



Radon levels and indoor air quality after application of thermal retrofit measures—a case study

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Abstract

This study was conducted to evaluate the influence of thermal retrofit on radon levels in workrooms, and to determine whether the radon concentration in the building changes after the application of retrofit measures. In the first survey, digital Airthings Corentium Home radon detector was used for 1-month radon measurements during the heating season 2018/19. The daily averaged radon concentrations varied from 37 to 573 Bq/m³ for 10 selected workrooms, while hourly averaged radon measurements showed extreme variations from 6 to 1603 Bq/m³ due to radon fluctuations. In second survey, passive radon technique based on charcoal canister test kit was conducted in all basement workrooms in spring 2021. The averaged radon concentrations grouped according to flooring type in workrooms were 327 Bq/m³ for parquet, 227 Bq/m³ for ceramic tiles, 146 Bq/m³ for vinyl flooring and 71 Bq/m³ for laminate. Besides thermal insulation and airtight windows, noticeable differences in indoor radon concentration within the renovated building are primarily caused by different types of flooring. It includes various types of insulation from the ground/concrete slab: laminate, parquet (wood blocks), vinyl flooring, and ceramic tiles. Detailed analysis point out that laminate is more efficient way for radon protection than other types of flooring. An efficient ventilation system should be installed to avoid increasing occupational radon exposure and to provide healthy and comfortable indoor environment.

Keywords Building · Flooring type · Indoor radon · Thermal retrofit · Workroom

Introduction

An increased awareness of energy saving policy, and also living/working in more energy efficient buildings with retrofits to save warmth should improve multiple indoor environmental quality parameters. These circumstances may decrease the heat exchange by thermal radiation, particularly in winter. On the other side, this can be highly related to the current situation with COVID-19 pandemic, and the people's tendency

to stay more indoors in low air exchange rate conditions. A reduction of air exchange in turn causes an increase of health-relevant indoor air contaminants, such as radioactive gas radon. Consequently, seemingly thermal comfort environment can pose an important health problem. The World Health Organization (WHO) has identified radioactive gas radon and its progeny as the second leading cause of lung cancer (WHO 2009). As a lung cancer has the highest mortality rate of all cancers (SEER Cancer Statistics 2017) the concern of occupants about health risks from radon exposure in dwellings and/or workplaces is justified (Neri et al. 2018). Recently, the Council of the European Union has adopted Directive 2013/59/EURATOM to renew European legislation on radiation protection in which EU Member States are obliged to establish 300 Bq/m³ as a national action level for indoor radon concentrations; to identify areas/buildings (dwellings and workplaces) in which the mean annual radon concentration exceeds the relevant national reference level and encourage to decrease the radon concentration in these buildings; to provide information locally and nationally about radon exposure and corresponding health risks (European Council 2014).

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It is known that outdoor radon levels are usually low due to atmospheric dispersion and dilution. However, indoor air might be particularly contaminated if radon accumulates at high levels. Geology, building materials and type of construction, ventilation rate and meteorological parameters are the prevailing factors affecting the indoor radon levels (Borgoni et al. 2014). Indoor radon concentration is usually higher in older buildings and primarily associated with foundation type (Collignan et al. 2016). Assuming the constant radon potential in the ground around the building, the parameters affecting the indoor radon concentration are indoor depressurization of a building and its air exchange rate. “Stack effect” (chimney effect) occurs due to difference in indoor/outdoor air density resulting from temperature and moisture difference; intensity of this effect depends on building height, air permeability of façade cladding, wind force/direction and type of ventilation (Collignan and Powaga 2019).

In order to satisfy policy of reducing energy consumption in a building, the existing (mainly wooden) windows are usually replaced with polyvinyl chloride (PVC) ones to disable air leakage. Protection of walls by inside or outside thermal insulation also follows the renovation of old buildings, although dilution by outside air is more effective in less tight building (Korhonen et al. 2000). Consequently, thermal retrofitting of windows, roofs, walls, and floor is usually associated with enhanced radon level.

This study was performed in order to get prompt information about indoor radon levels in workplace after applications of retrofit measures. The main goals were.

- i) To analyze the causes of different radon concentrations obtained for basement workrooms in thermally renovated building, and characteristics of building materials responsible for radon accumulation;
- ii) To evaluate the influence of different flooring types on indoor radon concentrations;

- iii) To compare two independent radon surveys with some measurements reported before renovation.

Materials and methods

Underlying geology and climate

Kosovska Mitrovica is situated in a mining area of “Trepča” complex. The region covers an area of 30 km² and belongs to a zone of tertiary magmatic activity which produced large masses of extrusive rocks and pyroclastics (Dimitrijevic 1997). Magmatic activity also caused deep fault zone which stretches in NNW-SSE direction. A climate is moderate continental; temperature ranged from −4 to +18 °C in winter season 2018/2019 (RHMS 2019).

