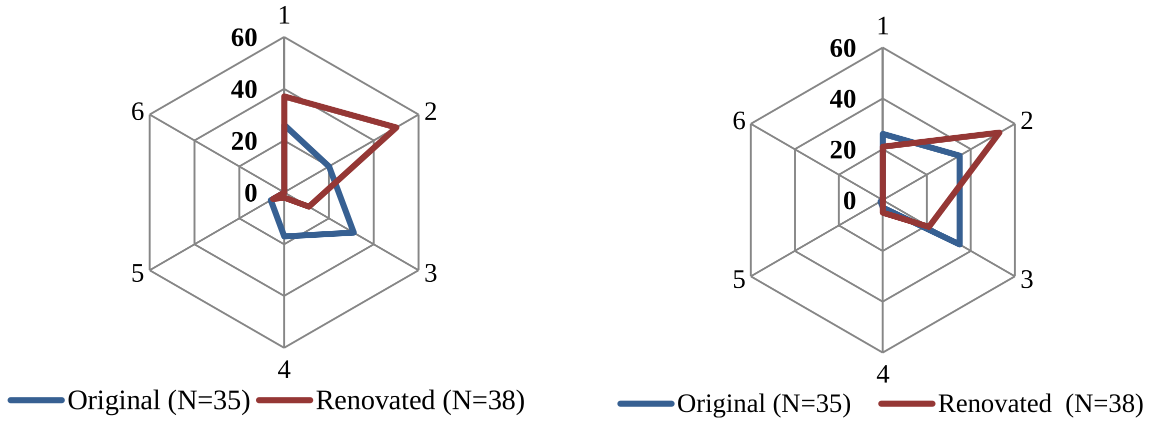


Figure 4.26 Summary of answers to the questions “How unpleasant do you think the IAQ is in your bedroom during night/in the morning?”(left), and “How unpleasant do you think the IAQ is in your apartment?”(right). The results show summer season.

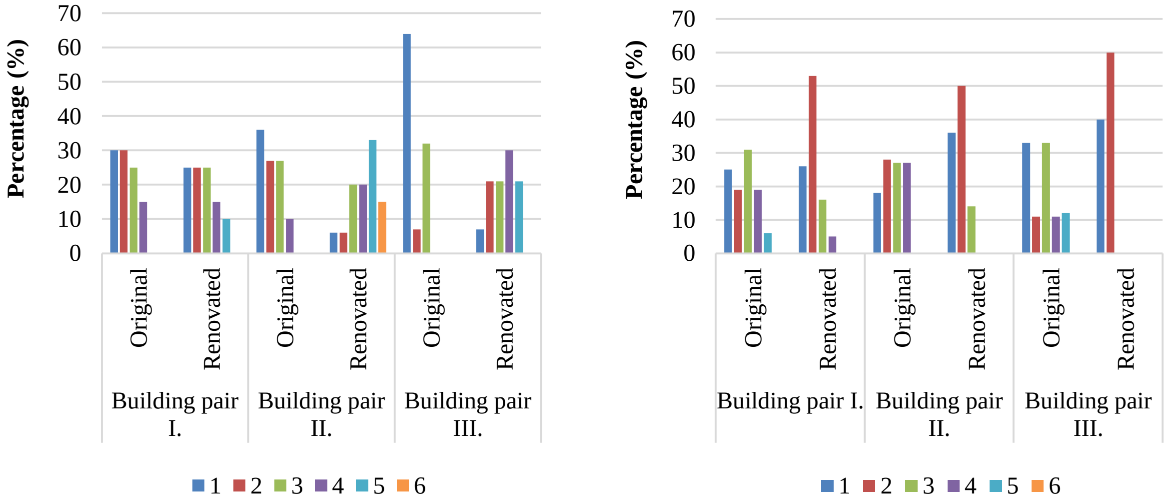


Figure 4.27 Summary of answers to the questions “How unpleasant do you think the indoor air quality is in your bedroom during night/in the morning?” The results are presented for each of the investigated residential building in winter (left) and summer (right).

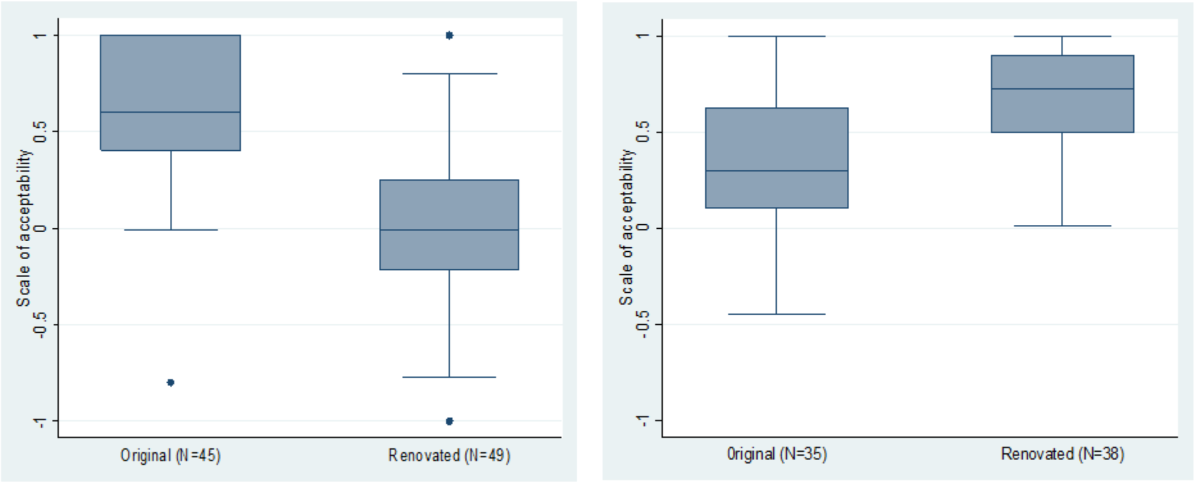
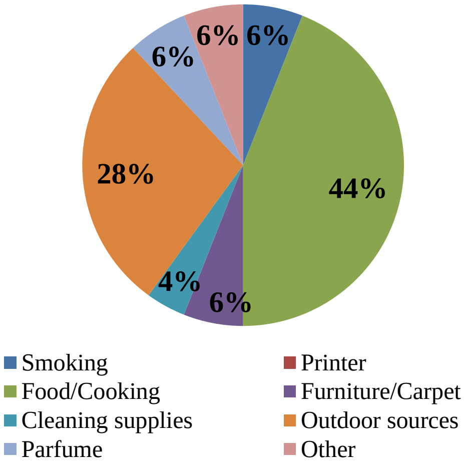


Figure 4.28 Boxplots of the acceptability of indoor air quality in the original and the renovated residential buildings in winter (left) and summer (right).

**Figure 4.29** and **Figure** 4.30 illustrate the distribution of the answers to the question “Which odors do you think contribute to unpleasant indoor air in your apartment?” From winter to summer there was a decrease in “food/cooking” (both building types) and “smoking” (renovated buildings) and increase was observed in “outdoor sources” (both building types) and “other sources” (renovated buildings), likely reflecting higher outdoor air ventilation in summer. In both winter and summer the original buildings had lower contribution of “printer”, “smoking” and higher perceived contribution of “outdoor sources” compared to the renovated dwellings. Smoking is always bigger portion in renovated buildings. According to the questionnaire survey higher percentage of occupants were smokers in the renovated buildings (38%) compared to the original buildings (27%). The differences in the winter may reflect higher AER in the original buildings. However the similar differences in the summer may indicate other reasons, such as socioeconomic differences between the occupants of the different buildings.



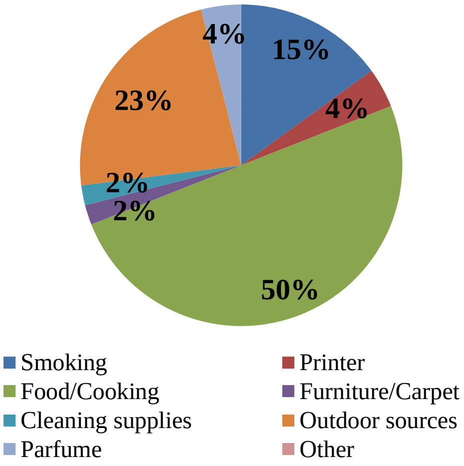


Figure 4.29 Percentage distribution of answers to the question “Which odours do you think contribute to unpleasant indoor air in your apartment?” in the original (left) and the renovated (right) residential buildings in winter.

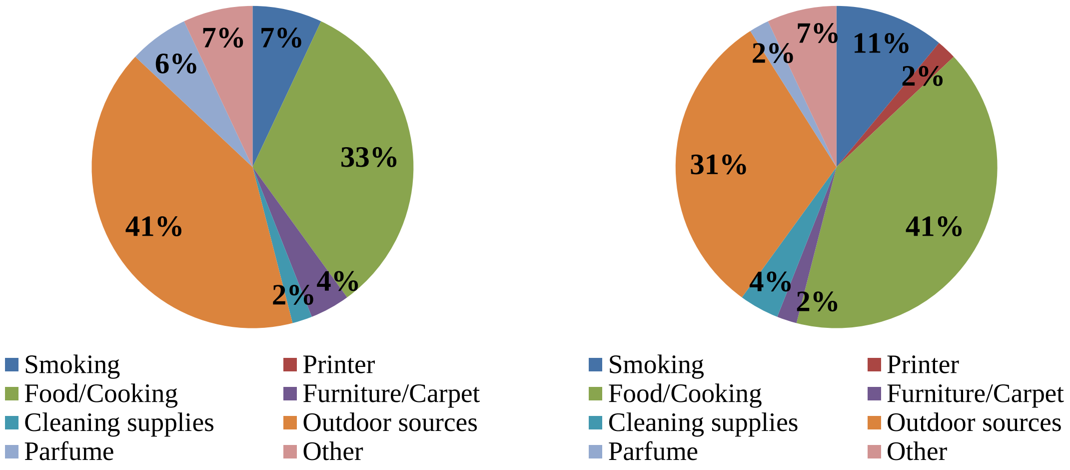


Figure 4.30 Percentage distribution of answers to the question “Which odours do you think contribute to unpleasant indoor air in your apartment?” in the original (left) and the renovated (right) residential buildings in summer.

### 4.2.2.4 Occupants´ airing habits

**Figure 4.31** shows the frequency of airing out in the bedrooms during day time (left) and at night (right). In winter, the frequency of airing out in the bedrooms was the same in the original and the renovated buildings during day-time. The majority of occupants aired out “more than once per day” (57%) or “daily or almost daily” (41%) in both building types. The rest of the occupants indicated to air out “at least once per week” (2%). In summer the majority of the occupants indicated to air out “more than once per day” during day-time in both types of dwellings with higher percentage obtained in the renovated buildings (84%) compared to the original buildings (67%).  28% of the residents in the original building and 16% in the renovated buildings aired out “daily or almost daily”. The rest of the occupants in the original building (5%) indicated that they are airing “at least once per week”.

At night, the percentage distribution of airing frequency was similar in both types of the dwellings both in winter and summer. In winter, 42% of the occupants in the original buildings and 47% in the renovated ones never aired out during night-time. 53% of resident in the non-renovated buildings and 45% in the renovated dwellings aired out only sometimes. Just a very small fraction of the occupants indicated that they air out often at night; 5% in the original and 8% in the renovated residential buildings. In summer, the majority of the occupants in both, the original (77%) and the renovated (79%) dwellings kept opened their windows at night.

The winter results show similar frequency of airing within the building types, both during day and night. While the duration of airing during the day was similar in the two building types (~70% ventilated less than 20 min.), during the night the residents in the original buildings indicated that they air out for longer periods (~60% longer than 45 min.), compared to the occupants in the renovated dwellings (~30% longer than 45 min.). This is consistent with the higher night time AER in the bedrooms of the original buildings. In the summer, residents in the renovated buildings aired out longer (<80% longer than 1 hour, >20% shorter than 45 min.), while shorter airing was more frequent in the original buildings (~60% 1 longer than 1 hour, ~40% for 45 min or less).

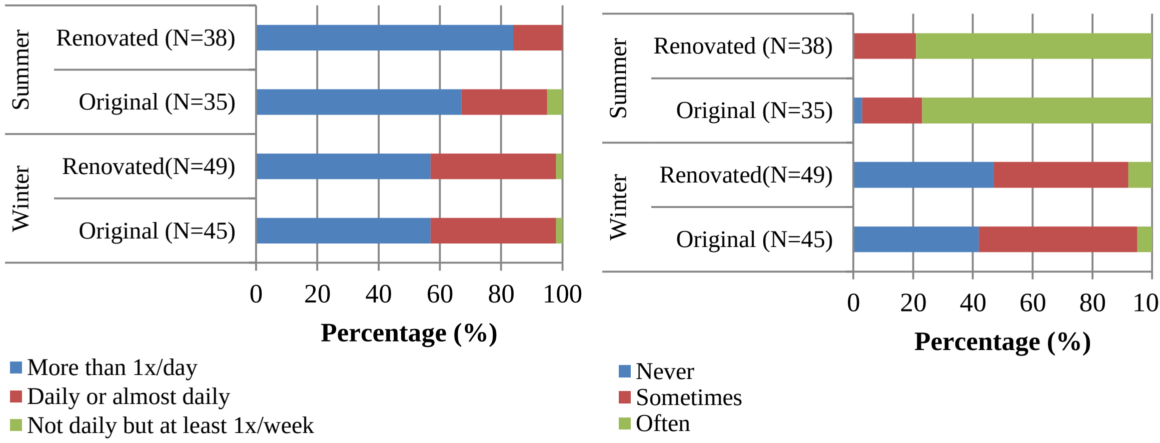


Figure 4.31 Frequency of airing in the bedrooms of the original and the renovated residential buildings during day-time (left) and at night (right), in winter and summer.

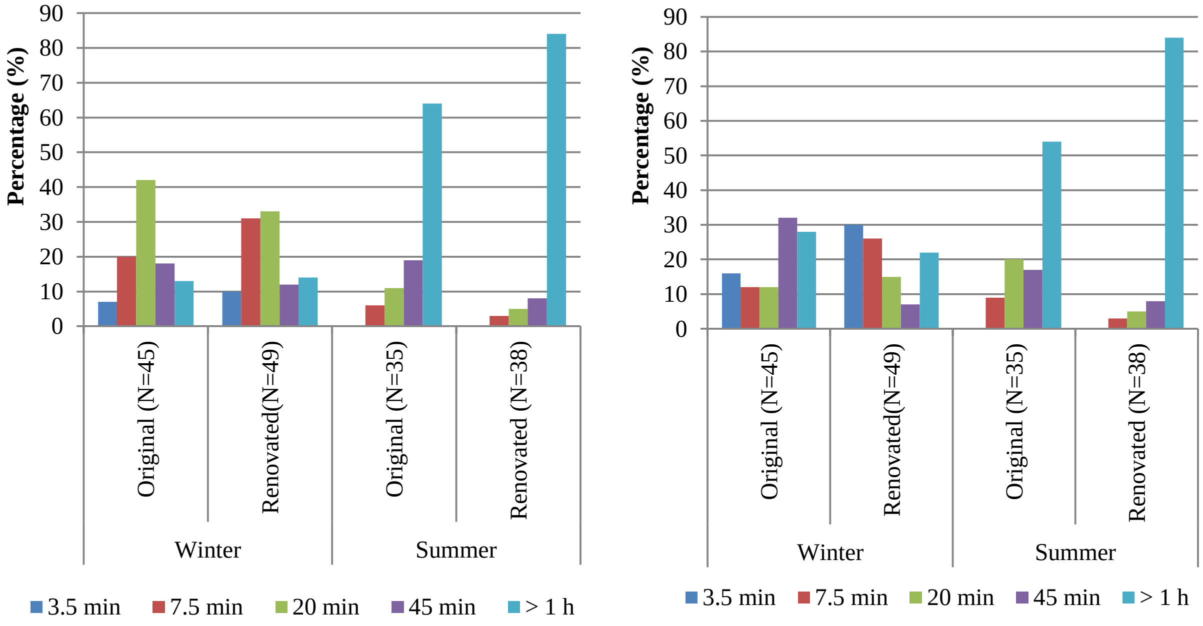


Figure 4.32 Duration of airing in the apartments of the original and the renovated residential buildings during day-time (left) and at nights (right), in winter and summer.

A large fraction of the occupants (78%) did not change their airing habits in winter after energy renovation took place **(Figure 4.33**). Only 22% of the residents indicated that they air more often than before renovation. This may have contributed to the lower AER in the retrofitted dwellings and 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.

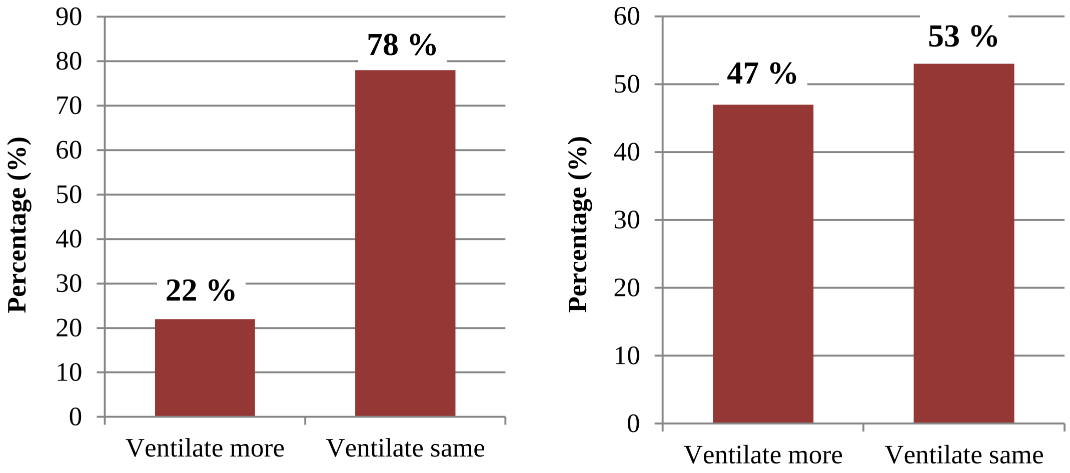


Figure 4.33 Change in the occupants' airing habits after renovation in winter (left) and summer (right).

#### 4.2.2.5 Sick building syndrome symptoms

The frequencies of sick building syndrome symptoms are shown in **Figure 4.34**, **Figure** 4.35, **Figure** 4.36**, Figure** 4.37 and **Figure** 4.38. 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). Positive ORs were found for $CO_2$ also for headache (OR=2.18, p=0.20) and fatigue (OR=2.00; p=0.19).

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.

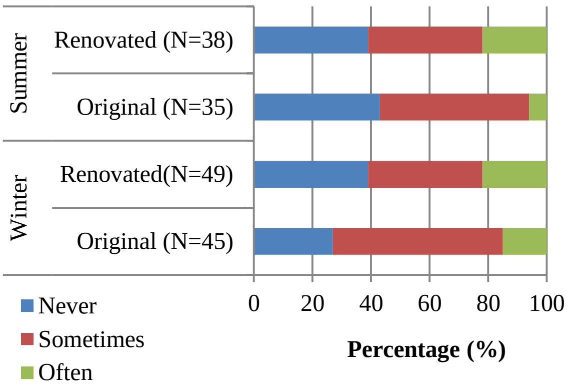


Figure 4.35 Headache

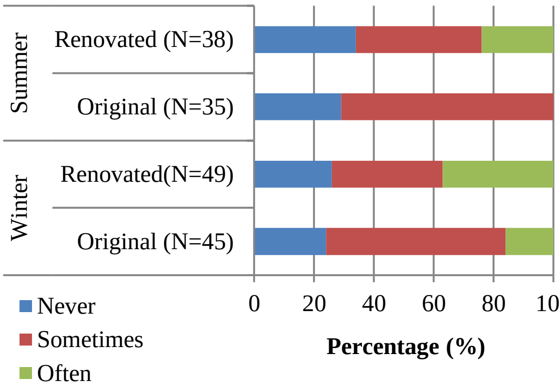


Figure 4.34 Fatigue

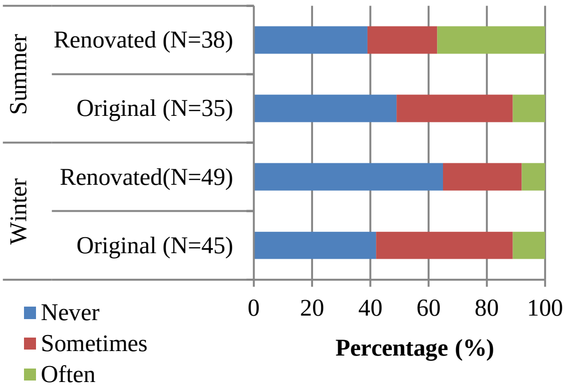


Figure 4.37 Itchy eyes

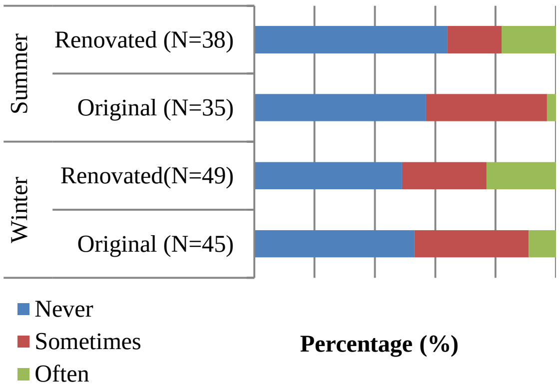


Figure 4.36 Nausea

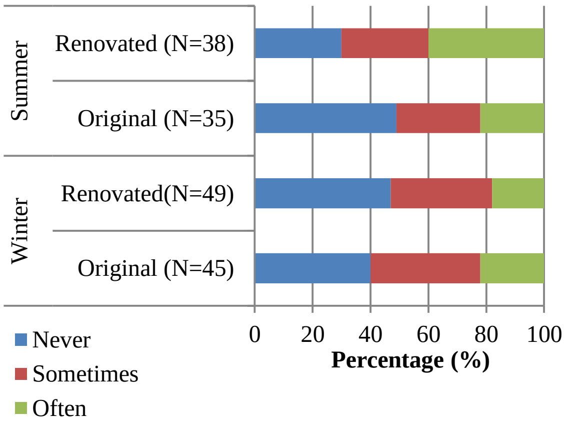


Figure 4.38 Dry skin

Table 4.9 Logistic regression of the occurrence of SBS symptoms (a-itchy eyes, b-headache, c-fatigue) in the investigated dwellings in winter.

a) Itchy eyes

| **Parameter/Itchy Eyes** | **OR** | **Std. Error** | **95% CI** | | **P-value** |
|---|---|---|---|---|---|
| $CO_2$ | 2.94 | 1.71 | 0.93 | 9.22 | 0.07 |
| Gender | | | | | |
| Reference: Female (N=54) | | | | | |
| Male (N=40) | 1.92 | 0.93 | 0.74 | 4.99 | 0.17 |
| Age | | | | | |
| Reference: <30 (N=11) | | | | | |
| 31-40 (N=19) | 0.96 | 0.86 | 0.16 | 5.61 | 0.96 |
| 41-50 (N=15) | 3.67 | 3.37 | 0.61 | 22.17 | 0.15 |
| 51-60 (N=12) | 2.07 | 2.02 | 0.31 | 14.03 | 0.45 |
| 61-70 (N=22) | 0.91 | 0.83 | 0.15 | 5.45 | 0.92 |
| >70 (N=15) | 2.32 | 2.25 | 0.35 | 15.48 | 0.38 |

b) Headache

| **Parameter/Headache** | **OR** | **Std. Error** | **95% CI** | | **P-value** |
|---|---|---|---|---|---|
| $CO_2$ | 2.18 | 1.33 | 0.66 | 7.21 | 0.20 |
| Gender | | | | | |
| Reference: Female (N=54) | | | | | |
| Male (N=40) | 1.19 | 0.57 | 0.46 | 5.88 | 3.08 |
| Age | | | | | |
| Reference: <30 (N=11) | | | | | |
| 31-40 (N=19) | 2.62 | 2.30 | 0.47 | 14.65 | 0.27 |
| 41-50 (N=15) | 13.33 | 16.56 | 1.16 | 152.24 | 0.04 |
| 51-60 (N=12) | 2.61 | 2.50 | 0.40 | 17.07 | 0.31 |
| 61-70 (N=22) | 2.02 | 1.82 | 0.35 | 11.83 | 0.43 |
| >70 (N=15) | 2.57 | 2.47 | 0.39 | 16.93 | 0.33 |

c) Fatigue

| **Parameter/Fatigue** | **OR** | **Std. Error** | **95% CI** | | **P-value** |
|---|---|---|---|---|---|
| $CO_2$ | 2.00 | 1.18 | 0.62 | 6.34 | 0.19 |
| Gender | | | | | |
| Reference: Female (N=54) | | | | | |
| Male (N=40) | 2.16 | 1.15 | 0.77 | 6.13 | 0.16 |
| Age | | | | | |
| Reference: <30 (N=11) | | | | | |
| 31-40 (N=19) | 2.53 | 2.19 | 0.46 | 13.78 | 0.28 |
| 41-50 (N=15) | 13.83 | 17.22 | 1.20 | 158.71 | 0.04 |
| 51-60 (N=12) | 2.00 | 1.81 | 0.34 | 11.80 | 0.35 |
| 61-70 (N=22) | 2.11 | 1.82 | 0.39 | 11.47 | 0.36 |
| >70 (N=15) | 2.36 | 2.15 | 0.39 | 14.07 | 0.32 |

## 4.3 Discussion

In the current case study, higher indoor air temperatures were observed in the renovated dwellings compared to the original buildings in both winter and summer season. The average indoor temperature was about 1°C higher in the retrofitted dwellings. It is currently unclear whether more airing was partly responsible for this temperature difference or whether better insulation lead to internal heat gains being trapped and the occupants aired out more especially, in the daytime, in order to decrease the indoor temperature. The indoor temperature may have been also influenced by solar shading and its operation. Although external shadings were observed in some of the apartments during the building visit, such data was however not available in this study. In addition, the summer indoor air temperatures in some apartments were lower than the average temperature of ~26°C. This was the case during one of the measurement weeks when the outdoor conditions were cooler. Decrease in outdoor temperature coupled with the occupants´ frequent airing habit in summer could be responsible for the decreased indoor temperature in some of the apartments.

In 18% of the apartments located in the original dwellings under-heating occurred (temperatures lower than 20°C) in winter. Kotol et al. (34) investigated Greenlandic households built in the second half of the 20th century. Under-heating was reported in 17% of the 79 investigated households. In Estonian (111) and Lithuanian (60) dwellings lower temperature than 20°C was found in about 30-40% of the studied apartments. Occupants may maintain low temperatures in order to minimize heating costs (112). However, some uninsulated dwellings built in the 20th century may have significantly lower temperatures during winter due to colder internal surfaces. Studies by Howden-Chapman et al (96), Liu et al (4) and Pustayova (76) concluded that fitting of older dwellings with insulation leads to significant increase of indoor air temperature and higher level of comfort in winter. In New Zealand households (96) 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 a Swedish study, the indoor temperature in retrofitted dwellings ranged between 21-25°C and in non-retrofitted homes it was between 19.7-21.8°C (4). In Slovak residential buildings (76) the average winter indoor temperature before implementing of energy saving measures was also lower (18.3-23.6°C) than in renovated dwellings (22.2°C-25.3°C).

Although under-heating was observed in some of the apartments in the original buildings, the occupants´ thermal acceptability in winter was similar in the original and the renovated dwellings. Residents in the original buildings indicated to be satisfied with lower average temperatures than in the renovated dwellings, where the inhabitants also felt comfortable in spite of higher obtained temperatures. In Sweden (4) after implementing energy saving measures neutral and slightly warm thermal sensation was observed and this corresponded to a relatively high satisfaction (10% dissatisfied).

Although the average indoor temperature in the summer was higher in the renovated dwellings, a trend towards warmer thermal sensation and significantly higher thermal acceptability was observed in the renovated buildings. Zhang et al (113) reported that people may indicate high thermal acceptability even at higher indoor temperatures. According to that study, significant drop-off below 80% satisfied occurred at 30°C in summer. The satisfaction with the thermal environment was within 80 and 90% at temperature range 24-29°C. The winter outcomes also showed fairly high percentage of satisfaction (75-90%) at temperatures between 17-25°C. It should be noted that the interpretation of our data is limited due to incomplete data on additional factors that might affect occupants´ thermal comfort (e. g. surface temperatures, air velocities, draft, occupants´ activity and their clothing insulation) (114).

In our study the implementation of energy saving measures was not combined with measures to improve the indoor environmental quality. This explains the lower AERs and higher $CO_2$ concentrations in the renovated buildings in the winter. An association was found between $CO_2$ concentration and building renovation, occupancy of the apartments and bedrooms, and occupants´ smoking habits. Smoking was always bigger portion in renovated buildings. According to the questionnaire survey higher percentage of occupants were smokers in the renovated buildings than in the original buildings. That might also contribute to poorer indoor air quality in the renovated dwellings. However, a stronger model could be achieved with the availability of additional parameters that influence natural ventilation, such as home location, orientation, indoor-outdoor temperature difference, wind conditions, position of windows, etc. (98; 115).

Kotol et al (34) assumed that in Greenlandic dwellings built after 1990 higher $CO_2$ concentrations were caused by tighter envelopes and thus lower ventilation rate due to lower infiltration. In homes built in the 1990´s the $CO_2$ concentration was 1490 ppm while in dwellings built within 1970-1990 the $CO_2$ concentration was lower, about 1245 ppm in average. The ventilation rate in Danish homes (115) built after 1993 was also significantly lower (0.53 $h^{-1}$) than in homes built between 1977-1993 (0.73 $h^{-1}$). The authors also attributed this to the fact that older buildings are leakier and newer ones are more air-tight, due to improved construction techniques and stricter regulations.

The winter results show similar frequency of airing within the building types, both during day and night. While the duration of airing during the day was similar in the two building types, during the night the residents in the original buildings indicated that they air out for longer periods compared to the occupants in the renovated dwellings. In the present study 22% of the occupants in the renovated buildings indicated that they air out more often during the winter than before renovation. However, this percentage did not seem to be adequate enough to achieve better IAQ. Results of the physical and subjective measurements indicate the need for more frequent airing in the renovated dwellings. In summer, 44% of the occupants reported that they ventilate more in their apartments after building renovation. Although they reported less frequent airing in the renovated buildings during daytime, airing lasted longer both during day and night, compared to the original buildings. Factors related to occupant behaviour (34; 116; 117) may also explain some of the differences in ventilation rates between the investigated buildings. People ventilate more often at higher ambient temperature. This contributes to significantly higher AERs in naturally ventilated buildings during summer (109; 118; 119) compared to winter.

It should be noted that these data rely on occupant reports. Monitoring of occupant behaviour related to airing would provide more reliable data. Even if in reality the people aired more in the renovated buildings, this airing might not have been sufficient to offset the lower infiltration after renovation. Also, airing in winter mainly occurs in the daytime and your AERs are determined for the night time. Moreover, Bekö et al (103; 115) reported that the position of the doors to the adjacent rooms may influence the total airflows into the bedrooms. However, in our study we did not find strong relationship between the AERs and the position of the bedroom door. This may have been the case because some of the questions related to occupant behaviour were asked only generally, without specifically referring to the week when the measurements were carried out.

Low ventilation rates have been linked to perception of poor indoor air quality (35; 120). In winter the occupants in the original buildings, where the AERs were significantly higher, perceived the indoor air quality to be better than in the renovated buildings, with lower AERs. Air tightness and insufficient ventilation in apartments in the renovated buildings may negatively impact the perceived indoor air quality. This is especially the case in winter, when air exchange rates in naturally ventilated dwellings are low. In summer the indoor air quality was perceived to be better in the renovated buildings. Airing out lasted longer in these dwellings. Interestingly, more acceptable indoor air quality in the original buildings was found in the winter, compared to summer ($p<0.05$). In the renovated buildings, the trend was opposite, poorer indoor air was observed in winter ($p<0.01$).

Earlier studies reported that the PAQ may be affected by renovation and age of the buildings. Jurelionis et al (95) found higher occurrence of stuffy air (64%) in the Lithuanian multifamily dwellings after their renovation than in their original condition (18%). The ventilation system was not refurbished so insulated walls and new windows decreased air infiltration creating more stuffy conditions. $CO_2$ concentrations reached up to 2000 ppm before renovation and 3000 ppm in the apartments located in the renovated building during regular occupation of the space. In a Swedish survey (63), occupants in dwellings constructed between 1986 and 2005 reported problem with perceived air quality. Stuffy air and unpleasant smell was the major concern. Problems with unpleasant smell were found to have the highest impact on overall satisfaction for the youngest respondent group (≤ 35 years). Occupants´ perception of indoor air quality was affected by the number of hours that they spent in their apartments during the weekdays. For occupants who left the apartment for less than 4 hours, the problems that had the highest impact on overall satisfaction were problems with unpleasant smell and dust ($p<0.01$). The acceptability with indoor air quality slightly increased in those cases where the residents were away for 5-9 hours and more than 10 ($p<0.05$). Moreover, occupants who left the apartment for 5–9 h on weekdays were found to be more sensitive to unstable temperature. The analysis also indicated that people who smoke were more sensitive to air quality.

In the current study higher $CO_2$ concentrations in the apartments were associated with higher prevalence of itchy eyes, fatigue and headache. The strongest association was found for itchy eyes. Building tightening followed by insufficient ventilation may explain this observation. Reducing ventilation rates to improve energy efficiency and lower carbon emissions, without providing effective ventilation strategy may cause occurrence of symptoms of SBS as well as long-term impact on human health (114; 120; 121). However, additional indicators of IAQ, such as concentrations of TVOC, formaldehyde and particles, together with data on the occupants' health and predisposition would be needed to more reliably disentangle the relationship between the changes in IAQ due to renovation and the observed symptoms.

Lessons can be learned from recent studies comparing IAQ in green or low energy houses with that in conventional buildings. Colton et al (122) investigated health benefits of green housing compared to conventional units. Adults living in green units reported fewer SBS symptoms than those living in conventional homes. Asthmatic children living in green homes experienced substantially lower risk of asthma symptoms than children living in conventional public housing. The authors concluded that green construction or renovation could simultaneously reduce harmful indoor exposures, promote resident health, and reduce operational costs.

# 5. INDOOR AIR QUALITY (CASE STUDY II)

## 5.1 Materials and methods

### 5.1.1 Studied buildings

The second case study was performed in one the previously investigated residential buildings (**Chapter 4.),** before and after its renovation (**Figure 5.1**). Taking into account the time aspects of building renovation process, the non-retrofitted dwelling from building type I was chosen for further investigation. The selected building was a nine storey residential dwelling with forty apartments located in the building 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, replacement of old windows for new energy efficient ones and hydraulic balancing of the heating systems.

The questionnaire survey and the measurement campaign were carried out during two winter seasons (**Figure 5.2**). 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 residential building, equally distributed on the lower, middle and highest storeys of the building. The same apartments were investigated in both winter seasons during a period of eight days.

Figure 5.1 View on the residential building in its original (left) and renovated (right) condition (Source: Author)

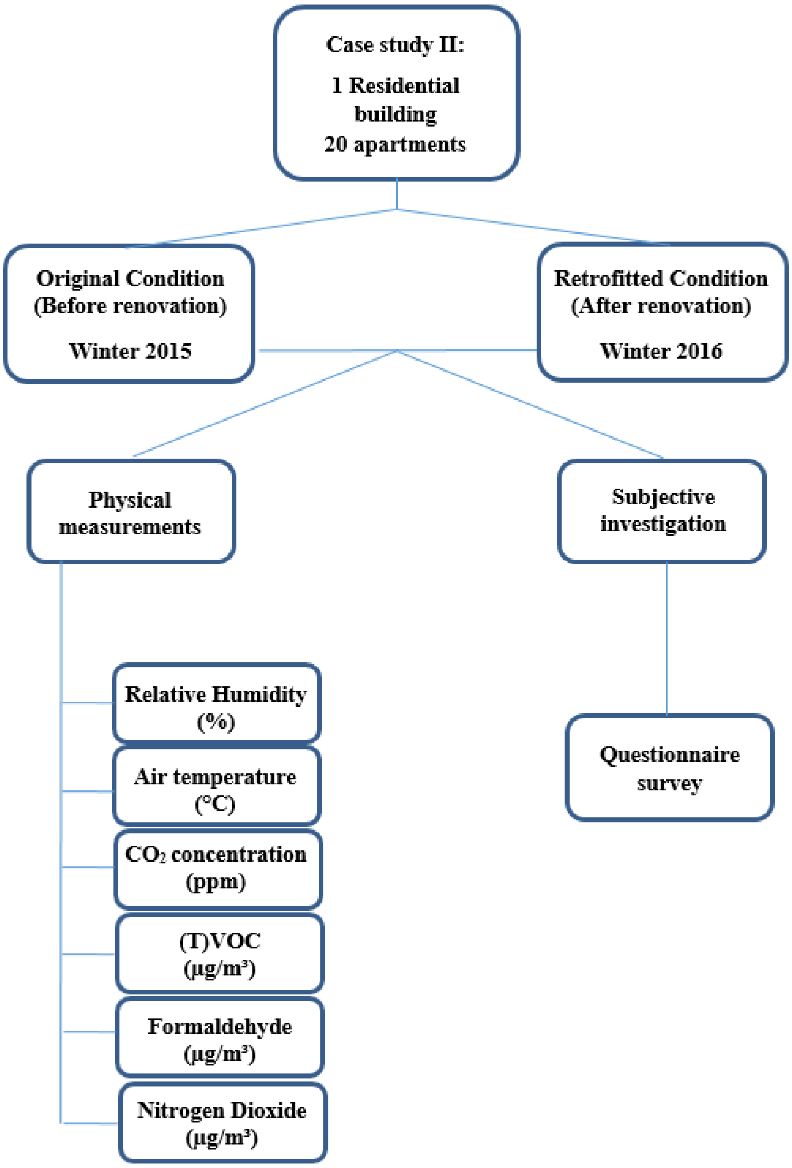


Figure 5.2 Data collection methodology for case study II

## 5.1.2 Data collection

### 5.1.2.1 Physical measurements

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 (**Chapter 4.**). HOBO U12-012 data loggers and CARBOCAP $CO_2$ monitors (**Figure 5.3**) were used for data recording. All the devices were calibrated before the measurement campaign began. The data were recorded in 5 minutes intervals for eight days in each apartment.

