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Effects of Energy Retrofits on Indoor Air Quality in Three Northern European Countries

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Abstract

According to an assessment protocol developed as a part of the INSULAtE project, indoor air quality measurements were conducted in three Finnish and Lithuanian multifamily buildings before and after energy retrofits. Additional cases from Estonia included one retrofitted and two non-retrofitted buildings. Measured gaseous pollutants included carbon dioxide (CO_2), volatile organic compounds (VOCs), formaldehyde (CH_2O), and nitrogen dioxide (NO_2). Low CO_2 concentrations in Finland could be attributed to common use of mechanical exhaust ventilation. WHO guidelines for CH_2O were not exceeded in any of the measured apartments. No statistically significant changes were seen in VOC or NO_2 after retrofits.

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Keywords: retrofits; multi-family buildings; indoor air quality; thermal comfort; gaseous pollutants; questionnaire

1. Introduction

Assessment of building retrofits improving energy efficiency (EE) has traditionally been based on economic aspects – performing cost-effective retrofit actions assuming further savings in energy costs, whereas possible changes

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in indoor environmental quality (IEQ) has not been considered in depth. The World Health Organization (WHO) resolution on environment and health has called for policies to protect public health from the impacts of major environment-related hazards such as those arising from climate change and housing [1]. Therefore, a more comprehensive analysis on IEQ is essential. Recent research has demonstrated that it is possible to improve indoor environmental quality (IEQ), health and wellbeing of building occupants along with improved energy efficiency. However, the impacts are influenced by several factors (e.g., building, climatic, cultural, social, economic) and often differ from country to country [2].

The countries within European Union have assumed commitments to build energy efficient buildings from 2019 to 2021 [3]. Especially new buildings are targeted, promoting nearly zero-energy buildings [4], but also existing buildings should be improved by energy retrofits [5,6,7,8]. This usually means improving air tightness of the building envelope. The modifications, including changes in structures (e.g. insulation of external walls), and heating, ventilation and air conditioning (HVAC) systems, as well as installing new building materials, may have a significant influence on indoor air quality (IAQ) [9,10,11]. Release of pollutants from some building materials may decay in days or weeks, such as the smell of fresh wood or new carpet, while others may persist as long as the material is present [12]. IAQ is one of the main indoor environment parameters contributing to satisfactory indoor environment [13, 14], which in turn affects human health. There are examples when indoor climate has either improved or decreased as a result of improved EE [15,16].

In many Northern European countries (including Finland, Estonia, and Lithuania) the renovation programs for multifamily apartment buildings are gaining their momentum. Along with demonstrating the effects of improving energy efficiency on IEQ and health, the INSUALtE project (www.insulateproject.eu) has developed a comprehensive assessment protocol. The assessment protocol has been tested in numerous case studies performed in multi-family buildings in Finland, Estonia and Lithuania. In this paper we present the results of the selected case study buildings from three countries and discuss about observed differences before and after retrofits.

2. Methods and materials

2.1. Case study buildings and retrofit actions

The case study buildings were selected from different regions in Finland (Tampere, Lempäälä), Tallinn region in Estonia, and Kaunas region in Lithuania. The primary criteria were planned retrofits, which had to be related to EE. Recruited apartments were selected from volunteering occupants, who did not receive any monetary compensation for participating in the study. In Finland and Lithuania, IEQ was assessed in the same buildings before and after retrofit activities. The retrofit usually took place in the following year after the baseline measurements.

In this paper we present results from one 6-storey (retrofit activities were completed in 2014) and two 8-storey (retrofit activities completed in 2015) buildings from Finland. The buildings were more than 40 years old (built before 1975). Nineteen apartments were measured in the 8-storey buildings with average occupancy of 1-2 persons per apartment (maximum 3), while five apartments were measured in the 6-storey building with average of one person per apartment. Both of these buildings had mechanical ventilation.