Characteristics of building and workrooms

The studied building is a school located in Kosovska Mitrovica (42.89233°N, 20.86867), Serbia. It has a semi-excavated basement and three stories. Building is constructed from concrete, red brick and lime in the 1970s, and it is renovated in the 2018’s (Fig. 1). Some interior walls were subsequently partitioned with plasterboards. The partitioned walls exist between workrooms 3 and 4, 4 and 5; 6 and 7, 7 and 8; all walls on the side where laminate flooring exists are partitioned (Fig. 2).

The subject of this research was the basement with ground surface of about 400 m². The scheme of surveyed workrooms is presented in Fig. 2. The north side of studied part of building is under the ground about 1.8 m, while the south side is about 1.3 m under the ground. Energy renovation procedures of building were performed 2 months prior to first survey of radon measurements. The exterior walls of the building have been thermally insulated with Styrofoam, and all the windows have been replaced



Fig. 1 Studied building before and after renovation

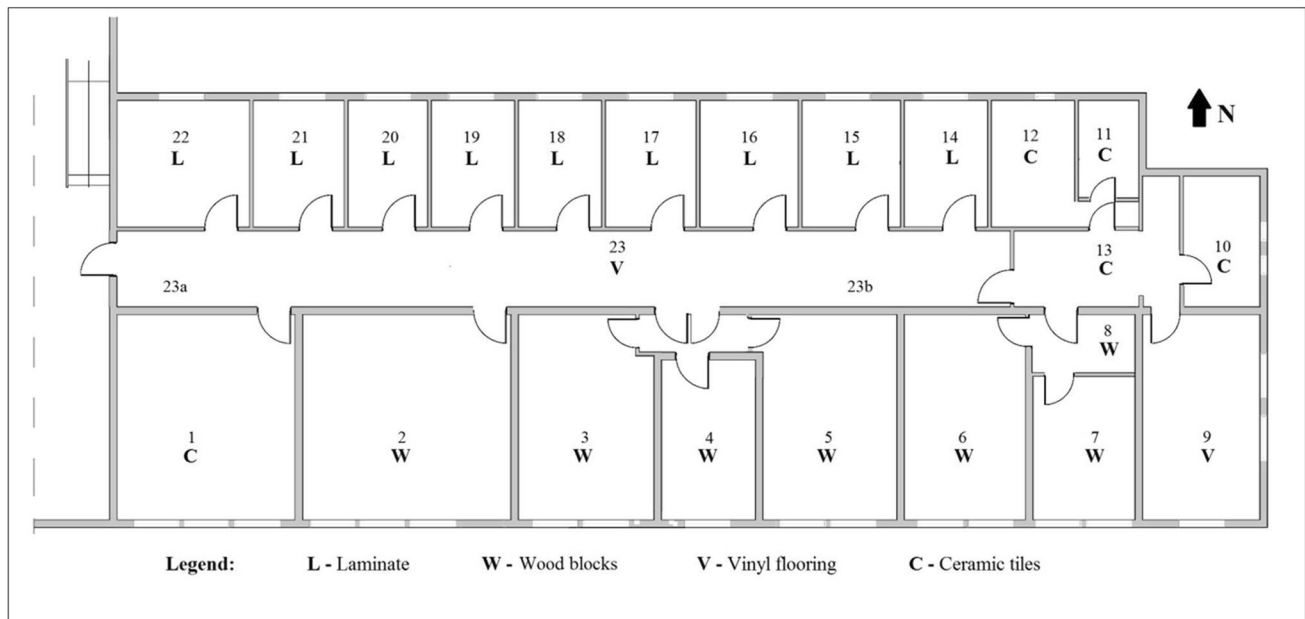


Fig. 2 Scheme of the building and floor characteristics of studied workrooms

with more leak-proof PVC frame, double-glazed windows. In addition to windows replacement and thermal insulation of exterior walls, thermal retrofit also included partial floor renovation: old, wooden floors were replaced by laminate, ceramic tiles and vinyl flooring. Workrooms 2–8 were excluded from floor renovation activities. The outside thermal insulation is considered to have a greater impact on the building airtightness than the inside thermal insulation; thermal insulation allows decrease in air permeability of the building, which could increase the depressurization indoors and increase the radon infiltration rate (Collignan and Powaga 2019). This occurs in lower part of building, particularly in cold seasons, because of indoor/outdoor temperature differences; indoor air exchange rate is generated since lighter (hot) air moves upwards.