Figure 5.3 HOBO U12-012 and CARBOCAP CO2 monitors (Source: Author)

A set of passive samplers for $NO_2$, formaldehyde and VOC were placed centrally in living rooms of each investigated apartment (**Figure 5.4**). The samplers were always positioned at least 1.5 m above floor level. Locations near windows and radiators were avoided. One HOBO logger (temperature, relative humidity) with a $CO_2$ monitor, as well as an $NO_2$ sampler were placed on one of the balconies located on the third floor of the residential building, in order to monitor the outdoor conditions.

Figure 5.4 Set of passive samplers placed in one living rooms (Source: Author)

Sampling of $NO_2$ was carried out using IVL´s (Swedish Environmental Research Institute) diffusive samplers (**Figure 5.5**) (123; 124). The samplers had cylinder shape with a diameter of 25 mm and height of 13 mm. They were kept in a plastic semi-transparent container sealed with a cap during the transport and storage. The containers were also sealed in plastic bags. When the measurement started the sampler was removed from its storage container. The capped container unit was saved until it was time to put the exposed sampler back again. The removed sampler from the container was fixed firmly to the tool holder with the grey net mesh pointing downwards. The outdoor $NO_2$ sampler was protected by plastic shelter from rain and snow. Exposure started as soon as the containers became opened. The gas molecules diffused into the sampler where they were quantitatively collected, which gave a concentration value integrated over time. The uptake rates were not experimentally determined but they were calculated using Fick's first law of diffusion and they were validated against calibrated $NO_2$ monitor. The obtained results were concentrations integrated over the time of sampling. It was used to determine the average concentration of the target pollutant in the air during the measured time period. $NO_2$ was analysed by wet chemical techniques using a spectrophotometric method. The sampling and analytical procedures were accredited by the Swedish accreditation agency SWEDAC. The measurement uncertainty was 10% at 95% confidence level and the measurement range for one week sampling was 0.4 – 400 $\mu g/m^3$. The exact start and stop date and time, average indoor temperature and sampling location were noted on the field protocol. After the measurements finished the samplers were returned to IVL´s laboratory for analyses.

Figure 5.5 $NO_2$ sampler (Source: Author)

Formaldehyde was sampled using DSD-DNPH UmeX-100 (SKC Inc., Eighty Four, PA, USA). The sampling period and the analytical technique followed the ISO 16000-4 (125). The samplers (**Figure 5.6, Figure 5.7**) comprised of a porous polyethylene tube, which acts as the diffusive membrane, to which is attached a small polypropylene syringe used for the elution of the analyses from the adsorbent. Because the diffusive membrane is round, it permits exposure from all sides, making it unique compared to other diffusive samplers. Silica gel coated with 2.4-dinitrophenylhydrazine (DNPH) acts as the adsorbent and moves from the diffusive end during sample collection to the syringe end for sample extraction, by inverting the device. The limit of detections were 0.03 $\mu g/m^3$ and 0.05 $\mu g/m^3$ for formaldehyde and acetaldehyde, respectively.

The formaldehyde tubes were sealed in aluminium laminated bags and stored in refrigerator at 4°C before the measurement started. Sampling started as soon as the tubes were taken out from the aluminium bag and the plastic tube shelter was removed. The absorbent from the PP reservoir was moved to the connected diffusion filter by orienting the PSP tube vertically. The vertically oriented tubes were hanged on the same tool holder as the $NO_2$ samplers. Aldehydes in gases were trapped in the diffusive sampling device by reacting with DNPH in the sampler to form stable hydrazine derivatives. After the measurement period, exposure was ended by inverting the sampling tubes to return the absorbent from the sampler holder to the plastic shelter and packed to the aluminium bags. The start and stop date and time, and sampling location were noted on the field protocols situated on the front side of the aluminium bags. High performance liquid chromatography analyses of the samplers were carried out in laboratory of IVL.

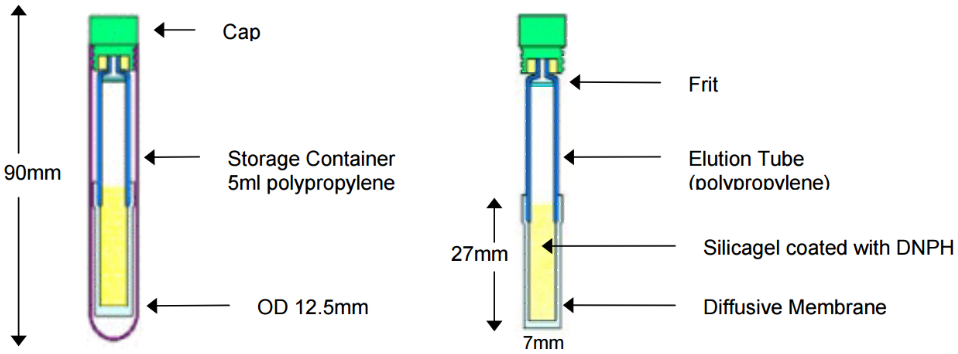


Figure 5.6 Identification of parts of the DSD-DNPH formaldehyde tubes (Source: www.sigmaaldrich.com)

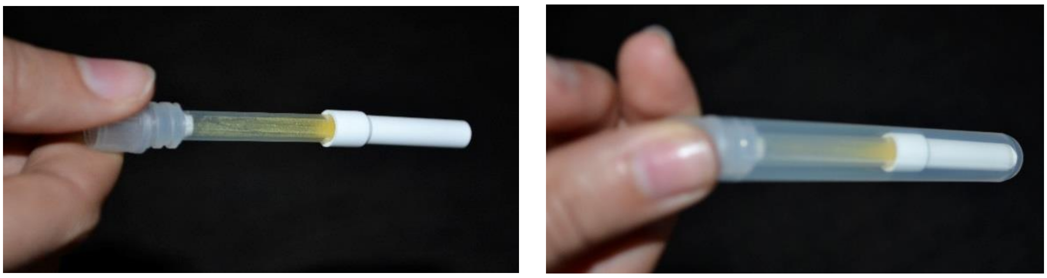


Figure 5.7 Formaldehyde tube (Source: Author)

Perkin-Elmer adsorption tubes (**Figure 5.8**) filled with 200 mg Tenax TA, were used for passive sampling of VOC, and their analyses was carried out in compliance with ISO 16017-2 (126). This tube is characterised by its chemical inertness, capacity to trap compounds with a large range of volatility and highly hydrophobic nature. It consists of a 90 mm long stainless steel tube with outside diameter of 6.3 mm, within which the adsorbent is retained. The tubes were plugged on both ends with plastic or brass swagelock caps with PTFE ferrules. 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. The sampling started after the cap was removed. The tube was hanged on the tool holder and oriented to vertically position with its opened edge pointing to the direction of the floor. After the measurement ended the sampler was closed by its cap. The time details of the measurement were noted in the time protocol. After the Tenax tubes were shipped back to Sweden, a gas chromatography/mass spectrometry analysis of the tubes was carried out. The gas chromatogpraph oven temperature program was started at 60 °C, held for 2 minutes then increased to 100 °C at 4 °C/min, then increased to 280 °C at 6 °C/min, with hold time 15 minutes. The limit of detection for the individual VOC was 0.2 µg/m$^3$ based on 3 times the signal-to-noise ratio.

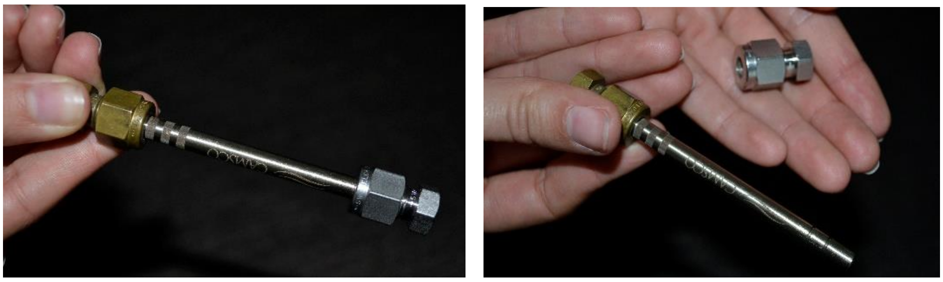


Figure 5.8 VOC Tenax tube (Source: Author)

### 5.1.2.2 Questionnaire survey

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 (**Chapter 4.**). However minor modifications were implemented in some of the questions.

### 5.1.2.3 Air exchange rate calculation

The air exchange rate calculation followed the methodology presented in **Chapter 4**. Briefly, the $CO_2$ concentration build-up period was used to estimate the air exchange rates for each respective night in the occupants´ bedrooms across the twenty investigated apartments. Decays of the $CO_2$ concentration were used when the $CO_2$ level began to fall towards the background level in the air, i.e. when the room was already occupied in the evening and the occupants indicated to ventilate before falling asleep. However, this case occurred rarely. Sometimes, the build-up or decay was not clearly defined within the selected data. In such a situation the air exchange rate was determined using a mass balance model applied on the estimated steady-state $CO_2$ concentration. $CO_2$ concentrations obtained between 20:30 and 6:30 each measurement night, occupants´ body weight and height and room volume were used in the calculation.

### 5.1.2.4 Data analysis

STATA statistical tool was used for data analyses. Pearson's correlation coefficient (r) and the corresponding significance (p-value) was used to look for correlations between variables. When the data followed a normal distribution, paired t-test was used to compare the obtained results from the investigated apartments before and after renovation. P-value lower than 0.05 was considered statistically significant. P-value between 0.05 and 0.1 was considered moderately significant. The nonparametric Wilcoxon signed rank test was used to compare two sets of not normally distributed data that was obtained from the same participants. Logistic regression was used to look for associations between the symptoms of sick building syndrome and a variety of variables. More detailed description of the regression test is presented in **Chapter 4**.

## 5.2 Results

### 5.2.1 Temperature and relative humidity

**Table 5.1** presents the descriptive statistics for indoor air temperature and relative humidity. Both, the data of temperature and the relative humidity were lognormally distributed. The overall average air temperature was significantly higher in the dwelling after renovation ($p \leq 0.01$). The average temperature was 20.9 °C before the renovation and it increased to 22.2 °C after renovation (**Figure 5.9, left**).

Although, the grand mean air temperature met the thermal comfort criteria during the heating season (110) under both the original and the renovated condition, the average temperatures in 25% of the apartments before renovation did not fulfil the criterion of the optional range (20-24°C) (**Figure 5.10, left**). Under-heating occurred in these particular apartments, where the mean temperature ranged between 18.3 °C and 19.7 °C. Similar finding was observed in Case study I (**Chapter 4**). After renovation all the twenty apartments met the required range of the thermal comfort criteria. The average temperature was within 20.6 °C and 24 °C in the bedrooms.

Table 5.1 Descriptive statistics of the indoor air temperature and relative humidity

| **Descriptive statistics** | **Before Renovation (N=20)** | | **After Renovation (N=20)** | |
|---|---|---|---|---|
| | **Temperature (°C)** | **Relative Humidity (%)** | **Temperature (°C)** | **Relative Humidity (%)** |
| Grand Mean<br>(Min.-Max.) | 20.9<br>(18.7-23.9) | 46<br>(34-61) | 22.2<br>(20.6-24.0) | 48<br>(39-59) |
| Geometric Mean | 20.8 | 46 | 22.2 | 48 |
| Median | 20.8 | 45 | 22.3 | 48 |
| Std. Dev. | 1.5 | 7.8 | 0.9 | 5.8 |
| Std. Err. | 0.32 | 1.74 | 0.20 | 1.29 |
| 95% CI | 20.3-21.6 | 43-50 | 21.8-22.7 | 45-51 |

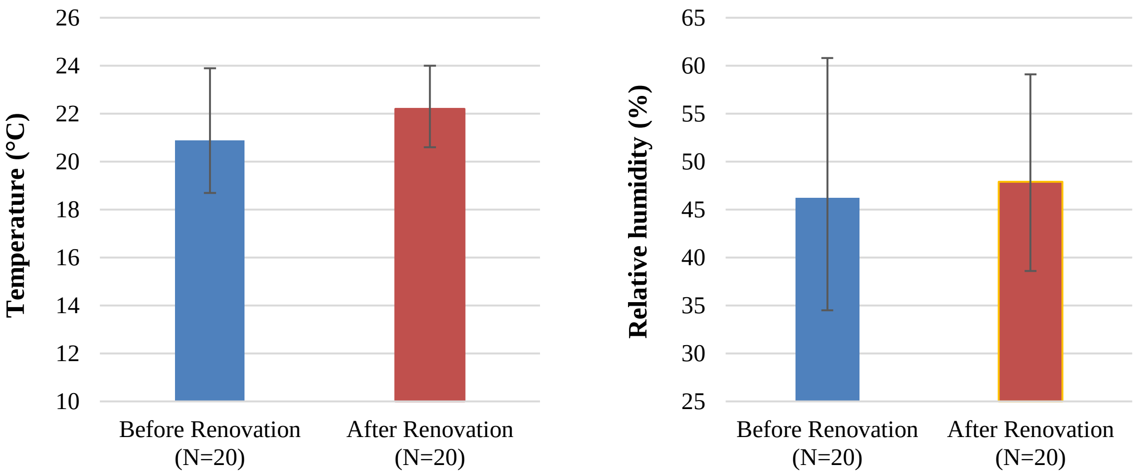


Figure 5.9 Grand average of indoor air temperature (left) and relative humidity (right) before and after renovation of the residential building in winter. The whiskers represent the minimum and maximum average values.

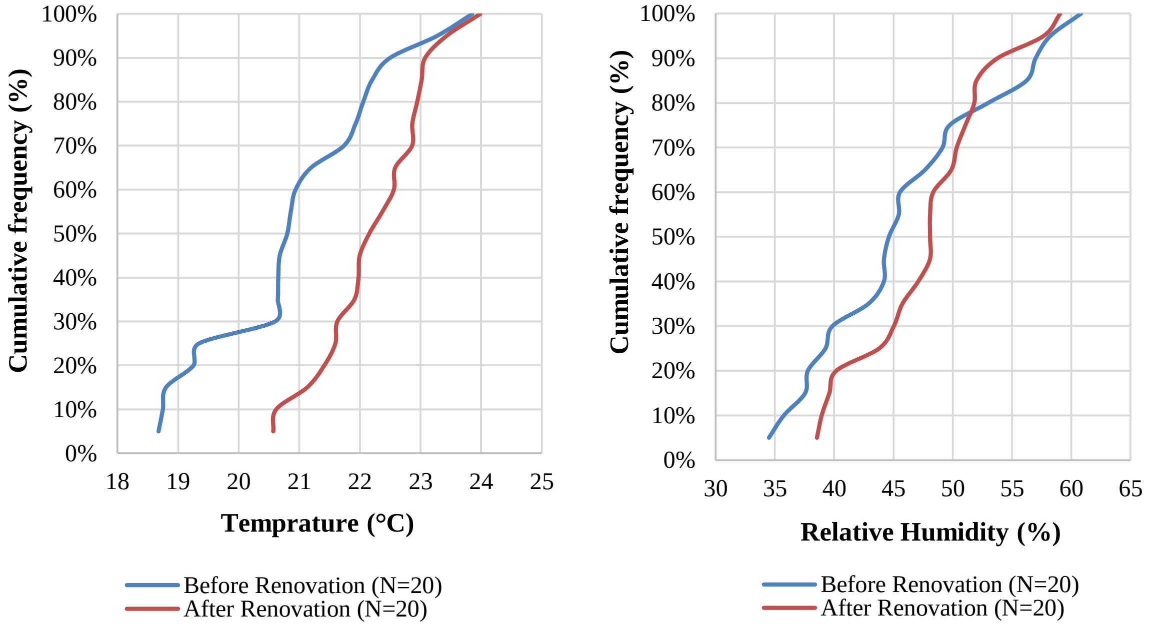


Figure 5.10 Cumulative frequency distribution of the average indoor air temperature (left) and relative humidity (right) in the bedrooms before and after renovation of the residential building in winter.

The grand mean of relative humidity was slightly lower before renovation (46%) than after renovation (48%), (**Figure 5.9, right**). The difference in relative humidity between the two conditions was not statistically significant (p>0.1). Before the renovation, the average relative humidity in one of the apartments exceeded the maximum recommended limit. In the post-renovated condition all the apartments were within the recommended comfort range (**Figure 5.10**, **right**), (110).

The average outdoor temperature was slightly higher during the first round of measurements (3.3 °C; ranged between -2.0 and 8.0°C) than within the period of the second round of the experiments (2.8 °C; ranged between -5.9 and 11.3°C). The lowest values were measured during the night-time. The outdoor relative humidity was similar between the two periods. 80% average humidity was observed during the first period of experiments (ranged from 58 to 89 %), and it was 77% (ranged within 49 and 86%) one year later when the measurements were repeated.

### 5.2.2 $CO_2$ concentration

**Figure 5.11** presents boxplots of the indoor $CO_2$ concentration before and after renovation of the buildings. The obtained data were log-normally distributed. In the boxplots, the bottom and the top of the boxes represent the 25th and 75th percentiles and the line near the middle of the box is the median. The ends of the whiskers indicate the 10th and 90th percentiles. The grand averages are presented by empty circles in the middle of the boxes. The difference in $CO_2$ concentration between the pre-retrofit and post-retrofit condition of the dwelling showed to be statistically significant ($p<0.05$). The grand average was 1205 ppm, and the median was 1190 ppm before renovation. After implementing energy saving measures the $CO_2$ concentration visibly increased. The mean was 1570 ppm and the median was 1510 ppm. The day and night-time division of the data presented in **Table 5.2** also showed to be statistically significant ($p<0.05$).

The overall means obtained for each of the apartment were compared before and after the building renovation. **Figure 5.12** shows the average $CO_2$ concentration during the day-time across the investigated apartments. In 70% of the apartments the $CO_2$ concentration increased after renovation. The ratio of $CO_2$ concentration after renovation to that before ranged between 1.09 and 3.2 (average ratio was 1.52). In the rest of the apartments the $CO_2$ concentration during the day-time did not change significantly after renovation. The ratio range was from 0.73 to 0.93 (average ratio was 0.85). It should be noted however, that the day-time occupancy between the two measurement weeks a year apart may have been different. However, the measured bedrooms were likely unoccupied during most of the day-time periods.

Night-time occupancy is more likely unchanged between the two measurement periods. During night-time increase of $CO_2$ concentration was observed in each of the investigated apartments (**Figure 5.13**). The ratios presenting the changes in $CO_2$ concentration before and after renovation were between 1.03 and 3.6 (average ratio after-to-before was 1.49). According to the questionnaire survey, no obvious changes were observed in occupancy of bedrooms during the two weeks measurement periods which were a year apart.

Table 5.2 Descriptive statistics of the $CO_2$ concentrations (ppm)

| **Descriptive statistics** | **Before Renovation (N=20)** | | **After Renovation (N=20)** | |
|---|---|---|---|---|
| | **Day** | **Night** | **Day** | **Night** |
| Grand Mean<br>(Min.-Max.) | 1040<br>(595-1550) | 1410<br>(750-2665) | 1320<br>(790-2210) | 1925<br>(865-3575) |
| Geometric Mean | 1005 | 1325 | 1265 | 1825 |
| Median | 1030 | 1300 | 1300 | 1870 |
| Std. Dev. | 280 | 515 | 400 | 660 |
| Std. Err. | 62.6 | 114.7 | 89.7 | 146.8 |
| 95% CI | 910-1170 | 1170-1650 | 1130-1510 | 1620-2235 |

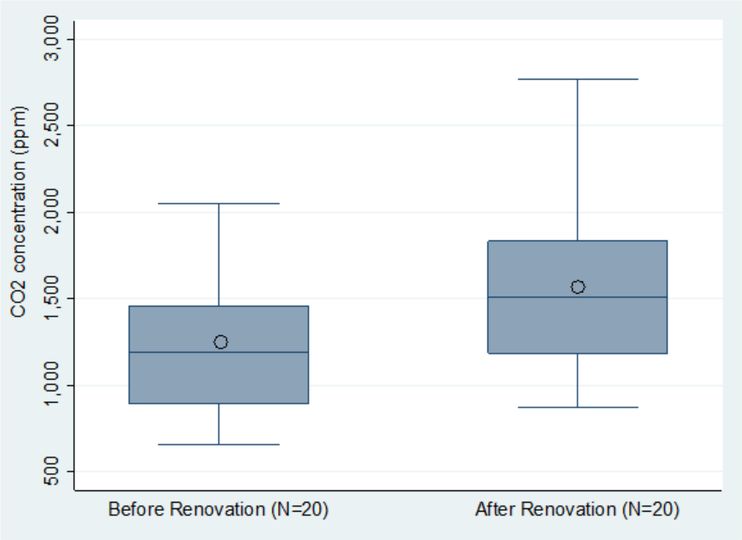


Figure 5.11 Boxplots showing the $CO_2$ concentration before and after renovation of the residential building.

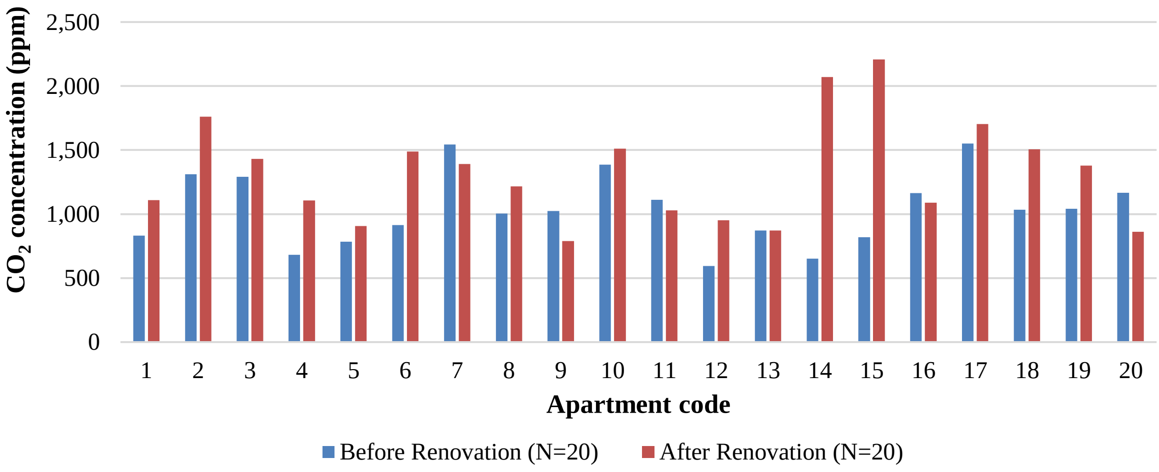


Figure 5.12 Average $CO_2$ concentration in each of the apartments during the day before and after renovation of the residential building.

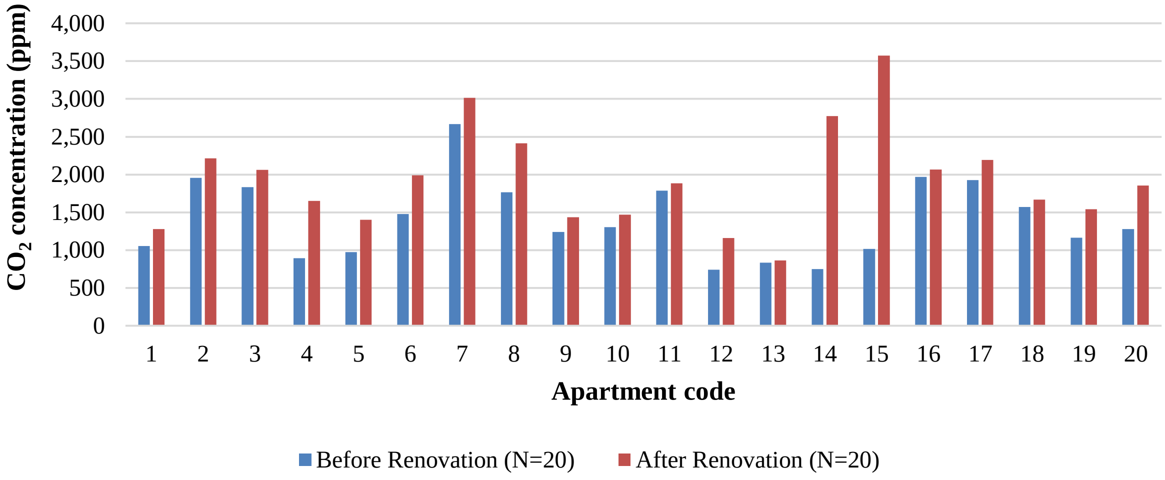


Figure 5.13 Average $CO_2$ concentration in each of the apartments during the night-time before and after renovation of the residential building.

The frequency distribution of the average $CO_2$ concentrations is shown in **Figure 5.14**. The fractions of the apartments where the average $CO_2$ concentration exceeded 1000, 1500, 2000, 2500 and 3000 ppm, both for day and night-time, are presented in **Table 5.3**. Higher number of the apartments exceeded 1500 ppm and upper concentrations during both, day and night time after renovation than before renovation.

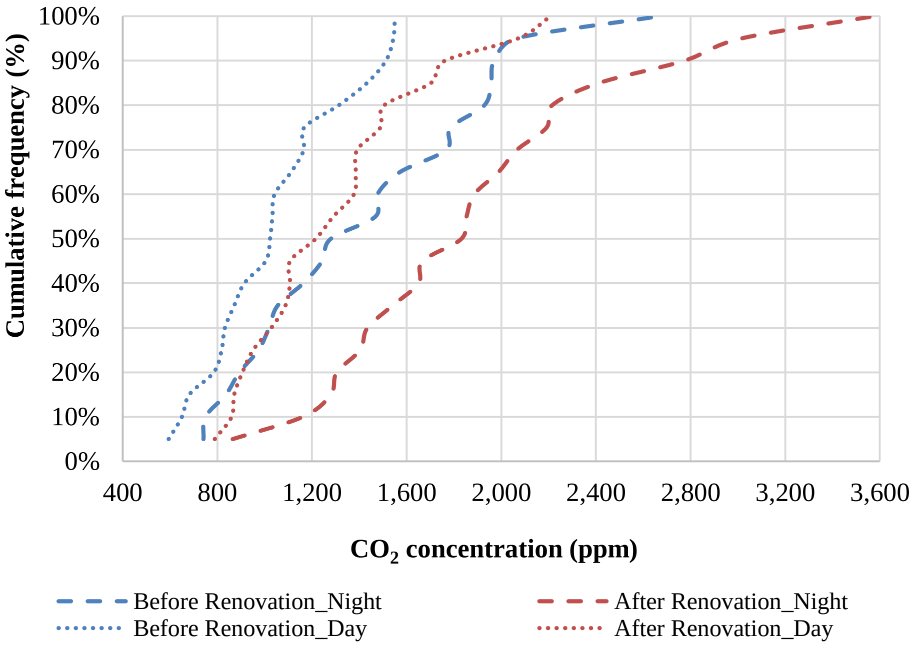


Figure 5.14 Cumulative frequency distribution of the average $CO_2$ concentration in the bedrooms during the day and night-time before and after renovation of the residential buildings.

Table 5.3 Number of average day and night-time $CO_2$ concentrations above four cut-off values in the residential building before and after its renovation

| **Cut-off values of $CO_2$ concentrations** | **Day** | | **Night** | |
|---|---|---|---|---|
| | **Before Renovation (N=20)** | **After Renovation (N=20)** | **Before Renovation (N=20)** | **After Renovation (N=20)** |
| $CO_2$ >1000 ppm | 12 (60%) | 15 (75%) | 15 (75%) | 19 (95%) |
| $CO_2$ >1500 ppm | 2 (10%) | 6 (30%) | 8 (40%) | 14 (70%) |
| $CO_2$ >2000 ppm | 0 | 2 (10%) | 2 (10%) | 8 (40%) |
| $CO_2$ >2500 ppm | 0 | 0 | 1 (5%) | 3 (15%) |
| $CO_2$ >3000 ppm | 0 | 0 | 0 | 2 (10%) |

### 5.2.3 Air exchange rate (AER)

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 5.15**, **Table 5.4)**. The correlation between the one week average night-time $CO_2$ concentrations and AERs is presented in **Figure 5.17**. The values obtained before and after renovation are presented together, and each dot characterises one apartment.

Table 5.4 Descriptive statistics of the air exchange rate ($h^{-1}$).

| **Descriptive statistics** | **Before Renovation (N=20)** | **After Renovation (N=20)** |
|---|---|---|
| Grand Mean<br>(Min.-Max.) | 0.61<br>(0.32-1.15) | 0.44<br>(0.21-0.76) |
| Geometric Mean | 0.58 | 0.42 |
| Median | 0.59 | 0.45 |
| Std. Dev. | 0.20 | 0.13 |
| Std. Err. | 0.04 | 0.03 |
| 95% CI | 0.51-0.70 | 0.38-0.50 |
| p-value | 0.001 | |

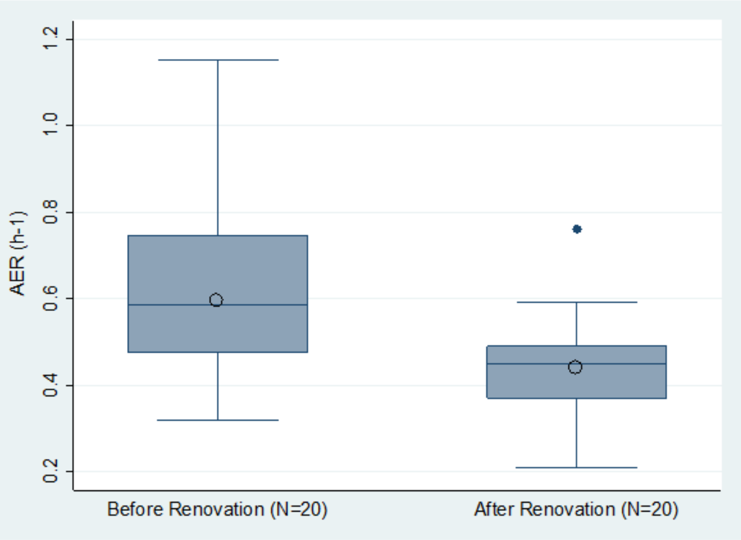


Figure 5.15 Boxplots showing the AER before and after renovation of the residential building

The cumulative frequency of AERs (**Figure 5.16**) and the distribution of average AER by apartments ( **Figure** 5.18) show that 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 in 85% of the apartments (ranged from 0.21 to 0.49 $h^{-1}$) lower AER than 0.5 $h^{-1}$ was observed. In the rest of the apartments the AER also dropped, but the values still were above the minimum requested criterion (ranged from 0.50 to 0.76 $h^{-1}$). AERs dropped after renovation in 19 apartments (95%). Ratios showing by how much the changes occurred in AERs across those apartments where the AER dropped after renovation (N=19) was within 0.04 to 0.77.

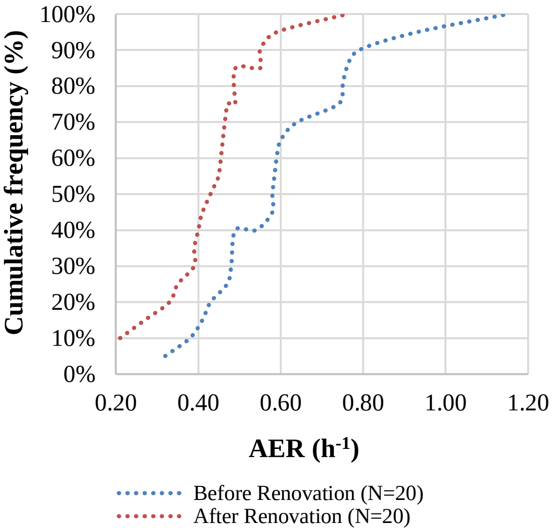


Figure 5.16 Cumulative frequency distribution of the average air exchange rates in the bedrooms before and after renovation of the residential building.

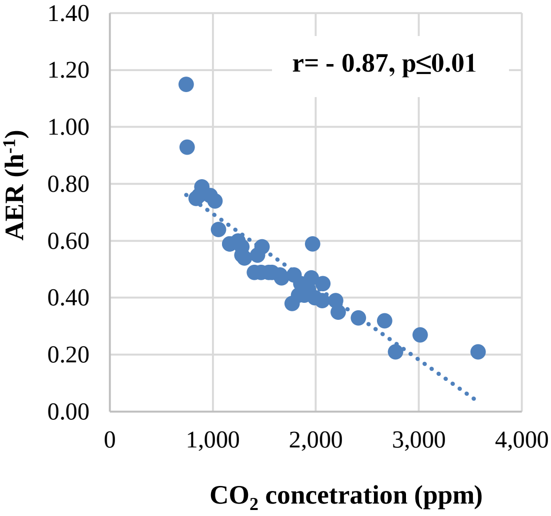


Figure 5.17 Correlation between AER rate and night-time $CO_2$ concentration. One dot represents one apartment (N=40).

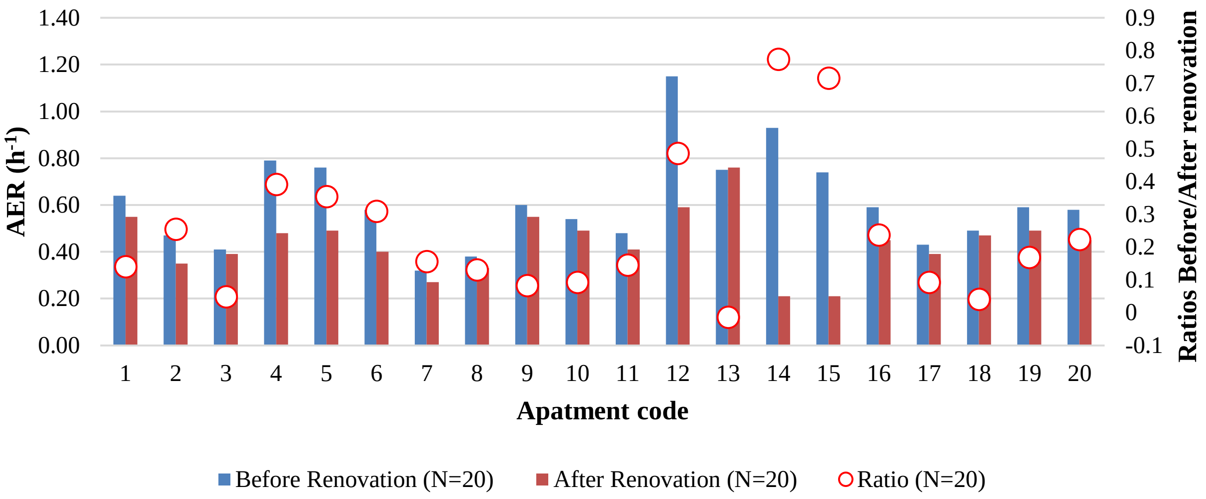


Figure 5.18 Average AERs in each of the apartments before and after renovation of the residential building.