In Estonia two buildings (5- and 9-storey) were controls (no retrofits took place) and one was assessed after completion of retrofit activities (9-storey building, retrofit finished in 2014). All buildings were situated near busy roads. The average age of the buildings was about 40 years. Eight apartments were measured in the control buildings with average occupancy of 3-4 persons per apartment, while two apartments were measured in the retrofitted building with two persons per apartment. Control buildings had natural ventilation, while mechanical ventilation with heat recovery (exhaust air heat pump) was installed in the retrofitted building.

From Lithuania, results from one 5-storey (retrofitted in 2015) and two 9-storey buildings (both retrofitted in 2014) are presented. All buildings were located in densely populated areas and they had natural ventilation before and after retrofits. The average age of the buildings was about 35 years (built before 1982). Ten apartments were measured in the 9-storey buildings with average occupancy of two persons per apartment (maximum 4), while five apartments were measured in the 5-storey building with average of two persons per apartment. Lithuanian buildings were same construction type as the Estonian buildings: large-panel concrete and bricks were used as construction materials. This building type is common in all Baltic countries and is known for leaky envelope, low thermal insulation, unbalanced heating, and natural ventilation systems.

2.2. Environmental monitoring

Data loggers and passive samplers were set up during the first visit in each apartment. The visits were primarily conducted during heating seasons in order to minimize outdoor impacting the results. Follow-up visits (after retrofits) were done during corresponding season as the first visits.

Temperature (T) and relative humidity (RH) was continuously monitored for at least two months by two data loggers. One logger was placed to the coldest spot, i.e. place where coldest inner surface temperature was detected by thermographic camera or IR-thermometer (usually by the balcony door). The other logger was placed to the occupied zone, e.g., middle of the living room (height of 1.2-1.5 m above ground, i.e. human breathing zone as seated). All units used in the study were new and recently calibrated by the manufacturer.

For carbon dioxide (CO_2) and carbon monoxide (CO) measurements, new, factory calibrated sensors were utilized. Side-by-side simultaneous tests before and after the baseline measurements were conducted, based on which replicate precision ranged from 5% to 11%, and sensors were sent to the manufacturer for calibration as needed.

Formaldehyde (CH_2O) samplers were analysed with ultra-fast liquid chromatography coupled with UV/VIS and diode matrix detectors system (Prominence UFLC, Shimadzu, Japan). The analysis of VOCs samples was performed by gas chromatography (GC MS-QP2010 Ultra, Japan) coupled to mass spectrometer (GC/MS) using helium (He) as a carrier gas. The equipment was calibrated before the analyses by injecting standard solutions of compounds: BTEX (benzene, toluene, ethylbenzene, and xylenes). Nitrogen dioxide (NO_2) samples were analysed by Gradko, which laboratory was accredited by United Kingdom Accreditation Service. CH_2O, VOCs, and NO_2 were measured by passive sampling methods.

In addition to the gaseous pollutant measurements, concentrations of particulate matter, radon, microbial content in the settled dust, and ventilation rates were assessed in Finland and Lithuanian buildings [17]. Occupant surveys were used to collect information concerning occupant perceived housing satisfaction, including thermal comfort, satisfaction with IAQ, lighting, and noise disturbance (data not shown).

3. Results and Discussion

3.1. Temperature and Relative Humidity

Based on Finnish housing and health guidelines [18], recommended room T is 21 ºC (acceptable T is 18 ºC), and it should not exceed 23-24 ºC during the heating season, whereas recommended range for RH is 20-60 %. Mean T varied between 20.9-24.1 °C and 20.3-24.1 °C in not retrofitted and retrofitted buildings, respectively. Recommended national guidelines for T was exceeded in five (21 %) and one apartment (6 %) pre and post retrofits, respectively. Mean T below recommended minimum was not observed in any of the measured apartments. Before retrofits, RH fell within recommended range in 20 out of 24 measured apartments (83 %) with the lowest RH value of 15 %. After retrofits, all investigated apartments were within recommended range (observed range 23% - 36 %).

