NATIONAL INSTITUTE FOR HEALTH AND WELFARE

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Improving energy efficiency of multi-family buildings, impacts on indoor environmental quality and health

Highlights

- Energy retrofits improved occupants' satisfaction with indoor air quality.
- Indoor air quality appeared to be improved in buildings with mechanical ventilation, whereas the opposite trend was seen in some buildings with natural ventilation.
- In Lithuanian buildings, thermal comfort was also substantially increased.
- Lowering high indoor temperatures in Finnish buildings during heating seasons could help to save energy and maintain more acceptable relative humidity.

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INTRODUCTION

National and international efforts are needed in order to mitigate climate change. It has been estimated that the largest potential for decreasing greenhouse gas emissions is in the building sector, where some 27% of energy is used in residential buildings. Within the EU, the Energy Efficiency Directive and the Energy Performance of Buildings Directive (EPBD) are the main legislative tools aimed at improving the energy efficiency (EE) of both new and existing buildings. The legislation is being implemented through national policies and programs, which usually focus on lowering the energy consumption of buildings. Improving EE can also impact indoor environmental quality (IEQ) and occupants' health and wellbeing, though information on these effects is sparse.

The aim of the INSULAtE-project was to demonstrate the effects of improved EE on IEQ and occupants' health in residential buildings, and to develop a comprehensive assessment protocol. In this 5-year project (2010–2015) we assessed building-, IEQ-, and health-related outcomes of EE retrofits in a number of case studies in Finland and Lithuania (see Figure 1 for the regions in which buildings were recruited).

Figure 1. Study locations, and regions of recruited buildings in Finland and Lithuania.

A majority of the assessed buildings were multi-family apartment buildings built in the period 1960–1980, and undergoing EE-improving retrofits. The assessment was done by means of various measurements and questionnaires both before and after the retrofits. The protocol was also tested in some buildings in Estonia, Latvia, and the UK.

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Material and methods

Assessments were performed in a total of 46 Finnish and 20 Lithuanian apartment buildings (about 5 apartments per building) on two occasions: 1st assessment at the baseline (before retrofits in the case buildings) and 2nd (follow-up) assessment (after retrofits in the case buildings). Assessments were performed mainly during the heating seasons. Assessment included the following measurements of indoor environmental quality parameters that may impact the health and wellbeing of residents:

- Indoor temperature (T) and relative humidity (RH)
- Air change rate (ACR)
- Carbon dioxide (CO_2) and carbon monoxide (CO)
- Particulate matter ($PM_{2.5}$, PM_{10})
- Nitrogen dioxide (NO_2)
- Volatile organic compounds (VOC)
- Formaldehyde ($CH_2$0)
- Radon
- Microbes and fibres in settled dust.

In addition, information was gathered from the occupants by using self-administered housing and health questionnaires and diaries.

- The questionnaire included 49 questions, mainly related to the dwelling and its surroundings, hygiene, indoor environmental issues, and health and wellbeing.
- The questionnaire was based on a formerly developed Housing and Health questionnaire, which has been used to collect data from random samples of Finnish dwellings in 2007 and 2011 [1, 2].
- The diary was filled once a day for a two-week period, and it included questions about time spent in the home and undertaking activities (such as opening windows for ventilation).

The assessment protocol is explained in detail in the project website (www.insulateproject.eu).

CASE STUDIES

Selected case buildings were multi-family buildings that were earmarked for retrofitted during the period of the project. An example of a case building before and after retrofit is shown in Figure 2. Also some buildings that were not retrofitted during the project were included as controls. Participation by residents was voluntary.

Figure 2. Case study building before and after energy retrofit.

In Finland, 46 apartment buildings (241 apartments) were assessed at baseline. Of these, 39 buildings were retrofitted (referred to as 'cases'), while the rest were 'controls' (no retrofit works). The buildings were mainly located in the Tampere and Kuopio areas. A majority of buildings had mechanical exhaust ventilation (<10% had natural ventilation). Figure 3 shows the distributions by year of construction and the different types of retrofits done in the case buildings.