### 5.2.4 $NO_2$ concentration

The $NO_2$ concentration was characterised by log-normal distribution. According to the WHO Guidelines for Indoor Air Quality the recommended maximum value of $NO_2$ concentrations indoors is 40 $\mu g/m^3$ (127). The average concentrations across all apartments were lower than the maximum recommended limit in both conditions of the dwelling (Table 5.5 Descriptive statistics of the indoor NO2 concentration ($\mu g/m^3$)**Table 5.5**). The maximum recommended limit of $NO_2$ concentration was exceeded in only one apartment, where the $NO_2$ was slightly above the maximum recommended value (42.1 $\mu g/m^3$) before renovation (**Figure 5.20 and 5.21**). Lower average $NO_2$ concentration was observed in the apartments before renovation (**Figure 5.19**). 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).

Table 5.5 Descriptive statistics of the indoor $NO_2$ concentration ($\mu g/m^3$).

| **Descriptive statistics** | **Before Renovation (N=20)** | **After Renovation (N=20)** |
|---|---|---|
| Grand Mean (Min.-Max.) | 15.4 (6.1-42.1) | 16.5 (4.5-36.2) |
| Geometric Mean | 13.4 | 14.5 |
| Median | 13.5 | 16.3 |
| Std. Dev. | 8.9 | 8.3 |
| Std. Err. | 1.9 | 1.8 |
| 95% CI | 11.2-19.6 | 12.6-20.3 |
| p-value | 0.68 | |

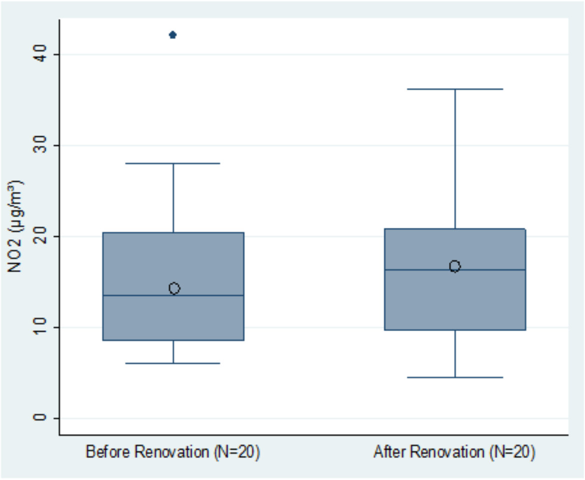


Figure 5.19 Boxplots showing the $NO_2$ concentration before and after the renovation of the residential building.

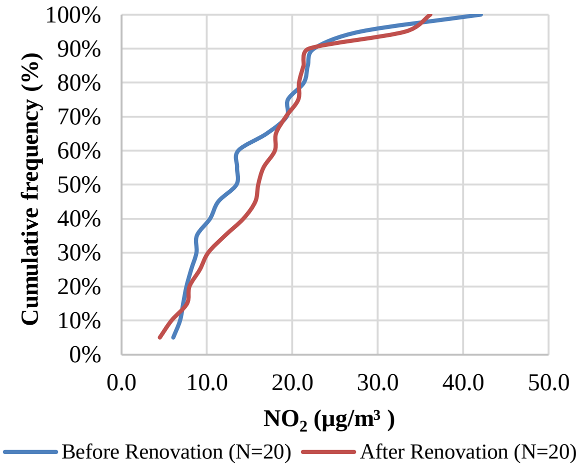


Figure 5.20 Cumulative frequency distribution of the $NO_2$ concentration in the apartments before and after renovation of the residential building.

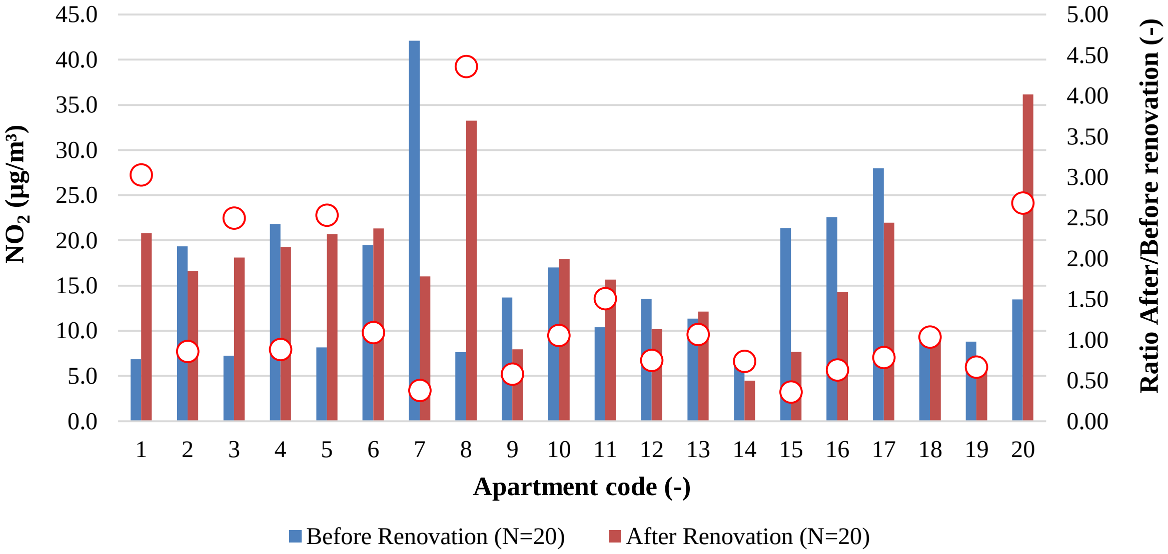


Figure 5.21 $NO_2$ concentration in each of the apartments before and after renovation of the residential building. The circles present the ratio between the obtained concentrations (after/before renovation).

The outdoor concentration of $NO_2$ was 10.1 and 14.6 µg/m³ during the first round of the measurements. During the second round of measurements the outdoor concentration was 12 µg/m³. The ratios between the indoor and outdoor concentration showed that in many apartments the indoor $NO_2$ was higher than the outdoor concentration (**Figure 5.22**). Higher indoor $NO_2$ concentrations compared to outdoors indicate the presence of indoor sources (32; 98).

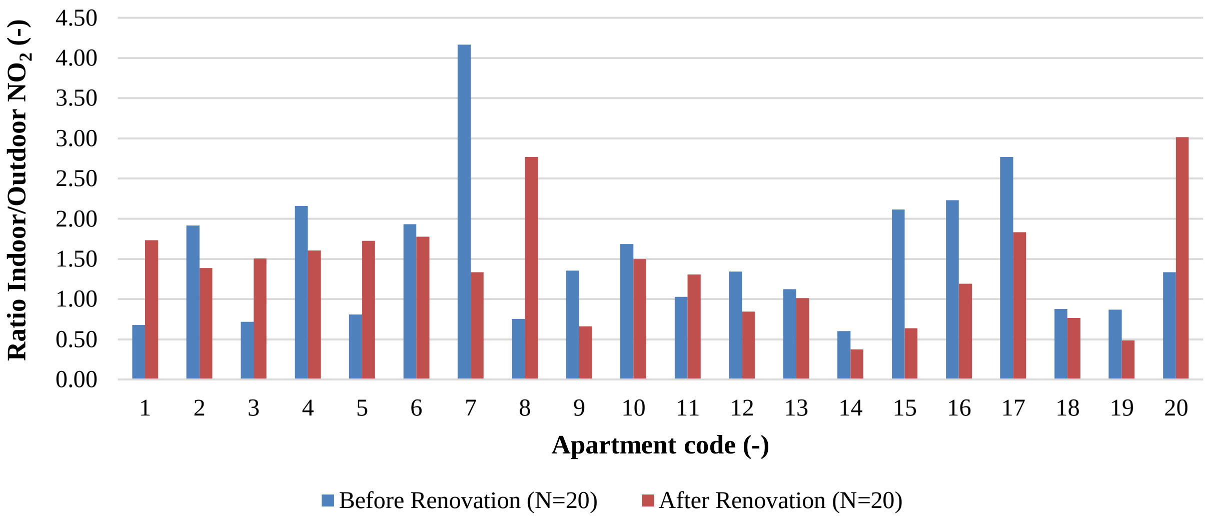


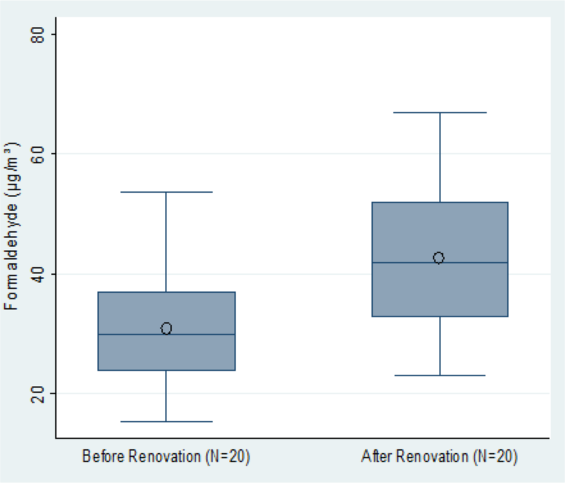
Figure 5.22 Ratios between indoor and outdoor $NO_2$ concentration before and after renovation of the residential building

### 5.2.5 Formaldehyde

**Figure 5.23** shows boxplots of the formaldehyde concentrations before and after renovation of the building. In both cases the data were log-normally distributed. The difference between results 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 (**Table 5.6**). The World Health Organisation recommends a maximum formaldehyde concentration of 100 µg/m³ (127). 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 (**Figure 5.24**). Among these apartments, the ratio of formaldehyde concentrations after and before renovation was between 1.09 and 2.5 (average range was 1.62); (**Figure 5.25**). In the rest of the apartments only slight decrease was observed in formaldehyde concentrations (ratio between 0.82 to 0.94; average 0.89).

Table 5.6 Descriptive statistics of the formaldehyde concentration (µg/m³)

| Descriptive statistics | Before Renovation (N=20) | After Renovation (N=20) |
|---|---|---|
| Grand Mean<br>(Min.-Max.) | 32<br>(15-54) | 43<br>(23-67) |
| Geometric Mean | 30 | 41 |
| Median | 30 | 42 |
| Std. Dev. | 9.4 | 12.9 |
| Std. Err. | 2.1 | 2.9 |
| 95% CI | 27-36 | 37-49 |
| p-value | 0.002 | |



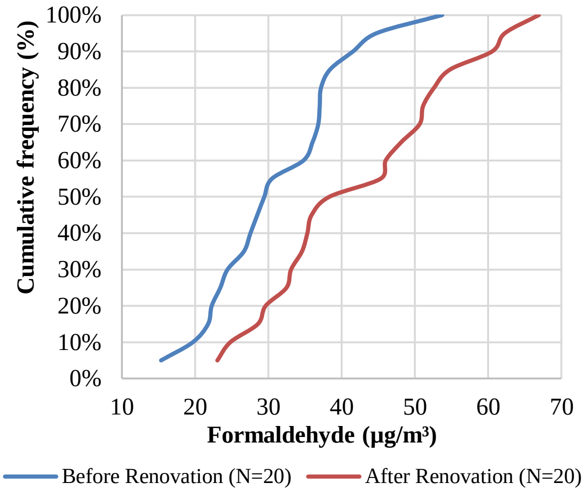


Figure 5.23 Boxplots showing the formaldehyde concentration before and after the renovation of the residential building.

Figure 5.24 Cumulative frequency distribution of formaldehyde concentration in the apartments before and after renovation of the residential building.

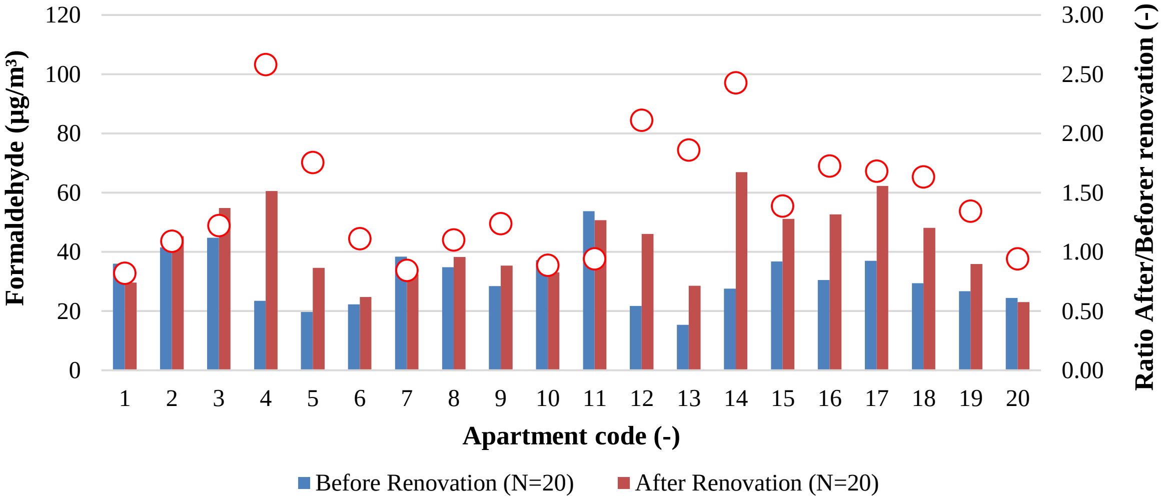


Figure 5.25 Formaldehyde concentration in each of the apartments before and after renovation of the residential building. The circles present the ratio between the obtained concentrations (after/before renovation).

### 5.2.6 Individual and total volatile organic compounds (VOCs and TVOCs)

In total fifty individual VOCs were identified in the investigated residential building before and after renovation. The majority occurred very rarely. **Table 5.7** summarizes the concentration of the most abundant individual VOCs in the TVOC´s samples and number of apartments above the limit of detection (LOD) 0.2 μg/m³. 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 renovated building.

Table 5.7 Concentrations of the most abundant individual VOCs (µg/m³) in the samples with TVOC above the LOD.

| Compound | Before Renovation (N=20) | | | | After Renovation (N=20) | | | |
|---|---|---|---|---|---|---|---|---|
| | N>LOD | AM<br>(Min-Max) | GM | Median | N>LOD | AM<br>(Min-Max) | GM | Median |
| Heptane$^{***}$ | 20 | 3.2<br>(0.9-9.1) | 2.5 | 2.6 | 18 | 12.4<br>(0-137.8) | 6.8 | 5.5 |
| Limonene$^{**}$ | 20 | 29.6<br>(4.6-90.7) | 19.8 | 19.17 | 20 | 162.9<br>(10.9-810.3) | 85.15 | 88.9 |
| a-pinene | 20 | 4.2<br>(0.4-14.1) | 2.5 | 2.4 | 20 | 7.2<br>(1.0-51.4) | 3.73 | 2.6 |
| 3-carene | 15 | 1.8<br>(0-8.3) | 3.8 | 0.9 | 19 | 5.2<br>(0-48.9) | 2.6 | 1.7 |
| Benzene$^{*}$ | 20 | 3.9<br>(0.4-11.4) | 3.1 | 3.1 | 19 | 2<br>(0-3.3) | 2.1 | 2 |
| Ethyl Benzene | 20 | 3.9<br>(1.2-13.5) | 3.2 | 3.1 | 20 | 6.4<br>(1.4-38.2) | 4.4 | 4.5 |
| Mp-Xylene | 20 | 6.9<br>(1.9-24.9) | 5.2 | 5.3 | 20 | 9.3<br>(2.5-48.2) | 6.9 | 6.3 |
| Toluene | 20 | 16.2<br>(4.2-57.5) | 12.1 | 11.1 | 20 | 14.6<br>(4.1-53.8) | 11.9 | 11.6 |
| Hexanal$^{***}$ | 18 | 7.5<br>(0-31.9) | 5.6 | 4.5 | 20 | 10<br>(2.3-28.1) | 8.5 | 8.6 |
| Nonanal | 19 | 6.7<br>(0-50.8) | 6.4 | 6.1 | 20 | 4.7<br>(0.4-13.7) | 3.7 | 3.92 |
| 1-Butanol | 20 | 12<br>(3.3-24.8) | 10.5 | 11.5 | 20 | 12.7<br>(2.7-25.4) | 11 | 11.7 |
| Isobutanol$^{**}$ | 20 | 2.0<br>(0.4-7.4) | 1.6 | 1.5 | 18 | 3.5<br>(0-11.1) | 3.1 | 2.8 |
| 1-Pentanol | 17 | 1.6<br>(0-5.5) | 1.2 | 1.3 | 20 | 1.8<br>(0.7-6.7) | 1.4 | 1.2 |
| Hexanoic acid$^{*}$ | 20 | 5<br>(1.4-15.7) | 3.9 | 4.2 | 16 | 0.8<br>(0-2.3) | 0.91 | 0.76 |

$^{*}$p<0.001, $^{**}$p<0.05, $^{***}$, 0.05<p<0.1; AM Arithmetic mean, GM Geometric mean.

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), (**Table 5.8**, **Figure 5.27**). Over 80% of apartments had a TVOC concentration above the limit recommended by the WHO (300 µg/m³) (127), (**Figure 5.28, Table 5.9**).

The TVOC concentration exceeded 1000 µg/m³ in one apartment before renovation and in five apartments after renovation (**Figure 5.26**). After renovation, in three apartment 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 7.6 times higher after then before renovation in apartment “12”, 6.2 times higher in apartment “13”, and 8.4 times higher in apartment “19”.

Table 5.8 Descriptive statistics of the TVOC concentration (μg/m³)

| Descriptive statistics | Before Renovation (N=20) | After Renovation (N=20) |
|---|---|---|
| Grand Mean (Min.-Max.) | 569 (179-1805) | 773 (185-2362) |
| Geometric mean | 489 | 623 |
| Median | 500 | 575 |
| Std. Dev. | 357.4 | 568 |
| Std. Err. | 79.9 | 127.1 |
| 95% CI | 402-736 | 507-1039 |
| p-value | 0.12 | |

Table 5.9 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%) |

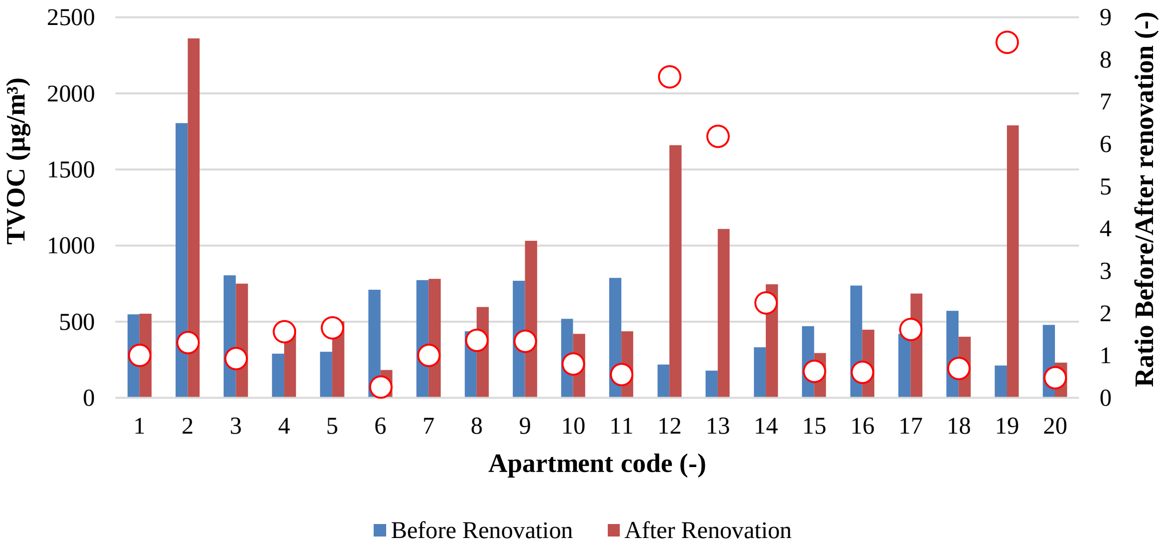
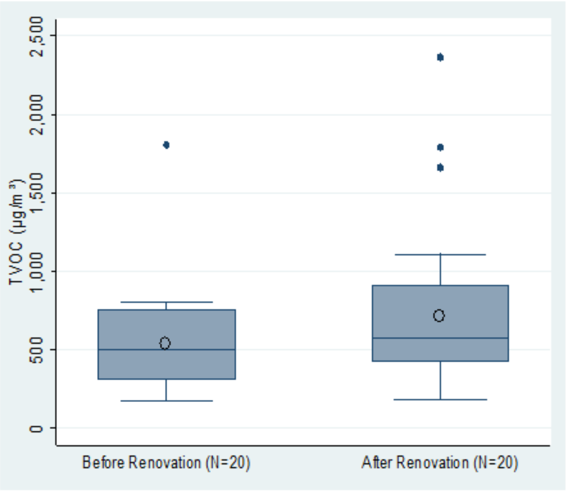


Figure 5.26 TVOC concentration in each of the apartments before and after renovation of the residential building. The dots present the ratio between the obtained concentrations before and after renovation.



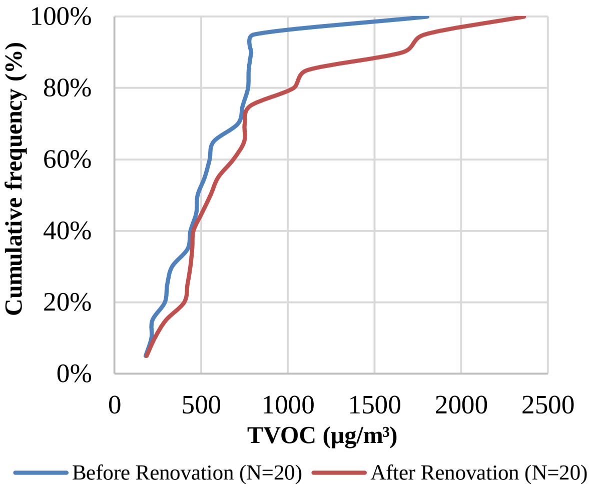


Figure 5.27 Boxplots showing the TVOC concentrations before and after the renovation of the residential building.

Figure 5.28 Cumulative frequency distribution of the TVOC in the apartments before and after renovation of the residential building.

### 5.2.7 Perceived air quality (PAQ)

The following figures present the occupants´ perception and acceptability with indoor air quality in the living rooms and bedrooms before and after 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 (**Figure 5.29**).

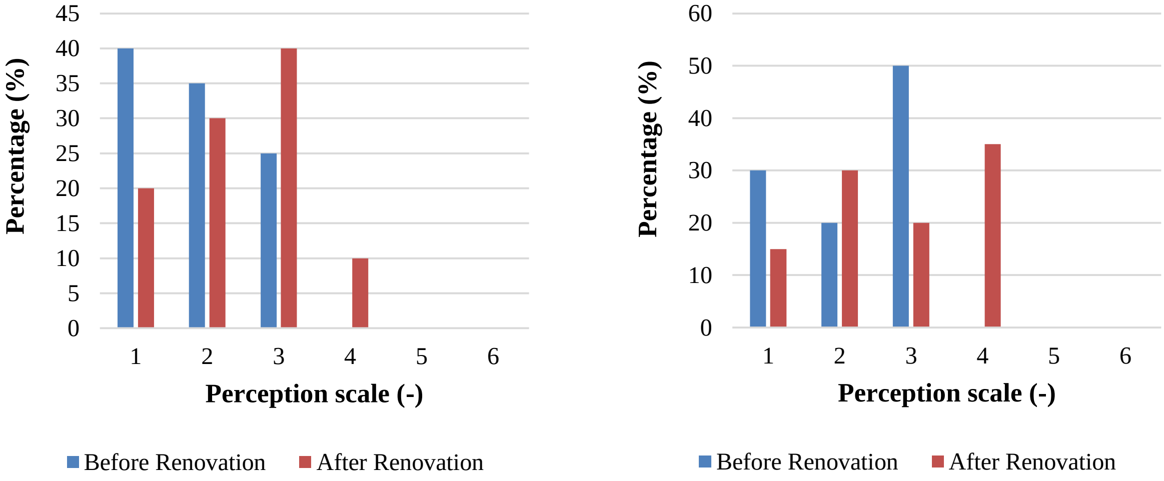


Figure 5.29 Summary of answers to the questions “How unpleasant do you think the indoor air quality is in your living room”(left), and “How unpleasant do you think the indoor air quality is in your bedroom?”(right). Possible answers were from 1 to 6, where number 1 represented “perceived air quality was not a problem” and number 6 presented “unpleasant indoor air quality”.

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); (**Figure**

**5.30**). Higher acceptability with 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.

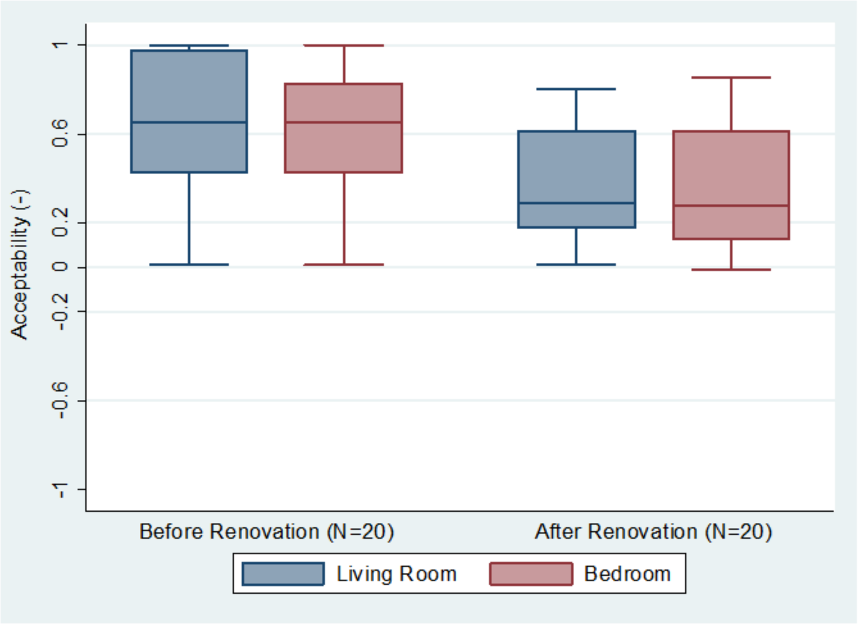


Figure 5.30 Acceptability with indoor air quality in the living rooms and bedrooms before and after renovation

### 5.2.8 Occupants´ airing habits

Characteristics of the occupants´ airing habits are presented in **Table 5.10**. 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.

No information was obtained about the frequency and duration of airing in the living rooms in the pre-retrofit condition of the building. However, residents shared information about their airing habits in the apartments in general.  We assumed that, those data might partly identify their routine of airing in living rooms before the building renovation. The summary of the responses is shown in **Table 5.10.**

Table 5.10 Frequency and duration of airing in the residential building

| Airing | Before Renovation (N=20) | | After Renovation (N=20) | |
|---|---|---|---|---|
| | Apartment* | Bedroom | Living Room* | Bedroom |
| Frequency | | | | |
| More than 1x per day | 70 | 40 | 60 | 30 |
| Daily or almost daily | 30 | 60 | 40 | 70 |
| Duration<br>(Average per day) | | | | |
| 3.5 min | 25 | 15 | 15 | 15 |
| 7.5 min | 35 | 20 | 40 | 20 |
| 20 min | 15 | 30 | 20 | 40 |
| 30 min | 25 | 35 | 25 | 25 |

*Questions were asked generally for the whole apartment before renovation, specifically for living room after renovation.

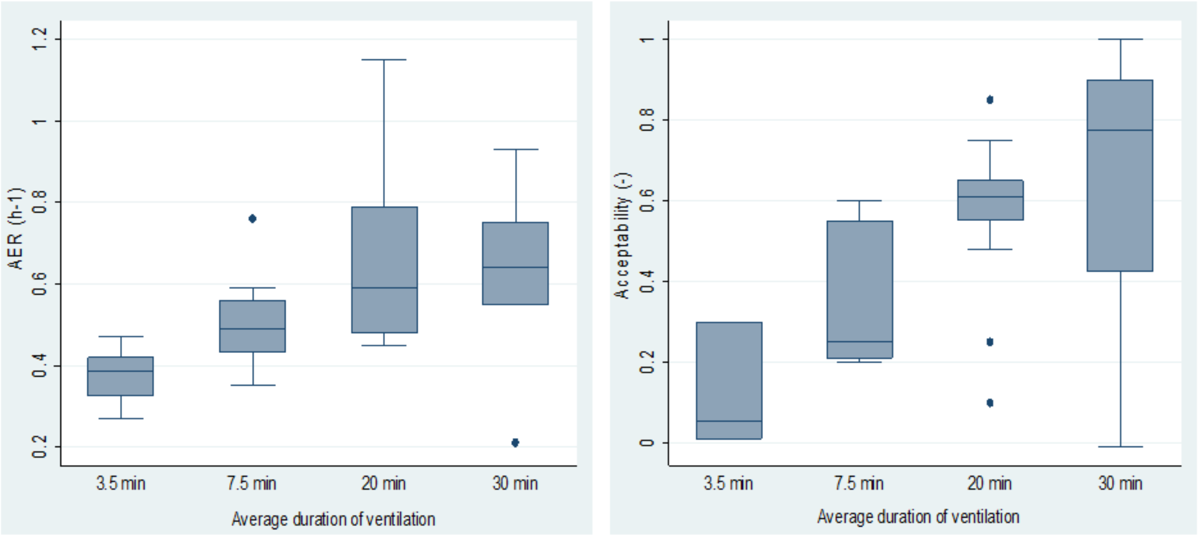


Figure 5.31 Relationship between AER (left) and occupants´ acceptability of indoor air quality (right) and the reported average duration of daily airing in bedrooms. The figures are based on data before and after renovation together (N=40).

**Figure 5.31** shows the relationship between the average duration of daily airing and AER (left) and acceptability of the indoor air quality (right) in bedrooms. 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.

### 5.2.9 Sick building syndrome symptoms

The frequency of selected symptoms occurring among the occupants (those filling the questionnaire) before and after the renovation is shown in **Figure 5.32**. 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 (**Table 5.11**). 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).

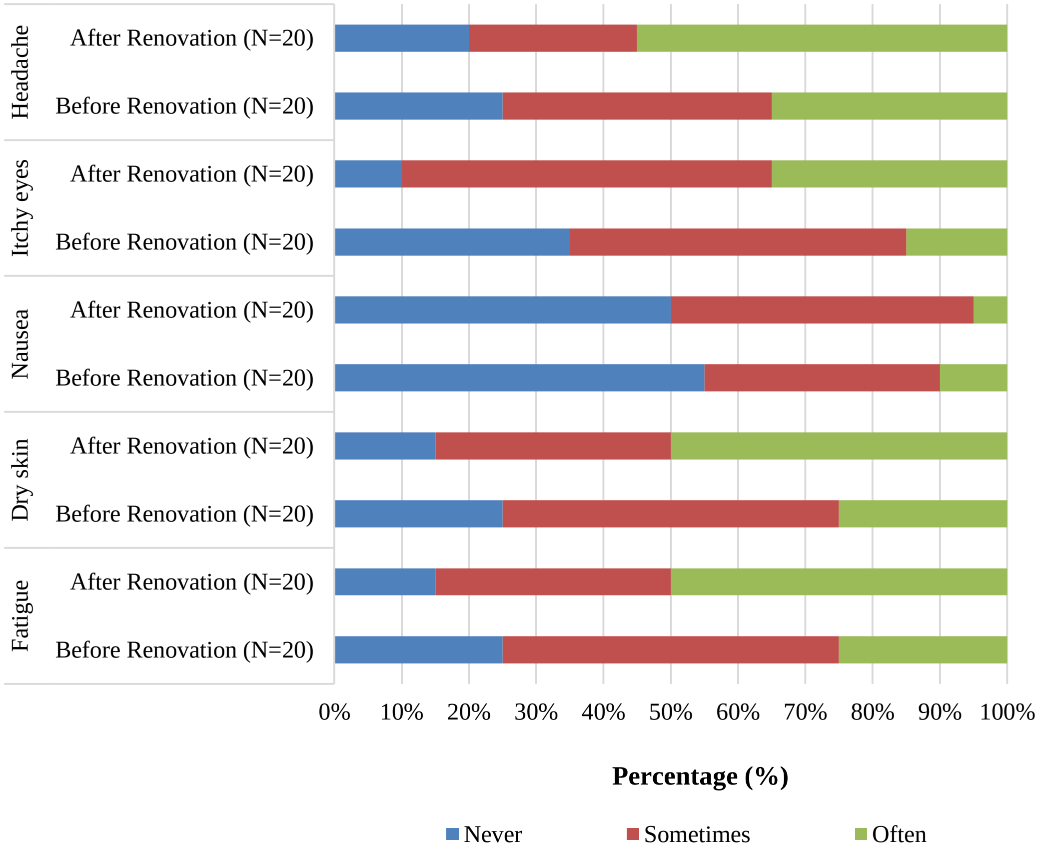


Figure 5.32 Frequency of sick building syndrome symptoms before and after renovation. The results are based on answers to the question: “Do you feel fatigue, headache, nausea, itchy eyes and dry skin during your stay in your apartment?”.

Table 5.11 Logistic regression of occurrence of SBS symptoms (a-itchy eyes, b-headache) in the investigated residential building.

a) Itchy eyes

| **Parameter** | **OR** | **Std. Error** | **95% CI** | | **P-value** |
|---|---|---|---|---|---|
| Building type<br>Reference: Before renov.<br>After renovation | 7.12 | 7.29 | 0.95 | 52.94 | 0.05 |
| Gender<br>Reference: Female<br>Male | 2.32 | 2.33 | 0.32 | 16.59 | 0.40 |
| Age<br>Reference: 20-40<br>41-60<br>>60 | 11.51<br>6.38 | 15.55<br>6.61 | 0.81<br>0.84 | 162.8<br>48.59 | 0.07<br>0.07 |

b) Headache

| Parameter | OR | Std. Error | 95% CI | | P-value |
|---|---|---|---|---|---|
| Building type | | | | | |
| Reference: Before renov. | | | | | |
| After renovation | 1.38 | 1.11 | 0.28 | 6.71 | 0.19 |
| Gender | | | | | |
| Reference: Female | | | | | |
| Male | 0.55 | 0.47 | 0.10 | 2.99 | 0.35 |
| Age | | | | | |
| Reference: 20-40 | | | | | |
| 41-60 | 0.71 | 0.69 | 0.11 | 4.81 | 0.73 |
| >60 | 4.73 | 5.05 | 0.57 | 38.39 | 0.14 |

## 5.3 Relationships between the measured 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 5.12)**. 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 (**Figure 5.33**). 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 ($r=0.14$, $p>0.1$); (**Figure 5.34**). The 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 ($r=-0.21$, $p>0.01$); (**Table 5.12**).

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 5.12 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$^{*}$ | - |

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

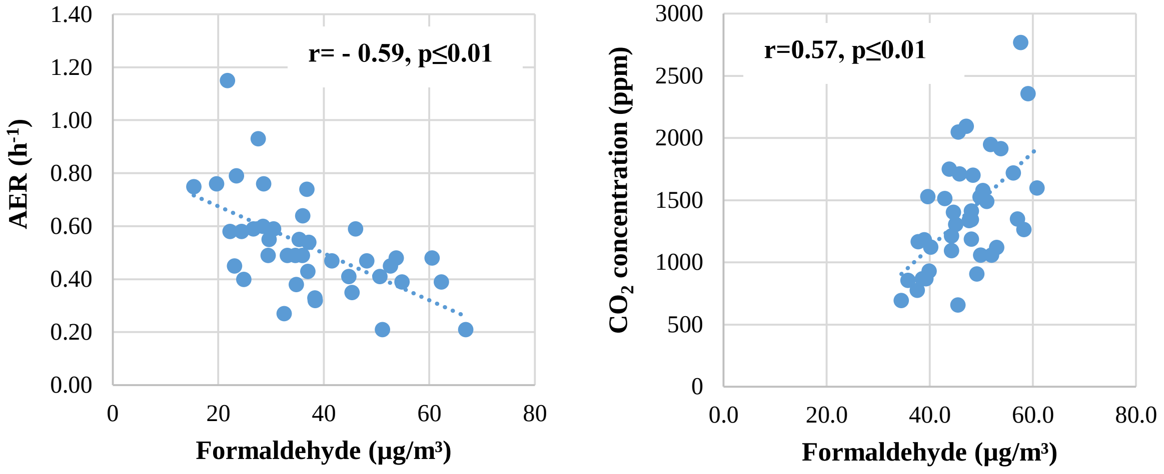


Figure 5.33 Linear relationship between formaldehyde and AER and $CO_2$ concentration.