The studied building has poor concrete slab constructed on the sandy soil. During the heating season, the windows were not often open, only for a while (briefly) in the morning of the day. Before the renovation, all workrooms had parquet or vinyl flooring. After renovation of the building, there are four flooring types: parquet wood flooring (non-renovated), laminate (vinyl tiles plus foil), vinyl flooring, and ceramic tiles as it is presented in Fig. 2. Volume of studied workrooms ranges from 20 m³ (storage room 11) to 140 m³ (laboratory 2, hallway 23). Only natural ventilation existed in the building (air inlet and outlet providing the air renewal by opening the windows). There is water supply system and a small, covered opening in floor (manhole) in some workrooms (Table 1). Central heating was supplied via

a network of fluid distribution pipes about half of the year (October–April), but electric heaters were also used.

Design and methods of indoor radon surveys

Indoor radon concentrations typically show seasonal variations due to the changing of meteorological parameters. Therefore, some authors suggested that it would be best to expose radon detectors during the heating season, i.e., in the period October/November–March/April (if it was not possible to measure radon concentration throughout the year) (Čeliković et al. 2015; Xie et al. 2015). These measurements provide a reliable representation of the average annual indoor radon concentration, in accordance with ISO 11665–8 standard (Collignan and Powaga 2019; ISO 11665-8, 2012). The current study included two surveys that followed one from the other:

1. The first 1-month survey was conducted during the heating season of 2018/2019, aiming to estimate the level of radon exposure risk for students and staff. Airthings Corentium Home radon detectors were employed, and ten most frequently occupied rooms were selected for monitoring.
2. Since unexpectedly high variation in radon concentration was observed among the rooms in the first survey, the second 48-h survey was carried out in 2021, employing charcoal canisters. This survey included all 23 rooms in

Table 1 Comparison of radon results from different surveys conducted in the building before (Gulan et al. 2017) and after renovation (current study)

No	Before renovation		Difference between surveys				Building characteristics					
	Survey 2010/2011 CR-39, 6 months [Bq/m ³]	Survey 2018/2019 Radon detector, 1 month [Bq/m ³]	Survey 2021, Charcoal canisters, 48h		2018 and 2010		2021 and 2018		Type of floor	Purpose of workroom	Water supply	Manhole
			Shelf (> 1 m height) [Bq/m ³]	Floor [Bq/m ³]	Variation	Variation	Variation vs. initial value					
1.	87	98 ± 5	97 ± 5	11	13%	Laboratory	Yes	No				
2.	364	247 ± 8	262 ± 8	- 117	- 32%	Laboratory	Yes	Yes				
3.		270 ± 8	306 ± 9			Classroom	No	No				
4.	573	231 ± 8	358 ± 9	- 342	- 60%	Laboratory	No	Yes				
5.		379 ± 10	357 ± 7			Classroom	No	No				
6.		438 ± 10	540 ± 12			Cabinet	No	Yes				
7.	153	272 ± 6	278 ± 9	55	31%	Cabinet	No	No				
8.		332 ± 9	313 ± 10			Cabinet	No	No				
9.	189	163 ± 5	182 ± 7	- 26	- 14%	Laboratory	Yes	No				
10.		273 ± 9	291 ± 9			Classroom	No	No				
11.	52	412 ± 12	375 ± 8	360	692%	Storage room	No	No				
12.		152 ± 6	201 ± 7			Restroom	Yes	No				
13.		181 ± 7	187 ± 8			Foyer	No	No				
14.	125	63 ± 4	46 ± 3	- 93	97%	Office	No	No				
15.		57 ± 4	55 ± 4			Office	No	No				
16.		83 ± 5	51 ± 4	46	124%	Office	No	No				
17.		48 ± 3	35 ± 3			Office	No	No				
18.		45 ± 3	28 ± 3			Office	No	No				
19.		58 ± 3	44 ± 3			Office	No	No				
20.		81 ± 4	75 ± 5			Laboratory	No	No				
21.		87 ± 4	106 ± 5			Buffet	Yes	No				
22.	370	171 ± 6	147 ± 6	- 199	- 54%	Office	Yes	No				
23.	200	116 ± 4	104 ± 5	- 84	- 42%	Hallway	No	No				
23b	200	113 ± 6	147 ± 7	- 87	- 44%	Hallway	No	No				

order to investigate the effect of floor renovation as well as different floor types on indoor radon levels.

Radon sampling method of Airthings Corentium Home is based on passive diffusion chamber, while detection method is alpha spectrometry. Detector Corentium Home is unaffected by other radiation, and measures in the range from 0 to 9999 Bq/m³. Uncertainty of device for 1-month measurement is less than 10%, and accuracy at typical 200 Bq/m³ is 5–10% for measurement period from 7 days to 2 months. The detector shows first result after 6–24 h: long-term (LT) and short-term (ST) average radon concentration. The LT average represents average radon value for current measurement (updated once a day). The ST average changes between showing last-day radon values (updated hourly) and values for the last seven days (updated daily) (Airthings Corentium Home n.d). The values of LT average radon concentrations identify potential health risk; the last values of measurements were averaged (by detector itself) during 1 month, while ST values of average radon concentration were used for preliminary indication of radon levels and for evaluating the necessary measures (such as increased ventilation) for radon reducing. In the current study, detectors were placed 1.5 m from the floor, at least 2 m from windows/doors in purpose-equipped workrooms. Students and staff were allowed to perform regular activities in the workrooms during the first survey. The reading of detectors was done on Monday, Wednesday, and Friday during 1 month measurement.