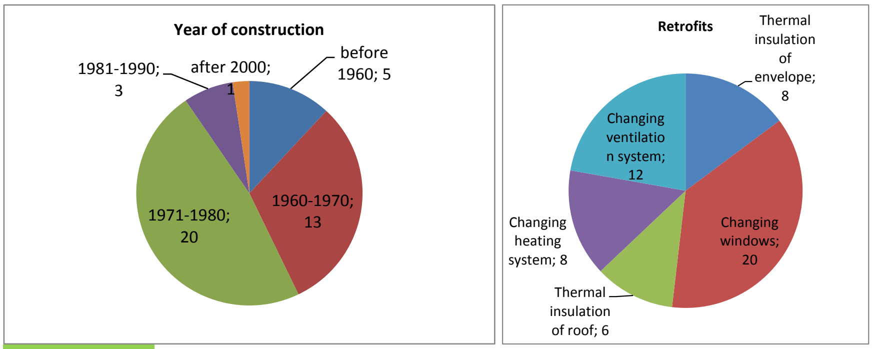

Figure 3. Distributions of year of construction and different types of retrofits in the Finnish cases.

In Lithuania, 20 apartment buildings (96 apartments) were assessed at baseline. Out of these buildings, 15 buildings were retrofitted ('cases'), while the rest served as 'controls'. A majority of the buildings were in the Kaunas area. A majority of the buildings had natural ventilation, with only a few buildings having mechanical exhaust from the kitchen and bathroom. The distributions for the year of construction and the performed retrofits are shown in Figure 4.

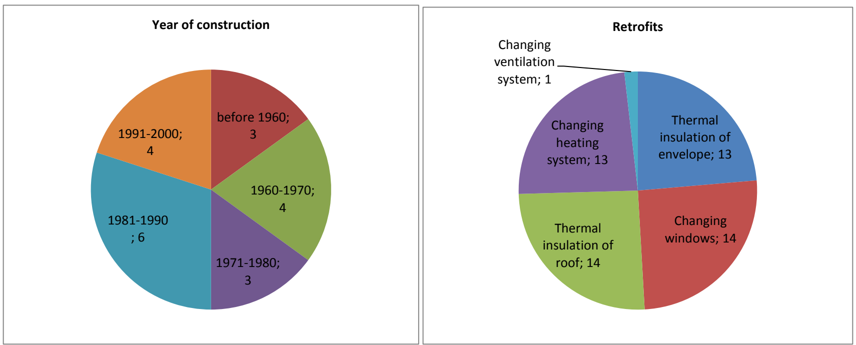

Figure 4. Distributions of the year of construction and the different types of retrofits in the Lithuanian cases.

Roles of the objective and subjective assessments

Comparison of measurement results with guidelines and recommendations can benefit the building owners and occupants by ensuring that IEQ is within the recommended levels.

IEQ and health perceived by the occupants can differ from the measured one.

The occupants' perceptions of comfort and safety are important, since the occupants can affect not only IEQ and health by means of their own actions, but also energy consumption. They can for example turn off the ventilation due to noise disturbance, which can impair indoor air quality. Also, opening the windows due to poor indoor air quality or raising indoor temperature due to a draught can substantially increase energy consumption.

METHODS

IEQ was assessed objectively by conducting measurements, comparing the measurement results to known guidelines and recommendations, and in addition, observing the possible changes between the first and second assessments. In each building, both 1st and 2nd assessments were made, if possible, during the same season (mainly during heating seasons). Figure 5 shows an example of the placement of measurement devices in an apartment.

Figure 5. Measurement devices in a Lithuanian apartment.