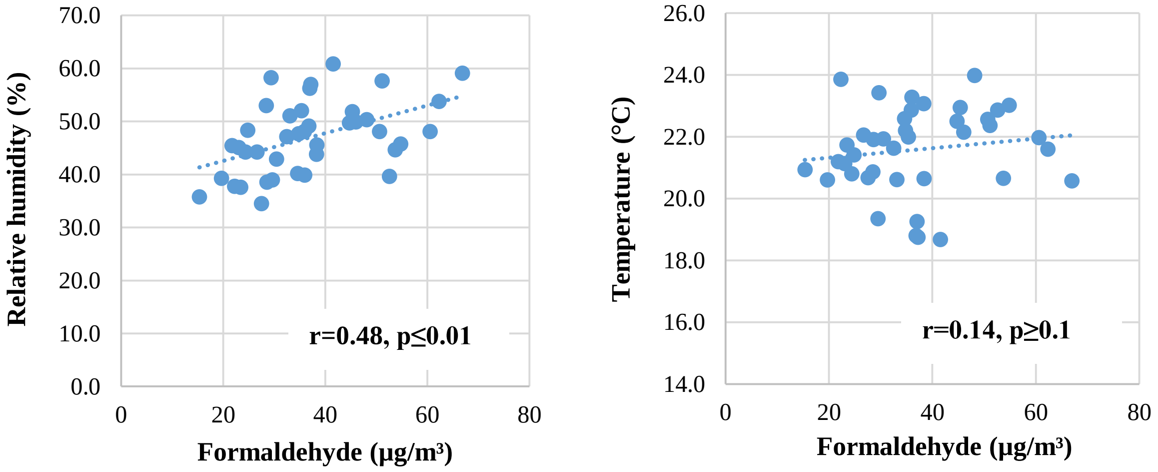


Figure 5.34 Linear relationship between formaldehyde and relative humidity and indoor air temperature.

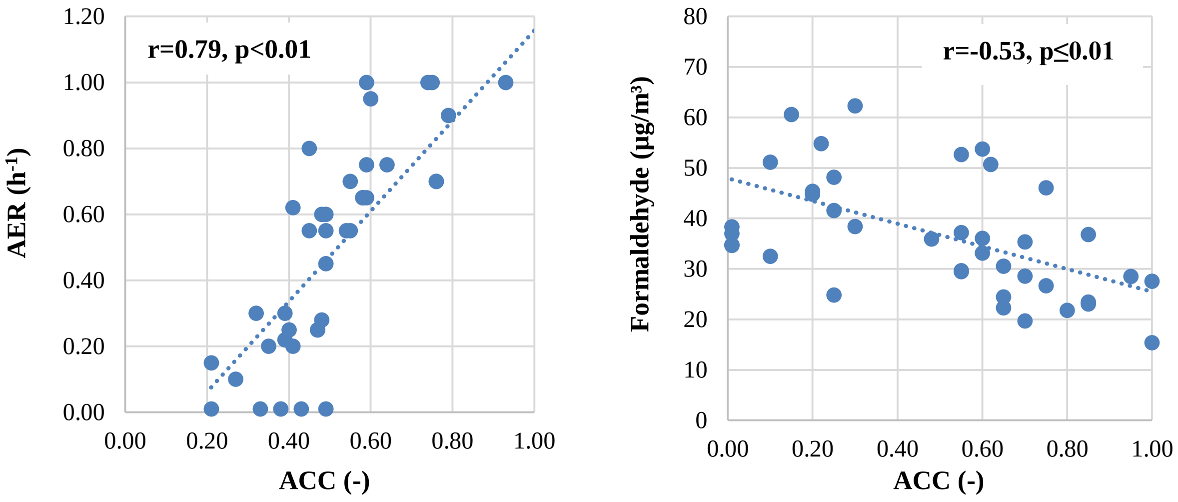


Figure 5.35 Linear relationship between ACC of PAQ and AERs and formaldehyde

The association of formaldehyde with AER, temperature and relative humidity was confirmed by regression analysis (**Table 5.13** and **Figure 5.36)**. 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 $R^2=0.48$. This exercise was not done for $NO_2$ and TVOC from reason of week correlations between the concentration of pollutants and measured parameters.

Table 5.13 Linear regression of logarithmically transformed formaldehyde concentrations. Model created after identifying predictor variables with inclusion criteria of $p < 0.2$, $R^2 = 0.48$.

| **Parameter** | **Factor** | **Std. Error** | **95% CI** | | **P-value** |
|---|---|---|---|---|---|
| AER | -0.32 | 0.15 | -0.630 | -0.004 | 0.04 |
| Temperature | 1.44 | 0.78 | -0.140 | 3.027 | 0.07 |
| Relative humidity | 1.07 | 0.41 | 0.246 | 1.895 | 0.01 |
| Constant | -5.21 | 3.47 | -12.25 | 1.82 | 0.14 |

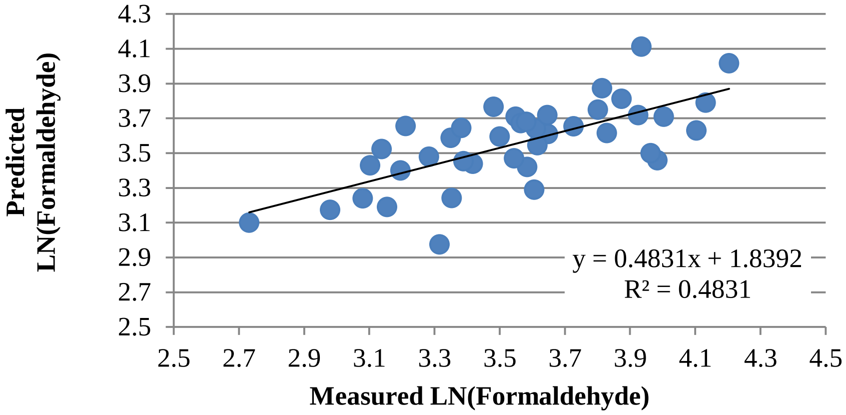


Figure 5.36 Logarithm of the measured formaldehyde plotted against the predicted values from regression model created after identifying predictor variables with inclusion criteria of $p < 0.2$.

The results suggest that both the concentration of pollutants and occupants´ perception of IAQ may be affected by low AERs. However, multivariate models did not produce significant p-values for these associations. This may in part be due to the low number of observations. Further analyses of the relationship between SBS symptoms and AER in larger number of dwellings and apartments are warranted.

## 5.4 Discussion

Indoor air quality is a dominant contributor to total personal exposure because most people spend a majority of their time indoors. The findings presented in this measurement campaign further support the conclusions of the precious chapter that deterioration of the indoor air quality followed the energy renovation.

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 average $NO_2$ concentration in the current study was well below the 40 µg/m³. The obtained values were similar to what were measured in Finland (14.7 µg/m³) (128) and England (12.1 µg/m³) (129). Higher $NO_2$ concentration was observed in Czech Republic (37.7 µg/m³) and Switzerland (23.8 µg/m³) (128). Indoor-to-outdoor ratios of $NO_2$ varied between apartments and measurement years, may indicate the presence of indoor combustion sources in some of the apartments where higher concentrations were sampled indoors than outdoors. 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 (98). Measurements of longer duration and detailed identification of the sources of $NO_2$ would validate the current results.

The TVOC concentrations exceeded 300 µg/m³ in a large fraction of the apartments already before renovation. Slight increase of TVOC after renovation was observed in 25% of the apartments (after/before ratio between 1.01 and 1.36). In another 20% of apartments this ratio was even higher (1.57-2.25). More than 100% increase of TVOC was observed in 15% of the apartments (apartments No: 12, 13, and 19). In these three apartments furniture replacement was reported after the first round of measurements. In "apartment 12" carpet was added to the living room, in "apartment 13" old carpet was replaced for new one, and in "apartment 19" there was a new sofa. 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 (130; 131). Park et al. (132) reported increased levels of organic compounds in older homes after renovation (from 250 µg/m³ to 400 µg/m³).

Formaldehyde is one of the most common VOCs indoors. Construction materials may strongly influence the indoor air quality due to their large surface area (133). An earlier review of formaldehyde in indoor environment reported that insulation materials could be one of the major sources of formaldehyde (134). The report indicates that high emissions may be caused by using foam board materials. The same type of material was used for envelope insulation in the current case study. The combination of the selected insulation material potentially acting as a source of pollutants that could explain the increased formaldehyde concentrations in most of the apartments. However, additional experiments on the presence on foam board materials as source of pollutants would strengthen the hypothesis about the impact of this specific material on indoor concentration of formaldehyde.

Moreover, fitting of the residential building with the given insulation resulted in a tighter building construction and decreased ventilation in the apartments after renovation. The significant negative correlation between AER and formaldehyde concentration ($r=-0.59$, $p<0.01$) reflects the fact that decreased ventilation contributed to increased formaldehyde concentrations. Furthermore, significant correlation was found between relative humidity and formaldehyde ($r=0.48$, $p<0.01$), which is in line with expectations (135). Formaldehyde concentrations seemed to be slightly higher at higher temperatures, but the correlation was weak ($r=0.14$, $p>0.1$). This may be explained by moderate changes in temperature levels and acceptable temperature ranges in the apartments.

The effect of ventilation on indoor formaldehyde concentrations has been shown in several earlier studies (32; 136). In the Swedish housing stock negative correlation coefficient was observed between AERs and formaldehyde levels ($r=-0.31$, $p\leq0.01$) (32), indicating that increased ventilation would decrease the concentrations of formaldehyde originating from indoor sources. Salthammer et al (136) reported similar results in German residences. A negative correlation was observed between formaldehyde and AER ($r=-0.21$, $p<0.01$). In addition, a weak not strong but statistically significant correlation was found between formaldehyde and relative humidity ($r=0.23$, $p<0.01$), and weak correlation was observed between formaldehyde and temperature. The authors concluded, that in many cases low AER, which supports the accumulation of volatile organics in indoor air, contributes to higher formaldehyde levels. In a Japanese study the highest formaldehyde concentrations were associated with insulated houses without an active ventilation system (ranged from 45 to 95 $\mu g/m^3$) (137). Those houses that were built within the last five years were equipped with ventilation systems, and had lower formaldehyde concentrations than older dwellings. A negative relationship between dwelling age and formaldehyde concentration was also found in Australia (138). The study indicated that regulations aimed at reducing demand controlled ventilation for energy efficiency had a negative effect on indoor air quality in dwellings built in recent decades and resulted in increased indoor concentrations of formaldehyde and TVOC.

The results of the subjective evaluation of indoor air quality before and after renovation of the selected building were similar to those presented in Case study I. 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 ($r=0.79$, $p<0.01$), and negative correlation was observed between formaldehyde concentrations and acceptability of IAQ ($r=-0.53$, $p<0.01$). Similar results were reported by Maddalena et al (139). Low acceptability with PAQ was observed when the concentration of pollutants increased, which was the case at lower ventilation rates. Wolkoff (140) 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 products from linseed oil and skin oils) and limonene (a common fragrance used in numerous consumer products) may be some of the most important compounds. These three individual VOCs occurred significantly in our study as well. Higher concentration of hexanal and limonene was observed after renovation, while the concentration hexanoic acid was higher in the original state of the dwelling. It should be recognized that a large number of other VOCs may be present and adversely impact the IAQ (140). The literature on the impact of various physical and subjective factors, such as building renovation, air-tightness (61; 62; 95) , building age (63), occupant age, occupancy time and smoking habits (63), on PAQ is summarized in more detail in **Chapter 1** and discussed in **Chapter 4**.

The current results indicated higher prevalence of most SBS symptoms after renovation of the apartment building. No significant association was observed between these symptoms and the concentration of the measured indoor air pollutants. However, it must be noted that chemical substances emitted from building materials, including formaldehyde and other organic compounds (136; 138), may be associated with SBS symptoms (136). In our case the number of observations may have been insufficient to produce statistically significant associations. In order to more thoroughly address the potential impacts of indoor pollutants on human health and well-being following similar energy renovation without considering its impact on IAQ, more research is warranted. It is important to mention, however, that numerous studies have reported decrease in SBS symptoms and improvement of occupant health after moving into green buildings, both new and newly renovated (141; 142). These findings are consistent with exposure assessments that measured lower levels of several key pollutants, such as particles, $NO_2$, VOCs and allergens in green buildings (97; 141; 142). The study presenting the health benefits of green public housing in Boston (122) reported fewer SBS symptoms, lower risk of asthma symptoms and hospital visits among people living in green buildings compared to those in conventional public houses. These studies could provide some lessons to be learned on the utilization of the opportunity to improve indoor air quality, when planning energy retrofitting of existing buildings.

# 6. ENERGY EFFICIENCY OF BUILDINGS

## 6.1 Materials and methods

### 6.1.1 Studied buildings

Buildings investigated in this work were selected specifically for this project. The detailed description of the building selection methodology and the investigated buildings are presented in **Chapter 4**.

### 6.1.2 Energy investigation

The detailed methodology of comparing energy efficiency of the original and renovated buildings followed in this work is shown in **Figure 6.1**. 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. The input data (**Table 4.1**, **Table 6.1**) used in 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.

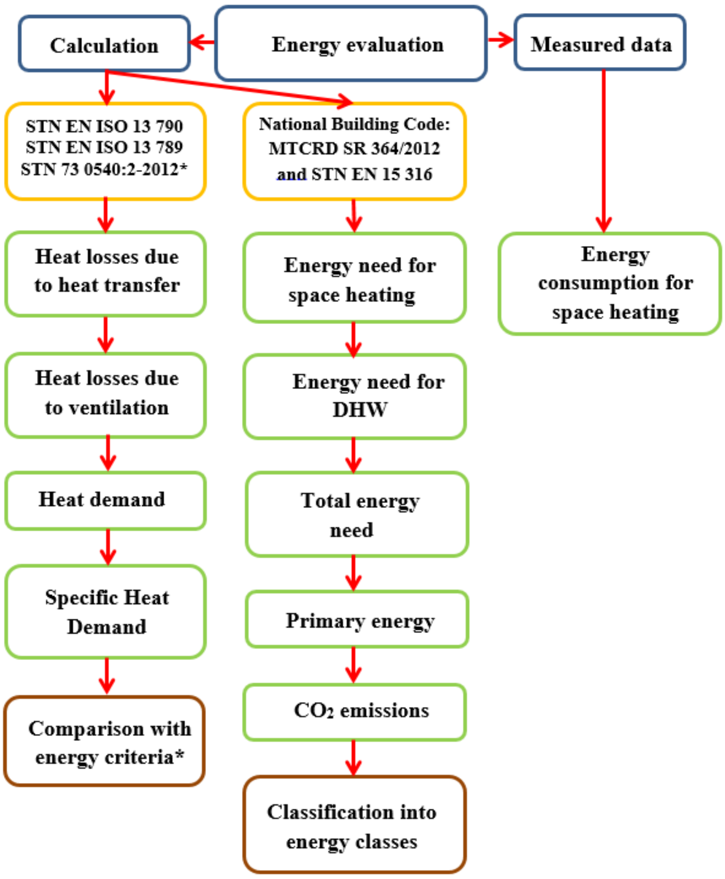


Figure 6.1 Conceptual outline of the energy investigation methodology

Table 6.1 Calculated U-values of main building constructions compared to the normalized requirements (W/m$^2$K); (Source: Housing association institutes).

| Building pair | I. | | II. | | III. | | Current requirements by standard |
|---|---|---|---|---|---|---|---|
| Building condition | Original | Renovated | Original | Renovated | Original | Renovated | |
| U-values | Calculated | | | | | | |
| Average* | 1.28 | 0.32 | 0.72 | 0.30 | 0.92 | 0.28 | |
| External walls | 1.59 | 0.36 | 0.75 | 0.30 | 0.98 | 0.29 | 0.32 |
| | 1.60 | 0.37 | 0.63 | 0.28 | 0.95 | 0.27 | |
| Roof | 0.80 | 0.22 | 0.62 | 0.21 | 0.63 | 0.18 | 0.20 |
| Ceiling above the basement | 1.12 | 0.33 | 0.88 | 0.41 | 1.10 | 0.39 | 0.85 |
| Transparent constr. | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.20 | 1.40 |

*Averages were including U-values of constructions except windows. The total averages were 0.97 W/m$^2$K for the original constructions and 0.30 W/m$^2$k for the renovated ones.

### 6.1.2.1 Heat demand determination and its comparison with energy criteria

Calculation of heat demand reflects characteristics of indoor and outdoor environment, the requirements of thermal protection of buildings as well as the thermal properties of building constructions and used building materials. The heat demand is specified theoretically for comparative standardized conditions and represents a comparative value of buildings´ assessments (77).

Determination of the heat demand was calculated according to STN EN ISO 13 790 (143). Seasonal method of calculation was carried out with consideration of the heating season duration. The general mathematical formula is defined as:

$$Q_H = Q_{ht} - \eta_{gn} \, . \, Q_{gn} \qquad \text{(kWh)} \qquad (6.1)$$

Where:

$Q_{ht}$ total energy losses during the heating season (kWh),

$\eta_{gn}$ heat gain utilization factor (-),

$Q_{gn}$ total heat gains during the heating season (kWh).

The heat demand was calculated using normalized number of heating degree days (3422 K.day). 20 °C requested indoor temperature, 3.68 °C average outdoor temperature, and 212 days (duration of the heating season) were used as the input parameters for buildings with steady heating. According to the National building code presented by the Ministry of Transport, Construction and Regional Development of Slovak Republic (144), in the heat demand calculation minimal air infiltration rate of 0.5 $h^{-1}$ has to be used. If the calculated air infiltration rate is higher than 0.5 $h^{-1}$, then the heat demand is determined for the calculated value of the air infiltration rate.

Buildings meet the energy criteria, if their specific heat demand is lower than the required (normalized and recommended) values of specific heat demand (77). The specific heat demand is calculated as a ratio of the total heat demand per year (kWh/year) and the building area ($m^2$). The required specific heat demand is defined by the building shape factor. It is a ratio between the total area of the building envelope elements and the building (converted) area. The required values for intermediate values of the building are determined by linear interpolation of table values presented in STN 73 0540:2-2012; (31).

### 6.1.2.2 Determination of total energy need for classification of the buildings into energy classes

In Slovakia, the responsibility of the energy performance and certification system as well as the energy database falls under the jurisdiction of the Ministry of Transport, Construction and Regional Development. 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 (144), based on European Parliament, Directive 2010/31/EU (6) and the Codex of Laws No. 300/2012 (145). 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 (144). The process of energy classification is based on calculation of heat demand presented above as well as on calculation of energy need for space heating and DHW preparation using standardised conditions for determination of building energy efficiency

### A) Energy demand for space heating

Energy demand for space heating is determined as sum of heat demand and heat losses from subsystems of the heating system. According to STN EN 15 316-1 (146) the energy need for space heating is defined as listed below:

$$Q_{HEAT} = Q_H + Q_{em,Is} + Q_{H,dis,Is,an} + W_{H,dis,\,aux,am} \quad \text{(kWh)} \qquad (6.2)$$

Where:

| | |
|---|---|
| $Q_H$ | heat demand (kWh) |
| $Q_{em,Is}$ | heat loss of the system via heat transfer (kWh) |
| $Q_{H,dis,Is,an}$ | heat losses via distribution system (kWh) |
| $W_{H,dis, aux,am}$ | annual actual energy consumption of circulation pumps (kWh). |

**B) Energy demand for DHW preparation**

Energy demand for DHW preparation was determined as sum of heat demand needed for DHW and heat losses from the subsystems of DHW with consideration all heat losses from distribution system, transmission and regulation (144; 147).

$$Q_{HW} = Q_W + Q_{W,d} + W_{W,d,pump} \qquad \text{(kWh)} \qquad (6.3)$$

Where:

| | |
|---|---|
| $Q_W$ | heat demand needed for DHW (kWh) |
| $Q_{W,d}$ | heat losses via distributions system (kWh) |
| $W_{W,d,pump}$ | energy needed for operation of circulating pumps (kWh). |

**C) Building classification into energy classes**

The investigated residential buildings were classified into energy classes (**Table 6.2**) based on the calculated energy demand for space heating, energy demand for DHW and total energy demand presented as a sum of calculated energy demand for space heating and DHW (144). The primary energy and $CO_2$ emissions were determined according to given factors presented in the National Building Code MTCRD SR 364/2012 (144).

Table 6.2 Energy classes of space heating, DHW, total and primary energy need for building category of residential buildings, in kWh/$m^2$year (144).

| 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 |

### 6.1.2.3 Real energy consumption data gathering

Data on the actual energy consumption of the examined buildings were provided by the respective housing associations. 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.

## 6.2 Results

### 6.2.1 Annual heat demand for space heating

The heat losses due to heat transfer via building constructions and ventilation for building pair I. are shown in Figure 26. The results for the other building pairs are presented in Appendix C. 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.

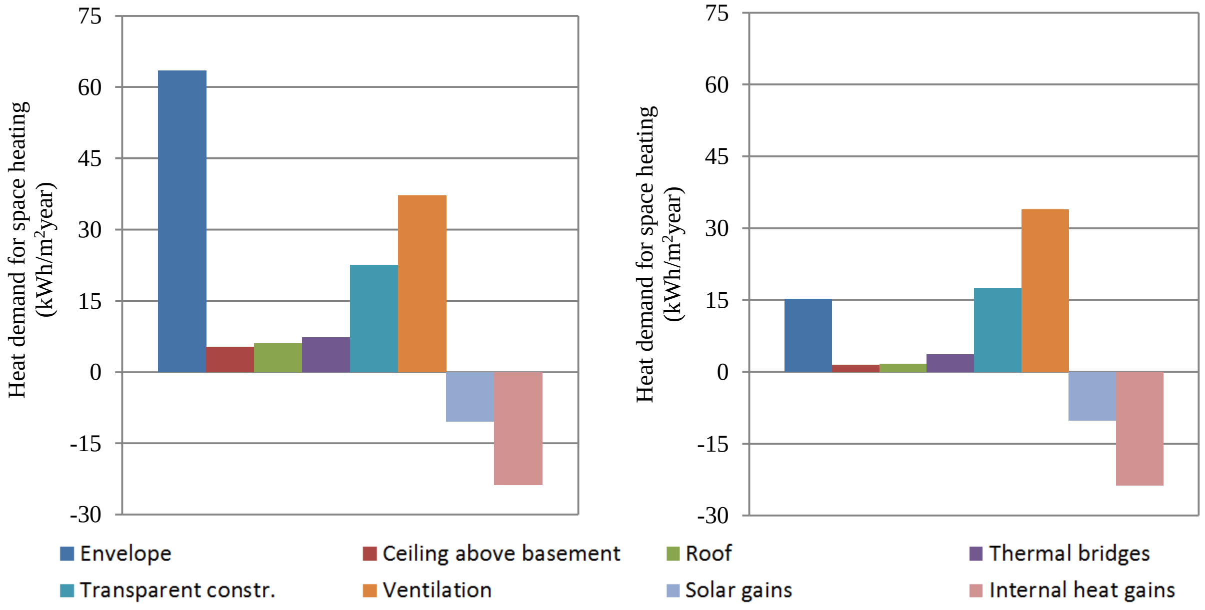


Figure 6.2 Calculated annual values of heat losses due to heat transfer via building constructions and ventilation as well as of produced heat gains for building pair I: the original building (left), the renovated building (right).

**Table 6.3** presents the calculated annual heat demands for all the investigated buildings. The annual values were converted to heat demand per unit of floor area, defined as specific heat demand. The original buildings are compared against 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 (31). 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 more strict than the normalized. However, the specific heat demand in the original buildings did not fulfil the normalized criteria.

Table 6.3 Calculated annual (specific) heat demand for the investigated residential buildings compared to the standardized values.

| Building pairs | Building condition | Heat demand ($Q_H$) | | | Specific heat demand | | |
|---|---|---|---|---|---|---|---|
| | | kWh/year | GJ/year | Difference (%) | Calculated $Q_{H,nd}$ | Normalized $Q_{H,nd,N}$ | Requested $Q_{H,nd,N,rl}$ |
| | | | | | kWh/m$^2$.year | kWh/m$^2$.year | 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 | | |

### 6.2.2 Energy demand and classification into energy classes

**Table 6.4** 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 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 (**Table 6.2),** 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.) (**Table 6.4)**. 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 6.4**) and $CO_2$ emissions (**Figure 6.3**) in the original buildings compared to the renovated dwellings.

Table 6.4 Classification of the residential buildings into energy classes based on their annual energy demand for space heating and DHW preparation and total energy demand

| Build. pairs | Building condition | Energy demand for space heating | | | Energy demand for DHW | | | Total energy demand | |
|---|---|---|---|---|---|---|---|---|---|
| | | 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 |

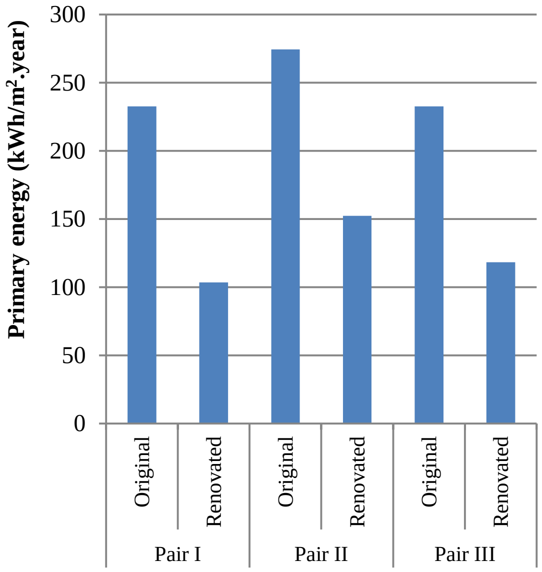


Figure 6.4 Calculated annual primary energy need per floor area in the original and renovated residential buildings

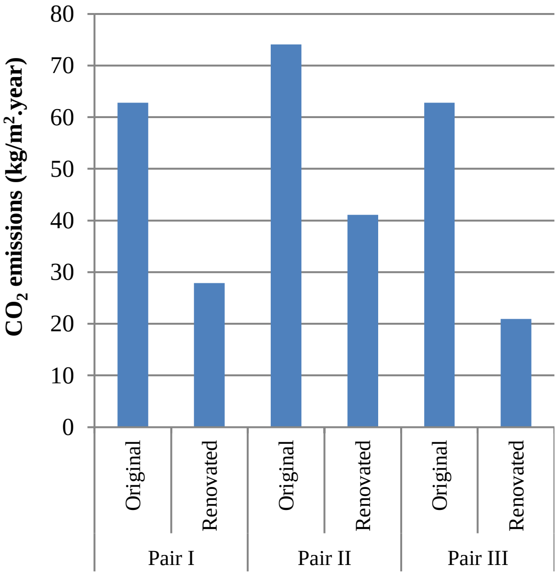


Figure 6.3 Calculated annual $CO_2$ emissions per floor area in the original and renovated apartment buildings.

### 6.2.3 Measured energy consumption for space heating

The data of the real heat consumptions used for space heating are shown in **Table 6.5**. 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 significant decrease might be explained by the outdoor weather conditions during the winter season. According to the Slovak Hydrometeorological Institution (148), 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 6.5 Heat consumption for space heating for heating seasons 2010-2014; (Source: Housing association companies).

| Building pairs | 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 represents the energy consumption of the renovated building, after retrofit.

**Figure 6.5** presents the annual measured energy consumption compared to the calculated energy need for space heating. The results show that real energy consumption was always lower than the calculated values that indicates reserves in the calculation outcomes compared to the measured values.

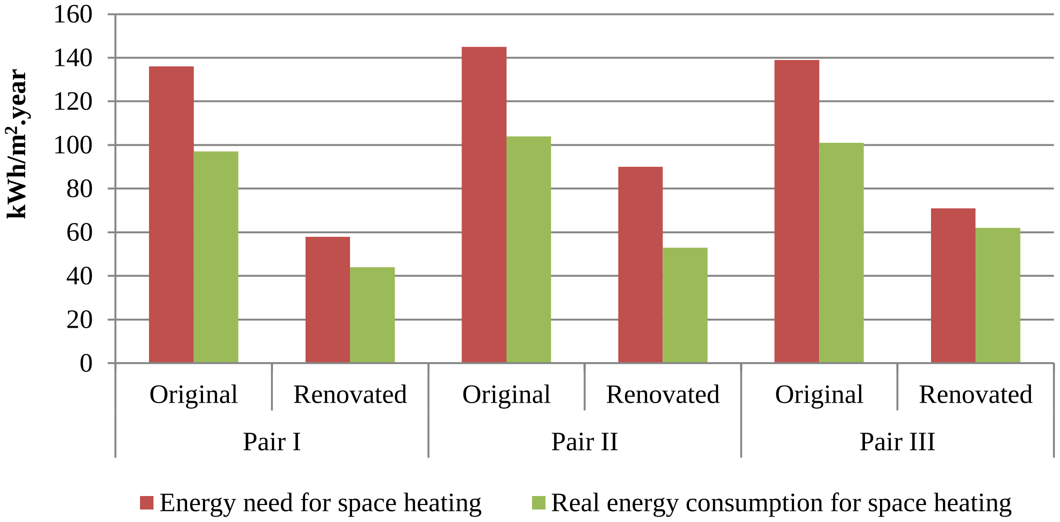


Figure 6.5 Comparison of the measured heat consumption (2013) and the calculated energy need and heat demand for space heating in the investigated residential buildings

## 6.3 Discussion

According to the European Parliament, Directive 2010/31/EU (7) and the Slovak National Building Code (144) there is a national obligation to implement various energy conservation measures in all energy end-use sectors, including residential buildings, in order to achieve at least B class for total energy demand by 2016. The key task in the implementation of the renovation strategy is to achieve in the very short period (2015-2020) energy efficiency of existing buildings by gradually of the building constructions. Implementation of energy saving measures could lead to significant reduction in the annual heat demand for space heating and the energy consumption during the heating seasons. A disappointing fact is that none of the original buildings fulfilled the criteria of the national standards and building code.

This study demonstrates that the energy performance of the investigated multifamily residential buildings can be significantly improved by added external thermal insulation of the envelope and reduced heat losses of the heating system. The highest energy savings were attributable to improved building envelope. By implementing energy saving measures and taking into account requirements of the national standards and directives, it is possible to significantly reduce energy demand, primary energy as well as $CO_2$ emissions and reach energy class B for existing buildings.

The averages of the heat consumption in the examined buildings were compared with the average consumption levels for buildings of the Slovak building stock built in different periods (**Figure 6.6**), according to BPIE and Eurostat inspections (1; 25). The average heat consumption in the original buildings (101 kWh/m$^2$.year) was equal to values characterised period between 1981 and 2010. The mean energy consumption for space heating representing the renovated buildings (53 kWh/m$^2$.year) was lower by 48% compared to the non-renovated dwellings. The renovated buildings matched the heat consumption of buildings built after 2011.

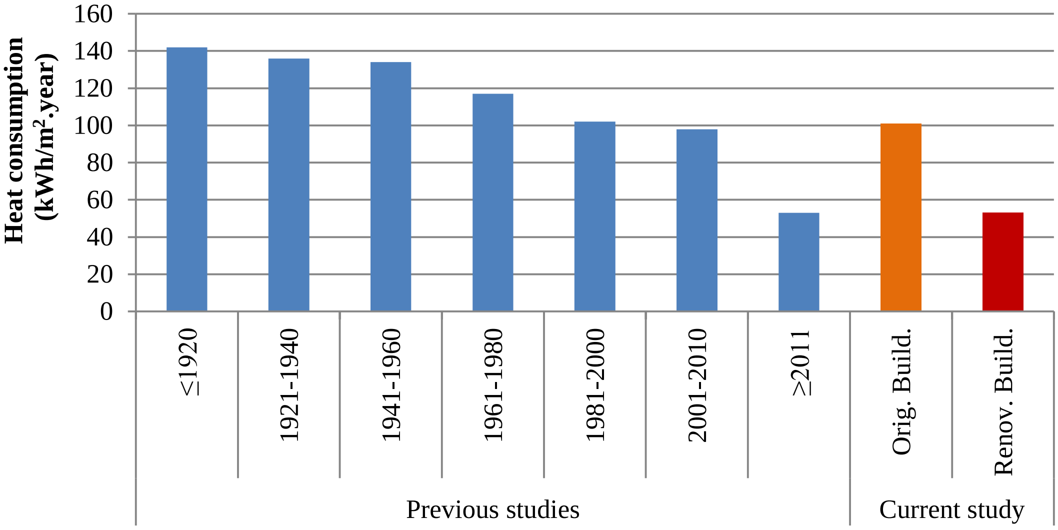


Figure 6.6 : Consumption levels of space heating in the Slovak residential sector by age of apartment buildings (1; 15) compared to the average heat consumption (2013) in the original and the renovated buildings.

# 7. SIMULATIONS

The results presented in the previous chapters showed that renovation reduced energy consumption, but aggravated indoor air quality. From our list of the dwellings 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.

## 7.1 Methodology

### 7.1.1 IDA Indoor Climate and Energy software

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 a buildings (149). As a whole-building simulator, it can perform assessments of all issues fundamental to a successful building design: form, fabric, glazing, HVAC systems, controls, light, indoor air quality, comfort, etc. for advanced energy and indoor climate analysis. The version used in the current work is IDA ICE 4.6.2, released in 2014.

### 7.1.2 One zone simulation model

The geometry of the Building type I was used for creating the simulation model. The dwelling consisted of nine identical floors. On each of the storeys four apartments were located. To avoid repetition of the results and for smooth run of the simulations only one representative floor (located on the fourth storey) was constructed (**Figure 7.1**) and used for further assessments. Although the work focuses on one zone, also one floor zone-model needed to be created, to ensure the indoor climate conditions in the neighbouring zones as in real. The floor model was divided into twenty-nine zones in total. Each apartment consisted of seven zones: two bedrooms, one living room, one corridor, one kitchen, one bathroom and one toilet. In addition separate zone was created for the staircase (**Figure 7.2**).

In order to validate the model by comparison to the measured data, the final model was created for one bedroom (Bedroom 1) located in one of the selected apartments (Apartment 4); (**Figure**

7.3). The examined apartment was oriented to South-East and the bedroom had Eastern orientation. The total area of the apartment was about 68 m$^2$, and the bedroom had 13.5 m$^2$.

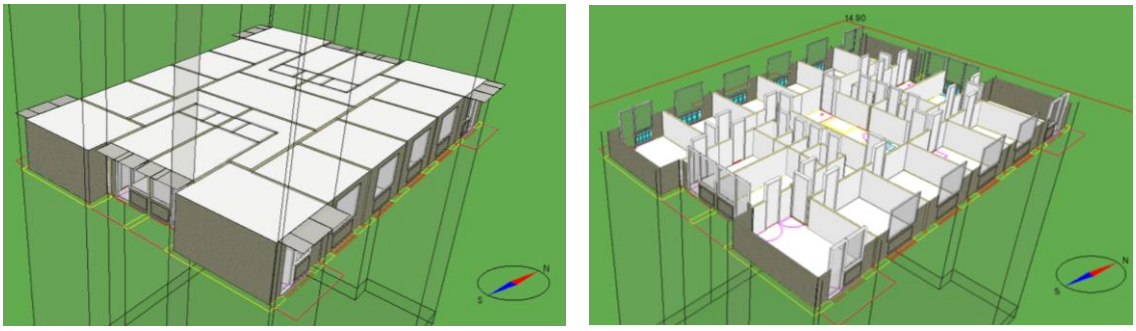


Figure 7.1 The 3D model of the typical floor

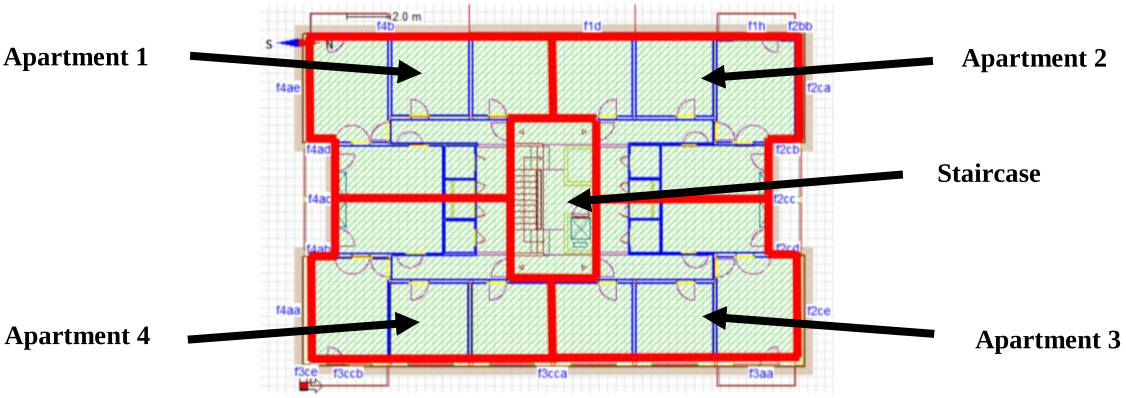


Figure 7.2 The floorplan of the typical floor

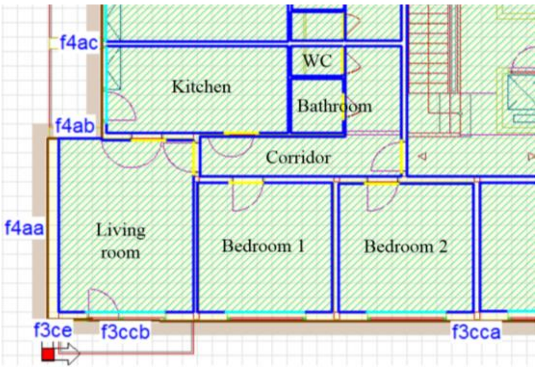


Figure 7.3 The floorplan of Apartment 4 selected for the simulation study

### 7.1.3 Input parameters

#### A) Weather data

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). The obtained hourly weather data (outdoor temperature and humidity, wind speed, direct and diffusive solar radiation) were used in the weather file that we implemented in IDA ICE model for the required simulations. The hourly data for outdoor air temperature and relative humidity are presented in **Figure 7.4** and **Figure 7.5**.

