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Impacts of energy retrofits on indoor CO_2 concentration and air change rate

Virpi Leivo[1,*], Tadas Prasauskas[2], Anu Aaltonen[1], Dainius Martuzevicius[2], Ulla Haverinen-Shaughnessy[1,3]

[1] Tampere University, P.O.Box 600, 33014 Tampere University, Finland,
[2] Kaunas University of Technology, K. Donelaičio g. 73, Kaunas 44249, Lithuania,
[3] National Institute for Health and Welfare, P.O.Box 95, 70701 Kuopio, Finland
[*] virpi.leivo@tuni.fi

Abstract. Impacts of energy retrofits on IAQ were studied in two European countries, Finland and Lithuania. Air change rates were estimated based on air flows measured through ventilation outlets and 24-hour monitoring of CO_2 concentrations before and after various energy retrofits in multi-family buildings. The air change rates (ACR) after retrofits were higher in apartments with mechanical ventilation in Finland. The ACR after retrofits were smaller in all study groups in Lithuania, yet noticeably smaller in apartments with mixed ventilation. CO_2 concentrations in all study groups in Finland were lower than in Lithuania. Also, some decrease in CO_2 concentrations was noticed after retrofits in Finland, whereas an opposite trend was observed in Lithuania. In conclusion, impacts of energy retrofits were mainly marginally positive in Finland and mainly negative in Lithuania. Positive impacts were typically noticed in apartments with mechanical ventilation and "good" IAQ before retrofits. On contrary, negative impacts were noticed in apartments with natural ventilation and "adequate" IAQ. It was concluded that IAQ should be assessed before and after retrofits.

1. Introduction

According to the newest Energy Performance Building Directive [1] it is necessary to progress towards the transformation of existing buildings into nearly zero-energy buildings, in particular by increasing deep renovations. The aim is to achieve a highly energy efficient and decarbonised building stock. In terms of energy performance upgrades of existing buildings, their contribution to achieving a healthy indoor environment should also be supported. One of the main attributes is indoor air quality (IAQ), which is maintained by adequate outdoor air ventilation.

Total ventilation rate (including intentional air change and unintentional infiltration) is difficult to measure exactly mainly due to constantly changing infiltration parameters (such as buoyancy effect due to temperature difference and wind pressure effect). In many instances, measurement of carbon dioxide (CO_2) concentration (as a tracer gas) is used to assess ventilation adequacy with respect to IAQ. Along with high CO_2 concentrations, occupants commonly perceive air stuffiness and related discomfort.

Impacts of energy retrofits on IAQ were studied in Finland and Lithuania. The purpose of the whole project (INSULAtE) was to demonstrate impacts of energy retrofits on IAQ, occupant health and wellbeing, and to develop a common assessment protocol. The objective of this study was to assess the impact of energy retrofit, either positive or negative, on IAQ by measuring air change rates and CO_2 concentrations. In addition, the effects of ventilation system (natural vs. mechanical) and retrofit level (deep retrofit vs. single retrofit action) were studied.

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2. Material and methods

Case study buildings, including 119 apartments in Finland and 53 in Lithuania, were selected from volunteering multi-family buildings that were planned to be retrofitted during the project, and where approximately five apartments per building were willing to participate in the measurements. In addition, some buildings, which were not retrofitted during the project, were included as control buildings. The case study buildings were chosen from southern and central regions in Finland, and Kaunas region in Lithuania. More detailed information about the case study buildings is presented by Du et al [2]. The measurements were performed during heating season. The average outdoor temperatures were quite similar in both countries: T_{out}=+0.9 °C (before retrofit) and T_{out}=+2.6 °C (after retrofit) in Finland and T_{out}=-0.3 °C and T_{out}=+3.1 °C in Lithuania, respectively.