Guidelines for IEQ parameters such as the maximum levels of pollutants to prevent adverse impacts on health and wellbeing have been published by the World Health Organization [3] and the EU [4]. In Finland, the former housing health guideline and manual [5, 6] were replaced in 2015 by the decree on housing health [7] and its implementation guideline [8]. In addition, some guidelines can be found from the indoor climate classification [9]. In Lithuania, guidelines can be found from hygiene standards [10, 11]. Guideline values for selected indoor air quality (IAQ) parameters are shown in Table 1.

Table 1. International and national guideline values for selected measured indoor air quality parameters.

Parameter	Unit	WHO	EU	National guidelines	
				Finland	Lithuania
T	°C	-	-	18-26[a]	18-22
RH	%	-	-	20-60	35-60[b]
CO_2	ppm	-	-	1150 > outdoor	1200
CO[c]	ppm	8.6 (8h); 25 (1h)	10 (8h)	7	2.43 (24 hr)
$PM_{2.5}$	µg/m³	25 (24 hr)	25 (yr)	-	40 (24hr)
PM_{10}	µg/m³	50 (24 hr)	50 (24 hr); 40 (yr)	-	50 (24hr)
NO_2	µg/m³	40 (yr); 200 (hr)	200 (hr); 40 (yr)	-	40 (24 hr)
CH_2O	µg/m³	100 (30 min)	-	50 (yr)	100 (30 min) 10 (24 hr)
Radon	Bq/m³	100 (yr)	-	100/200/400[d]	400
TVOCs	µg/m³	-	-	400	100[e]

[a] *'Good' level of room temperature is 21 °C ('adequate' level is 18 °C), and should not be above 26 °C, unless the high temperature is due to outdoor temperature. During the heating seasons, indoor temperature should not exceed +23…24 °C.*
[b] *In Lithuania, the values for RH only refers to heating season.*
[c] *Values refer to maximum daily 8-hour mean.*
[d] *Guideline values in Finland: 100 Bq m^{-3} (new buildings); 200 Bq m^{-3} (built after 1992).*
[e] *Lithuanian guideline is for aliphatic hydrocarbons of C1-C10 structure (100 mg/m³).*

Main findings

Group-level results indicate mainly improved living conditions after retrofits, for example:

- Thermal conditions in Lithuanian buildings improved significantly

➔ ***Energy retrofits could substantially improve occupants' wellbeing***

- Finnish buildings exceeded the maximum recommended indoor temperature during heating seasons (23 °C) for about 40% of the time both before and after retrofits, while relative humidity was often below recommended (RH <20%)

➔ ***Lowering high indoor temperatures could help to save energy and maintain more acceptable RH***

- Indoor air quality appeared to be improved in buildings with mechanical ventilation, whereas the opposite trend was seen in some buildings with natural ventilation

➔ ***Ventilation adequacy needs to be checked and systems need to be balanced after energy retrofits***

- A majority of the apartments fulfilled the national guideline values for IEQ parameters, but after the retrofits some indoor pollution sources emerged

➔ ***Special attention should be paid to pollution source control***

RESULTS

Buildings and energy

Buildings were divided based on the level of retrofitting: focused energy retrofits included system upgrades, e.g. HVAC equipment or replacing windows; while deep energy retrofits represented more comprehensive energy efficiency measures, addressing multiple systems at once.

In Finland 29 buildings had focused retrofits and nine buildings had deep energy retrofits. An average 21% reduction in the normalized heating energy consumption was observed after the retrofits.

In Lithuania, two buildings had focused retrofits and 13 buildings had deep retrofits. In the latter group, the reduction in energy consumption varied from 30 to 60% in buildings with district heating (12 buildings). Two of these buildings had installed solar panels, which helped to reduce energy consumption by 56% in both cases. Three buildings had individual space heating systems (gas boiler), and their energy consumption decreased by 40%. An average 10% reduction in the heating energy consumption was observed in partially retrofitted buildings.