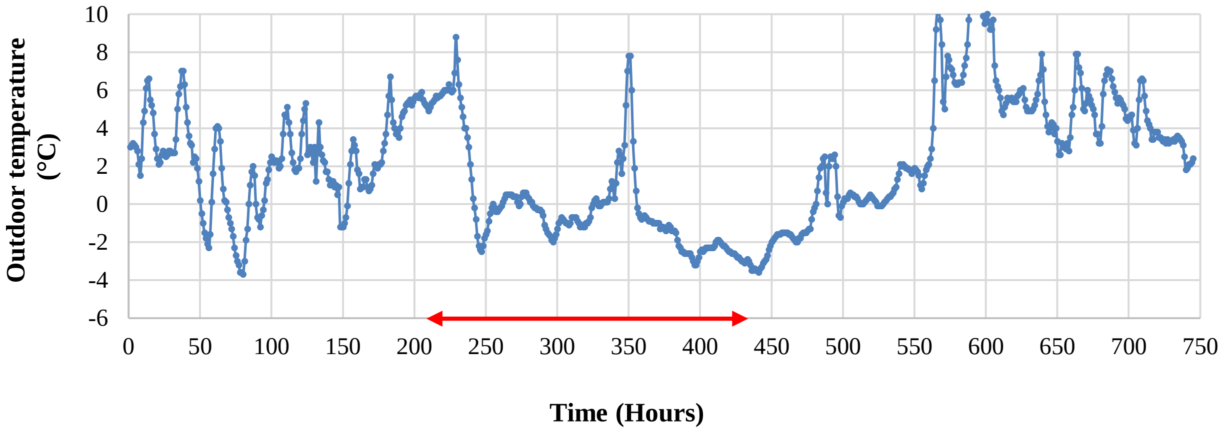


Figure 7.4 The hourly outdoor temperature data for December 2013. The red arrow represents the measurement period. (Source: SHMI)

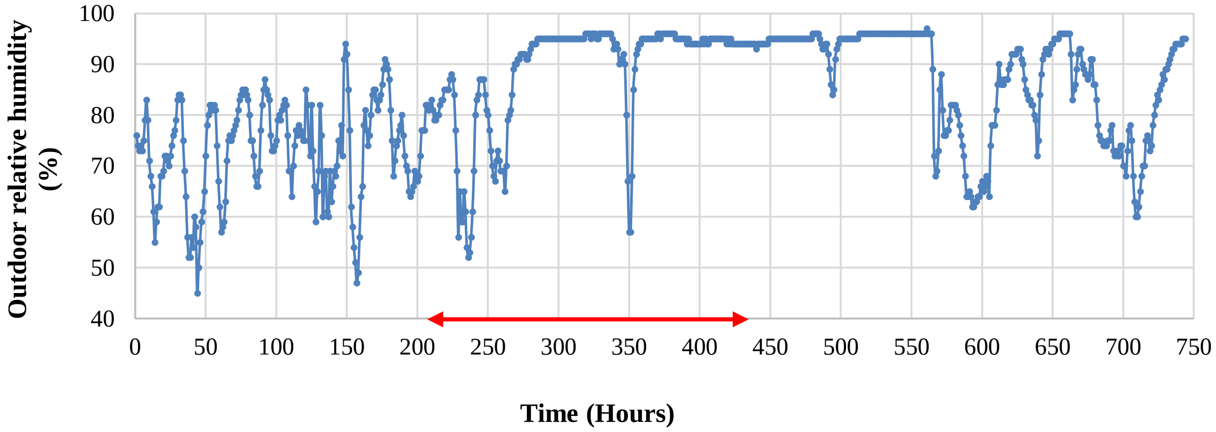


Figure 7.5 The hourly outdoor humidity data for December 2013. The red arrow represents the measurement period. (Source: SHMI)

## B) Building constructions and building services

The building envelope components and constructions details as well as the heating and domestic hot water systems were designed as in reality. The original blue prints and corresponding information for the changes due to renovation provided the necessary data about the building materials and their physical characteristics used in the construction and the building retrofit process. The heat transfer coefficients of the building constructions that were used in the simulation model are presented in **Chapter 6**. The characteristics of building services are described in **Chapter 4**.

Based on the technical report of the renovation project, we assumed that the infiltration coefficient was 0.6 $h^{-1}$ before renovation, and 0.4 $h^{-1}$ after renovation. According to the predefined conditions in IDA, the thermal bridges were considered as “poor” in the non-renovated dwelling and “good” in the retrofitted building. District heating with radiators was used for space heating. In average 40 L/(occupant and day) hot water was assumed for the domestic hot water use. According to information obtained during the building inspection, the distribution system losses of the domestic hot water circuit and the heating system were considered as “poor” in case of the non-retrofitted dwelling and “good” in the retrofitted building. The actual building model was built according to the fact that natural ventilation was used across the apartment and exhaust system was installed only in the bathrooms and toilets. This state is based strictly on the blueprints, which describe the building as it was originally designed.

### C) Supplementary input data

Additional information, such as internal heat gains, data about the heating units, and window and door opening were obtained from questionnaire survey and home inspection. The supplementary data are presented in **Table 7.1**.

Table 7.1 Supplementary input data of the bedroom

| **Internal gains** | |
|---|---|
| Number of occupants (Occupancy period: 20.30 - 06.30) | 2 |
| Equipment | 75 W |
| Installed lighting | 60 W |
| Window shading | No shading |
| Daylight | 200/500 lx |
| **Heating unit** | |
| Temperature set-point | 20/25 °C |
| Radiator power | 1500 W |
| Supply/Return temperature at the max. power | 90/70 °C |
| Controller | Proportional |
| Sensor | Operative temperature |
| Relative humidity set-point | 30/60% |
| **Window/Door opening** | |
| Door to the bedroom | Partly opened |
| Window | Opened between 7:00-7:30 and 19:00-19:30. |

### 7.1.4 Data calibration

The calibration methodology encompasses the analysis of the actual and the theoretical building model performance in terms of indoor climate. The actual building model (original and renovated) was created and later calibrated using measured data (**Figure 7.6**). This data set consists of two values, the theoretical (simulated) and the actual (measured), which reflect the value of the same parameter in the actual and in the theoretical state of the residential building, correspondingly. Detailed investigation of the indoor environment parameters (temperature, relative humidity and $CO_2$ concentration) with comparative-iterations in zone level (bedroom) was performed. The main calibration was carried out for one day period.

The simulated and the measured parameters were compared within the same time interval. For accuracy reason, 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 first was the Root Mean Square Error (RMSE) (150) that is defined as the deviation between the predicted and observed values in each hour of the examining period (**Equation 7.1**). It is calculated as follows:

$$\text{RMSE} = \sqrt{\frac{\sum_{i}^{n}\left(X_{obs,i} - X_{pred,i}\right)^{2}}{n}} \tag{7.1}$$

Where:

$X_{obs,i}$ is the observed value in each particular hour of the calibration period

$X_{pred,i}$ is the predicted value in each particular hour of the calibration period

n is number of examined hours

The second index was the coefficient of variation of Root Mean Square Error (CV(RMSE)). It expresses the ratio of the root mean square deviation and the mean observed values (**Equation 7.2**). The coefficient of variation is a measure of how data points disperse around the mean of a data series and expresses the degree of variation between two data series (simulation and measurement outcome); (150).

$$\text{(CV)RMSE} = \frac{RMSE}{\overline{X_{obs}}} \tag{7.2}$$

Where:

$\overline{X_{obs}}$ is the average of the observed values in the whole calibration period.

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. **Table 7.2** presents all the input variations in the model and the outcome of each applied adjustment.

Table 7.2 Summary of modifications in the IDA ICE model

| Reason | Adjustments in theoretical building model | Outcome after each alteration |
|---|---|---|
| **1.** T (simulated) > T (measured) | Adjust room thermostat set-point to 22°C/25°C | CV(RMSE) of T < 5% |
| **2.** $CO_2$ (simulated) < $CO_2$ (measured) | Set internal door to be always closed | CV(RMSE) of $CO_2$ >20% |
| **3.** $CO_2$ (simulated) < $CO_2$ (measured) | Increase occupancy by 1 person | CV(RMSE) of $CO_2$ > 20% |
| **4.** $CO_2$ (simulated) < $CO_2$ (measured) | Add occupancy period: 16:30-17:00 | CV(RMSE) of $CO_2$ < 20% |

After the deviation between the measured and simulated data reached the requested coefficient of variation of Root Mean Square Error, by using the same settings the calibrated model was run for a one week period. The model was considered calibrated when deviation between the measured and simulated data, expressed by coefficient of variation of Root Mean Square Error (CV(RMSE)) was less than 5% for air temperature and 20% for relative humidity and $CO_2$ concentration (150).

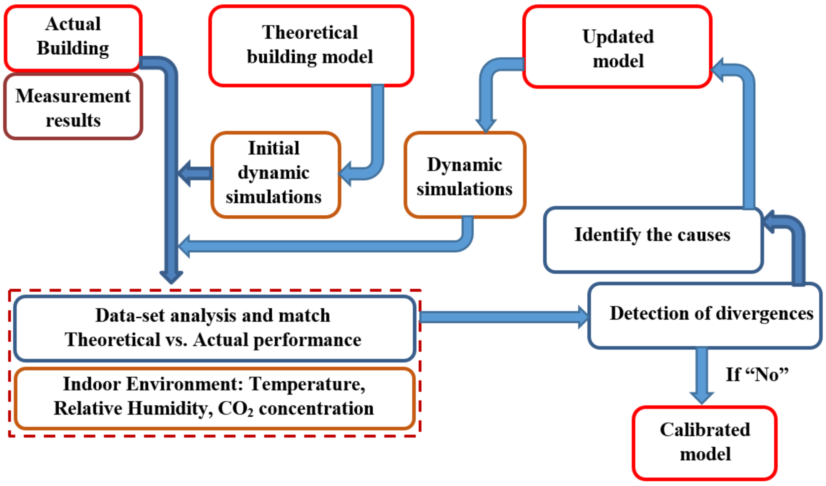


Figure 7.6 Description of methodology steps

### 7.1.5 Implementation of various alternatives of ventilation systems in the IDA ICE model

The calibrated model was used for further modelling of three alternatives of ventilation systems, presented for the renovated condition of the dwelling: natural ventilation (original state), demand controlled ventilation and constant air volume system (**Table 7.3**).

Table 7.3 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)<br>System type:<br>a) VAV, $CO_2$ and T control<br>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. |

Two system types of the demand controlled ventilation with variable air volume system (VAV) were applied in the study, separately. In one of the models “Temperature and $CO_2$ control” was used, while in another model ventilation system with “$CO_2$ control” was realized. **Figure 7.7** illustrates the way the demand controlled AHU was modelled in IDA ICE. This system consists of supply fan with pressure control, cooling and heating coil with liquid mass-flow control, air to air heat exchanger with control, supply air source, return fan with pressure control and exhaust air sink. The components of the AHU in the bedroom-zone **Figure 7.8** include supply inlet, supply terminal for VAV with “Temperature and $CO_2$ control” or just “$CO_2$ control”, exhaust inlet, and exhaust terminal for VAV. Sanitary room and kitchens are the prime sources of indoor odour and moisture pollutants. Therefore as the last alternative, using an exhaust systems (CAV) in the kitchen and sanitary rooms, and at the same time keeping the internal doors open was applied. The schematic presentation of the system is shown in **Figure 7.9**.

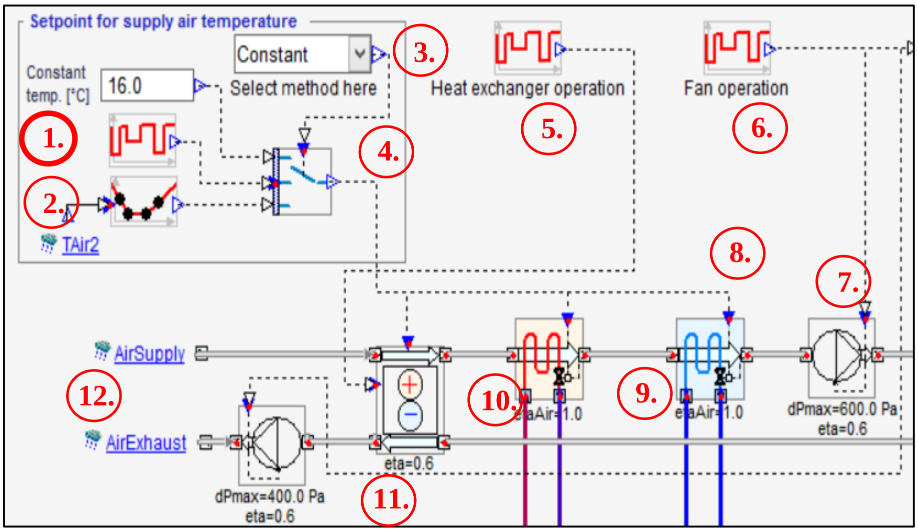


Figure 7.7 Schematic of the AHU in IDA ICE: 1-Supply schedule, 2-Supply air temperature set-point, 3-Air supply strategy, 4-Supply switch, 5-Heat exchanger operation, 6-Fan operation, 7-Supply fan with pressure control, 8-Cooling coil, 9-Heating coil, 10-Air to air heat exchanger, 11-Return air with pressure control, 12-Air supply and air exhaust.

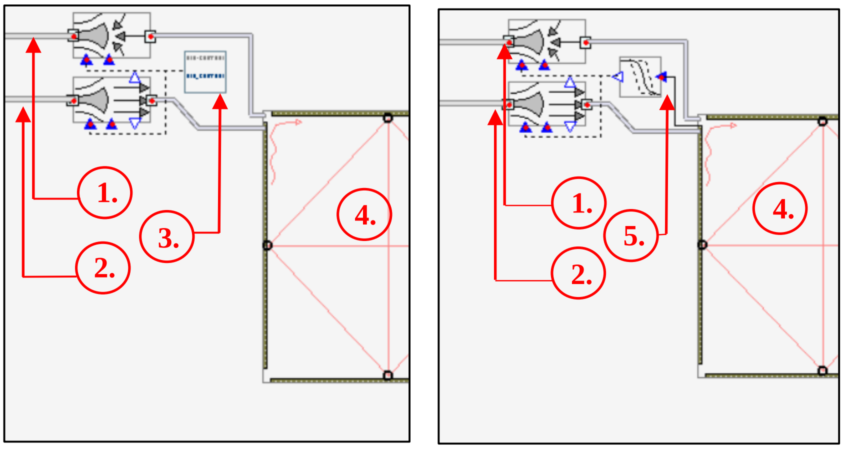


Figure 7.8 Components of “CO2 and T control” (left) and “CO2 control” (right) system types in bedroom: 1-Idealized exhaust terminal for VAV, 2-Idealized supply terminal for VAV temperature set-point, 3-CO2 and temperature control, 4-Investigated zone (Bedroom), 5-Air control.

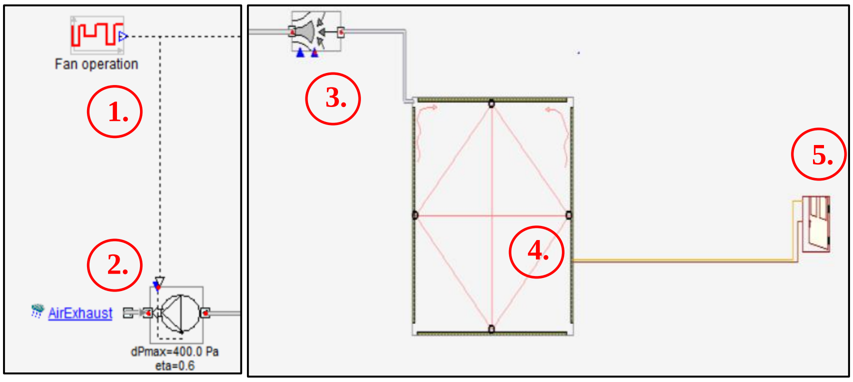


Figure 7.9 Schematic of the CAV system in the kitchen: 1-Fan operation, 2-Exhaust, 3-Idealized exhaust terminal for natural ventilation, 4-Kitchen, 5-Constaly opened doors

### 7.1.6 Systems´ energy performance

As the operation of the selected ventilation systems requires energy, each of the investigated alternatives was assessed from energy point of view. The energy performance of the ventilation alternatives were simulated for the whole building from January 2013 to December 2013. The final annual values were presented in unit of kWh/m$^2$. Due to missing weather data for some periods of the year, the simulated energy models were run by using the ASHRAE weather files for weather station of "Bratislava Airport" applied by the IDA ICE tool. Although this fact may cause inaccuracy in the results, we assume that the final values could give a general overview of the annual energy use for each of the proposed ventilation systems.

## 7.2 Results

### 7.2.1 Calibration

The coefficients of variation for the calibration model for the one day and the one week periods are presented separately in **Table 7.4** Coefficients of variation of Root Mean Square Error for one-day and one-week periods. After implementing the adjustments in the theoretical building model using natural ventilation, the one day coefficient of variation of Root Mean Square Error was sufficient. However, using the same adjustments for the one week calibration showed slightly higher coefficient of (CV) RMSE than the required value in $CO_2$ concentration. This deviation might be caused by lack of survey information, as well as we also assumed that inaccuracy may be affected by the mathematical model. Despite these facts, the one week model was still considered as adequate. The one-day and one-week calibration of the temperature and relative humidity data met the required limits of the coefficient of variation of Root Mean Square.

Table 7.4 Coefficients of variation of Root Mean Square Error for one-day and one-week periods

| Building condition | Calibration outcome ((CV) RMSE in %) | | | | | |
|---|---|---|---|---|---|---|
| | $CO_2$ (ppm) | | $T_{air}$ (°C) | | RH (%) | |
| | 1-day | 1-week | 1-day | 1-week | 1-day | 1-week |
| Original condition | 18 | 21 | 1.4 | 1.7 | 6 | 7.2 |
| Renovated condition | 19 | 23 | 1.5 | 1.7 | 7.5 | 7.8 |

### 7.2.2 Indoor environmental quality

Since the simulation study focused on finding solutions for improvement of the air quality in the renovated dwelling, the presented results are shown only for the renovated condition of the building. Higher temperatures were observed in the model with natural ventilation (**Figure 7.10**). There was no significant difference in temperature between the demand controlled ventilation with “$CO_2$ and T control” and “$CO_2$ control”. That is why on the figures presented below the grey line is hidden behind the yellow one. Very similar results were obtained with the CAV system with open doors compared to the. When demand controlled ventilation or exhaust systems were used and the zone was not occupied, the air temperature dropped to 19.7-19.9 °C. The relative humidity was acceptable in all cases of the investigated alternatives (**Figure 7.11**).

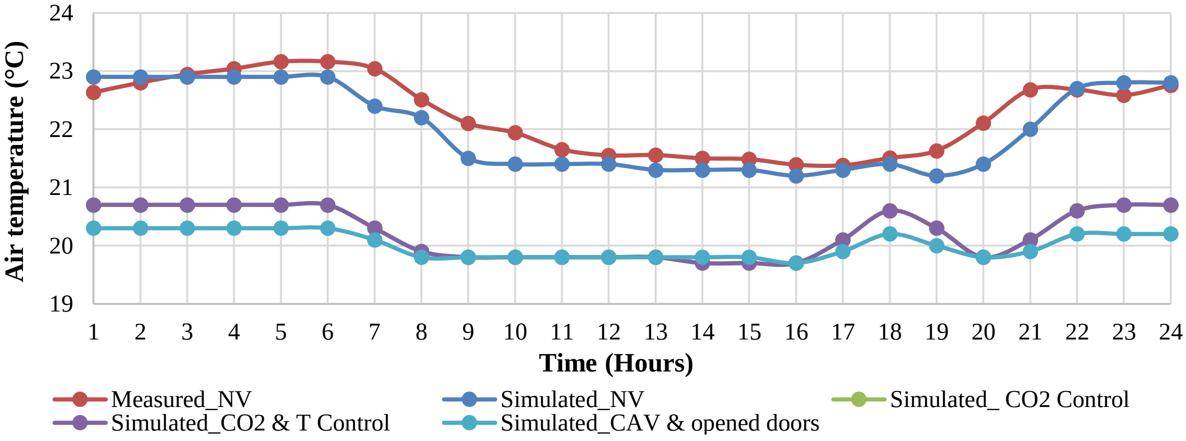


Figure 7.10 Hourly simulated versus measured values of air temperature in the “Bedroom 1” located in the renovated residential building. Data for “Simulated_$CO_2$ Control” is invisible due to overlap with “Simulated_$CO_2$ and T control”.

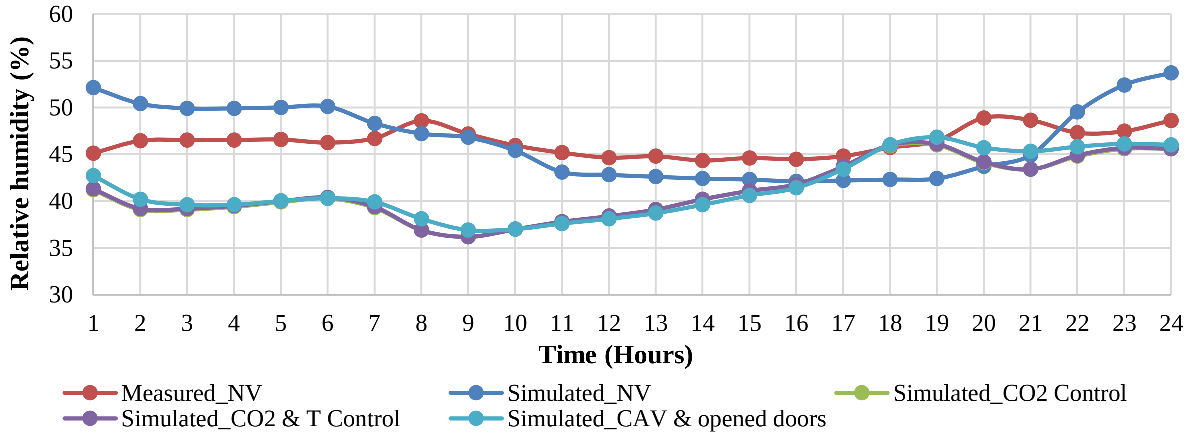


Figure 7.11 Hourly simulated versus measured values of relative humidity in the “Bedroom 1” located in the renovated residential building. Data for “Simulated_$CO_2$ Control” is invisible due to overlap with “Simulated_$CO_2$ and T control”.

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 (**Figure 7.12**). During occupied periods, especially overnight, the $CO_2$ concentration was above 2000 ppm. Using demand controlled ventilation or constant air volume ventilation lead 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.

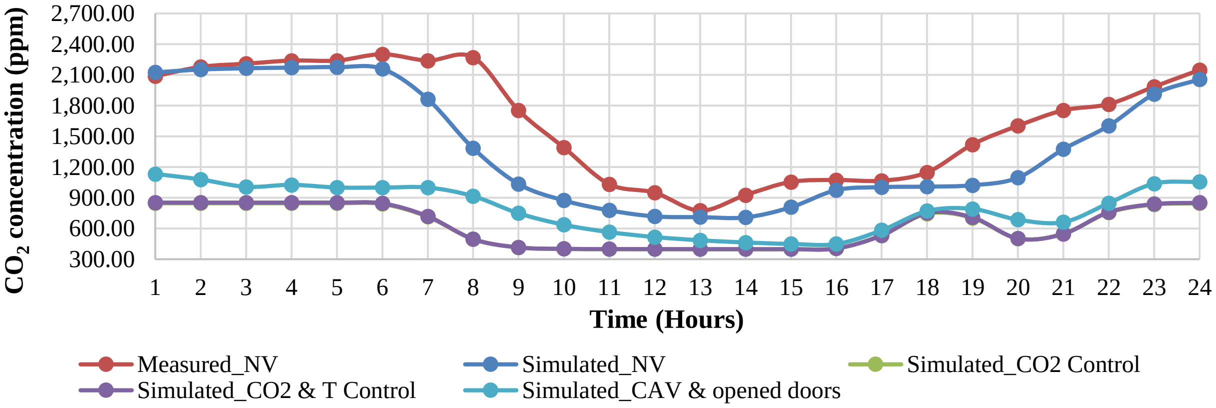


Figure 7.12 Hourly simulated versus measured values of $CO_2$ concentration in the Bedroom 1 located in the renovated residential building. Data for "Simulated_$CO_2$ Control" is invisible due to overlap with "Simulated_$CO_2$ and T control".

**Table 7.5** compares the one week night-time averages of the $CO_2$ concentrations obtained from physical measurements and simulations in the selected bedroom. The one-week averages of the airflows for each of the ventilation alternatives are also shown. The outflow and inflow through external walls was higher in the original condition of the dwelling than after the building envelope tightening. Using air handling unit showed mechanical in- and outflows 12.80 L/s (3.54 $h^{-1}$) by using "$CO_2$ and Temperature control" and 12.89 L/s (3.57 $h^{-1}$) when "$CO_2$ control" was used. In case of the exhaust system, high airflow was observed through the internal constructions. The average outflow through internal walls was 35.88 L/s (9.93 AER) and the inflow was 38.44 L/s (10.64 $h^{-1}$).

Table 7.5 Measured and simulated $CO_2$ averages, and simulated average airflows representing the one week measurement period in the selected bedroom

| Building condition | Ventilation | Average $CO_2$ (ppm) | | Average Airflow (L/s) (Simulated results) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Meas. | Sim. | Outflow through external walls | Inflow through external walls | Outflow through internal walls | Inflow through internal walls | Mechanical inflow | Mechanical outflow |
| Original | Natural vent | 1490 | 1290 | 6.22 | 10.70 | 0 | 0 | 0 | 0 |
| Renovated | Natural vent | 1930 | 1805 | 4.06 | 7.40 | 0 | 0 | 0 | 0 |
| Renovated | AHU ($CO_2$+T) | - | 780 | 4.10 | 7.60 | 4.10 | 0 | 12.80 | 12.80 |
| Renovated | AHU ($CO_2$) | - | 775 | 3.80 | 8.60 | 5.50 | 0 | 12.89 | 12.89 |
| Renovated | CAV (Exhaust) | - | 961 | 4.00 | 9.1 | 38.55 | 38.48 | 0 | 0 |

### 7.2.3 Energy consumption

The energy consumption of the investigated ventilation strategies was assessed. The use of an air handling unit requires more energy than the operation of system of exhaust fans. The monthly distribution of energy consumption of the demand controlled systems was similar in both cases of selected systems.

The annual energy consumption of the air handling unit with "$CO_2$ and temperature control" was 27 kWh/m$^2$ (**Figure 7.13**). The energy consumption of the AHU using "$CO_2$ control" was 29 kWh/m$^2$ (**Figure 7.14**). The annual energy consumption for the operation of the exhaust fans (CAV system) was 3.2 kWh/m$^2$. There was no monthly variation in this value.

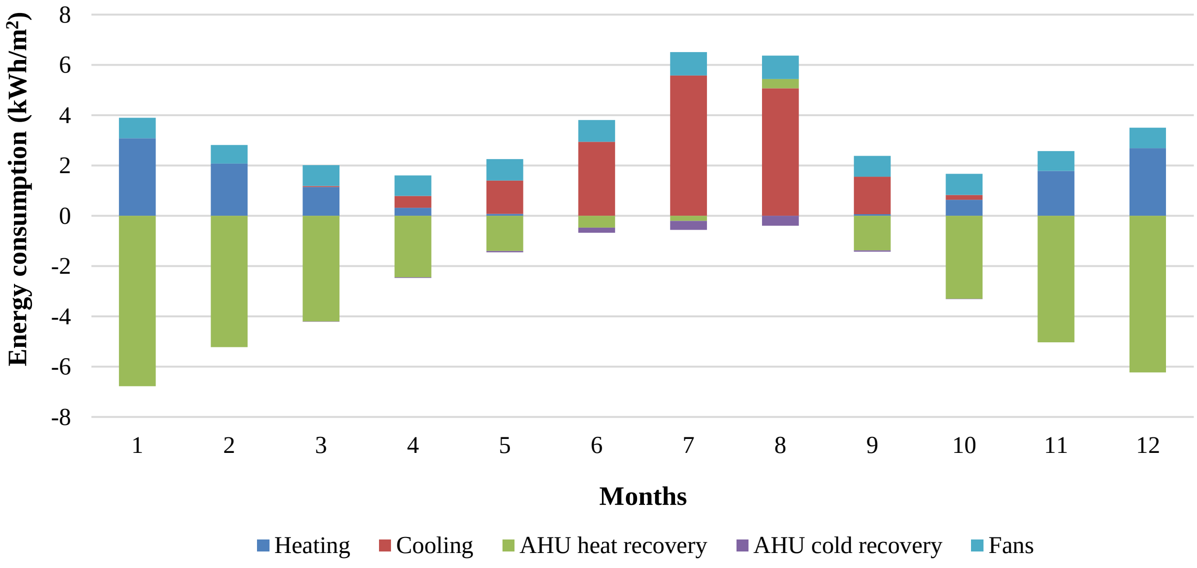


Figure 7.13 Monthly energy consumption of the AHU with "$CO_2$ and temperature control" presented for one year period

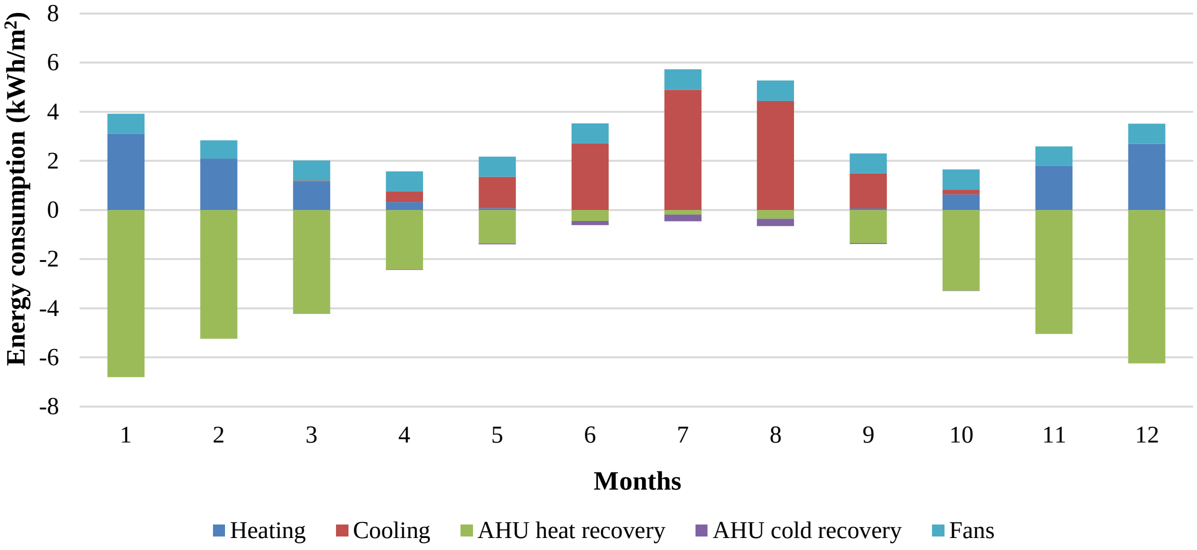


Figure 7.14 Monthly energy consumption of the AHU with “$CO_2$ control” presented for one year period

## 7.3 Discussion

The demand controlled systems with constant mechanical inflow and outflow resulted in a $CO_2$ concentration below 800 ppm in the zone. Using exhaust fans in the apartment caused a higher airflow through the internal constructions and ensured an average $CO_2$ concentration of 960 ppm in the investigated zone. Since the internal doors were open in the apartment, the air movement was likely influenced by the increased airflow towards the rooms where the fans were operating.  Although the two alternatives of the demand controlled system resulted in an acceptable level of the $CO_2$ concentration, the annual energy consumption of these systems was much higher than that of the exhaust systems. The relationship between the energy required to provide sufficient ventilation and the associated benefits in terms of health and comfort is a topic of wide discussion. Further research is needed to identify practical methods to increase ventilation rates without increasing energy consumption (35).

The present modelling exercise revealed possible solutions to reduce $CO_2$ concentration and increase air exchange rates in originally naturally ventilated residential buildings characterized by tight building constructions. Using exhaust systems in kitchens and sanitary rooms, and at the same time keeping doors of the rooms open may be one of the a low-cost ventilation strategies, which is able to provide improved indoor air quality in energy-retrofitted buildings with minimal additional energy penalty.

# 8. OVERALL DISCUSION

The energy use in the existing residential sector that was built in the second half of 20th century is considered a serious problem across the European Union (1; 19; 28; 151). The current focus on building energy retrofit provides an opportunity to simultaneously reduce energy use and $CO_2$ emissions of existing buildings (66; 4; 73; 76). Minimizing energy consumption with energy efficient building design is reasonable. However, the current national legislations and energy performance requirements are not complemented with appropriate requirements and recommendations to secure good IAQ. This dissertation thesis assessed the differences in IAQ and occupants´ well-being and behaviour between original and renovated multifamily residential buildings. The results indicated that renovation of apartment buildings in Slovakia may reduce the quality of the indoor environment in the apartments, especially in the winter season.

A number of physical and subjective indicators of IAQ were investigated in the study. The average air temperature was higher in the renovated dwellings in both winter and summer season. We found under-heating in several apartments in the original buildings in winter. Although earlier studies (3; 151) indicated that adding insulation to exterior walls or replacing single pane windows with efficient windows improves thermal comfort after renovation by decreasing drafts and reducing thermal radiation to cold walls and windows, the current study showed similar thermal sensation in both, original and renovated dwellings in winter. However, while the average acceptability of the thermal environment was similar in the original and the renovated dwellings, a greater fraction of occupants (95%) reported positive acceptability in the original buildings than in the renovated ones (43%). In summer, the results were opposite. Surprisingly, the residents in the renovated buildings preferred higher temperatures during the summertime. Zhang et al (113) reported that people may indicate high thermal acceptability even at higher indoor temperatures that may partly explain the current outcomes. Since the current work did not investigate the factors of local thermal discomfort that may have affected the occupants´ subjective evaluation (76; 110) especially in winter season, further research is needed to support the current results.

In winter, higher $CO_2$ concentration was observed in the renovated buildings, resulting in lower AERs. The greater fraction of the apartments located in the renovated buildings had lower AERs than 0.5 $h^{-1}$, while the AERs in the original dwellings met the recommended minimum level. Generally, when energy renovation, which often results in more airtight buildings, is performed, no assessment of its effect on ventilation is made. Therefore, often AERs below the required values are reported after renovation (32; 98; 115; 152). Older buildings are leakier, while currently renovated or newly built houses are better sealed due to improved construction techniques and stricter regulations (115). However, it must be noted that there are many other factors that can affect the level of AER. Occupants living near heavy trafficked roads trying to avoid street noise and traffic-related pollutants by keeping their windows closed, may experience lower AERs (115). Additional parameters that influence ventilation rate in naturally ventilated buildings are for instance home location, orientation, indoor-outdoor temperature difference, wind conditions, position of windows, volume and occupancy etc. (8; 98; 115). We found an association between IAQ and occupancy in the apartments and bedrooms and between IAQ and the occupants´ smoking habits. Higher percentage of occupants indicated to smoke in the renovated dwellings compared to the original buildings that could contribute to worse IAQ in the renovated residential buildings.

Lower AERs indicated increase of formaldehyde concentrations. Strong association was found also between levels of formaldehyde and relative humidity and TVOCs. Surprisingly greater fraction of the apartments exceeded the maximum recommended limit of 300 µg/m³ (127) already before renovation. However, even higher average TVOC was found in the renovated dwelling. Some of the individual VOCs, such as heptane, limonene, benzene, hexanoic acid, haxanal and isobutanol, indicated significant difference in concentrations before and after renovation. The average concentration of benzene decreased after renovation. High concentrations are expected to originate from cleaning products, buildings materials and furnishing (134; 136; 138), but such emissions usually decrease as buildings and materials age (136; 153). Three apartments reported recent replacement of furniture with new one. Much higher TVOC concentrations were measured in these particular apartments after renovation. At the outset of the 20th century there were approximately 50 materials used to construct buildings. By the end of the century this list had grown to around 55 000, with half of them being synthetic that may be implicated in indoor air quality toxicity (114). This may explain the increase of certain indoor pollutant concentrations, including irritating volatile and semivolatile organic compounds and products of their chemical reactions in the built environment (56; 10; 57), many of them with potential health implications. According to Salthammer (136) insulation materials, e. g. polystyrene, can be also one of the primary sources of indoor pollutants. Although the same type of material was used for envelope insulation in the current case study, additional research is needed to substantiate the negative impact of foam based insulation materials on indoor air quality.