During the second survey, 48 charcoal canisters were placed in each of 23 workroom on the shelves (at least 1 m from floor, away from windows/doors), and at the same time on the floor (facing up) to check possible radon source. In addition, four charcoal canisters were deployed on the floor (facing down) in the largest workrooms with various floor types (Fig. 3) to check radon exhalation flux density, according to the recommendations of the IAEA technical reports

(IAEA 2013). The workrooms were completely closed during the measurement procedure of 48 h (over the weekend period). Within this period values of outdoor temperature, moisture, and pressure were in the range: 2–18.1 °C, 19–84%, 950.5–957.8 hPa, respectively (RHSS 2021).

The passive radon charcoal canister is a small container (diameter of 10 cm) filled with 70 g of activated charcoal grains which 6 × 16 mesh approximately corresponds to the maximum efficiency for adsorption of radon from the air (Cohen and Cohen 1983). The relatively high gamma lines intensity of radon progenies ²¹⁴Pb and ²¹⁴Bi (²¹⁴Pb–295 and 352 keV; ²¹⁴Bi–609 keV and 1740 keV) enables indirect determination of indoor radon concentration at least three hours after the canisters are collected, to allow secular equilibrium to be established in activated carbon. Counting was performed using both the high-resolution HPGe detectors and NaI(Tl) scintillation spectrometer within low-level shielding chambers. To achieve 5% statistical accuracy at 100 Bq/m³, the time of measurement was estimated at 1 h. The detection efficiency was determined using the certified reference source of ²²⁶Ra in the same canister geometry in conformance with EPA standard procedures for radon measurement using charcoal canisters (EPA 520/5–87-005:1987), (Grey and Windham 1987). Although the charcoal sampler can be used to collect radon over a day to a week, the optimal time of exposure based on humidity calibration curves is 48 h and was used in this survey. The minimum detectable activity (MDA) for measuring radon using charcoal canisters is a function of the background counting rate of the spectrometer system and the counting time and assuming real exposure conditions and known counters efficiencies, MDA was less than 2 Bq/m³.

The adsorption method proposed by IAEA Technical Report Series no. 474 (IAEA 2013) was used for radon exhalation flux measurements using activated charcoal canisters placed face down to the flooring surface being investigated (Fig. 3). After such exposure, the canisters are again sealed

Fig. 3 Charcoal canisters deployed face up/down on different flooring types



and the activities of the radon progeny ^{214}Pb and ^{214}Bi are measured by gamma spectrometry method, following a period of 3 h to equilibrium with progenies be established. The radon exhalation flux density over the period of exposure can be estimated according to formula:

$$f = \frac{N t_c \lambda^2 e^{(\lambda t_d)}}{\varepsilon A [1 - e^{(-\lambda t_c)}] [1 - e^{(-\lambda t_c)}]} \quad (1)$$

where f is the radon flux density ($\text{Bq}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$); N is the net count rate, after background subtraction, obtained during the counting period (counts per s, or s^{-1}); t_c is the counting period (s); λ is the radioactivity decay constant for ^{222}Rn (s^{-1}); t_d is the delay period from the end of the exposure to the beginning of the counting interval (s); ε is the counting efficiency of the system relative to the activity of adsorbed radon; A is the area of the canister (m^2) and t_e is the period of exposure of the charcoal in the canister (s).

Results and discussion

The results of the first survey performed in ten selected workrooms shown that for LT monthly average radon concentrations varied considerably from 32 to 573 Bq/m^3 (Table 1); an average radon value for this set of data is 211 Bq/m^3 . A previous study conducted in primary schools of 13 municipalities of Southern Serbia measured radon concentrations in the range of 17–607 Bq/m^3 with the average of 119 Bq/m^3 and median of 97 Bq/m^3 (Bochicchio et al. 2014). An Irish national survey covering over 95% of all primary and post-primary schools in Ireland reported average radon concentration of 93 Bq/m^3 , but also found concentrations above 200 Bq/m^3 in about 25% of schools (Synnott et al. 2006). Azara et al. (2018) also indicated a risk of exposure to high radon concentrations in Italian schools highlighting the necessity of interventions to reduce indoor radon levels. Most school buildings in Serbia are old and need renovation; some of them underwent the procedure of insulating the walls and exchanging the windows, but there have been no studies dealing with radon levels after the application of thermal insulation measures.