Thermal conditions

Indoor temperatures (T) and relative humidity (RH) were monitored for at least two months during the heating season from two measurement points: 1) from the living area, reflecting the average conditions in the apartment and 2) near the coldest spot of the building envelope (based on the measured surface temperatures), which was usually close to the balcony door.

In Finland before the retrofits the average indoor T during the heating season was 22.7 °C and RH 27.0 %. The action limits for temperatures (<18 °C or >26 °C) [5] were not exceeded in any apartment. Based on the guidelines [6], temperatures should not exceed 23–24 °C during the heating season. It was found that 23 °C was exceeded 40% of the time, while 24 °C was exceeded 17% of the time (Figure 6). RH was below the recommended level (RH 20%) 20% of the time. After the retrofits, average indoor T was 22.6 °C and RH 29.0%. The recommended level (23 °C) was exceeded 39% of the time. RH was below the recommended level 11% of the time.

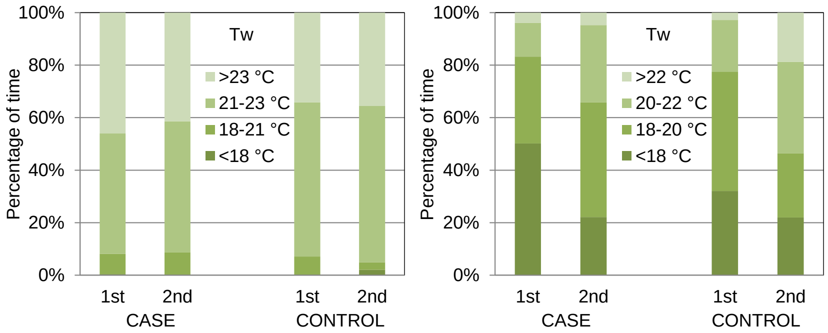

Figure 6. Percentages of indoor temperatures exceeding national guideline values before and after retrofits in Finland (left) and in Lithuania (right).

Additional findings

After retrofits,

- Satisfaction with indoor air quality was significantly improved in the case buildings, especially in Finland.
- In Lithuanian case buildings, thermal comfort was significantly improved
- The occupants reported less daily road traffic noise, but in the Finnish case buildings the occupants reported more noise related to ventilation and plumbing systems than before the retrofits

➔ ***Changes to ventilation systems should be done in a way that causes minimal disturbance to the occupants.***

In Lithuania, before the retrofits the average indoor T during the heating season was 19.5 °C and RH 43.4%. After the retrofits, average T was 20.4 °C and RH 48.7%. Based on Lithuanian guidelines, the recommended room T is between 20–40 °C, and recommended range for RH is 35–60%. It was found that the percentage of time with low T (< 18 °C) decreased by 28% in the case buildings as compared to a 10% decrease in the control buildings (Figure 6).

Indoor air quality

In Finland, the average air change rate (ACR) was slightly higher after the retrofits in the case buildings with mechanical ventilation (ACR 0.48 h^{-1}) than before the retrofits (ACR 0.45 h^{-1}), while it was the same before and after retrofits (ACR 0.25 h^{-1}) in the case buildings with natural ventilation. In the Lithuanian case buildings, average ACR was a bit lower after the retrofits (0.32 h^{-1}) than before (0.38 h^{-1}). However, average ACR was also lower in the control buildings during the second assessment (0.28 h^{-1}) than during the first assessment (0.40 h^{-1}), so at least part of the differences could be related to temporal variations; for example, the differences in climate between the two seasons may have resulted in different infiltration or different occupant behavior, such as regards window opening.

Carbon dioxide is an indicator of ventilation adequacy in an occupied space. In Finland, indoor CO_2 level was on average 731 ppm before and 722 ppm after the retrofits, which is considered good [5]. The level of 1000 ppm was exceeded in 9% and 1 % of the apartments, respectively. In Lithuania, 26% and 35% of the apartments had average CO_2 levels higher than 1200 pm based on the first and second assessment, respectively. The percentage of time with CO_2 levels exceeding 1200ppm was increased by 9% in the case buildings after retrofits, whereas there was an average 5% decrease in the control buildings at the same time.