The indoor-to-outdoor ratios of $NO_2$ indicated the presence of indoor combustion sources in a number of apartments. While none of the apartments had a gas burner, candle burning is common during the winter season (98; 154). Smokers also lived in a number of apartments. Human activities can affect the timing, location and degree of pollutant exposure, leading to substantial exposure variations (9). Cooking, tobacco smoking, candle and incense burning, and the use of gas and electric appliances can strongly affect the levels of $NO_2$, VOC but also ultrafine particles indoors (154; 155; 156). Measurements of longer duration and identification of the sources of $NO_2$ and other pollutants could improve the characterization of the impact of renovation on IAQ and the associated exposure assessment.

Lower AERs and higher concentrations of indoor air pollutants in the renovated dwellings were linked to insufficient airing out in the apartments as well as to the occupants´ lower satisfaction with PAQ. In most of the apartments the occupants ventilated as frequently after renovation as before renovation. This happened to be inadequate to avoid deterioration of the IAQ. In the first case study (six buildings), 22% of the occupants in the renovated buildings indicated that they air out more often during the winter than before renovation. Comparison of the occupants´ airing habits before and after renovation in the second case study indicated similar observations. Longer duration of airing out resulted in higher AERs and more acceptable IAQ. The results from the summer further support this observation; 47% of residents indicated that they have changed their airing habits and air out more often than they did before renovation. People air out more often at higher ambient temperatures. This leads to higher ventilation rates in summer than in winter (109; 118; 119).

The first case study indicated a positive association between some of the SBS symptoms such as itchy eyes, headache and fatigue and $CO_2$ concentration. In the second field study, association was found between itchy eyes and building type (original/renovated) and between headache and building type (original/renovated) and AER. The associations however lacked statistical significance. Measurements in a larger number of apartments and including more occupants may result in stronger associations. Nevertheless, the results indicate the need for further investigation of the impact of building renovation on occupant health and SBS symptoms. Earlier studies showed that insufficient ventilation, resulting in high concentration of $CO_2$ and other indoor pollutants in occupied spaces, is associated with adverse effects on human health, comfort and productivity, including the occurrence of SBS symptoms (46; 35; 12; 157).

The current work investigated only few selected pollutants indoors. Other indoor pollutants, such as particles, may also have an impact on occupants´ health and well-being. High concentrations of particles may pose cardiovascular, respiratory, and neurological health hazards (158; 159). Increasing attention is paid in recent years to ultrafine particle exposure in residencies. Future studies on the impact of renovation on IAQ should include measurements of ultrafine particle concentrations.

In our study, 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. Adding standard AHU 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. Lessons can be also learned from recent studies comparing IAQ in green or low energy houses with that in conventional buildings (122). Green (low energy, sustainable) buildings are built with focus on resource-efficiency both during the building process and throughout the building's life-cycle (160). They are created using the principles and methodologies of sustainable construction (161), which aim to construct energy-efficient, healthy, and productive buildings that reduce the significant impact of buildings on urban life and the global environment (162). Emission source control, ventilation, and indoor air measurement are the three main pathways used in green building schemes for IAQ management. Several building certification schemes have been created around the world, for instance LEED (USA), GREEN MARK (Singapore), BREEAM (UK), GREEN STAR (Australia), etc. Buildings can only be termed sustainable if they safeguard the interests of future generations. Certification schemes should thus also strongly emphasize IEQ, which besides reducing environmental impacts, are also expected to create conditions of health and comfort by advancing IAQ and as a consequence also improving productivity and reduce sick-leave (163). For an outstanding built environment, occupants must be prioritized, and placed in the center of the design. Energy efficiency should not overshadow occupant well-being. Recent schemes as the WELL building standard (164) are following this human centricity direction.

# 9. CONCLUSIONS, RECOMMENDATIONS AND LIMITATIONS

## 9.1 Conclusions

This thesis presented experimental investigation of the impact of building renovation on IAQ and occupant comfort in residential buildings. 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, AER, 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 this study can be summarized as follows:

**Thermal comfort:**

- Although under-heating and lower average indoor temperature was observed in the original buildings, higher percentage of occupants in the original building than in the renovated ones indicated the thermal environment to be acceptable.
- Although the average indoor temperature in the summer was higher in the renovated dwellings, 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 concentrations. 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 patterns. Ratios above one in a number of apartments indicate the presence of indoor combustion sources.

- The TVOC concentrations exceeded 300 µg/m³ 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 of the residential. This could result in lower AERs, higher concentrations of pollutants and poorer IAQ. Longer duration of airing leads to higher AERs and more acceptable 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 include improved has to consider aspects of ventilation in order to ensure sufficient air exchange rates and acceptable and healthy IAQ.

## 9.2 Recommendations

A key 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 pleasant indoor environment should be included. Such requirements should 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´ well-being. Such requirements should cover factors such as for example 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 should be integrated in the energy certification program of Slovakia.

## 9.3 Limitations

The baseline data collected as a part of this study appear useful for reference purposes, as long as more representative data do not exists. Reliable reference data are important when assessing the effects of changes on the population level, for example as a result of new policies and programs implemented in the housing stock. However, there are several limitations of the study presented in this work:

- More detailed thermal comfort study, including assessment of thermal discomfort parameters and occupants´ clothing habits could strengthen the current findings

- The statistical model describing the variation in the $CO_2$ concentrations across the investigated apartments would benefit from additional data on parameters that influence natural ventilation, such as home location, orientation, indoor-outdoor temperature difference, wind conditions, position of windows.
- The data on occupant behaviour and habits rely on occupant reports. Monitoring of occupant behaviour related to airing would provide more reliable data. Additionally, airing in winter mainly occurs in the daytime, while the AERs in this study were determined for the night-time.

- Measurements of longer duration, continuous measurement (as opposed to 1-week averages by passive samplers) and detailed identification of the sources of chemical pollutants would be recommended in future studies.
- Studies conducted in larger number of residential buildings and apartments of different types and in various regions would strengthen the validity of the results and provide a stronger incentive for better strategies to improve the indoor environment along with the environmental sustainability of existing buildings.

# RESUME IN SLOVAK LANGUAGE

## Úvod

Budovy sú zodpovedné za jednu tretinu globálnej spotreby energie. Preto potreba znížiť spotrebu energie a emisie skleníkových plynov sa stalo národnou prioritou vo všetkých členských krajinách Európskej únie (1; 2; 3; 4). Veľká časť európskej populácie žije v bytových objektoch (1). Z uvedeného dôvodu bytový sektor predstavuje potenciálnu cieľovú skupinu pre národné programy na podporu zlepšenia energetickej náročnosti existujúcich budov a zmiernenie klimatických zmien. Slovensko je jedným z európskych krajín, ktoré dobre reprezentuje stredoeurópsky bytový fond ako aj veľkú časť bytových domov v západnej a severnej Európe. Väčšina bytových domov bola postavená medzi 1948 až 1990, s najvyššou intenzitou bytovej výstavby v rokoch 1971 – 1980 (1). Väčšina týchto objektov (~70%) nespĺňa súčasné požiadavky na energetickú hospodárnosť budov (5). Celoštátne nápravné opatrenia boli prijaté na zlepšenie ich energetickej náročnosti a zníženie spotreby energie (6; 7). Avšak, tieto nápravné opatrenia nie sú systematicky hodnotené. Najmä hodnotenie vplyvu obnovy na kvalitu vnútorného vzduchu a pohodu obyvateľov je často zanedbané. V dôsledku toho, Slovensko, rovnako ako niekoľko ďalších východoeurópskych a stredoeurópskych krajín, v celoštátnom meradle neprijíma opatrenia na zlepšenie kvality vnútorného prostredia.

Zateplenie obvodového plášťa alebo výmena otvorových konštrukcií za nové plastové s izolačným dvoj-sklom prispieva k zníženiu spotreby energie a taktiež môže zvýšiť tepelnú pohodu so znížením výskytu prievanu a chladu od stien a podláh (3). Avšak, tesnenie obvodového plášťa budovy, bez kompenzačných opatrení, často vedie k zníženiu intenzity výmeny vzduchu, čo môže prispieť k zvýšeniu koncentrácií znečisťujúcich látok vo vnútornom vzduchu (8). Ľudia strávia 80% svojho času doma (9). Nízka intenzita výmeny vzduchu, ktorá je spôsobená vysokou vzduchotesnosťou obvodového plášťa, je spojená s výskytom mnohými dlhodobými a akútnymi zdravotnými účinkami, ako sú ochorenia dýchacích ciest, rakoviny, alergie, podráždenie zmyslových orgánov a taktiež príznakmi syndrómu chorých budov (10; 11; 12). Preto je potrebné zaviesť opatrenia na hodnotenie vplyvu aktuálne používaných renovačných praktík, s primárnym zameraním na úspory energie a kvality vnútorného prostredia, a poskytnúť odporúčania pre tvorcov zákonov, inžinierov a verejnosti.

Táto štúdia bola navrhnutá tak, aby na základe vyššie uvedených informácií ukázal súvislosť medzi obnovou bytových domov, energetickou náročnosťou, kvalitou vnútorného prostredia a zdravím a pohodlím obyvateľov.

## Ciele dizertačnej práce

Komplexným zámerom tejto dizertačnej práce bolo objektívne a subjektívne hodnotenie vplyvu obnovy bytových domov na kvalitu vnútorného prostredia, a to hlavne na kvalitu vnútorného vzduchu, a správanie sa obyvateľov.

Podrobné ciele dizertačnej práce:

- Analýza a hodnotenie v zmien fyzikálnych ukazovateľov kvality vnútorného vzduchu v neobnovených a obnovených bytových domoch.
- Analýza a hodnotenie v zmien výskytu koncentrácií znečisťujúcich látok vo vnútornom vzduchu v neobnovených a obnovených bytových domoch.
- Analýza subjektívneho hodnotenie kvality vnútorného prostredia v neobnovených a obnovených bytových domoch: analýza a hodnotenie vetracích návykov obyvateľov a hodnotenie pociťovanej kvality vzduchu a výskytu príznakov syndrómu chorých budov v závislosti od rôznych parametrov kvality vnútorného vzduchu.
- Podať komplexný pohľad na problematiku vzťahu obnovy a kvalitu vnútorného vzduchu, a porovnať výsledky štúdie s výsledkami, ktoré boli prezentované v predošlých publikáciách.
- Porovnať skutočné (namerané) výsledky s výsledkami získaných zo simulácií, a na základe konečných výsledkov zadefinovať riešenia a odporúčania pre prax a verejnosť.

Všeobecný pohľad na kvalitu vnútorného prostredia v neobnovených a obnovených bytových domoch podáva kapitola č. 4. Podrobná analýza a hodnotenie kvality vnútorného vzduchu je popísaná v kapitole č. 5. Kapitola č. 6 podáva komplexný pohľad na energetickú náročnosť hodnotených dvojíc bytových domov. Výstupy simulačnej štúdie sú spracované v kapitole č. 7.

# Kvalita vnútorného prostredia (Prípadové štúdia I.)

## i. Metodika

Prvá prípadová štúdia bola vykonaná v troch dvojiciach bytových domov (**Tab.1**). Dvojicu bytových domov tvorili domy postavené v rovnakej stavebnej sústave stojace vedľa seba s rovnakou orientáciou na svetové strany, pričom jeden z dvojice objektov bol v pôvodnom stave a druhý bol obnovený. Vybrané bytové domy boli vetrané prirodzene. Odsávanie bolo nainštalované iba v hygienických miestnostiach. Okná v neobnovených bytových domoch boli vymenené za nové plastové s izolačným dvojsklom. Ostatné konštrukcie sa nachádzali v pôvodnom stave. Na obnovených bytových domoch boli realizované nasledujúce energeticky úsporné opatrenia: zateplenie obvodového a strešného plášťa, hydraulické vyregulovanie vykurovacej sústavy a výmena okenných konštrukcií v spoločných miestnostiach bytového domu. Okenné konštrukcie v jednotlivých bytoch boli vymenené za plastové s izolačným dvojsklom ešte pred začatím realizácie obnovy.

Tab. 1. Charakteristika dvojíc bytových domov hodnotené v danom štúdiu

| Dvojica domov | I. | | II. | | III. | |
|---|---|---|---|---|---|---|
| Základné parametre | Pôvodný | Obnovený | Pôvodný | Obnovený | Pôvodný | Obnovený |
| |  |  |  |  |  |  |
| Rok výstavby | 1965 | 1970 | 1970 | 1972 | 1980 | 1983 |
| Orientácia na svetové strany | Východ | | Severozápad | | Sever | |
| Výška (m) | 27.71 | | 30.24 | | 13.05 | |
| Objem ($m^3$) | 9 412 | 9 683 | 5 936 | 6 114 | 6333 | 6 523 |
| Plocha ($m^2$) | 3 408 | 3 449 | 1 875 | 1 913 | 2 174 | 2 217 |
| Počet podlaží | 10 | | 9 | | 4 | |
| Počet bytov na jednom podlaží | 4 | | 2 | | 2 | |
| Počet vchodov | 1 | | 1 | | 3 | |

Z tejto štúdie bola získaná široká databáza údajov charakterizujúca kvalitu vnútorného prostredia. V zimnom období merania prebehli v 94 bytoch (45 bytov v pôvodnom stave; 49 bytov po obnove). Počas letných mesiacoch merania sa uskutočnili v 73 bytoch (35 bytov v pôvodnom stave; 38 bytov po obnove). V každom byte bol umiestnený jeden prístroj počas ôsmych nocí, a to v spálňach obyvateľov.

Zber dát vnútornej teploty, relatívnej vlhkosti a koncentrácie $CO_2$ sa uskutočnil pomocou HOBO ústredne a VAISALA $CO_2$ vysielača (**Obr. 1**). V HOBO záznamníku je vstavaný senzor pre meranie teploty a relatívnej vlhkosti. Monitor $CO_2$ bol pripojený k HOBO ústredne s káblom pre prenos signálu. Údaje boli zaznamenávané v intervale každých 5 minút. Skúmaná oblasť a umiestnenie prístrojov museli byť starostlivo vybrané. Prístroje boli umiestnené v reprezentatívnom bode skúmanej miestnosti, kde sa očakáva najvyššia možná účinnosť miešania vzduchu (102). Pri týchto typoch meraní je nutné sa vyhýbať umiestneniu prístrojov v blízkosti okien, stien, podlahy a rohov.

Obr. 1. Prístroj na meranie parametrov kvality vnútorného vzduchu

Intenzita výmeny vzduchu bola vypočítaná na základe nočnej koncentrácie $CO_2$ (od 20:30 do 6:30) nameranej v každom posudzovanom byte. Na výpočet bolo potrebné poznať aj fyzický stav obyvateľov (hmotnosť a výšku) a obsadenosť izieb počas nočných hodín (102; 103). Vo výpočte bola použitá metodika zvyšujúcej a znižujúcej sa koncentrácie $CO_2$ a ustáleného stavu (103).

Na subjektívne hodnotenie kvality vzduchu bol použitý dotazníkový prieskum, ktorý sa uskutočnil priebežne s fyzikálnymi meraniami. Dotazníkový prieskum sa zameriaval na hodnotenie tepelnej pohody, kvality pociťovaného vzduchu a vetracie návyky obyvateľov.

## ii. Výsledky

### A) Tepelná pohoda

Rozdiel priemernej vnútornej teploty v neobnovených a obnovených bytových domoch bol štatisticky signifikantný aj v zime ($p<0.01$) aj v lete ($p=0.01-0.05$). V zime priemerná vnútorná teplota bola 21.5°C v neobnovených bytových domoch, a 22.5°C v obnovených objektoch. V lete taktiež vyššia priemerná teplota bola zaznamenaná v obnovených domoch (26.6°C) ako v neobnovených objektoch (25.5 °C). Podrobné výstupy popisnej štatistiky sú zhrnuté v **Tab.**

**2**, pre denné aj nočné obdobie. Denné aj nočné výsledky boli štatisticky signifikantné a to aj v zimnom aj v letnom období.

Tab. 2. Výpis popisnej štatistiky pre vnútornú teplotu vzduchu

Zima

| **Popisná štatistika** | **Pôvodný (N=45)** | | **Obnovený (N=49)** | |
|---|---|---|---|---|
| | **Deň** | **Noc** | **Deň** | **Noc** |
| Priemer<br>(Min.-Max.) | 21.4<br>(17.6-25.1) | 21.7<br>(17.9-25.1) | 22.2<br>(19.2-25.6) | 22.7<br>(20.4-25.8) |
| Štandardná odchýlka | 1.9 | 1.7 | 1.5 | 1.4 |
| Štandardná chyba | 0.28 | 0.25 | 0.21 | 0.20 |
| 95% interval spol. | 20.8-21.9 | 21.3-22.3 | 21.7-22.6 | 22.3-23.1 |

**0.05<p<0.1**

**p<0.01**

Leto

| **Popisná štatistika** | **Pôvodný (N=35)** | | **Obnovený (N=38)** | |
|---|---|---|---|---|
| | **Deň** | **Noc** | **Deň** | **Noc** |
| Priemer<br>(Min.-Max.) | 25.7<br>(22.4-28.7) | 25.8<br>(22.4-28.5) | 26.7<br>(23.9-29.6) | 26.6<br>(23.8-28.6) |
| Štandardná odchýlka | 1.9 | 1.9 | 1.3 | 1.2 |
| Štandardná chyba | 0.31 | 0.31 | 0.20 | 0.19 |
| 95% interval spol. | 25.0-26.3 | 25.2-26.4 | 26.3-27.1 | 26.0-26.8 |

**p<0.01**

**0.05<p<0.1**

Podľa ISO 7730 odporúčaný rozsah vnútornej teploty v zimnom období je od 20 do 24°C (110). Túto požiadavku spĺňalo 78% bytov nachádzajúcich sa v neobnovených objektoch a 91% bytov v obnovených bytových domoch.. Avšak dlhšia doba s celkovými priemernými teplotami pod 20 °C bola pozorovaná v neobnovených domoch (18%), ako v budovách po rekonštrukcii (2%). Len veľmi malé percento bytov prekročilo maximálnu odporúčanú hodnotu 24 °C; 4% v neobnovených a 6% v obnovených bytových domoch.

V lete optimálny rozsah vnútornej teploty sa pohybuje medzi 23 °C a 26 °C (110). Túto požiadavku nespĺňalo 56% bytov v pôvodných bytových domoch. Teploty pod 23 °C malo 11% spální a vyššiu celkovú priemernú teplotu ako je odporúčané maximum malo 45% spální. Vnútorná teplota pod 23 °C bola pozorovaná v bytoch nachádzajúcich sa vo dvojici budov III.

Podľa Slovenského hydrometeorologického ústavu, v tom týždni keď sa meralo v spomínanom bytovom dome, boli zaznamenané nižšie priemerné vonkajšej teploty (17 °C) v porovnaní s ostatnými letnými dňami (20 °C). V obnovených objektoch 69% bytov malo vyššiu priemernú teplotu ako 26 °C. Nižšie percento bytov v obnovených budovách (29%) bolo v odporúčanom rozmedzí teplôt s porovnaní s percentom spální v pôvodných budovách (44%).

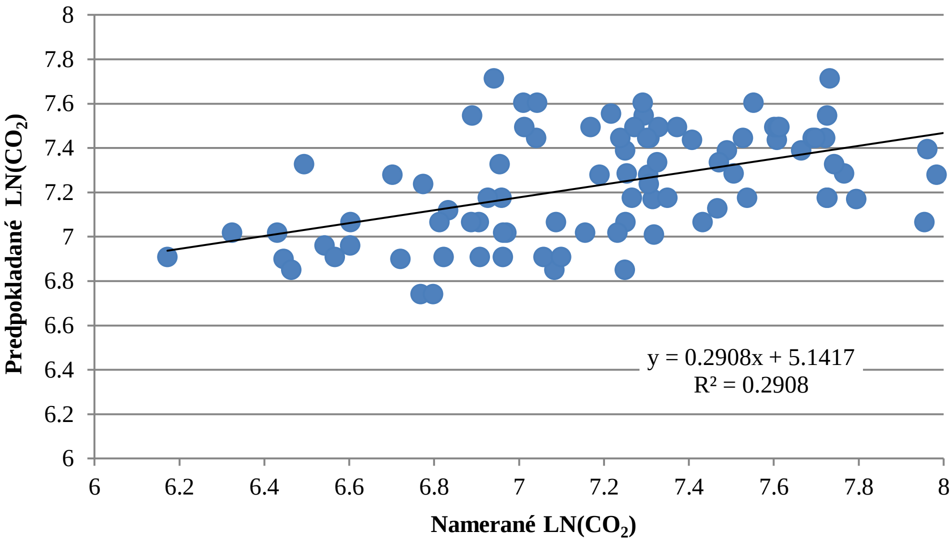
V zime priemerný tepelný pocit obyvateľov žijúcich v neobnovených bytových domoch bol 0.5, čo charakterizuje neutrálne až mierne teplé tepelné prostredie, zatiaľ čo v obnovených bytových domoch priemerný tepelný pocit bol 1.7, charakterizujúci mierne teplé až teplé prostredie, ($p<0.05$). Napriek tomu, že teplejšie prostredie bolo hlásené obyvateľmi v obnovených domoch, prijateľnosť s tepelným prostredím bola podobná v neobnovených (ACC=0.42) a obnovených (ACC=0.31) bytových domoch, ($p<0.05$). Je však potrebné si poznamenať, že väčšie percento obyvateľov v rekonštruovaných budovách hlásilo teplotu prostredia za neprijateľné, v porovnaní s pôvodnými budovami. V pôvodných budovách iba 5% obyvateľov bolo nespokojných teplotou prostredia (prijateľnosti pod nulou), zatiaľ kým v rekonštruovaných bytov viac ako polovica respondentov (57%) hlásilo negatívnu prijateľnosť.

V lete, tepelný pocit sa zvýšil až na úroveň medzi mierne teplé a teplé prostredie v neobnovených bytových domoch (TS = 1.7). V rekonštruovaných budovách obyvatelia mali podobný priemerný tepelný pocit (TS = 1.6, $p>0.1$) ako v zime, hoci výskyt pocitu neutrálneho alebo teplého prostredia bolo častejšie. So zvyšujúcim sa tepelným pocitom v pôvodných budovách zo zimy do leta, prijateľnosť s tepelným prostredím sa znížila medzi obyvateľmi (ACC=0.27). Naopak, to bolo v rekonštruovaných objektoch, kde sa mierne zvýšila prijateľnosť (ACC = 0.53; $p <0.05$), a to napriek nemenenému tepelnému pocitu zo zimy do leta a vyšším priemerným teplotám s porovnaní s pôvodnými budovami.

### B) Kvalita vnútorného vzduchu

Rozdiel v priemerných koncentráciách $CO_2$ medzi pôvodnými a obnovenými budovami bol štatisticky signifikantný v zime ($0.05 <p <0.1$). V neobnovených bytových domoch medián bol 1110 ppm a celkový priemer bol 1180 ppm. V obnovených bytových domoch aj stredná hodnota (1290 ppm) aj celkový priemer (1380 ppm) boli mierne vyššie ako v neobnovených objektoch. V letných mesiacoch výsledky neboli štatisticky významné ($p> 0.1$), a aj v bytových domoch v pôvodnom aj obnovenom stave koncentrácie $CO_2$ boli podobné (~800-900 ppm).

Model regresnej analýzy ukázal súvislosť medzi koncentráciou $CO_2$ a obnovou objektu, obsadenosťou bytu a spální, a fajčiarskymi návykmi obyvateľov. Koeficient korelácie štatistického modelu bol $R^2=0.29$.



Obr. 2. Model regresnej analýzy ako vzťah medzi nameranou a predpokladanou koncentráciou $CO_2$

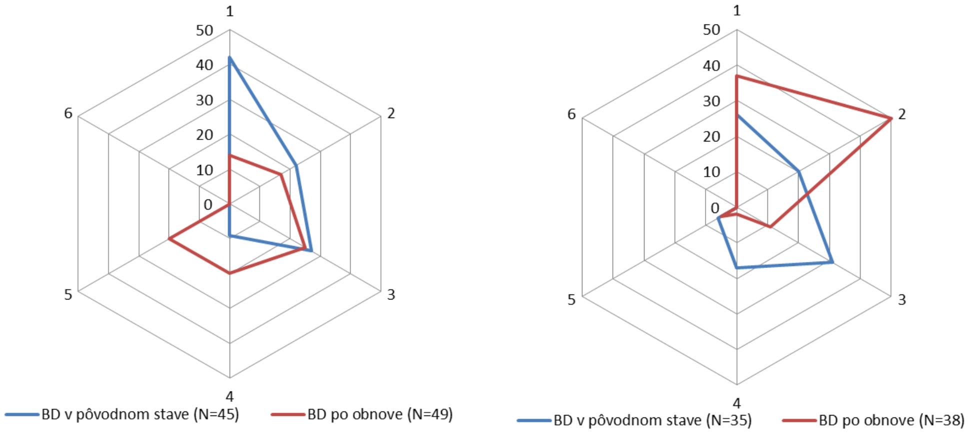
V zimnom období priemerná intenzita výmeny vzduchu v pôvodných bytových domoch bola výrazne vyššia ako v obnovených budovách ($p<0.01$). V zime v neobnovených bytových domoch celkový priemer intenzity výmeny vzduchu bol 0.79 $h^{-1}$. Intenzity výmeny vzduchu pre jednotlivé byty boli v rozmedzí od 0.22 do 3.69 $h^{-1}$. V obnovených objektoch celková priemerná intenzita výmeny vzduchu (0.48 $h^{-1}$) bola mierne nižšia, ako je odporúčané hygienické minimum (0.5 $h^{-1}$). V týchto budovách intenzita výmeny vzduchu sa pohybovala od 0.06 do 1.33 $h^{-1}$. V lete intenzity výmeny vzduchu boli podobné v oboch typoch bytových domoch ($p>0.05$). V pôvodných bytových domoch celková priemerná intenzita výmeny vzduchu bola 7.88 $h^{-1}$ a v obnovených objektoch 8.80 $h^{-1}$. V niektorej zo spální intenzita výmeny vzduchu dosiahla aj 19 $h^{-1}$.

Tab. 3. Výpis popisnej štatistiky pre intenzitu výmeny vzduchu

| **Popisná štatistika** | **Zima** | | **Leto** | |
|---|---|---|---|---|
| | **Pôvodný (N=43)** | **Obnovený (N=44)** | **Pôvodný (N=34)** | **Obnovený (N=38)** |
| Priemer<br>(Min.-Max.) | 0.79<br>(0.22-3.69) | 0.48<br>(0.06-1.33) | 7.88<br>(0.32-19.84) | 8.80<br>(0.39-19.82) |
| Štandardná odchýlka | 0.69 | 0.31 | 7.32 | 7.67 |
| Štandardná chyba | 0.11 | 0.05 | 1.26 | 1.24 |
| 95% interval spol. | 0.58-1.01 | 0.39-0.58 | 5.33-10.44 | 6.28-11.32 |
| p-hodnota | 0.007 | | 0.607 | |

## C) Pociťovaná kvalita vzduchu a vetracie návyky obyvateľov

Respondenti boli požiadaní aby odpovedali na otázku „Podľa Vás v akej miere máte nepríjemný (opotrebovaný) vzduch vo Vašom byte?“ a aby ich odpovede označili na 6-bodovej stupnici, kde číslo 1 znamenalo najlepšie hodnotenie a číslo 6 najhoršie. Ich odpovede sú znázornené na **Obr. 3a a 3b** tak pre zimné, ako aj letné obdobie. Odpovede obyvateľov jasne ukazujú, že počas zimných mesiacov prevládala väčšia spokojnosť s pociťovanou kvalitou vzduchu medzi obyvateľmi neobnovených objektoch (**Obr. 3a**), kým v lete boli opačné výsledky. Podľa respondentov obnovených bytových domov, úroveň opotrebovaného vzduchu bol menej nepríjemný, ako podľa obyvateľov bytových domov nachádzajúce sa v pôvodnom stave (**Obr. 3b**).



Obr. 3 Úroveň nepríjemného (opotrebovaného) vzduchu v jednotlivých bytoch nachádzajúce sa v hodnotených bytových domoch (1-nie je problém, 6-veľký problém) v zime (vľavo) a v lete (vpravo).

Na základe vyplnených dotazníkov v obnovených bytových domoch bolo možné určiť, že v tejto prípadovej štúdii iba 22% obyvateľov vetrá častejšie ako to robili pred rekonštrukciou objektov. Nedostatočné vetranie objektov môže prispieť k zvýšeniu koncentrácie $CO_2$ a taktiež horšej kvalite vnútorného prostredia (34; 116; 117). Výsledky letného prieskumu ukazujú, že 47% obyvateľov obnovených domov zmenilo svoje vetracie návyky a vetrajú častejšie ako pred komplexnou obnovou objektu. Bolo zistené, že ľudia vetrajú častejšia pri vyšších okolitých teplotách (109; 118; 119). Tento fakt potvrdzuje vyššiu intenzitu vetrania počas letných mesiacoch oproti zimnému obdobiu. Väčšie percento obyvateľov v rekonštruovaných bytových domoch, ktoré si zmenili vetracie návyky a vetrajú častejšie v letnom období (47%) oproti výsledkom zo zimného prieskumu (22%), môže čiastočne vysvetliť nižšiu koncentráciu $CO_2$ a väčšiu spokojnosť s vnímanou kvalitou vzduchu v obnovených objektoch počas letných mesiacov, na rozdiel od výsledkov zo zimných meraní.

## Kvalita vnútorného vzduchu (Prípadové štúdia II.)

### i. Metodika

Druhá prípadová štúdia bola vykonaná v jednom predošle hodnotenom bytovom dome, a to pred a po jeho obnove (**Obr. 4**). Z hľadiska časových aspektov obnovy bytového domu, neobnovená budova z dvojice č. I. bola zvolená na ďalšie hodnotenie. Vybraný objekt bol deväť podlaží bytový dom. V budove sa nachádzalo celkovo štyridsať bytov. Rekonštrukcia bytu zahŕňala realizáciu rovnakých energeticky úsporných opatrení ako to bolo zadefinovaná pri predchádzajúcej štúdii.

Obr. 4 Posudzovaný bytový dom v pôvodnom stave a po obnove

Dotazníkový prieskum a objektívne merania kvality vnútorného vzduchu boli vykonané v priebehu dvoch zimných období. Prvé kolo meraní bolo vykonané v januári 2015, kedy objekt bol ešte v pôvodnom stave. Druhé kolo sa uskutočnilo v januári 2016 po obnove bytového domu. Obe kolá meraní sa realizovali v tých istých dvadsiatich vybraných bytoch, a to počas doby ôsmich dní.

Boli merané nasledovné ukazovatele: teplota vzduchu, relatívna vlhkosť, koncentrácia $CO_2$, oxid dusičitého ($NO_2$), formaldehydu a prchavých organických látok. Teplota, relatívna vlhkosť a koncentrácie $CO_2$ boli merané v spálňach bytov s použitím rovnakej metodológie ako v prípade prvej štúdie. Na zaznamenávanie dát boli použité HOBO ústredňa a VAISALA $CO_2$ vysielač. Všetky zariadenia boli kalibrované pred začiatkom meracej kampane. Údaje boli zaznamenané v 5 minútových intervaloch, po dobu ôsmich dní v každom byte. Sady pasívnych vzoriek slúžiace na odber $NO_2$, formaldehydu a prchavých organických látok (**Obr. 5**), boli umiestnené centrálne v obývacích izbách jednotlivých bytov. Tieto vzorky boli vždy umiestnené najmenej 1.5 m nad úrovňou podlahy. Pri týchto typoch meraní je nutné sa vyhýbať umiestneniu prístrojov v blízkosti okien a radiátorov.

Dotazníkový prieskum bol vykonaný súbežne s fyzikálnymi meraniami pred a po obnove budovy. Dotazníky boli takmer totožné s tými, ktoré boli použité v prvej prípadovej štúdii. Avšak drobné úpravy boli realizované v niektorých z otázok.

Obr. 5 Vzorky slúžiace na odber koncentrácie $NO_2$ (vľavo), formaldehydu (v strede) a prchavých organických látok (vpravo)

## ii. Výsledky

### A) Objektívne hodnotenie kvality vzduchu

Vyššie koncentrácie $CO_2$, $NO_2$, formaldehydu a prchavých organických látok boli namerané po obnove bytového domu (**Tab. 5**). Avšak nie všetky výsledky boli signifikantné. Vplyv obnovy bytového domu najviac sa zvýraznil pri koncentrácii $CO_2$ a formaldehydu, a čiastočne mala vplyv na koncentráciu prchavých organických látok Popritom výrazne vyššie intenzity výmeny vzduchu boli vypočítané pre bytový dom pred obnovou ako po realizácii rekonštrukcie.

Tab. 5. Priemerné hodnoty jednotlivých parametrov kvality vnútorného vzduchu pred a po obnove bytového domu

| **Parameter** | **Pred obnovou (N=20)** | **Po obnove (N=20)** |
|---|---|---|
| $CO_2$ (ppm) | 1190 | 1570 |
| Intenzita výmeny vzduchu ($h^{-1}$) | 0.61 | 0.44 |
| $NO_2$ ($\mu g/m^3$) | 15.4 | 16.5 |
| Prchavé organické látky ($\mu g/m^3$) | 569 | 773 |
| Formaldehyd ($\mu g/m^3$) | 32 | 43 |

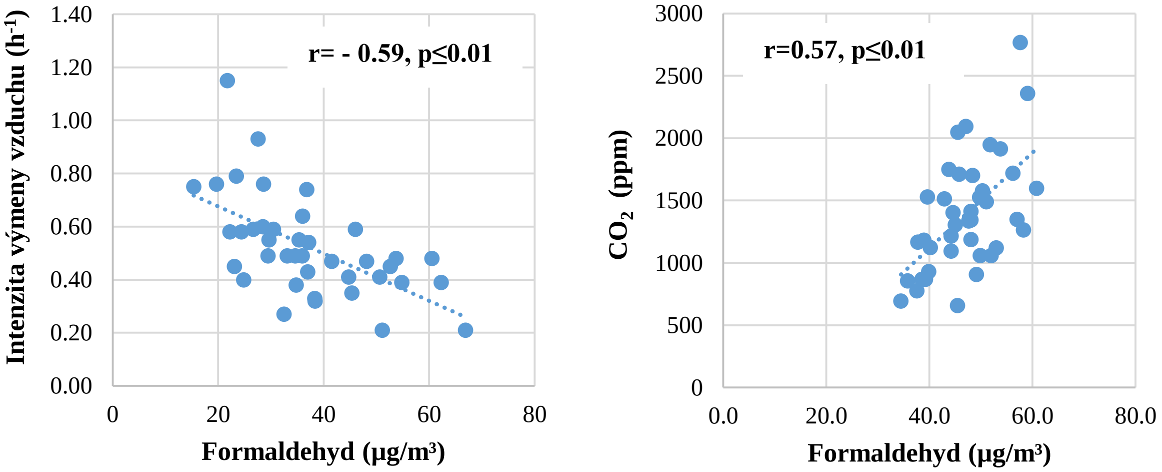
Nebola nájdená významná korelácia medzi koncentráciou $NO_2$ a ostatnými parametrami kvality vnútorného vzduchu. Avšak, výsledky ukázali významný vzťah medzi koncentráciou formaldehydu a intenzitou výmeny vzduchu, koncentráciou $CO_2$ a relatívnej vlhkosti (**Tab. 6**). Výsledky naznačujú, že pri vyššej koncentrácii $CO_2$ ($r=0.57$, $p<0.01$); a nižšej intenzity výmeny vzduchu ($r=-0.59$, $p<0,01$) sa zvýši koncentrácia formaldehydu (**Obr. 6**).

Vyššia relatívna vlhkosť tiež malo za následok zvýšenie koncentrácie formaldehydu ($r=0.48$, $p<0.01$). Koncentrácia formaldehydu sa zdala byť o niečo vyššia pri vyšších teplotách, ale korelácia bola slabá ($r=0.14$, $p> 0.1$); (**Obr. 7**). TVOC bola vyššia u vyšších koncentráciách formaldehydu ($r=0.27$, $0.05<p<0.1$) a mierne vyššia pri nižšej intenzite výmeny vzduchu, ale korelácia bola slabá a nebola štatisticky významná ($r = -0,21$, $p>0,01$); (**Tab. 6**).