ST radon measurements followed by hour-to-hour changes (which are daily updated) showed variations from 6 to 1603 Bq/m^3 ; these radon variations were presented for different flooring types (Fig. 4). A coefficient of variation based on ST values for workrooms varied from 14.5 to 55%. Correlation of ST radon concentrations with the outside temperature was investigated. The correlation was positive and ranged from negligible (Spearman's $\rho = 0.033$ for workroom 4) to moderate ($\rho = 0.470$, workroom 14). Some contradictory results can be found in literature regarding this issue. According to Rey et al. (2022), temperature

influences are anti-correlated with indoor radon. One-year study conducted by Xie et al. (2015) also found a negative correlation between indoor radon and outdoor temperature (correlation coefficient $R = -0.3$), but a later study (Xie et al. 2017) based on 3-month measurement, reported a positive correlation between these two variables.

A significant difference in indoor radon concentration was observed between the workrooms. As it will be discussed further, type of flooring could be a reason of this large indoor radon variability. An active radon mitigation system implies covering of porous floors with appropriate covers or materials which prevent radon leakage (Francisco et al. 2020).

The airtightness of PVC windows probably causes radon accumulation; Jiránek and Kačmařková (2014) considered that these practices could lead to 3.4 higher radon concentration, while Yang et al. (2019) reported 4–8 times increasing in radon concentration in some dwellings after thermal retrofitting. Also, lower radon concentrations were reported in old building with wooden joinery than in new building with PVC windows (Gulan 2017). Vasilyev et al. (2015) showed the significantly lower ventilation rate in the multi-storey buildings with PVC windows, which in turn causes a high indoor radon concentration.

The results of the second survey indicated noticeable difference in radon concentrations between workrooms with different flooring types (Table 1). The averaged radon concentrations grouped according to flooring type in workrooms were: 327 Bq/m^3 for old wooden floors (parquet), 227 Bq/m^3 for ceramic tiles, 146 Bq/m^3 for vinyl flooring and 71 Bq/m^3 for laminate. Normality of data sets was checked using the Shapiro–Wilk normality test and examination of residuals.

Since floor renovation was not carried out in all workrooms, the independent t test was employed to investigate the differences between radon concentrations measured in rooms with non-renovated and renovated floors. A significant difference between renovated and non-renovated floors was observed ($\text{Sig} = 0.000$) indicating a great impact of floor renovation on indoor radon levels. A higher average radon concentration was measured in rooms with non-renovated floors (327 Bq/m^3 vs. 129 Bq/m^3). These results are in line with the fact that underlying soil is usually considered as the main source of indoor radon.

According to Kruskal–Wallis test, a significant difference was also found between the groups of flooring types—parquet, laminate, vinyl flooring, and ceramic tiles ($\text{Sig} = 0.001$). It is interesting to notice that the workrooms on the north side of the building had lower radon concentration (mean 110 Bq/m^3 , median 67 Bq/m^3) compared to those in the south part (mean 279.9 Bq/m^3 , median 281.5 Bq/m^3) although the north side was more dug into the ground (due to the slope of the terrain). The difference between the concentrations measured in the north and the south wings was