According to Estonian guideline values, indoor T should range between 22±3 °C during the winter season and recommended RH values is 25-45 % during winter. With respect to T, all investigated apartments were within the recommended range [19]. Mean T varied between 20.1-24.4 °C and 22.0-22.5 °C in non-retrofitted and retrofitted buildings, respectively. RH values fell within the comfort range as defined by the Estonian guideline values only in three apartments from seven in non-retrofitted buildings, whereas three were below (RH=20-24 %) and one above (RH=50 %) recommended range. RH levels in retrofitted building were within recommended range (RH=44 % in both apartments.

In Lithuania [20], the recommended room T is between 18-22 ºC, and indoor RH levels should range between 35-60 % during the heating season. Mean T varied between 15.1-22.4 °C and 18.2-22.4 °C in non-retrofitted and retrofitted buildings, respectively. Lowest observed T increased by more than 3 degrees (from 15.1 to 18.2 °C) after retrofits, and compliance with national guidelines increased in 29 % (from nine to thirteen apartments). RH levels were in better compliance with national guidelines after retrofits as well. In non-retrofitted buildings one apartment was above (RH=67 %) and four below (RH=27-34 %) the recommended value. After retrofits only one apartment (RH=33 %) did not meet the guidelines.

Based on these case studies, results indicated mainly improved thermal conditions after retrofits. Highest improvement in thermal conditions was observed in the Lithuanian buildings after retrofits. RH levels were meeting the national guidelines after retrofits in all countries. It should also be noticed that different national guidelines for T and RH levels can influence the interpretation of the results by countries. However, can be concluded that energy retrofits have the potential to substantially improve the thermal comfort.