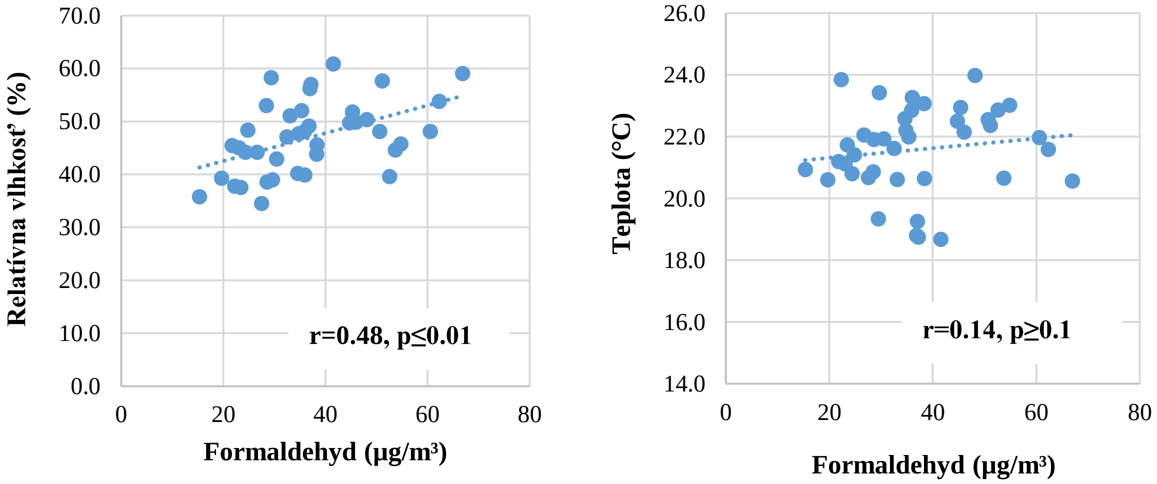
Tab. 6 Korelačné koeficienty medzi hodnotenými parametrami kvality vnútorného vzduchu

| **Parameter** | **$NO_2$** | **Formaldehyd** | **Prch. org. látky** | **$CO_2$** | **Teplota** | **Relat. vlhkosť** | **Int. vým. vzd.** |
|---|---|---|---|---|---|---|---|
| **$NO_2$** | - | - | - | - | - | - | - |
| **Formaldehyd** | -0.09 | - | - | - | - | - | - |
| **Prch. org. látky** | -0.09 | $0.27^{***}$ | - | - | - | - | - |
| **$CO_2$** | 0.2 | $0.57^{*}$ | 0.16 | - | - | - | - |
| **Teplota** | -0.12 | 0.14 | 0.09 | 0.06 | - | - | - |
| **Relat. vlhkosť** | -0.05 | $0.48^{*}$ | $0.3^{**}$ | $0.57^{*}$ | $0.56^{*}$ | - | - |
| **Int. vým. vzd.** | -0.19 | $-0.59^{*}$ | -0.21 | $-0.87^{*}$ | -0.16 | $-0.51^{*}$ | - |

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



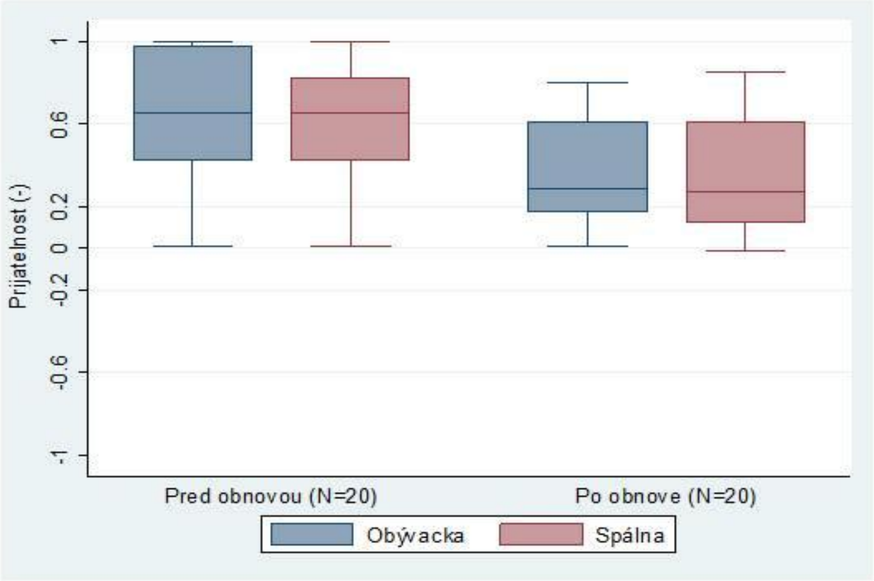
Obr. 6 Lineárny vzťah medzi koncentráciou formaldehydu a intenzitou výmeny vzduchu a koncentráciou $CO_2$



Obr. 7 Lineárny vzťah medzi koncentráciou formaldehydu a relatívnou vlhkosťou a teplotou vnútorného vzduchu

### B) Subjektívne hodnotenie kvality vnútorného vzduchu a vetracie návyky obyvateľov

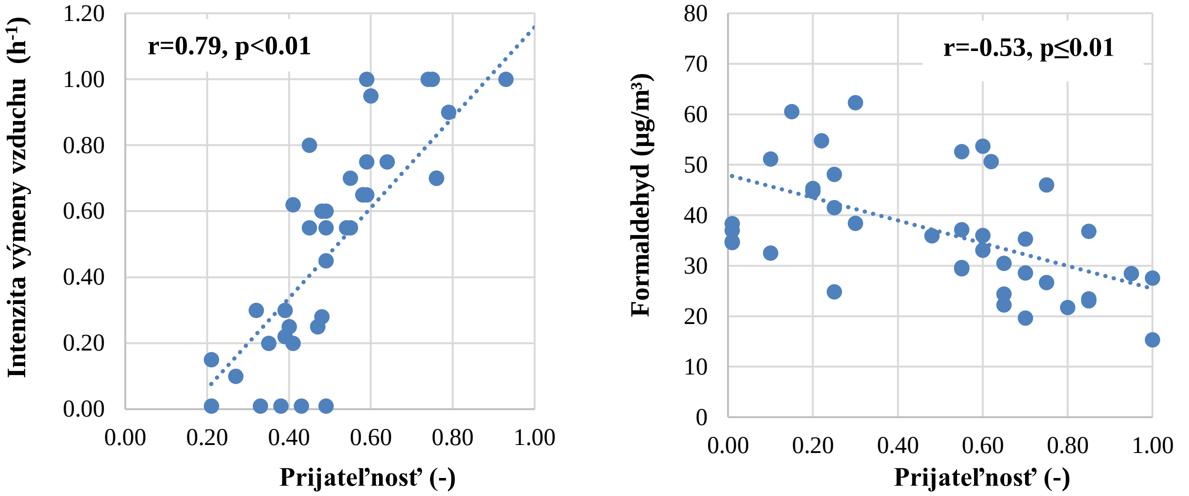
Pred rekonštrukciou bytového domu prijateľnosť s pociťovanou kvalitou vzduchu bola značne vyššia ako po obnove objektu ($p<0.01$). Priemerná prijateľnosť s kvalitou vzduchu bola podobná v obývačkách (0.64) a spálňach (0.60) pred rekonštrukciou. Po rekonštrukcii v oboch typoch miestnostiach priemerná prijateľnosť s kvalitou vzduchu bola opäť podobná. Avšak, priemerné hodnoty sa znížili na 0.38 v obývačkách a na 0.37 v spálňach (**Obr. 8**).



Obr. 8 Prijateľnosť pociťovanej kvality vzduchu v obývačkách a spálňach pred a po obnove bytového domu

Intenzita výmeny vzduchu a koncentrácie formaldehydu mala dopad aj na vnímanie pociťovanej kvality vzduchu. So znižujúcou sa intenzitou výmeny vzduchu ($r=0.79$, $p<0.01$) a zvyšujúcou koncentráciou formaldehydu ($r=-0{,}53$, $p<0.01$) sa znížila spokojnosť obyvateľov s kvalitou vnútorného vzduchu (**Obr. 9**).

Výsledky vo vetracích návykoch obyvateľov naznačujú, že obyvatelia domu nezmenili svoje návyky po obnove objektu (**Tab. 7**). Väčšina obyvateľov v obývačke vetrá častejšie ako 1x za deň, pričom priemerná doba vetrania je 7.5 minút. V spálni väčšina obyvateľov vetrá denne alebo skoro denne, a nie každý deň. Pred obnovou najvyššie percento obyvateľov vetralo 7.5 minút. Po obnove, doba vetrania sa mierne zvýšila, a väčšina ľudí sa vyjadrilo k 20 minútam. **Obr. 10** ukazuje vzťah medzi dobou vetrania a intenzitou výmeny vzduchu a taktiež vzťah medzi dobou vetrania a prijateľnosťou pociťovanej kvality vzduchu. Výsledky jasne ukazujú, že so zvyšujúcou dobou vetrania sa dosiahne vyššia intenzita výmeny vzduchu a aj väčšia spokojnosť obyvateľov s pociťovanou kvalitou vnútorného vzduchu.

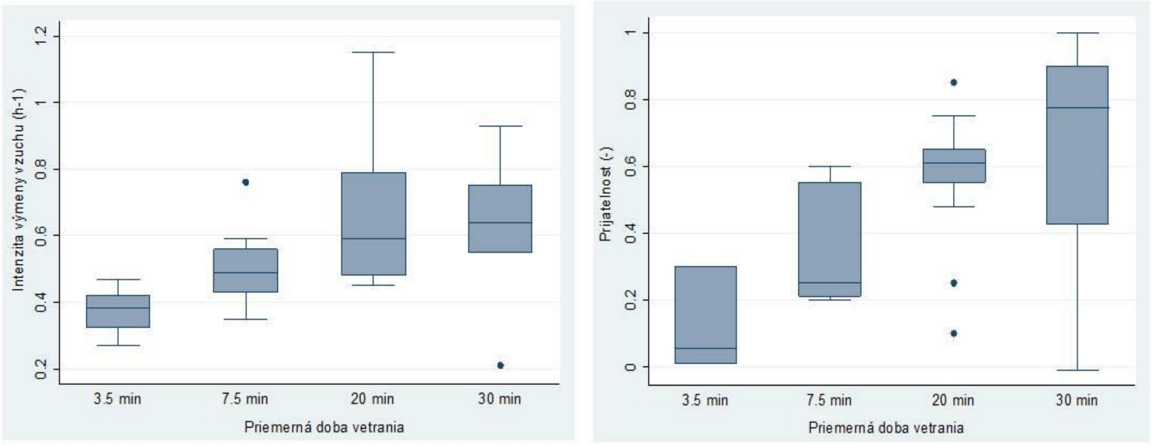


Obr. 9 Lineárny vzťah medzi prijateľnosťou kvality vzduchu a intenzitou výmeny vzduchu a koncentráciou formaldehydu

Tab. 7 Vetracie návyky obyvateľov pred a po obnove bytového domu

| Vetranie | Pred obnovou (N=20) | | Po obnove (N=20) | |
|---|---|---|---|---|
| | Byt* | Spálňa | Obývačka* | Spálňa |
| Frekvencia | | | | |
| Viac ako 1x za deň | 70 | 40 | 60 | 30 |
| Denne alebo skoro denne | 30 | 60 | 40 | 70 |
| Trvanie (V priemere za deň) | | | | |
| 3.5 min | 25 | 15 | 15 | 15 |
| 7.5 min | 35 | 20 | 40 | 20 |
| 20 min | 15 | 30 | 20 | 40 |
| 30 min | 25 | 35 | 25 | 25 |

*Otázky boli položené všeobecne pre celý byt pred rekonštrukciou, konkrétne pre obývacia izba po rekonštrukcii.



Obr. 10 Vzťah medzi dobou vetrania a intenzitou výmeny vzduchu (vľavo), a závislosť medzi dobou vetrania a prijateľnosťou pociťovanej kvality vzduchu (vpravo)

# Závery

Obe štúdie ako aj výsledky simulácií (prezentované v kapitole č. 7) potvrdili, že obnova bytových domov bez zváženia dodatočného vetrania v bytoch, môže zvýšiť nielen koncentráciu $CO_2$ ale aj koncentráciu iných znečisťujúcich látok nachádzajúce sa vo vnútornom vzduchu. Pridanie štandardnej vetracej jednotky v spálňach, alebo použitie odsávacích systémov v kuchyniach a hygienických miestnostiach, môže výrazne prispieť k zlepšeniu kvality vnútorného vzduchu v obnovených bytových domoch. Poučenie by sa malo brať z nedávno publikovaných štúdií, ktoré porovnávali kvalitu vnútorného prostredia v zelených a nízkoenergetických domov oproti bežným stavbám (122). Zelené budovy sú postavené s dôrazom na efektívne využívanie zdrojov energie a to nie len v priebehu stavebného procesu, ale po celú dobu životného cyklu budovy (160). Tieto budovy sú vytvorené na základe zásad a metodík udržateľného stavebníctva (161), ktorých cieľom je postaviť energeticky úsporné a zdravé budovy, ktoré významne znižujú vplyv stavby na každodenný život ich užívateľov a globálne životné prostredie (162). Riadenie zdrojov emisií, vetranie a sledovanie kvality vnútorného vzduchu sú tri hlavné kroky používané v ekologických stavebných systémoch pre správu kvality vnútorného vzduchu. Boli vytvorené rôzne certifikačné systémy budov po celom svete, ako napríklad LEED (USA), GREEN MARK (Singapur), BREEAM (UK), GREEN STAR (Austrália), atď. Budovu možno nazvať udržateľnou len vtedy, ak chránia záujmy budúcich generácií. Certifikačné systémy by mali teda tiež silne zdôrazniť kvalitu vnútorného prostredia, od ktorých sa okrem zníženia vplyvov na životné prostredie tiež očakáva vytvorenie podmienok pre zdravé a pohodlné vnútorné prostredie (163). Kvalitným vnútorným prostredím sa nazýva prostredie kde komfort človeka je uprednostnený. Energetická účinnosť budov by nemala zatieniť pohodu obyvateľov. Schéma nedávno vydanej normy nazývanou „WELL Building standard“ (USA) pristupuje k hodnoteniu certifikácii budov a vnútorného prostredia z pohľadu komfortu užívateľa (164).

# REFERENCES

1. **BPIE.** Buildings Performance Institute Europe: Europe´s buildings under the microscope. A country-by-country review of the energy performance of buildings. . 2011.

2. **F. Meijer, L. Itard, M. Sunikka.** Comparing European residential building stocks, performance, renovation and policy opportunities. Building Research and Information. 2009, Vol. 37, 5-6.

3. **F. Noris, W. W. Delp, K. Vermeer, G. Adamkiewicz et al.** Protocol for maximizing energy savings and indoor environmental quality improvements when retrofitting apartments. Energy and Buildings. 61, 2013, pp. 378-386.

4. **L. Liu, B. Moshfegh, J. Akander, M. Cehlin.** Comprehensive investigation on energy retrofits in eleven multi-family buildings in Sweden. Energy and Buildings. 84, 2014, pp. 704-715.

5. **Ministry of Transport, Construction and Regional Development of Slovak Republic.** Residential and Non-Residential Building Stock Renovation Strategy, Slovak Republic. 2014.

6. **European Parliament.** Directive 2002/91/EC of The European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. Official Journal of the European Union. L1/65, 2003 04.1.

7. **European Parliament.** Directive 2010/31/EU of The European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union. L153/13, 18.6.2010.

8. **L. Øie, H. Stymne, C. A. Boman, V. Hellstrand.** The ventilation Rate of 344 Oslo Residences. Indoor Air. 8, 1998, pp. 190-196.

9. **N. Klepeis, W. C. Nelson, W. R. Ott el al.** The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. Journal of Exposure Analysis and Environmental Epidemiology. 11, 2001, pp. 231–252.

10. **K. Engvall, C. Norrby, J. Bandel, M. Hult, D. Norbäck.** Development of a multiple regression model to identify multi-family residential buildings with a high prevalence of sick building syndrome (SBS). Indoor Air. 10, 2000, pp. 101-110.

11. **O. A. Seppänen, W. J. Fisk.** Summary of human responses to ventilation Vol. . Indoor Air. 14, 2004, Vol. 7, pp. 102-118.

12. **P. Wargocki, D. P. Wyon, J. Sundell et al.** The efefcts of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. Indoor Air. 10, 2000, pp. 222-236.

13. **D. Ürge-Vorsatz, N. Eyre , P. Graham, D. Harvey, E. Hertwich, Y. Jiang et al.** Energy End-Use: Buildings. Cambridge : Cambridge University Press, 2012. pp. 649-760.

14. **S. Salat.** CO2 Emissions and Building Stocks: Morphologies, Typologies, Energy Systems and Behaviour. Building Research and Information. 2009, Vol. 37.

15. **M. Carvalho.** EU Energy and Climate Change Strategy. Energy. 2012, Vol. 40, pp. 19-22.

16. **N. Kohler, U. Hassler.** The building stock as a research object. Building research and Information. 2002, Vol. 30, 4.

17. **A. Thomsen, K. Van der Floer.** Updating the housing stock; the need for renovation-based approaches. Proceedings of the International Research Conference on Housing Cultures– Convergence and Diversity. ENHT and Europa forum Wien. 2002.

18. **M. Sunikka.** Policies for Improving Energy Efficiency in the European Housing Stock. Delft : Delft University Press,, 2006.

19. **A. Thomsen, F. Meijer.** Sustainable housing transformation; quality and improvement strategies of the ageing private housing stock in the Netherlands. Proceedings of the International Conference on Sustainable Areas, EBHR Congress. 2007.

20. **G. P. Panayiotou, S. A. Kalogirou, G. a. Floride set al.** The characteistics and the energy behaviour of the residentail building stock of Cyprus in view of Directive 2002/91/EC. Energy and Buildings. 42, 2010, pp. 2083-2089.

21. **M. Castelli, L. Trujillo, L. Vanneschi, A. Popovič.** Prediction of energy performance of residential buildings: A genetic programming approach . Energy and Buildings. 102, 2015, pp. 67-64.

22. **R. Holopainen, K. Salmi, E. Kähkönen, P. Pasanen, K. Reijula.** Primary energy performance and perceived indoor environment quality in Finnish low-energy and conventional houses . Building and Environment. 87, 2015, pp. 92-101.

23. **L. Mazzarella.** Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. Energy and Buildings. 95, 2015, pp. 23-21.

24. **M. H. Wahlström, B. Harsman.** Residential energy consumption and conservation. Energy and Buildings. 102, 2015, pp. 58-66.

25. **Eurostat, Statistics Database.** Energy statistics – Supply, Transformation, Consumption. 2010.

26. **J. A. Clarke.** Energy Simulation in Building Design. Oxford : Butterworht-Heinemann, 2011.

27. **EuroACE.** Towards Energy Efficient Buildings in Europe. (available at: http://ec.europa.eu). 2004.

28. **EURIMA – European Insulation Manufacturers Association.** Analyses of Cost Effective Climate Protection in the EU Building Stock. Ecofys Report No. VI (available at: http://www.eirima.org). 2007.

29. **HealthVent.** Health-Based Ventilation Guideline for Europe. Workpackage no. 5: Existing buildings, building codes, ventilation standards and ventilation in Europe. s.l. : REHVA (Federation of European Heating, Ventilation and Air-Conditioning Associations), 2012.

30. **A. Jámbor, Z Šternová, P. Briatka, D. Kahálová et al.** Analyses of the National Status Quo – Slovakia. Build-up Skills Slovakia. 2013.

31. **STN 73 0540-2.** Thermal performance of buildings and components. Thermal protection of buildings. Part 2: Functional requirements. 2012.

32. **S. Langer, G. Bekö.** Indoor air quality in the Swedish housing stock and its dependence on building characteristics. Building and Environment. 69, 2016, pp. 44-45.

33. **Y. Zhao.** Indoor air environment of residential buildings in Dalian, China. Energy and Buildings,. 36, 2004, pp. 1235-1239.

34. **M. Kotol, C. Rode, G. Clausen, T. R. Nielsen.** Indoor environment in bedrooms in 79 Greenlandic households Vol. 81. Building and Environment. 81, 2014, pp. 29-36.

35. **O. A. Seppänen, W. J. Fisk, M. J. Mendell.** Association of ventilation rates and CO2-concentrations with health and other responses in commercial and institutional buildings. Indoor Air. 9, 1999, pp. 252-274.

36. **L. Kajtár, L. Herczeg, E. Láng.** Examination of influence of CO2 centration by scientific methods on the laboratory. Proceedings of Healthy Buildings, Singapore. 2003.

37. **U. Satish, M. J. Mendell, K. Shekhar et al.** Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance. Environ Health Perspect. 120, 2012, Vol. 12, pp. 1671-1677.

38. **J. J. Zhang, K. R. Smith.** Indoor air pollution: a global health concern Vol. 68,. British Medical Bulletion. 68, 2003, pp. 209-225.

39. **G. Adamkiewicz, A. R. Zota, M. P. Fabian ez al.** Moving environmental justice indoors: understanding structural influence on residential exposure patterns in low-income communities. Am J Public Helath. 101, 2011, pp. 238-245.

40. **O. A. Seppänen, W. J. Fisk, D. Faulkner.** Cost benefit analysis of the night-time-ventilative cooling of office buildings. Proceedings of Healthy Buildings, Singapore. 2003.

41. **C. G. Bornehang, G. Blomquist, F. Gyntelberg et al.** Dampness in buildings and healths. Indoor Air. 11, 2001, pp.72-86.

42. **C. Dimitropolou.** Ventilation in European dwellings: A review. Building and Environment. 47, 2012, pp.109-125.

43. **G. Emenius, M. Svartengren, J. Korsgaard et al.** Indoor exposures and recurrent wheezing in infants: a study in the BAMSE cohort. Acta Paediatr. 93, 2004, pp. 899–905.

44. **G. Emenius, M. Svartengren, J. Korsgaard et al.** Building characteristics, indoor air quality and recurrent wheezing in very young children (BAMSE). Indoor Air. 14, 2004, pp. 34–42.

45. **L. Øie, P. Nafstad, G. Botten, P. Magnus, et al.** Ventilation in homes and bronchial obstruction in young children. Epidemiology. 10, 1999, pp. 294–299.

46. **O. A. Seppäanen, J. Jaakkola.** Factors that may affect the result of indoor air quality studies in large office buildings. Design Protocol for Monitoring Indoor Air Quality. ASTM STP. 1989, pp. 1002.

47. **S. Brasche, W. Bischof.** Daily time spent indoors in German homes – Baseline data for the assessment of indoor exposure of German occupants. International Journal of Hygiene and Environmental Health. 208, 2005, Vol. 4, pp. 247-253.

48. **EPA, U.S.** Exposure factors handbook. Office of Helath and Environmental Assessment: Washington DC. 1990.

49. **S. Stubenrauch, R. Hemfling, P. Doetsch et al.** Vorschläge zur Charakterisierung und Quantifizierung pfadübergreifender Schadstoffexpositionen. Umweltwiss. 11, 1999, 219.

50. **World Health Organisation.** Formaldehyde. Consice International Chemical Assessment Document. 40, 2002.

51. **B. Berg-Munch.** The influence of ventilation, humidification and temperature on sensation of freshness and dryness of air. Proceedings of International Conference on Building Energy Management, Portugal. 1980.

52. **L. Fang, G. Clausen, P. O. Fanger.** Impact of temperature and humidity on the perception of indoor air quality during immediate and longer whole-body exposures. Proceedings of Healthy Buildings.Washington USA. 1997, pp.231-236.

53. **L. Fang, G. Clausen, P. O. Fanger.** Impact of temperature and humidity on the perception of indoor air quality. International Journal of Indoor Air Quality and Climate. 8, 1998, pp. 80-90.

54. **M. A. Humphreys, J. F.Nicol, K. J. McCartney.** An analysis of some subjective assessments of indoor air quality in five European countries. Proceedings of the 9th International Conference on Indoor Air Quality and Climate. 2002, pp. 86-91.

55. **M. J. Finnegan, C.A. Pickering, P.S. Burge.** The sick building syndrome: prevalence studies. British Medical Journal. 289, 1984, pp. 1573–1575.

56. **U. Norlen, K. Andersson.** An indoor climate survey of the Swedish housing stock. Indoor Air. 1993, pp 743–748.

57. **K. Engelvall, C. Norrby, D. Norbäck.** Sick building syndrome in relation to building dampness in multi-family residential building in Stockholm. Int Arch Occ Env Heal. 74, 2001, 270-278.

58. **J. Wang, B. Z. Li, Q. Yang.** Sick building syndrome among parents of preschool children in relation to home environment in Chongqing, China. Chin Sci Bull. 58, 2013, pp. 4267-4276.

59. **Z. Lin, T. Wang, D. Norback, H. Kan et al.** Sick building syndrome, perceived odors, sensation of air dryness and indoor environment in Urumqi, China. Environmental Science and Technology. 59, 2014, Vol. 35, 5153-5160.

60. **L. Du, T. Prasauskas, V. Leivo, M, Turunen et al.** Assesment of indoor environmental quality in existing multy-family buildings in North-East Europe. Environment International. 79, 2015, pp. 74-84.

61. **M. B. Natka.** Indoor Conditions in Silesian Buildings with Natural Ventilation. Indoor and Built Environment. 15, 2006, pp.571-582.

62. **P. Batog, M. Badura.** Dynamic of changes in carbon dioxide concentration in bedrooms. Procedia Engineering – 11th International Conference on Modern Building Materials, Structures and Techniques. 2013, pp. 175-18.

63. **A. Zalejska Jonsson, M. Wilhelmsson.** Impact of perceived indoor environment quality on overall satisfaction in Swedish dwellings. Building and Environment. 63, 2013, pp. 134-144.

64. **M. Frontczak., R. V. Andersen, P. Wargocki.** Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing. Building and Environment,. 50, 2012, pp. 56-64.

65. **G. Klunder.** Sustainable Solutions for Dutch Housing Reducing the Environmental Impact of New and Existing Houses. SUA Series. OTP Thesis. Delft University Press. 2005.

66. **L. Liu, P. Rohdin, B. Moshfegh.** Evaluating indoor environment of a retrofitted multi-family building with improved energy performance in Sweden. Energy and Buildings. 102, 2015, pp. 32-44.

67. **G. Verbeeck, H. Hens.** Energy savings in retrofitted dwellings: economically viable? . Energy and Buildings. 37, 2005, pp. 747–754.

68. **B. S. Darup.** Energetische Gebäudesanierung mit Faktor 10. Deutsche Bundesstiftung Umwelt (DBU), Osnabrück, Germany. 2008.

69. **European Comission.** Insulation Measures for Retrofitting of Residential Buildings. THERMIE PROGRAMME ACTION No. B48. 1995.

70. **S. Kamper, A.S. Worm.** Energirenovering af Langkærparken . Proceedings of Passivhus Norden Conference, Aalborg, Denmark, October 7–8. 2010. . 2010.

71. **H. Tommerup, M.K. Tafdrup, S. Svendsen, M. Morelli.** Holistic energy retrofitting of multi-storey building to low energy level. . Proceedings of the 9th Nordic Symposium on Building Physics, Tampere, Finland, May 29–June 2. 2011. 2011, pp. 1323–1330.

72. **M. Morelli, L. Rønby, S. E. Mikkelsen, M. G. Minzari et al.** (2012) Energy retrofitting of a typical old Danish multi-family building to a “nearly-zero” energy building based on experiences from a test apartment. Energy and Buildings. 54, 2012, pp.395–406.

73. **D. Matic, J. R. Calzada, M. Eric, M. Babin.** Economically feasible energy refurbishment of prefabricated building in Belgrade, Serbia. Energy and Buildings. 98, 2015, pp. 74-81.

74. **S. H. Hong, T. Oreszczyn, I. Ridley.** The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings. Energy and Buildings. 38, 2006, pp. 1171–1181.

75. **C. A. Balaras, K. Droutsa, A. A. Argiriou, D. N. Asimakopoulos.** Potential for energy conservation in apartment buildings. Energy and Buildings. 31, 2000, Vol. 2, pp. 143–154.

76. **H. Pustayova.** Evaluation of energy performance and thermal comfort of dwellings in the proces of refurbishment. Doctoral thesis. Bratislava, Slovakia. 2013.

77. **T. Dahlsveen, D. Petráš.** Energy audit of buildings. . Jaga GROUP, Bratislava . 2005.

78. **M. Jaggs, J. Palmer.** Energy performance indoor environmental quality retrofit - a European diagnosis and decision making method for building refurbishment. Energy and Buildings . 31, 2000, pp. 97-101.

79. **F. Flourentzou, C. A. Roulet.** Elaboration of retrofit scenarios. Energy and Buildings. 34, 2002, pp. 185-192.

80. **T. Loga, N. Diefenbach.** Use for building typologies for energy performance assessment of national building stocks, existent experiences in European countries and common approach. Available from: www.building-typology.eu. 2010.

81. **E. G. Dascalaki, K. G. Droutsa, C. A. Balaras, S. Kontoyiannidis.** Buildingtypologies as a tool for assessing the energy performance of residential buildings – A case study for the Hellenic building stock. Energy and Buildings. 43, 2011, pp. 3400-3404.

82. **Z. Ma, P. Cooper, D. Daly, L. Ledo.** Existing building retrofits: methodology and state-of-the-art. Energy and Buildings. 55, 2012, pp. 889–902.

83. **E. Asadi, M.G. Silva, C.H. Antunes, L. Dias.** Multi-objective optimization for building retrofit strategies: a model and an application. Energy and Buildings. 41, 2012, pp. 81–87.

84. **J. Jokisalo, J. Kurnitski, J. Vinha.** Building leakage, infiltration and energy performance analyses for Finish detached houses. Proceedings of CLIMA 2007-Well-being indoors. Helsinki. 2007.

85. **W. Pan.** Relationship between air-tightness and its influencing factors of post 2006 new-build dwellings in the UK. Building and Environment. 45, 2010, Vol. 11, pp. 2387-2399.

86. **M. H. Sherman, W. R. Chan.** Building airtightness: research and practice. Lawrence Berkeley National laboratory, LBNL-53356. 2003.

87. **G. Villi, C. Peretti, S. Graci, M. Carli.** Building leakage analysis and infiltration modelling for an Italian multi-family building. Journal of Building Performance Simulation. 6, 2013, pp. 98-118.

88. **J. Korsgaard.** Changes in indoor climate after tightening of apartments. Environment International. 9, 1983, Vol. 2, pp. 97-101.

89. **W. J. Fisk.** Health and productivity gains from better indoor environments and their relationship with building energy efficiency. Annual Review of Energy and the Environment. 25, 2000, pp. 537-566.

90. **A. P. Jones.** Indoor air quality and health. Atmospheric Environment,. 33, 1999, pp. 4535-4564.

91. **Ch. J. Weschler, H. C. Shields.** The influence of ventilation on reactions among indoor pollutants: modelling and experimental observations. Indoor Air. 10, 2000, pp. 92-100.

92. **P. G. Schild.** State-of-the-art of low energy residential ventilation. Contributed Report 07. Air infiltration and and Ventilation Centre. 2007.

93. **D. Grimsrud, D. Clemets-Croome, D. D´Alesandro, J. Heinonen.** WS2 design criteria for healthy buildings. Workshop summaries. Espoo, Finland. Proceedings of Healthy Buildings. 2000, pp. 9-15.

94. **B. Seifert.** Ways to specify, reach and check guideline values for indoor air quality. Espoo, Finland. Proceedings of Healthy Buildings. 2000, pp. 3-12.

95. **A. Jurelionis, L. Seduikyte.** Assessment of indoor climate conditions in multifamily buildings in Lithuania before and after renovation. 2nd International conference advanced construction. Kaunas, Lithuania. 2010.

96. **P. Howden-Chapman, A. Matheson, J. Crane, H. Viggers, M. Cunningham, T. Blakely et al.** Effect of insulating existing houses on health inequality: cluster randomised study in the community. . BMJ. 334, 2007.

97. **F. Noris, G. Adamkiewicz, W. Delp, T. Hotchi, M. Russel, B. Singer, M. Spears, W. Fisk.** Indoor environmental quality benefits of apartment energy retrofits . Building and Environment. 68, 2013, pp. 170-178.

98. **S. Langer, Bekö G., Bloom E., A. Widheden et al.** Indoor air quality in passive and conventional new houses in Sweden. Building and Environment. 93, 2015, Vol. 1, pp. 92-100.

99. **M. Derbez, B. Berthineau, V. Cochet, M. Lethrosne et al.** Indoor air quality and comfort in seven newly built, energy eddicient houses in France. Building and Environment. 72, 2014, pp. 173-187.

100. **M. Derbez, B. Berthineau, V. Cochet, C. Pignin et al.** A 3-year follow-up of indoor air quality and comfort in two energy-efficient houses. Building and Environment. 82, 2014, pp. 288-299.

101. **R. Holopainen, K. Salmi, E. Kähkönen, P. Pasanen, K. Reijula.** Primary energy performance and perceived indoor environment quality in Finnish low-energy and conventional houses. Building and Environment. 87, 2015, pp. 92-101.

102. **A. K. persily.** Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide. ASHRAE Transactions. 103, 1997, Vol. 2.

103. **G. Bekö, T. Lund, J. Toftum, G. Clausen.** Ventilation rates in bedroom of 500 Danish children. Building and Environment. 45, 2010, pp. 2289-2295.

104. **ASTM standard D 6245-98.** Standard guide for using indoor carbon dioxide concentrations to evaluate indoor air quality and ventilation. American Society for testing and Materials. 2002.

105. **Y. Sun, Z. Wang, Y. Thang, J. Sundell.** In China, Students in Crowded Dormitories with a Low Ventilation Rate More Common Colds: Evidence for Airbone Transmission. Plos One. 6, 2011, Vol. 11.

106. **M. Frontzak, R. Vither Andersen, P. Wargocki.** Questionnaire survey on factors influencing comfort with indoor environmental quality in Danish housing. Building and Environment. 50, 2012, pp. 56-64.

107. **G. Iwashita, K. Kimura, S. Tanabe, S. Yoshizawa.** Indoor air quality assessment based on human olfactory sensation. Journal of Architecture. Planning and Environmental Engineering. Journal of Architecture. 1990, pp.9-19.

108. **European Standard EN 15251.** Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, therlmal environment, lighting and acoustics. Brussles: European Committee for Standardization. 2007.

109. **L. A. Wallace, S. J. Emmerich, C. Howard-Reed .** Continuous measurements of air change rates in an occupied house for 1 year: the effect of temperature, wind, fans, and windows. Expo Anal Environ Epidemiol. 12, 2002, Sv. 4, pp. 296-306.

110. **ISO 7730.** Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. 2005.

111. **T. Kalamees.** Indoor Climate Conditions and Ventilation Performance in Estonian Lightweighted Detached Houses. Indoor and Built Environment. 15, 2006, 555.

112. **M. Kotol.** Survey of occupants behaviour, enery use and indoor air quality in Greenlandic dwellings. 2012.

113. **H. Zhang, E. Arens, P. Wilmer.** Air temperature thresholds for indoor comfort and perceived air quality. Building and Environment. 84, 2015, pp. 10-21.

114. **S. Howieson, T. Sharpe, P. Farren .** Building tight – ventilating right? How are new air tightness standards affecting indoor air quality in dwellings? Building Services Engineering Research Technology. 35, 2014, Vol. 5, pp. 475-487.

115. **G. Bekö., J. Toftum, G. Clausen.** Modeling ventilation rates in bedrooms based on building characteristics and occupant behaviour. Building and Environment. 46, 2011, pp. 2230-2237.

116. **G. Iwashita, H. Akasaka.** The effect of human behaviour on natural ventilation rate and indoor air environment in summer – a field study in southern Japan. Energy and Buildings. 25, 1997, Vol. 3, pp.195-205.

117. **B. Kvisgaard, P. F. Collet.** The user´s influence on air change rate. In: Sherman M, editor. Air change rate and air tightness in buildins. STP 1067 Philadelphia: American Society for Testing and Materials. 1990, pp. 67-76.

118. **C. Dubrul.** Inhabitant behaviour with respect to ventilation – a summary report of IEA Annex VIII. Technical Note AIVC 23. Berkshire, UK: Air Infiltration and ventilation Centre. 1988.

119. **C. Howard-Reed, L. A. Wallace, W. R. Ott.** The effect of opening windows on air change rates in two homes . Air Waste Manage Assoc. 52, 2002, Sv. 2, pp. 147-159.

120. **P. Wargocky, D. P. Wyon.** Providing better thermal and air quality conditions in school clasrooms would be cost-effective. Built. Env. 59, 2013, pp. 581-589.

121. **A. Norhidayah, L. Chia-Kuang, M. K. Azhar et al.** Indoor Air Quality and Sick Building Syndrome in three selected buildings. Procedia Engineering . 53, 2013, pp. 93-98.