The studied buildings in both countries are quite comparable in terms of construction type and common building materials. The external walls were commonly made of prefabricated concrete elements (with thermal insulation in between the panels) in both countries. Also, the average size of the apartments was almost the same in both countries, 66 m^2 in Finland and 64.3 m^2 in Lithuania. The majority of the buildings were built in 1960–1980. However, there were major differences in the types of ventilation system and thermal resistance (U-values) of the building envelope. Majority of the measured apartments (about 92%) in Finland had a mechanical exhaust ventilation system, with or without heat recovery units. The ventilation systems are typically operated so that more efficient exhaust is turned on for two hours once or twice a day, in the morning (10 am–2 pm) and in the afternoon (4 pm–6 pm). On the contrary, majority of the buildings in Lithuania had natural ventilation, which in 44% of the apartments had been improved with occupant-controlled fan-driven exhaust in the kitchen and natural/mechanical exhaust in the bathroom. The ventilation systems of the case buildings were typical in each country: in Northern Europe (especially in Scandinavian countries), the most common ventilation system is mechanical exhaust ventilation, whereas in other parts of the Europe, natural ventilation is more common (3). The average U-values of envelope structures before and after retrofit are presented in Table 1.

Table 1. Average U-values of envelope structures before and after retrofits in Finland (FI) and Lithuania (LT)

	FI		*LT*	
U-values, W/m^2 K	*Before*	*After*	*Before*	*After*
Outer walls	0.40…0.28	same	1.27…0.88	0.2
Roofs	0.40…0.36	same	0.85	0.16
Floors	0.40…0.29	same	0.71	same
Windows	2.1	1		1.4

Three retrofit schemes were recognized: no retrofits (CONTROL), focused (FER) and deep retrofit (DER). Deep energy retrofits (DER) with several retrofit actions were performed in 11% of the case buildings in Finland and 87% in Lithuania. Focused retrofits (FER) with minor retrofit action(s) most commonly included changing new windows and/or installing heat recovery system into exhaust ventilation system. Summary of performed retrofit actions is presented in Figure 1.

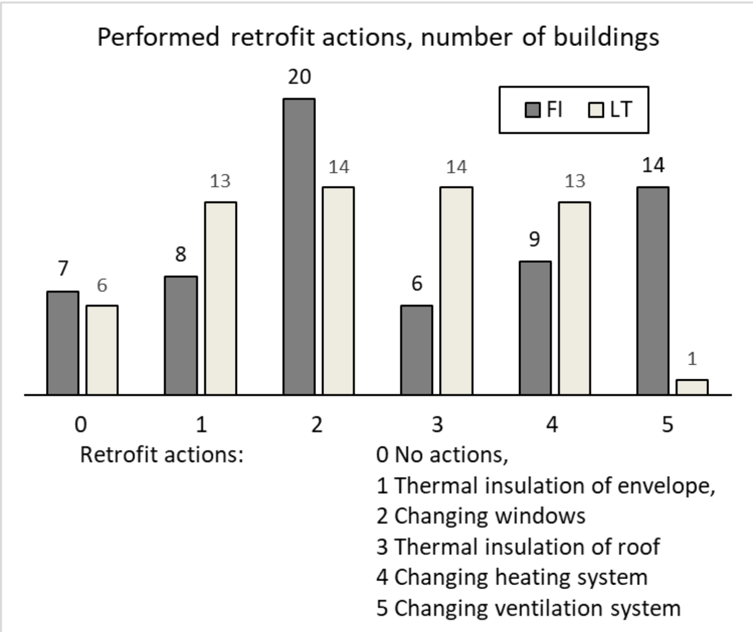

Figure 1. Retrofit actions performed the case buildings in Finland (FI) and Lithuania (LT).

Ventilation or air change rate (ACR, 1/h) was calculated based on measured airflows from ventilation outlets and information on the apartment air volume. A new rotating vane anemometer with a built-in 100 mm vane and temperature probe (Testo 417, +0.3 to +20 m/s measurement range, ± (0.1 m/s +1.5% of mv) accuracy and 0.01 m/s resolution) was used to measure air flows. Each ventilation outlet was measured, but the measured values were found unreliable if the outlet was irregular or the airflow was too small. Carbon dioxide (CO_2) and carbon monoxide (CO) concentrations were measured every minute during a 24-hour period using new, factory calibrated sensors (HD21AB/HD21AB17, Delta OHM, Italy. Range 0 - 5000 ppm, accuracy ±50 ppm or ± 3%).