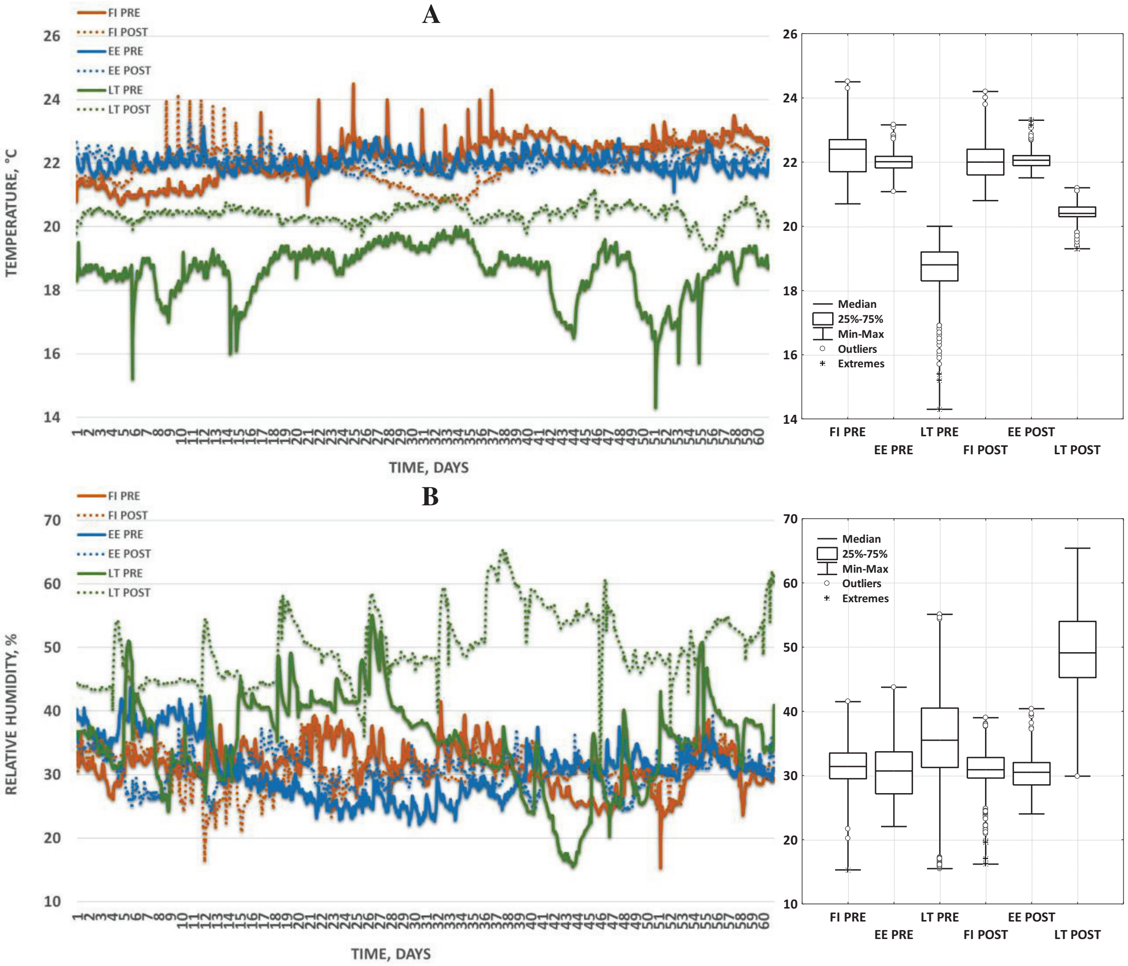

Fig. 1. Temperature (A) and relative humidity (B) temporal variations before and after retrofits in three European countries (FI – Finland, EE – Estonia, and LT – Lithuania; PRE – pre retrofit data, POST – post retrofit data).

Figure 1 represents temporal variation graphs and box plots of T and RH in one selected apartment per each country before and after retrofits. Consistent to the group level observations, Lithuanian apartment appear to have relatively lower T and higher RH. The same trend can be observed based on the box plot. Even though indoor T was substantially higher after retrofits in Lithuania, it is still about two degrees lower than in the other two countries. Higher RH levels in some Lithuanian apartments after retrofits could be associated with tighter building envelope and lack of ventilation. Graphs illustrate that increase in T (above recommended range) and decrease in RH (below recommended range) appeared simultaneously after retrofits in Finland, therefore lowering high indoor temperatures could help to save energy and maintain more acceptable RH.

3.2. Gaseous pollutants: CO_2, CH_2O, BTEX and NO_2

CO_2 levels were mostly within guidelines in all countries both before and after retrofits (Table 1). CO_2 was slightly lower after retrofits, but the difference was not statistically significant. Highest mean CO_2 concentration (before - 882±282 ppm, after - 878±380 ppm) was observed in Lithuania, however values fell within the national guidelines (1200 ppm) in 85 % of measured apartments both before and after retrofits. In Estonia, higher CO_2 concentrations in the non-retrofitted buildings could be related to the higher occupancy during the measurement period. Significantly lower 95th percentile (982 ppm before and 866 ppm after retrofits) in Finland could be related to the use of mechanical ventilation in all measured apartments.

With respect to CH_2O concentrations, WHO guideline value (100 $\mu g/m^3$) was not exceeded in any of the measured apartments. Highest mean CH_2O concentrations were assessed in Lithuanian cases both before (27.4±10.9 $\mu g/m^3$) and after (43.0±15.0 $\mu g/m^3$) retrofits. In Finland, an opposite trend was observed: CH_2O concentrations were lower after the retrofits (22.7±8.4 $\mu g/m^3$ before and 20.3±7.3 $\mu g/m^3$ after retrofits), thus we do not attribute these changes to retrofit process per se. Generally, the concentrations of these pollutants could increase if the retrofit activities included indoor installations, such as new flooring or furniture. In Estonia CH_2O concentrations were lower in the retrofitted building too, with overall mean value of 7.0±0.8 $\mu g/m^3$, however it is not possible to draw any strong conclusions due to a relatively small sample size.