122. **M. D. Colton, J. G. Laurent., P. MacNaughton et al.** Health Benefits of Green Public Housing: Associations With Asthma Morbidity and Building-Related Symptoms. American Journal of Public Health. 105, 2015, Vol. 12, pp. 2482-2489.

123. **M. Ferm M. and H. Rodhe .** Measurements of air concentrations of SO2, NO2 and NH3 at rural and remote sites in Asia. Journal of Atmospheric Chemistry. 27, 1997, pp. 17-29.

124. **M. Ferm.** The theories behind diffusive sampling. Proc. from International Conference Measuring Air Pollutants by Diffusive Sampling, Montpellier, France 26-28 September 2001. 2001, pp. 31-40.

125. **ISO 16000-4.** Indoor air – part 4: determination of formaldehyde – diffusive sampling method. Geneva: International Organization of Standardization. 2004.

126. **ISO 16017-2.** Indoor, ambient and workplace air e sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography – Part 2: diffusive sampling. Geneva: International Organization of Standardization. 2003.

127. **World Health Organization (WHO).** Selected pollutants. WHO indoor air quality guidelines. Copenhagen. WHO Regional Office for Europe. 2010, pp. 1-454.

128. **A. Kousa, C. Monn, T. Rotko et al.** Personal exposure to NO2 in the EXPOLIS-study: relation to residential indoor, outdoor and work-place concentration in Basel, Helsinki and Prague. Atmospheric Environment. 35, 2001, pp. 3405-3412.

129. **G. J. Raw, S. K. D. Coward, V. M. Brown et al .** Exposure to air pollutants in English homes . Exp. Anal. Environ. Epidemiol. 14, 2004, pp. 85-94.

130. **H. S. Mann., D. R Crump .** Formaldehyde in new and refurbished homes. Proceedings of Indoor Air 1999. 1999, pp. 153-159.

131. **P. Wolkoff, U. D. Kja, H. N. Knudsen H. N et al.** Characterization of emissions from building products: long-term chemical evaluation. The impact of air velocity and concentration. Proceedings of Indoor Air. 1996, Vol. 4, pp. 337-342.

132. **J. S. Park, K. Ikeda.** Variations of formaldehyde and VOC levels during three years in new and older homes. Indoor Air. Indoor Air. 16, 2006, pp. 129-135.

133. **Z. Guo .** Review of indoor emission source models. Part 1. Overview. Environment. Pollut. 130, 2002, pp. 533-549.

134. **T. Salthammer, F. Fuhrmann, S. Kaufhold, B. Meyer,.** Effects of Climatic Parameters on Formaldehyde Concentrations in Indoor Air. Indoor Air. 5, 1995, pp.120-128.

135. **S. Parthasarathy , R. L. Maddalena et al.** Effect of temperature and humidity on formaldehyde emissions in temporary housing units. Journal of the Air & Waste Management Association. 61, 2011, Vol. 6, pp. 689-695.

136. **T. Salthammer, S. Mentese, R. Marutzky .** Formaldehyde in the Indoor Environment. Chem. Rev. Chem. Rev. 110, 2010, pp. 2536-2572.

137. **Y. Maruo, T. Yamada, J. Nakamura et al .** Formaldehyde measurements in residential indoor air using a developed sensor element in the Kanto area of Japan. Indoor Air. 20, 2010, pp. 486-493.

138. **S. B. Molloy, I. E. Cheng, I. E. Galbally, M. D. Keywood et al.** Indoor air quality in typical temprerate zone Australian Dwellings. Athmospheric Environment. 54, 2010, pp. 400-407.

139. **R. Maddalena, M. J. Mendell., K. Eliseeva , et al.** Effects of ventilation rate per person and per floor area on perceived air quality, sick building syndrome symptoms, and decision making. Indoor Air. Indoor Air. 25, 2015, Vol. 4, pp. 362-370.

140. **P. Wolkoff.** Indoor air pollutants in office environments: Assesment of comfort, heath, and performance. International Journal of Hygiene and Environmental Health. 216, 2013, 371-394.

141. **J. A. Leech, M. Raizennne. J. Gusdorf.** Health in occupants of energy efficient new homes. Indoor Air. 14, 2004, Vol. 3, pp. 169-173.

142. **M. D. Colton, P. MacNaughton, J. Vallariono.** Indoor air quality in green vs conventional multifamily low-income housing. Environ. Sci. Technol. 48, 2014, Vol. 14, pp. 7833-7841.

143. **STN EN ISO 13790.** Energy performance of buildings. Calculation of energy use for space heating and cooling (ISO 13790:2008). 2008.

144. **MTCRD of Slovak Republic.** National building code presented by the Ministry of Transport, Construction and Regional Development of Slovak Republic MTCRD SR 364/2012. 2012.

145. **Codex of Laws No. 300/2012 .** Act No. 555/2005 Coll. on Energy Performance of Buildings, amended by Act. No. 300/2012 Coll. Slovak Republic. 2012.

146. **STN EN 15316-1.** Heating systems in buildings. Method for calculation of energy requirements and systems´ efficiencies. Part 1: General.

147. **STN EN 15316-3-1.** Heating systems in buildings. Methods for calculation of energy requirements and systems´ efficiencies. Part 3-1: hot water supply system, including efficiency preparation and the requirements for water discharge.

148. **Slovak hydrometeorological institute (SHMI).**
URL link: http://www.shmu.sk/en/?page=1.

149. **P. Sahlina, L. Erikssona, P. Grozmana et al.** Whole-building simulation with symbolic DAE equations and general purpose solvers. Building and Environment. 39, 2004, pp. 949-958.

150. **P.Paliouras, N.Matzaflaras, R.Peuhkuri, J.Kolarik.** Using measured indoor environment parameters for calibration of building simulation model – A passive house case study. 6th International Building Physics Conference, IBPC 2015. Energy Proceedia. 2015.

151. **BPIE.** Building Performance Institute Europe: Renovation strategies of selected European countries. 2014.

152. **R. Routsalainen, R. Rönneberg, J. Majanen et al.** Indoor climate and the performance of ventilation in Finish residences. Indoor Air. 2, 1992, pp. 137-145.

153. **P. Dingle, P. Franklin.** Formaldehyde levels and the factors affecting these levels in homes in Perth, Western Australia. Indoor Built Environment. 11, 2002, pp. 111-116.

154. **G. Bekö, Ch. J. Weschler, A. Wierzbicka et al.** Ultrafine Particles: Exposure and Source Apportionment in 56 Danish Homes. Environmental Science and Technology. 47, 2013, pp. 10240−10248.

155. **L. Wallace.** Indoor sources of ultrafine and accumulation mode particles: Size distributions, size-resolved concentrations, and source strengths. Aerosol Sci. Technol. 40, 2006, pp. 348−360.

156. **S. Bhangar, N. A. Mullen, S. V. Hering et al.** Ultrafine particle concentrations and exposures in seven. Indoor Air. 21, 2011, pp. 132–144.

157. **E. T. Gall, T. Cheung, I. Luhung et al.** Real-time monitoring of personal exposures to carbon dioxide. Building and Environment. 104, 2016, pp. 59-67.

158. **G. Oberdörster.** Pulmonary effects of inhaled ultrafine particles. Archives of Occupational and Environmental Health. 74, 2001, pp. 1-8.

159. **A. B. Knol, J.J. de Hartog, H. Boogaard et al.** Expert elicitation on ultrafine particles: likelihood of health effects and causal pathways. Part. Fibre Toxicol. 6, 2009, Vol. Article 19.

160. **U.S. Environmental Protection Agency (EPA).** Green building basic information. Retrieved Oct. 14th, 2014. URL: URL http://www.epa.gov/greenbuilding/. 2014.

161. **C. J. Kibert.** Sustainable construction: green building design and delivery. 3rd ed. John Wiley & Sons, Inc; 2012, ISBN 978-1-118-33013-5.

162. **J. Judelson .** The green building revolution. Island Press; ISBN 978-1-59726-178-4. 2007.

163. **W. Wenjuan, R. Olivier, M. Corinne.** Indoor air quality requirements in green building certifications. Building and Environment. 92, 2015, pp. 10-19.

164. **Delos Living LLC.** THE WELL BUILDING STANDARD V1.0. 2014.

# APPENDIX A

## Questionnaire survey

### I. BASIC INFORMATION ABOUT OCCUPANTS

**1. How old are you?** ________
**2. What is your gender?** Male☐ Female☐
**3. What is your education level?** University degree☐ high school☐ other ___
**4. How many people live in the apartment?** ________ Age of others: ____________
**5. Floor area of your apartment:** ________ $m^2$
**6. On which cardinal direction is your apartment situated?** ________
**7. On which floor do you live?** ________
**8. How long have you been living in this apartment?** ________years
**9. Do you have any allergic diseases?** Yes☐ No☐
If yes, please choose from the following options:
☐Asthma ☐Hay fever ☐Skin inflammation ☐Food allergy ☐other _________

### II. BUILDING CONSTRUCTION

**10. Are your windows in original condition?** Yes☐ No☐
If no, when did you replace them (year) ________
**11. What type of glazing do your windows have?** Single☐ Double☐ Triple☐
**12. Do you have balcony or loggia?** Yes☐ No☐
**13. Is your balcony or loggia glazed?** Yes☐ No☐
**14. Do you have wet ceilings because of leaky roof?** Never☐ Sometimes☐ Often☐
**15. Do you have molds on the ceiling in your apartment?** Yes☐ No☐
**16. Do you have wet walls because of leaky envelope?** Never☐ Sometimes☐ Often☐
**17. Do you have molds on the walls in your apartment?** Yes☐ No☐

**18. Flooring materials in your apartment:**

- Rooms: PVC☐ wooden floor☐ carpet☐ cork☐ other______
- Kitchen: PVC☐ wooden floor☐ tiles☐ cork☐ other______
- Bathroom: PVC☐ wooden floor☐ tiles☐ cork☐ other______
- Hallway: PVC☐ wooden floor☐ tiles☐ cork☐ other______

**19. Do you have damaged floor from reason of leaks or high humidity?**
Never☐ Sometimes☐ Often☐

**20. Types of surface layers on your walls:**

- Rooms: wallpaper☐ paint☐ tiles☐ other ___________
- Kitchen: wallpaper☐ paint☐ tiles☐ other ___________
- Bathroom: wallpaper☐ paint☐ tiles☐ other ___________
- Hallway: wallpaper☐ paint☐ tiles☐ other ___________

**21. Considering energy use, how efficiently do you think your building is performing?**

Very efficiently Not efficiently at all

1 2 3 4 5 6

## III. BASIC HABBITS OF OCCUPANTS

- **Smoking**

**22. Do you have any smokers in your apartment?** Yes☐ No☐

**23. If yes, where does he/she smoke?**

On balcony☐ In kitchen☐ In bathroom☐ In rooms☐

**24. How many cigarettes does he/she smoke per day?**

Less than 3 pcs☐ 4 – 10 pcs☐ More than 10 pcs☐

- **Houseplants**

**25. Do you have any houseplant in your apartment?** Yes☐ No☐

**26. How many plans do you have in your apartment?** 1 - 5☐ 6 - 10☐ More than 10☐

- **Cooking**

**27. How often do you cook?**

Never☐ 2x – 3x per week☐ Every day☐ Other__________

**28. Which type of stove do you use?** Gas ☐ Electric☐

- **Pets**

**29. Do you have any pets in your apartment?** Yes☐ No☐

**30. If yes, which type of pets do you have?** Cat☐ Dog☐ Bird☐ Other__________

- **Cleaning**

**31. How often do you clean up the floor in your apartment?**

Every day☐ 1x/week☐ 2x – 3x/week☐ Other_________

**32. Do you use cleaning detergents?** Yes☐ No☐

**33. Do you use the following devices in your apartment? If yes, please tick which one.**

Vacuum cleaner☐ Humidifier☐ Dehumidifier☐ Air cleaners☐ Fans☐

## IV. SICK BUILDING SYSNDROM

**34. Do you feel tired?** Never☐ Sometimes☐ Often☐

If yes, do you think is it caused by indoor environmental quality? Yes☐ No☐

**35. Do you have headache?** Never☐ Sometimes☐ Often☐

If yes, do you think is it caused by indoor environmental quality? Yes☐ No☐

**36. Do you feel nausea?** Never☐ Sometimes☐ Often☐

If yes, do you think is it caused by indoor environmental quality? Yes☐ No☐

**37. Do you feel itching, burning or irritation of eyes?** Never☐ Sometimes☐ Often☐

If yes, do you think is it caused by indoor environmental quality? Yes☐ No☐

**38. Do you have dry skin?** Never☐ Sometimes☐ Often☐

If yes, do you think is it caused by indoor environmental quality? Yes☐ No☐

## V. EXPERIMENTAL MEASUREMENTS

The next questions are related to **PERIOD OF EXPERIMENTAL MEASUREMENTS!!!**

**A) Basic information about the room, where the exp. measurements will be carried out (bedroom)**

**39. Dimensions of the room** width .......... m x length .......... m x height .......... m

**40. On which cardinal direction is your room situated? ...........................**

**41. How many people did sleep in the room?** (During the measurements)

1. day ............ 2.day ............ 3.day ............ 4.day ............ 5.day ............
6. day ………. 7. Day ……… 8. Day ………

**42. Height and weight of people, who slept in the room** (During the measurements):
Person 1:Height:.............Weight:............. Person 2:Height:............. Weight:.............
Person 3:Height:............. Weight:............. Person 4:Height:............. Weight:.............

**43. Which person(s) did sleep in the room during the following days of the measurements?**

| | | | |
|---|---|---|---|
| 1.night: person 1☐ | person 2☐ | person 3☐ | person 4☐ |
| 2.night: person 1 ☐ | person 2 ☐ | person 3 ☐ | person 4☐ |
| 3.night: person 1 ☐ | person 2 ☐ | person 3 ☐ | person 4☐ |
| 4.night: person 1 ☐ | person 2 ☐ | person 3 ☐ | person 4☐ |
| 5.night: person 1 ☐ | person 2 ☐ | person 3 ☐ | person 4☐ |
| 6.night: person 1 ☐ | person 2 ☐ | person 3 ☐ | person 4☐ |
| 7.night: person 1 ☐ | person 2 ☐ | person 3 ☐ | person 4☐ |
| 8.night: person 1 ☐ | person 2 ☐ | person 3 ☐ | person 4☐ |

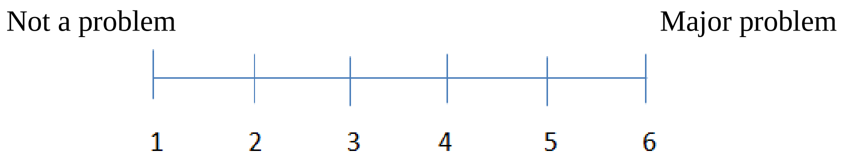
**44. How much time do you spend in the room (daily/from-to)? ............................**

**45. Position of the door(s) in the room:**

- Nights: Closed☐ Partly opened☐ Opened☐
- Daytimes: Closed☐ Partly opened☐ Opened☐

## B) Airing out / indoor air quality

**46. How unpleasant do you think the indoor air quality is in the room?**



**48. How often do you air out during the day?**
☐More than once per day ☐Daily or almost daily ☐Not every day, but at least once a week

**49. How long do you usually keep the windows opened (daytimes)?**
☐Less than 2 minutes/day ☐2 - 5 minutes/day ☐ 5 - 10 minutes/day
☐10 - 30 minutes/day ☐30 – 60 minutes/day ☐more than one hour

**50. Do you keep opened the windows in your bedroom at night?**
Never☐ Sometimes ☐ Often☐

**51. How long do you usually keep the windows opened at night?**
☐Less than 2 minutes/day ☐2 - 5 minutes/day ☐ 5 - 10 minutes/day
☐10 - 30 minutes/day ☐30 – 60 minutes/day ☐more than one hour

## C) Sleeping quality (during the measurements)

**52. Did you have a deep sleep?** Yes☐ No☐
**53. Did you wake up during the night?** Yes☐ No☐
**54. Did you have problem to wake up early mornings?** Yes☐ No☐
**55. Did your sleeping habits change during the measurements?** Yes☐ No☐

**56. What time did you go sleep?**
1. day ............. 2.day ............. 3.day ............. 4.day ............. 5.day .............
6. day ………. 7. Day ……… 8. Day ………

**57. What time did you wake up?**

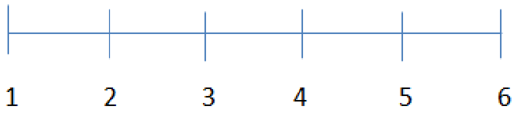
1. day ............ 2.day ............ 3.day ............ 4.day ............ 5.day ............
6. day ………. 7. Day ……… 8. Day ………

## VI. INDOOR AIR QUALITY AND AIRING OUT

The next questions refer to the whole apartment – during the heating season!!!

**58. How unpleasant do you think the indoor air quality is in your apartment?**

Not a problem Major problem



**59. How do you perceive the indoor air quality in your apartment?**
You can tick the scale anywhere.

**60. How often do you air out?**
☐ More than once per day ☐ Daily or almost daily ☐ Not every day, but at least once a week

**61. How long do you usually keep the windows opened?**
☐Less than 2 minutes/day ☐2 - 5 minutes/day ☐ 5 - 10 minutes/day
☐10 - 30 minutes/day ☐30 – 60 minutes/day ☐more than one hour

**62. If you feel the indoor air is unpleasant in your apartment, which of the following sources do you think contribute to the odour?**
☐Smoking
☐Printer
☐Meal
☐Carpet/Furniture
☐Chemical cleaners
☐Outdoor sources
☐Perfumes
☐Other...................................

## VII. THERMAL COMFORT

The next questions refer to the whole apartment – during the heating season!!!

**63. Please assess the thermal comfort in your apartment by marking the following scales.**

How do you assess the thermal sensation in your apartment?

Hot
Warm
Slightly warm
Neutral
Slightly cool
Cool
Cold

How do you perceive the indoor temperature in your apartment?

Clearly acceptable
Just acceptable
Just unacceptable
Clearly unacceptable

Which thermal sensation would you like to be satisfied?

Hot
Warm
Slightly warm
Neutral
Slightly cool
Cool
Cold

Do you want the room temperature?

Higher ☐
No change ☐
Lower ☐

**64. Do you have an ability to control the temperature on your radiators?** Yes☐ No☐
**65. If yes, do you use this possibility?** Never☐ Sometimes☐ Often☐
**66. Do you turn lower the temperature in the apartment during the night?**
☐Yes, I lower the temperature in some rooms, but not throughout the apartment
☐Yes, I lower the temperature throughout the apartment
☐No, I do not lower the temperature during the night
☐Do not know

**67. How often do you change the temperature on your radiators?**
☐Daily or almost daily
☐Not daily but at least once a week
☐Not more than once or twice the last two weeks
☐Do not change

**If you have any comments, please write them here:**

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**Thank you!**

## APPENDIX B

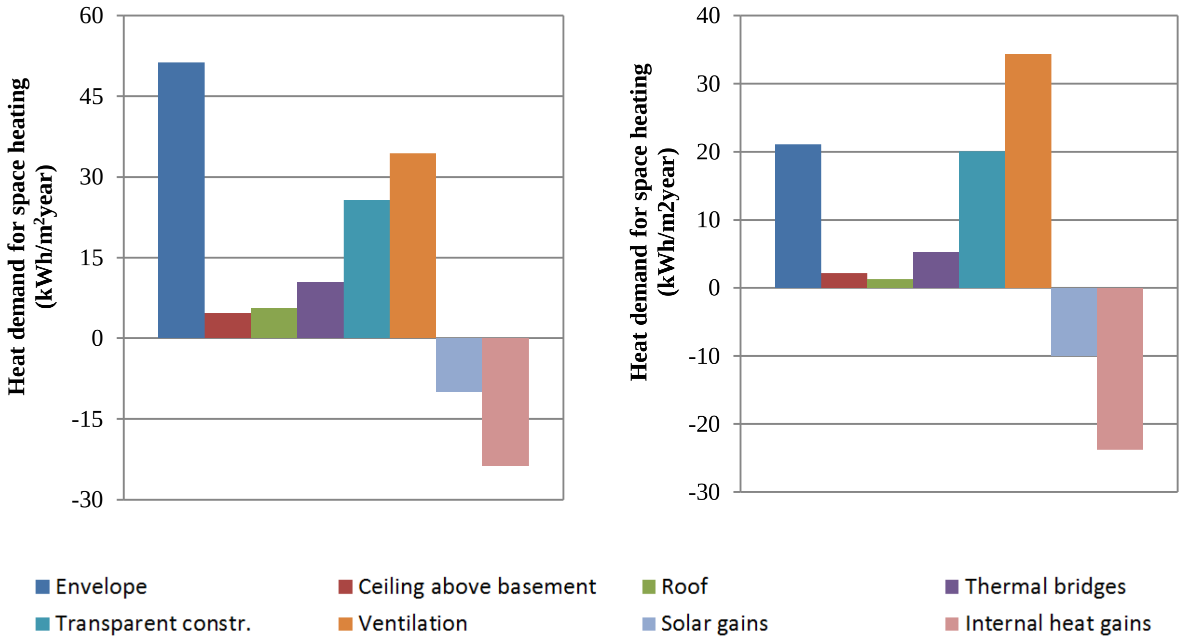
Individuals' characteristics by percentage distribution of their gender, age, and education level in the original and the renovated residential buildings in the first case study. The numbers depict period of winter, as a reference season.

| Individuals´ characteristics | Binary variables | Original (n=45) | Renovated (n=49) |
|---|---|---|---|
| | | Percentage (%) | |
| Gender | Female | 51 | 63 |
| | Male | 49 | 37 |
| Age | < 30 | 10 | 13 |
| | 31-40 | 15 | 24 |
| | 41-50 | 15 | 17 |
| | 51-60 | 12 | 15 |
| | 61-70 | 32 | 17 |
| | 71-80 | 12 | 9 |
| | > 80 | 4 | 5 |
| Education level | University degree | 22 | 25 |
| | High School | 24 | 18 |
| | Secondary vocational school | 26 | 44 |
| | Other | 28 | 13 |
| Health | Smoker | 27 | 38 |
| | Non-smoker | 73 | 62 |
| | Allergic | 36 | 31 |
| | Non-allergic | 64 | 69 |

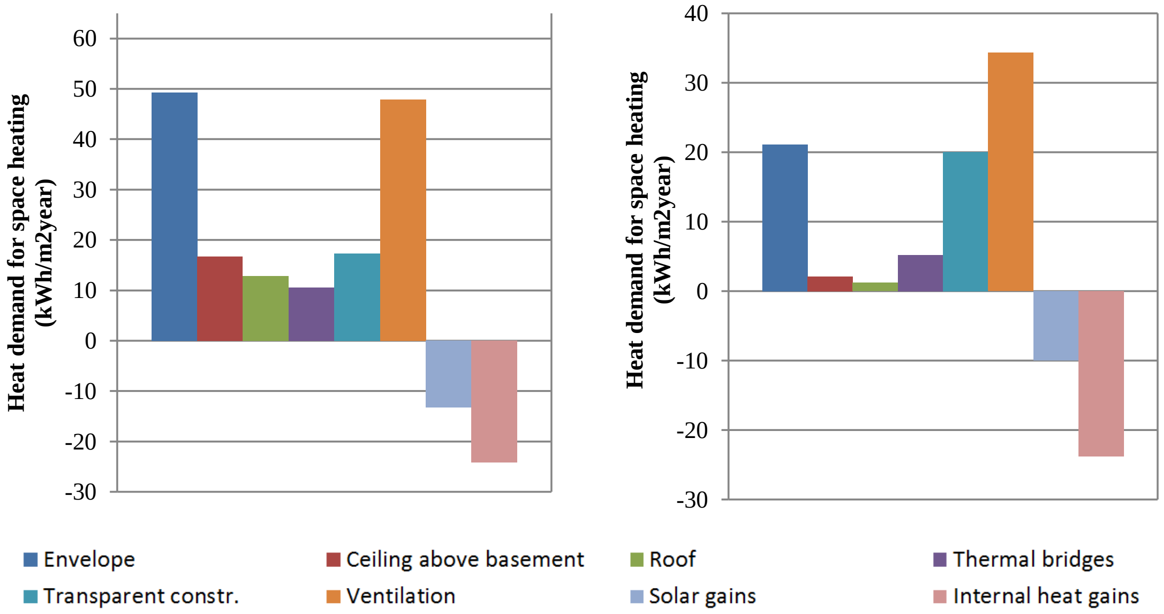
# APPENDIX C

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 II (a) and III (b): the original building (left), the renovated building (right).

a) Building pair II:



b) Building pair III:



## LIST OF PUBLICATIONS ACCORDING TO ISO 690

### ADE Scientific papers in other foreign magazines/journals

ADE01 FÖLDVÁRY, Veronika - BORISOVÁ, Lucia - PETRÁŠ, Dušan. Energy use and thermal comfort of two apartment buildings before and after refurbishment in Slovakia. In REHVA European HVAC Journal. Vol.50, Iss. 5 (2013), s.52-56. ISSN 1307-3729.

ADE02 FÖLDVÁRY, Veronika - BUKOVIANSKA, Hana [Pustayová, Hana] - PETRÁŠ, Dušan. Evaluation of indoor environment and energy consumption in dwellings before and after their refurbishment. In REHVA European HVAC Journal. Vol.53, Iss. 2 (2016), s.13-20. ISSN 1307-3729.

### ADF Scientific papers in other domestic magazines/journals

ADF01 FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Vplyv komplexnej obnovy na kvalitu vnútorného vzduchu : Ako dopadol prieskum vo vybraných bytových domoch? In TZB Haustechnik. Roč. 22, č. 5 (2014), s. 52-54. ISSN 1210-356X.

### AFC Published papers on international scientific conferences

AFC01 FÖLDVÁRY, Veronika - BORISOVÁ, Lucia - PETRÁŠ, Dušan. Evaluation of energy performance and thermal condition of apartment buildings before and after refurbishment. In E-NOVA 2013 : Internationaler Kongress. Nachhaltige Gebäude.Pinkafeld, Österreich,13.-14.11.2013. Pinkafeld : Fachhochschule Burgenland GmbH, 2013, s.477-483. ISBN 978-3-9502452-4-0.

AFC02 FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Indoor air quality in apartment buildings in Slovakia and its dependence on renovation. In ROOMVENT 2014 : Proceedings of the 13th SCANVAC International Conference on Air Distribution in Rooms: New ventilations strategies with base in active and passive technology in building and for comfort in airplanes, Sao Paulo, Brazil, 19. - 22. 10. 2014. 1. vyd. Sao Paulo : IPT Instituto de Pesquisa Tecnologica, 2014, P. 104-109. ISBN 978-85-68864-00-5.

AFC03 FÖLDVÁRY, Veronika - BEKÖ, Gabriel - PETRÁŠ, Dušan. Impact of energy renovation on indoor air quality in multifamily dwellings in Slovakia. In INDOOR AIR 2014 : proceedings of the 13th International Conference on Indoor Air Quality and Climate, Hong Kong, China, 7. - 12. 7. 2014. 1. vyd. Pokfulam : The University of Hong Kong, 2014, S. 644-646. ISBN 978-962-85138-6-4.

AFC04 FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Comparison of carbon dioxide concentration and air change rates in two identical dwellings before and after renovation in Slovakia. In E-NOVA 2014 : Internationaler Kongress. Nachhaltige Gebäude. 1. vyd. Graz : Leykam Buchverlagsgesellschaft, 2014, S. 251-255. ISBN 978-3-7011-0316-4.

AFC05 FÖLDVÁRY, Veronika - BEKÖ, Gabriel - PETRÁŠ, Dušan. Seasonal variation in indoor environmental quality in non-renovated and renovated multifamily dwellings in Slovakia. In Healthy Buildings Europe 2015 : proceedings. Eindhoven, Netherlands, 18. - 20. 5. 2015. Eindhoven : Eindhoven University of Technology, 2015, USB kľúč, [5] s. ISBN 978-90-386-3889-8.

AFC06 FÖLDVÁRY, Veronika - BUKOVIANSKA, Hana [Pustayová, Hana] - PETRÁŠ, Dušan. Analysis of energy performance and indoor climate conditions of the Slovak housing stock before and after its renovation. In Energy Procedia [elektronický zdroj] : 6th International Building Physics Conference, IBPC 2015. Vol. 78, (2015), online, s. 2184-2189. ISSN 1876-6102.

## AFD Published papers on domestic conferences

AFD01 BUKOVIANSKA, Hana [Pustayová, Hana] - FÖLDVÁRY, Veronika. Vplyv obnovy na kvalitu vnútorného prostredia v obytných budovách. In Vnútorná klíma budov 2015 : zborník prednášok z 26. vedeckej konferencie. Energetické a environmentálne aspekty pri komplexnej obnove budov. Štrbské Pleso, SR, 8. - 9. 12. 2015. 1. vyd. Bratislava : Slovenská spoločnosť pre techniku prostredia, 2015, S. 121-125. ISBN 978-80-89216-84-0.

AFD02 FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Energetické hodnotenie a tepelný stav bytového domu pred a po obnove. In Vykurovanie 2013 : zborník prednášok z 21. medzinárodnej konferencie na tému "Energetické, environmentálne a ekonomické aspekty pri prevádzke vykurovacích systémov". Ľubovnianske kúpele, SR, 4. - 8. 3. 2013. 1. vyd. Bratislava : SSTP, 2013, s.317-320. ISBN 978-80-89216-53-6.

AFD03 FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Evaluation of indoor air quality in residential buildings. In Indoor Climate of Buildings 2013 : Indoor environment and energy performance of HVAC-R systems in buildings. 8th International Conference.Štrbské pleso,SR,1.-3.12.2013. 1. vyd. Bratislava : SSTP, 2013, s.43-50. ISBN 978-80-89216-59-8.

AFD04 FÖLDVÁRY, Veronika. Hodnotenie vnútorného prostredia bytových domov v procese obnovy. In Advances in Architectural, Civil and Environmental Engineering [elektronický zdroj] : 23rd Annual PhD student conference. Bratislava, SR, 30. 10. 2013. Bratislava : Nakladateľstvo STU, 2013, s.CD-ROM, s.679-685. ISBN 978-80-227-4102-6.

AFD05 FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Objektívne a subjektívne hodnotenie kvality vnútorného vzduchu pred a po komplexnej obnove bytového domu. In Komplexná obnova bytových domov 2014 : zborník prednášok z VIII. medzinárodnej vedecko-odbornej konferencie. Od energetickej efektívnosti po trvalú udržateľnosť. 1. vyd. Martin : Združenie pre podporu obnovy bytových domov, 2014, S. 59-62. ISBN 978-80-227-4272-6.

AFD06 FÖLDVÁRY, Veronika. Vplyv komplexnej obnovy na kvalitu vnútorného vzduchu v bytových domoch. In Advances in architectural, civil and environmental engineering [elektronický zdroj] : 24rd Annual PhD Student Conference on Architecture and Construction Engineering, Building Materials, Structural Engineering, Water and Environmental Engineering, Transportation Engineering, Surveying, Geodesy, and Applied Mathematics. 1. vyd. Bratislava : Slovenská technická univerzita v Bratislave, 2014, CD ROM, 761-767. ISBN 978-80-227-4301-3.

AFD07 PETRÁŠ, Dušan - HURTÍKOVÁ, Daniela - FÖLDVÁRY, Veronika. Kvalita vnútorného vzduchu - východisko pre návrh systémov vetrania a klimatizácie. In Vetranie a klimatizácia 2015. Systémy "Vetrania a klimatizácie" v procese energetického auditu budov : zborník prednášok zo 17. vedecko-odbornej konferencie. Horný Smokovec, SR, 2. - 3. 6. 2015. 1. vyd. Bratislava : Slovenská spoločnosť pre techniku prostredia, 2015, S. 3-8. ISBN 978-80-89216-74-1.

AFD08 PUSTAYOVÁ, Hana [Pustayová, Hana] - FÖLDVÁRY, Veronika. Obnova bytových domov z pohľadu zabezpečenia kvality vnútorného vzduchu. In Komplexná obnova bytových domov 2013 : VII. Medzinárodná odborná konferencia. Legislatívne a technické nástroje znižovania energetickej náročnosti bytových domov. Podbanské,SR,20.-22.11.2013. Bratislava : Združenie pre podporu obnovy bytových domov, 2013, s.43-46. ISBN 978-80-227-4037-1.

**BDE Publications in other foreign magazines/journals**

BDE01 BORISOVÁ, Lucia - FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Energetické a environmentálne posúdenie bytových domov. In Energeticky soběstačné budovy. Roč. 2, č. 3 (2013), s.40-44. ISSN 1805-3297.

BDE02 FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Panelházak energiafogyasztása es hőállapota. In Magyar Épületgépészet. Vol. 62, No. 1-2 (2013), s.35-37. ISSN 1215-9913.

### BDF Publications in other domestic magazines/journals

BDF01 BORISOVÁ, Lucia - FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Energetické a environmentálne hodnotenie bytových domov. In Eurostav. Roč.19, č.1-2 (2013), s.28-31. ISSN 1335-1249.

BDF02 FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Energetická náročnosť a tepelný stav bytového domu pred a po komplexnej obnove. In Správca bytových domov. Roč. 8, č. 1 (2013), s.47-49. ISSN 1336-7919.

BDF03 FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Zabezpečenie kvality vzduchu a vetracie štandardy v bytových domoch. In Eurostav. Roč. 20, č. 9 (2014), s. 34-37. ISSN 1335-1249.

### BED Publications in domestic reviewed proceedings

BED01 FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Hodnotenie energetickej náročnosti a tepelného stavu bytového domu pred a po obnove. In Vnútorná klíma budov 2012 : environmentálne verzus energetické aspekty návrhu budov. Zborník prednášok z 23. konferencie. Štrbské pleso,SR,29.-30.11.2012. Bratislava : SSTP, 2012, s.93-96. ISBN 978-80-89216-52-9.

BED02 PUSTAYOVÁ, Hana [Pustayová, Hana] - PETRÁŠ, Dušan - FÖLDVÁRY, Veronika. Vplyv komplexnej obnovy na tepelný stav vykurovaných interiérov. In Komplexná obnova bytových domov 2012 : VI. medzinárodná odborná konferencia: Legislatíva, financovanie, architektúra, materiály a technológie pre KOBD. Podbanské 20.-22.11.2012. 1. Martin : Združenie pre podporu obnovy bytových domov, 2012, s.75-78. ISBN 978-80-227-3833-0.

### BEE Publications in other foreign conference proceedings

BEE01 FÖLDVÁRY, Veronika - PETRÁŠ, Dušan. Panelházak energetikai elemzése és hőállapota felújítás előtt és után. In ÉPKO 2013 : 17th International conference on civil engineering and architecture, Csíksomlyó, Rumunsko, 13.-16.6. 2013. Cluj : Hungarian Technical Scientific Society of Transylvania, 2013, s.108-113.

BEE02 PETRÁŠ, Dušan - FÖLDVÁRY, Veronika - PUSTAYOVÁ, Hana [Pustayová, Hana]. Evaluation of indoor environment in apartment buildings before and after their refurbishment. In Advanced HVAC and Natural Gas Technologies : proceedings of REHVA Annual Conference 2015, Riga, Litva, 6. - 9. 5. 2015. 1. ed. Riga : RTU Press, Riga Technical University, 2015, P. 23-25. ISBN 978-9934-10-685-9.

**Recently published conference papers (not registered in the University online library yet):**

D. L. Loveday, L. H. Webb, P. Verma, M. J. Cook, R. Rawal, K. Vadodaria, P. Cropper, G. Brager, H. Zhang, **V. Foldvary**, E. Arens, F. Babich, R. Cobb, R. Ariffin, S. Kaam, L. Toledo. The Role of Air Motion for Providing Thermal Comfort in Residential / Mixed Mode Buildings: Multi-partner Global Innovation Initiative (GII) Project. Proceedings of 9th Windsor Conference: Making Comfort Relevant. Cumberland Lodge, Windsor, UK, 7-10 April 2016. Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

**Future publications on international conferences:**

FÖLDVÁRY, Veronika – KOLLÁŘIK, Jakub - BEKÖ, Gabriel - PETRÁŠ, Dušan. Effect of building renovation on energy use and indoor environment: Comparison of simulations and measurements in six apartment buildings. Indoor Air 2016. The 14th International Conference of Indoor Air Quality and Climate. Ghent, Belgium, July 3-8. 2016. **Status: Accepted.**

BEKÖ, Gabriel - FÖLDVÁRY, Veronika – LANGER, Sarka – ARRHENIUS, Karine. Indoor air quality in a multifamily apartment building before and after energy renovation. The Fifth International Conference on Human-Environment System. ICHES2016 Nagoya, October 29 - November 2, 2016. **Status: Abstract accepted.**