3. Results

Calculated air change rates based on outlet air flow measurements are presented in Figure 2, divided by retrofit schemes (FER, DER) and ventilation systems (Natural, Mechanical exhaust, Mixed (natural/mechanical)). In both countries, ACR were higher in apartments with mechanical or mixed ventilation. The more efficient exhaust was usually off during the measurements in Finland. On contrary, the fan-driven exhaust was usually on during the measurements in Lithuania. This could explain why ACR were higher in Lithuania in apartments with mixed ventilation. The ventilation rates were about the same in naturally ventilated apartments in both countries. The average outdoor temperature during measurements was closely similar. Natural ventilation is driven by temperature difference between indoor and outdoor or stack effect (buoyancy). The ACR after retrofits were higher in apartments with mechanical ventilation in Finland. It is common that after retrofits, especially if installing new windows with inlets, the ventilation is balanced. The ACR in apartments with mechanical ventilation were noticeably higher after DER retrofit, but small sample size (N=13 (Pre)/8 (Post)) limits conclusions. The ACR after retrofits were smaller in all study groups in Lithuania, noticeably smaller in apartments with mixed ventilation. Improved energy efficiency by improving airtightness of building envelope reduces air infiltration through leakages, which could reduce ACR, if additional inlets are not installed.

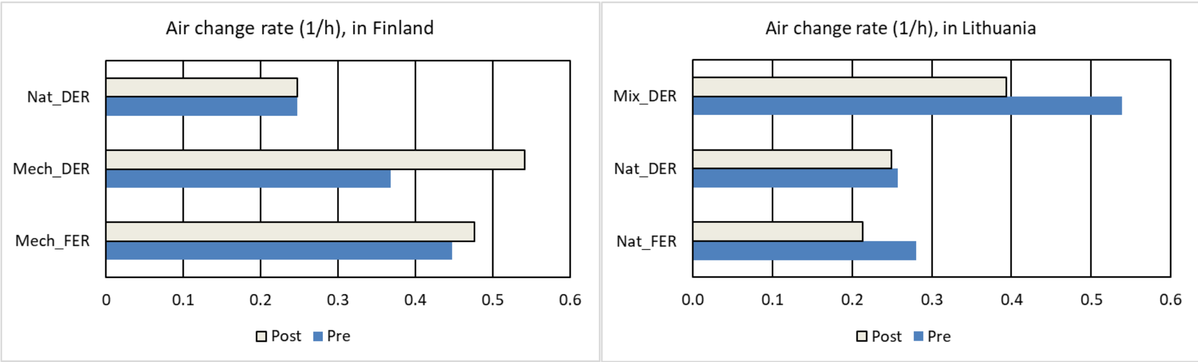

Figure 2. Measured air change rates before (Pre) and after (Post) retrofits in case buildings by country.

The 24-hour average CO_2 concentrations in all case groups in Finland were smaller than in Lithuania (Figure 3). A slight decrease in CO_2 concentration was noticed after retrofits in Finland, whereas an opposite trend was observed in Lithuania. Concentration of about 1000 ppm has become more or less "a de facto standard" for the maximum recommended value indoors [4], above which occupant perceived air stuffiness and related discomfort may increase. An "adequate level" of CO_2 concentration is 1200 ppm in Finland [5] and national guideline value is 1200 ppm in Lithuania [6]. Mixed ventilation system, afterwards installed by occupants, in Lithuanian apartments did not appear to improve IAQ based on CO_2 concentrations.

Besides ACR, the occupancy effects on indoor CO_2 concentrations. It was noticed that occupancy rate of the studied apartment was quite low in Finland: one occupant had an average of about 43 m^2 living space, while in Lithuania the average was about 23 m^2. Higher occupant density can at least partly explain higher CO_2 concentrations in Lithuania.