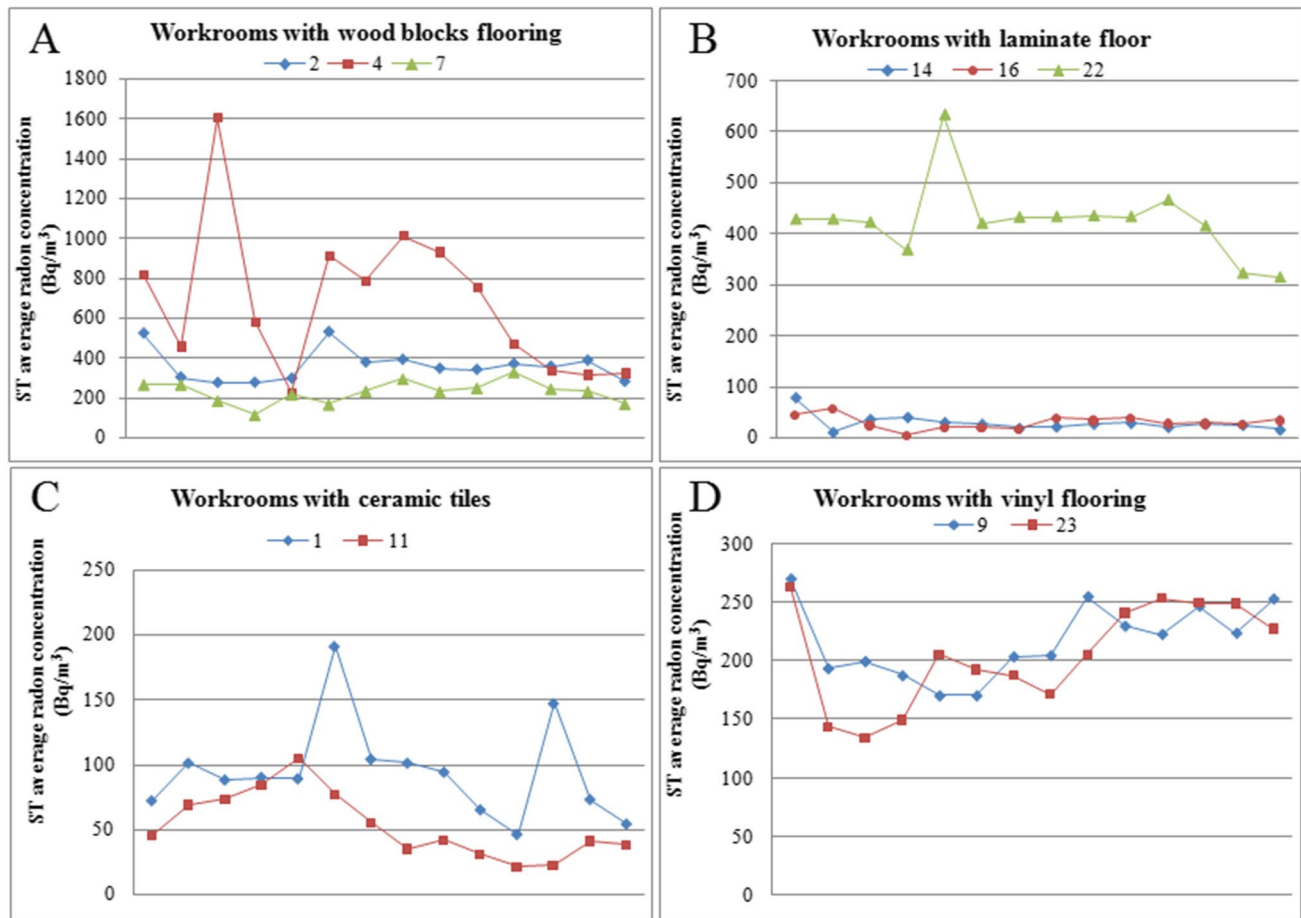


Fig. 4 Short-term (ST) average radon concentration (Bq/m^3) in workrooms with different flooring types: wood blocks (A), laminate (B), ceramic tiles (C), and vinyl (D)

statistically significant (Mann-Whitey U test, $Sig = 0.004$) supporting the fact that types of floors covering probably had a major impact on indoor radon concentration. In addition, the calculated values of radon exhalation flux density in the largest workrooms (namely, 1, 2, 9, and 22) with ceramic tiles, parquet, vinyl flooring, and laminate were: 30.9, 80.4, 27.6, and 20.5 $\text{Bq m}^{-2} \text{h}^{-1}$, respectively.

An average radon concentration for all parts of building (implying mean value of each workroom) is $189.5 \text{ Bq}/\text{m}^3$. However, the WHO recommends an annual average radon concentration limit lower than $100 \text{ Bq}/\text{m}^3$ which is exceeded in almost all workrooms, except in workrooms with laminate (WHO 2009). According to Directive 2013/59/EURATOM (European Council 2014), reference level of $300 \text{ Bq}/\text{m}^3$ is exceeded in four workrooms with parquet and in storage room with ceramic tiles.

Otherwise, high indoor radon levels in dwellings were reported for this region (Gulan et al. 2017). The main factors which influence the abilities of radon migration are the mining induced changes of rock body (exploitation of mineral

resources); in such regions, radon may exceed $300 \text{ Bq}/\text{m}^3$ in about 2% of buildings (Wysocka 2016). In earlier survey, indoor radon concentrations were measured with CR-39 detectors in this building in heating season (winter-spring, 6 months) in offices 7 and 14 (Table 1) (Gulan et al. 2017). There were double wooden windows in that moment, and vinyl tiles existed in office 14 before the renovation. Comparison of results leads to the conclusion that laminate (with appropriate underlying layers) seem to be a good choice for radon prevention, and airtightness of PVC windows probably caused radon accumulation.

Many studies showed that thermal renovation of buildings increased the indoor radon levels due to building airtightness, decreased air exchange rate and insufficient ventilation. Vasilyev et al. (2015) pointed out that the measures for increasing energy efficiency led to reduction in the ventilation rate and accumulation of higher radon concentrations indoors. Relatively higher levels of radon concentration in energy-efficient buildings may be associated with an insufficient average air exchange rate (Yarmoshenko et al. 2020). Fojtikova and Navratilova Rovenska

(2014) reported a mean increase of 63% in indoor radon levels in kindergartens when windows replacement was performed. It was observed that double glazed windows have the large association with indoor radon levels, 67% higher than dwellings with no recorded retrofit, while wall insulation have an association of 32% (Symonds et al. 2019). Some authors reported two times higher radon in renovated (energy-efficient) houses in comparison with low-energy (passive) ones in Germany (Meyer 2019), while another authors found a 20% increasing in radon levels after the energy renovation of buildings in Switzerland (Yang et al. 2019). Based on results of 11 studies conducted in Europe and USA, Fisk et al. (2020) pointed out that radon increases after retrofits were more common than decreases, and varied from a few percent to more than 100%. The variation of indoor pollutants is mainly influenced by the variation of meteorological conditions, impact of the air renewal and building depressurization levels (Collignan et al. 2020).