Slightly different pattern was observed with respect to BTEX concentrations (Finland and Lithuania): mean values were lower and median values higher after building retrofits. However, the differences were not statistically significant with the current sample size, suggesting that various processes related to building retrofitting may not have a noticeable effect on indoor BTEX levels. This can be supported by the fact that 95th percentile in the case buildings was much lower after retrofitting (decreasing from 33.0 to 17.8 $\mu g/m^3$ in Finland and from 111.4 to 51.6 $\mu g/m^3$ in Lithuania). In Estonia concentrations were found considerably higher in the retrofitted building with the mean value of 24.5±0.1 $\mu g/m^3$, whereas the mean BTEX concentration was 18.1±5.1 $\mu g/m^3$ in the control buildings.

With respect to NO_2 concentrations, only one apartment (in Lithuania, 43.8 $\mu g/m^3$) out of 47 measured apartments in the three countries exceeded maximum allowable concentration of 40 $\mu g/m^3$ (WHO guideline value for 24 hours) before the retrofits, while none of the apartment exceeded the limit after the retrofits. These results cannot provide any strong conclusions on possible NO_2 concentration reduction due to retrofit processes.

Table 1. Concentrations of gaseous pollutants in multifamily buildings in Finland, Estonia, and Lithuania (table shows number, average, standard deviation, median, 5th percentile, and 95th percentile).

		Pre						Post					
		N	Average	SD	Median	5th	95th	N	Average	SD	Median	5th	95th
CO_2	Finland	23	697	224	670	488	982	17	638	183	587	482	866
	Estonia	7	799	454	718	354	1471	2	740	133	-	-	-
	Lithuania	13	882	282	829	532	1283	13	878	380	849	488	1462
CH_2O	Finland	24	22.7	8.4	21.4	11.6	37.3	18	20.3	7.3	19.7	11.6	31.1
	Estonia	7	16.8	6.8	16.1	8.0	25.0	2	7.0	0.8	-	-	-
	Lithuania	15	27.4	10.9	24.9	11.5	43.6	15	43.0	15.0	38.0	27.0	64.7
BTEX	Finland	24	13.9	21.9	7.3	4.1	33.0	18	11.2	5.3	9.7	6.0	17.8
	Estonia	7	18.1	5.1	18.7	12.7	25.2	2	24.5	0.1	-	-	-
	Lithuania	15	39.8	37.8	22.6	5.6	111.4	15	30.0	13.4	28.0	14.9	51.6
NO_2	Finland	24	5.0	3.5	3.2	2.3	8.3	18	6.6	4.6	6.0	2.2	12.7
	Estonia	8	6.1	2.6	5.2	3.6	9.9	2	10.9	1.5	-	-	-
	Lithuania	15	17.2	11.4	13.3	4.1	37.2	15	16.5	10.1	15.3	4.2	32.3

4. Conclusions

Group level results have indicated mainly improved IEQ after retrofits in all countries. Highest improvement in thermal conditions was observed in Lithuanian retrofitted buildings. After retrofits RH levels met the national guidelines in all cases. Lowering high indoor temperatures in Finland could help to save energy and maintain more acceptable RH. Higher RH levels in some Lithuanian apartments can be associated with tighter building envelopes and lack of ventilation. Well balanced mechanical ventilation with heat recovery could improve the situation in terms of ventilation adequacy.

CO_2 levels were mostly within recommended guidelines in all cases both before and after retrofits. Remarkably low 95th percentile of CO_2 concentrations (982 ppm before and 866 ppm after retrofits) observed in Finland could be attributed to the use of mechanical ventilation in all measured apartments. CH_2O concentrations did not exceed WHO guideline value in any of the measured apartments. No statistically significant changes were observed in BTEX and NO_2 concentrations after building retrofits.

To conclude, both positive and negative differences in the gaseous pollutants concentrations were observed in retrofitted buildings as compared to the non-retrofitted buildings. However, these differences were not necessarily related to the retrofits per se. Cumulative one-week measurement campaign using passive samplers may not be ideal to reveal such effects, which, if any, may be overruled by other factors than the retrofitting.

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