Table 2 shows median values for selected IAQ parameters.

Table 2. Median values for selected IAQ parameters in Finnish and Lithuanian case and control buildings.

	Finland				Lithuania			
	Case		Control		Case		Control	
	1st (N)	2nd (N)[1]	1st (N)	2nd (N)	1st (N)	2nd (N)[1]	1st (N)	2nd (N)
CO_2, ppm	687 (186)	653 (133)	629(32)	609 (30)	957 (66)	993 (57)	1013 (22)	1002 (8)
$PM_{2.5}$, µg/m^3	5.3 (157)	4.3 (107)	4.4(18)	2.3 (13)	9.2 (71)	9.9 (55)	6.6 (22)	5.4 (8)
PM_{10}, µg/m^3	14.6 (157)	12.4* (107)	11.9(18)	9.6 (13)	18.5 (71)	24.8* (55)	17.8 (22)	18.3 (8)
CH_2O, µg/m^3	18.2 (140)	16.4* (103)	15.9 (16)	13.5 (13)	24.1 (71)	28.0*(57)	16.5 (24)	32.9* (8)
BTEX, µg/m^3	6.5(134)	9.1* (102)	5.4(16)	7.0 (13)	16.0 (71)	19.4 (55)	7.3 (24)	7.7 (8)
NO_2, µg/m^3	6.2(145)	6.0 (104)	3.9(16)	4.9 (13)	11.9 (71)	11.7 (57)	16.0 (22)	13.8* (8)
Radon, Bq/m^3	60(132)	50 (88)	40 (13)	40 (12)	28 (33)	38* (31)	14 (12)	18(4)

[1] *After retrofits; N corresponds with the number of observations*

**indicates that there is a statistically significant difference between first and second assessment ($p < 0.05$)*

Main outcomes

- A comprehensive protocol developed to assess the impacts of improving EE of multi-family buildings on IEQ and health.
- A set of indicators that could be used to assess IEQ in connection with energy retrofits and large scale renovations, as well as to complement energy audits.
- A large database consisting of data collected from Finnish and Lithuanian multi-family buildings before and after energy retrofits.

Additional surveys

- As a part of the INSULAtE protocol, we also tested occupant diaries. While the information gathered may provide additional information about IEQ and how it relates to occupant behavior, the method needs to be further developed.

In Finland, concentrations of PM, formaldehyde (CH_2O), and VOCs (BTEX, incl. benzene, toluene, ethylbenzene and xylenes) decreased after the retrofits. In Lithuania, concentrations of PM, CH_2O, and radon (for radon samplers used in the project, see Figure 7) were increased. However, similar differences were also observed in the control buildings, so these changes could not necessarily be attributed to the retrofits.

Figure 7. Radon samplers used in Finland (on the left) and in Lithuania.

With respect to particulate matter (PM), the indoor vs. outdoor concentration ratios (I/O ratio) are often used as an indicator of the magnitude of the indoor pollutant concentration against outdoor concentration. If I/O<<1, there are no indoor pollution sources and IAQ primarily is affected by outdoor air. In the case of 0.5<I/O<1, the presence of indoor sources is recognized, but they are not prevailing. In the case of I/O>1, there are strong pollution sources indoors, affecting IAQ.

Based on the results from Finland, median I/O ratios for PM2.5 were slightly higher at the follow-up (second assessment) in both the case and control buildings (see Figure 8). However, with respect to PM10, median I/O ratio increased in the case buildings, whereas the trend was opposite in the control buildings. Although the difference is not statistically significant, this could indicate that indoor sources of coarse particles may have more influence after retrofits, at least in some cases.