On the other side, laminate could be a good barrier for radon diffusion, since it was set up and lined with foil over vinyl tiles. Laminate floor in offices 14 and 16 showed some resistance to radon, but relatively high LT value in office 22 is probably due to existing of enhanced radon sources and water supply system. Relatively low radon fluctuations are noticed inside workrooms with laminate (Fig. 4B). Vinyl flooring (workrooms 9 and 23) did not show good properties as radon-resistant material for floor covering, probably because of its poor insulating with walls joints; ST values indicate a similar trend of radon fluctuations (Fig. 4D). Parquet (wood blocks) existed since the building was built (workrooms 2, 4, and 7), and cracks appeared after many years; through the cracks radon entries and reaches relatively high activity concentrations in comparison with other workrooms (Table 1). As a preventive measure, it is very important to seal all cracks in floor and walls to reduce advection transport of radon. In addition, indoor concentration due to diffusion transport is very sensitive to slab thickness and slab diffusion coefficient (Munoz et al. 2017). High radon concentrations in laboratories 2 and 4 could be related to existed manholes as direct tie with ground. However, ST values indicate high radon fluctuations (Fig. 4A) in laboratory 4, which could be related to blasting in nearby mine, since it has significant short-term effect on radon concentration. Namely, after blasting radon is released from fractured rocks for a short time; its concentration rises to a peak and then drops quickly (Sengupta 1990). It must be mentioned that ventilation is still natural, without forced ventilation systems.

Second survey showed a significant difference between the workrooms with various types of floors, and between renovated and non-renovated floors, as it was confirmed by statistical testing. High radon concentrations in workrooms with ceramic tiles (10, 11, 12, and 13) were noticed, which can be explained by high humidity yield which was

measured in charcoal canisters after exposure. High relative humidity enhances radon exhalation (Walia et al. 2005). However, authors of a study in India found lower indoor radon in houses with tiles in comparison with the houses constructed with mud/clay and suggested improving the ventilation system (Kamalakar et al. 2022).

Table 1 shows variations between the measurements 2010/2018 and 2018/2021. It is obvious that there was no uniform trend in the data change. Comparing the results before (2010) and after the application of retrofit measures (2018), it can be noticed that renovation significantly decreased radon level in workroom 14, while the opposite change was observed in workroom 7. However, it should be mentioned that windows were replaced in both rooms, but floor was renovated only in workroom 14 (not in workroom 7). It is hard to draw conclusions based on two samples, but it can be assumed that new laminate floor decreased radon diffusion from soil in room 14, leading to decrease in indoor radon concentration. On the other side, new airtight windows probably decreased ventilation rate leading to accumulation of radon entering through the old, wooden floor in room 7.

Spearman correlation analysis shows moderate correlation (Spearman's $\rho = 0.552$) between the concentrations measured by Airthings Corentium Home radon detectors in 2018 and average concentrations measured by charcoal canisters in 2021. However, this comparison should be considered with caution since different measuring periods were considered (1 month during the heating season of 2018/19 vs. 48 h in the spring of 2021). Due to radon variations caused by different environmental factors such as temperature, barometric pressure, and humidity (Xie et al. 2015), 1-month measurement certainly gives a better estimate of the average level of radon exposure, while 48-h measurement provides useful data for investigating the impact of different floor types. The disagreement between these two sets of results does not discriminate any of the measuring methods applied.

The highest difference between the results of two measurements (2018 vs. 2021) was observed in room 11. This is a storage room, and its volume is the smallest one. When 1 month measurement was performed, the storage room was frequently opened during the day. During 48-h measurement, it was completely closed, and radon was accumulated inside. This might be a possible explanation of such large difference between two measurements performed in this room.

Energy renovation of building could contribute to different radon levels: thermally insulation of walls with Styrofoam and replacing existing windows with PVC ones could keep radon inside the building; the proper floor coverings (such as laminate) in some extent could disable radon entry, probably due to the tight sealing properties of embedded material itself. The simulated energy-retrofit scenarios for Irish dwellings

predict when increased airtightness of the building and no additional ventilation measures were installed, a corresponding increase in the radon concentration goes up to 107% (McGrath et al. 2021). Also, Yarmoshenko et al. (2020) confirmed that increased airtightness for reducing the uncontrolled air exchange rate of building envelope achieved by applying wall insulations and sealed double-glazed PVC windows leads to increased radon accumulation in the buildings of four Russian cities. Some authors found that radon concentrations tended to increase as the buildings aged (Collignan and Powaga, 2019), as might be assumed in this case.