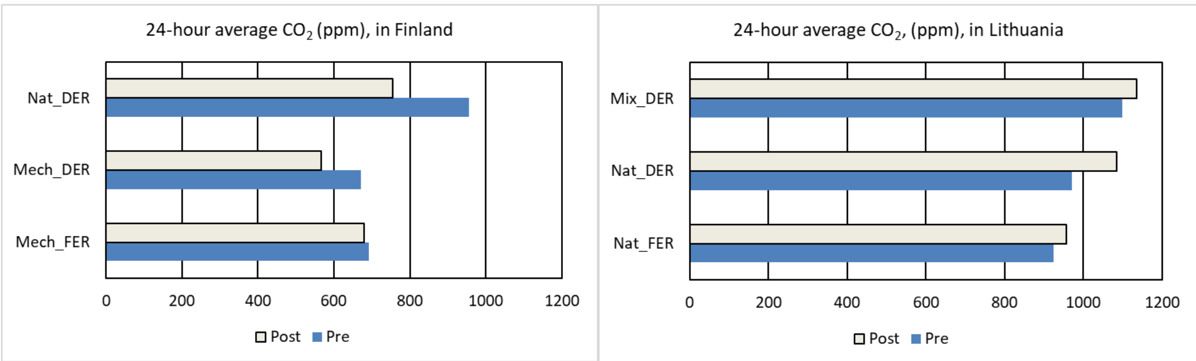

Figure 3. 24-hour average CO_2 concentrations before (Pre) and after (Post) retrofits by country.

Analyses related to ventilation rate and maximum night time CO_2 concentrations, also taking into account the number of occupants, has been reported previously [7]. Linear mixed models predicted average ventilation rate of about 2.6 l/s per person higher in Finnish buildings as compared to Lithuanian buildings, whereas maximum CO_2 level was significantly ($p<0.05$) lower (about 358 ppm) in Finland than in Lithuania, correspondingly. There was also a significant association between CO_2 concentration and number of occupants; the association was stronger in Lithuania where occupant density was higher and mechanical ventilation systems were not frequently used.

Table 2 shows the country specific average ACR and CO_2 concentrations divided by different retrofit schemes. Only minor positive changes (average 6.4% increase in ACR and 1.6% decrease in CO_2) were noticed in FER cases in Finland. There were larger changes (26.1% increase in ACR and 14.9% decrease in CO_2) in DER cases in Finland. In Lithuania, there were quite large negative changes in ACR in both

FER (23.7% decrease) and DER (17.9% decrease) cases. There were smaller negative changes in CO_2 concentration, 3.6% increase in FER and 7.9% increase in DER cases.

Table 2. Average change, % from before retrofit values, of air change rate (ACR) and CO_2 concentration in Finland (FI) and Lithuania (LT)

Change-%	*Sample size*	*ACR*	*CO_2*
FI: FER	96/63	6.4	-1,6
FI: DER	24/16	26.1	-14.9
LT: FER	9/3	-23.7	3.6
LT: DER	63/52	-17.9	7.9

Correlations between ACR and average CO_2 concentration are shown in Table 3. (Negative values indicate higher air change rate corresponding with lower CO_2 concentration.) The correlations are quite weak in most cases. Highest correlations are seen in Finnish apartments.

Table 3. Correlation coefficients between air change rate and average CO_2 concentration before and after retrofits in Finland (FI) and Lithuania (LT)

Correlation	*Sample size*	*Pre*	*Post*
FI: Nat_DER	11 (Pre)/8(Post)	-0.409	-0.294
FI: Mech_DER	13/8	-0.285	-0.212
FI: Mech_FER	96/63	-0.335	-0.394
LT: Mix_DER	30/26	-0.078	0.013
LT: Nat_DER	33/26	0.009	0.043
LT: Nat_FER	9/3	0.017	-0.101

4. Conclusions

The measured ACR after retrofits were higher in apartments with mechanical ventilation in Finland. The ACR after retrofits were smaller in all study groups in Lithuania, yet noticeably smaller in apartments with mixed ventilation. CO_2 concentrations in all study groups in Finland were smaller than in Lithuania. In addition, some decrease in CO_2 concentration was noticed after retrofits in Finland, whereas an opposite trend was observed in Lithuania. It can be concluded that the impact on retrofits were mainly positive (increased ACR and decreased indoor CO_2 concentration) in Finland. In addition, the impacts were depending on retrofits actions, i.e. more comprehensive retrofits resulted higher (positive) impacts. On the contrary, the impacts of retrofits were mainly negative in Lithuania. Larger negative changes were noticed in ACR with no clear dependency on the degree of retrofits. The increase in CO_2 concentrations seemed to be larger in the more comprehensive retrofit (DER) cases.

Based on the results, it seem that more comprehensive retrofits have higher positive or negative impacts on IAQ. IAQ is depended on ventilation system: higher ACR and lower indoor CO_2 concentration was measured in apartments with mechanical ventilation. A special attention on ventilation is required when retrofitting apartments with natural ventilation. Both ACR and CO_2 concentration measurements, performed before and after retrofits, are useful methods in indicating impact of energy retrofit on IAQ.

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