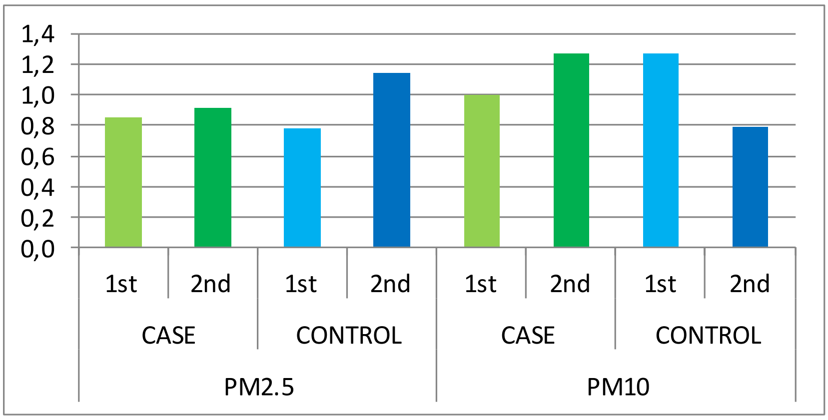

Figure 8. Indoor – outdoor concentration ratios for particulate matter in Finnish buildings.

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OCCUPANT SURVEYS

In Finland, altogether 234 occupants from 45 apartment buildings (response rate 94 %) participated in the first questionnaire (baseline assessment), whereas 187 occupants (response rate 75 %) participated in the second questionnaire, out of which 161 were living in a retrofitted building. The participants were on average 58 years old. In Lithuania, a total of 57 occupants from 96 apartment buildings (response rate 59 %) participated in the first questionnaire (baseline assessment), whereas 27 occupants (response rate 28 %) participated in the second questionnaire. The participants were aged on average 54 years old.

Table 3 shows some group-level results from the housing and health questionnaire. In the retrofitted buildings, the proportion of occupants satisfied with their dwelling increased by 11% in Finland and 16% in Lithuania. Satisfaction with indoor air quality was significantly increased in both countries: by 23% in Finland and 13% in Lithuania, correspondingly. With respect to thermal comfort, there were no significant changes seen in Finland, whereas in Lithuania, the proportion of occupants reporting a suitable temperature in winter increased from 31% to 78%. Occupants reporting daily or almost daily noise disturbance related to traffic or industry decreased in both countries: by 10% in Finland and 23% in Lithuania. In Finland, an opposite trend was seen in reporting noise disturbance related to plumbing, ventilation, electrical systems etc., which increased by 6%.

Table 3. Occupants' self-reported satisfaction with their dwelling, indoor air quality, indoor temperature, and noise disturbance among case and control groups.

Assessment	Case		Control	
	1st [a]	2nd [b]	1st	2nd
	% (N)	% (N)	% (N)	% (N)
Finland				
Satisfied with the dwelling	41 (82)	52 (82)	58 (18)	46 (5)
Satisfied with indoor air quality	22 (42)	41* (65)	45 (14)	36 (4)
Suitable indoor temperature				
In summer	58 (111)	57 (92)	48 (15)	73 (8)
In winter	64 (130)	65 (105)	55 (17)	55 (6)
Daily noise disturbance related to				
Traffic or industry	28 (52)	18* (26)	7 (2)	18 (2)
Ventilation, plumbing etc.	12 (22)	18 (26)	21 (6)	30 (3)
Lithuania				
Satisfied with the dwelling	19 (9)	35 (9)	22 (2)	-
Satisfied with indoor air quality	20 (9)	33* (9)	13 (1)	-
Suitable indoor temperature				
In summer	45 (23)	56 (15)	44 (4)	-
In winter	31 (16)	78* (21)	44 (4)	
Daily noise disturbance related to				
Traffic or industry	49 (19)	26* (6)	57 (4)	
Ventilation, plumbing, etc.	7 (2)	0 (0)	20 (1)	-

[a] *before retrofit*

[b] *after retrofit*

**p<0.05 for the difference between first and second assessments*

CONCLUSIONS

A comprehensive protocol was developed to assess the impacts on IEQ and health arising from improved EE in multi-family buildings. Based on both objective measurements and subjective evaluations before and after the energy retrofits, the group-level effects of improved EE on IEQ and health appeared to be mainly positive. Occupant satisfaction with the dwellings and IEQ was mostly increased.