In general, thermal retrofitting could pose a critical issue in trying to save energy in workrooms with higher radon. More precisely, thermal comfort and air pollution exposure are key factors that affect productivity and health in working environment (Che et al. 2019). Kang et al. 2017 reported that the indoor environmental quality in university research offices have significantly positive correlations with office productivity. Since the studied building is used as a faculty, health risk could be addressed to students and employed persons, which are at least eight hours exposed to enhanced radon levels. In this context, the measures for significant radon reduction must be applied for installation of balanced mechanical ventilation system which will effectively draw out radon. Also, full retrofitting of floors could be particularly advisable for workrooms covered with wood blocks; a selection of suitable radon-resistant floor covering is highly recommended to achieve optimal indoor environmental quality. Additionally, indoor radon quality in semi-underground buildings is much poorer than in aboveground buildings and implies necessary further improvement the radon control strategies (Yu et al. 2020). This also indicates a need for further radon monitoring since there are no studies or published data of radon levels in workplaces after energy renovation; new research must include other relevant factors such as archetypes, construction, internal furnishing, behavioral factors, as well as the influence of meteorological parameters, geographic location, and seasonal variability.

Conclusion

The study was conducted to estimate the level of radon exposure in a school building after the application of thermal retrofit measures as well as to investigate the impact of renovation process on indoor radon concentration. Two surveys were performed:

1. One-month survey performed by Airthings Corentium Home radon detectors in ten most frequently occupied rooms, and
2. 48 h–survey carried out in 23 rooms, employing charcoal canisters.

The study found the following:

- A large variability of indoor radon during month (37–573 Bq/m³), including large day-to-day fluctuations in ten basement workrooms of energy renovated building;
- The uneven values of radon concentration in workrooms grouped according to flooring type: 327 Bq/m³ for parquet, 227 Bq/m³ for ceramic tiles, 146 Bq/m³ for vinyl flooring and 71 Bq/m³ for laminate.

This study also emphasized that thermal insulation processes must be followed by an application of suitable flooring types to avoid the increases of radon concentration inside the building, besides other optimal measures, like using an adequate ventilation system. The enhanced ventilation is the first most important measure in radon mitigation protocols; this is an overall conclusion from many well-established studies. These activities should be provided to prevent radon variations and reduce the negative effects on health. The results from this study could be useful for better understanding indoor radon levels in energy renovated buildings, overcoming the problems with health risk and developing ways for radon control and mitigation measures.

This study was framed by the following practical implications:

- Thermal retrofitting could pose a critical issue in trying to save energy in workrooms with higher radon. The attention should be focused to protection of employed persons having in mind risk from permanent radon exposure in working hours.
- A convenient selection of flooring type for renovation could be of importance in terms of reducing radon levels and achieving the benefits from energy retrofitting.
- In the case of thermal retrofitting which include exchange with airtight PVC windows procedures for energy savings should be followed with an installing of appropriate ventilation systems to avoid increase of indoor radon.

As it has been shown in similar studies cited above, the expected radon concentrations after retrofitting measures may increase, but high radon levels in energy-efficient buildings are not inevitable in every case. This study finds that certain retrofit measures may improve comfort, but they do not achieve the desired reduction in radon concentration. From a policy perspective retrofit is effective in many cases, but it has been confirmed that even if retrofit measures achieve results in energy use, they may not consider the controlling indoor air pollution challenged by radon accumulation in buildings.

However, National radon action plan and National action plan for energy efficiency in Serbia need to be harmonized and offer a win–win outcome, in the terms of better living

conditions and healthy work environments. Since the main source of radon is the soil under the building, when renovations are planned for energy efficiency and radon mitigation in old ground-floor buildings, floor renovation should be considered, as shown in this study. Although, based on a small number of results, a simple comparison of indoor radon levels before and after energy retrofit does not show a clear dependence, it may indicate possible elevated radon levels, considering two independent surveys. Simple, cheap preventive radon interventions are curbing increases in radon that might otherwise occur after energy efficiency retrofit of the building. Energy efficiency programs and projects should include these measures, side-by-side with ventilation, well-installed ground/floor coverings and sealed cavities. These relatively simple radon interventions do not substitute for radon mitigation, but they help keep radon levels stable on the ground floor of the building. Above-mentioned efforts can help maintain health and safety environment while achieving energy efficiency benefits.

The major limitation of this study lies in the fact that there was not much data available on radon levels before the application of thermal retrofit measures. A more extensive data on prior radon levels along with a detailed monitoring of environmental factors would contribute to a better understanding of the impact of thermal retrofit on indoor air quality.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare that they have no conflicts of interest.

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