In Lithuania, thermal comfort was substantially increased, whereas ventilation adequacy may have been compromised in some cases. In Finland, the significance of indoor sources of pollutants appeared to increase in some cases. It should be noticed that long-term effects have not been studied so far.

The project results can be used to develop guidance and to support the implementation of the EPBD. Specifically, we have developed indicators that can be used for assessing IEQ in connection with energy retrofits and large-scale renovations, as well as to complement energy audits. On the level of individual apartments, the assessment protocol can be mainly used to ensure that IEQ complies with guidelines (see Figure 9, example of an IEQ report for a Finnish apartment). On the building level, the assessment could be used to provide useful information and support decisions and planning of retrofitting and renovation activities, and to give a more comprehensive picture of the condition and performance of the building, possibly complementing energy audits and certificates.

Indoor environmental quality assessment for [address] Report 05-10-2015

This report consists of results from the assessment of indoor environmental quality (IEQ) parameters conducted using a protocol developed in the INSULAtE –project. For more information on how to interpret the results, visit www.insulateproject.eu.

Parameter [unit]	Results		Interpretation based on housing health guidelines (2003), issued by the Finnish Ministry of Social Affairs and Health (http://pre20090115.stm.fi/pr1063357766490/passthru.pdf)
	Before retrofit	After retrofit	
T [°C]	🟥 24	🟥 24	Good temperature (T) is 21 °C and satisfactory T is 18 °C. When the heating is on, the indoor T should not exceed 23–24 °C.
RH [%]	🟩 32	🟩 32	Relative humidity (RH) should be about 20–60%.
TI	🟥 60	🟩 71	Thermal index (TI) is adequate at ≥61 and good at ≥65.
CO_2 [ppm]	🟥 1543	🟨 1246	Ventilation is not in compliance with the Finnish Health Protection Act if carbon dioxide (CO_2) concentration exceeds 1500 ppm. Adequate CO_2 concentration is about 1200 ppm.
CO [ppm]	🟩 0	🟩 0	Carbon monoxide (CO) concentration should not exceed 8 mg/m^3 (6.9 ppm).
CH_2O [$\mu g/m^3$]	🟩 22	🟩 21	Indoor formaldehyde (CH_2O) concentration should not exceed 100 $\mu g/m^3$.
Radon [Bq/m^3]	🟩 100	🟩 70	Annual mean radon concentration should not exceed 400 Bq/m^3.

Colour codes	T [°C]	RH [%]	TI	CO_2 [ppm]	CO [ppm]	CH_2O [$\mu g/m^3$]	Radon [Bq/m^3]
🟩 Good	18 ≤ T ≤ 21	20–60	≥ 65	< 1 200		< 35	< 200
🟨 Satisfactory	21 < T ≤ 24		≥ 61	1 200-1 500		< 100	< 400
🟥 Poor	T < 18, T > 24			> 1 500	> 6.9		

Figure 9. An example of an IEQ report developed by the project.

On the national level, similar surveys could be used to assess the effects of national policies and programs. The large database collected as a part of the project could be used as a reference until such a time as nationally representative databases emerge. Many countries do not have objective baseline information about the condition of their building stock and IEQ: for example, assessment of thermal conditions and ventilation on a national scale also provides information about over-heating/cooling issues, which are closely linked to energy consumption: simple adjustments could help to save a significant amount of energy and also to improve IEQ. On the EU level, at least some of the indicators could be incorporated into existing surveys and databases (e.g. Eurostat, WHO ENHIS).

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