INDOOR RADON ASSESSMENT IN SCHOOL BUILDINGS: WHERE, WHEN AND HOW TO MEASURE?

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ABSTRACT

A pre-selection procedure for sample choice in an extensive experimental campaign for indoor radon assessment is mandatory to ensure the homogeneity of the case study to be monitored. The implementation of a simple methodology for room selection guarantees more homogenized measurement results for later comparison and analysis. Hence, the case study for in-situ instrumentation must include a representative and homogeneous sample of the whole, with a particular focus on rooms occupied daily during the working day, namely offices and cabinets for staff. All buildings under monitoring hold a substantial number of rooms that should be assessed for radon potential evaluation, however, due to the reduced time frame for in-situ instrumentation and the shortage of radon detectors, only a representative sample can be picked for monitoring. Given the constraints, a straightforward methodology for sample selection based on the evaluation of the most relevant criteria that influence radon risk exposure – occupancy, site geology, room type, room size and floor location, air renovation, building materials, etc. – is a key process to ensure the quality of the experimental campaign. An experimental campaign for indoor radon assessment will be carried out during Spring of 2021 for evaluating the impact on indoor air quality (IAQ) during school reopening, after a long lockdown period due to COVID-19, which lasted from 15 January 2021 to 19 April 2021. The higher education institution to be evaluated includes six distinct schools spread in several geographically dispersed locations in the north region of Portugal and will be monitored to assess radon concentration, atmospheric pressure, and other hygrothermal parameters. In the end, the result will rely on a matrix that prioritizes the most relevant parameters on radon potential analysis by applying a three-level scale for scoring: low, moderate, and high. Each of these levels will be associated with a score scale allowing the design of a multicriteria analysis for the selected criteria, thus building a methodology for sample selection in complex scenarios for in-situ monitoring.

Keywords: IAQ, radon, assessment, sample selection, multicriteria analysis matrix.

1 INTRODUCTION

School buildings across Europe often present insufficient ventilation that is associated with high levels of chemical pollutants, mould problems and dampness, and Portugal is no exception [1]. The lack of air renovation in school buildings is linked with respiratory problems, infectious diseases, and reduced learning outcomes [2]. To tackle the problem, the Portuguese regulation for IAQ in school buildings demands a simplified annual assessment [3].

Concerning indoor radon, the regulation established a limit concentration of 300 Bq/m^3, without indicating the occupation period to be considered for measurement (full time or work time). Radon gas is a radioactive element of natural origin, colourless, odourless, and tasteless [4]. It results from the decay of uranium naturally present in the mineral grains of

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soils and granitic rocks and some construction materials and tends to accumulate inside buildings since it is heavier than air [4]. Very often, indoor radon levels tend to increase with buildings' energy efficiency reinforcement. The gas arising from subsoil enters the building through the ground and is captured inside of airtight constructions, most of them built or refurbished with well-insulated walls, roofs, and floors, and equipped with double-glazed windows, contributing to low airflow rates and aggravating IAQ [5]. Furthermore, indoor radon concentration varies widely throughout the day and the year, tending to reach higher values during the night period, for a daily cycle, and during the Winter season, for an annual cycle [2]. Indoor radon detection is separated into short-term and long-term assessments by using, more recently, advanced technology supported in digital solutions that have made radon measurements more convenient and accurate.

Due to seasonal fluctuations, long-term measurements for periods longer than 3 months are more suited for detailed characterization. Long-term radon detectors are based on alpha-track detection (AT) method by using containers that enclose small sheets of special plastic material to detect radiation [6]. In short, the alpha particles emitted by the radon gas will leave tracks on these plastic sheets for later evaluation, which may take anything from 3 months up to a year. Digital solutions, known as continuous radon monitors (CRM), are more convenient for measuring radon concentration by digitizing radon detection. This solution combines the advantages of old methods and brings flexibility, consistency, long lifetime, high accuracy, quick response time, continuous readings, and long-term and short-term capabilities. Short-term radon detection is suitable when a straightforward diagnostic is needed, and measurements will take between 2 days to 3 months. These types use charcoal-based methods to absorb the radon gas which is later resealed and returned to a lab for evaluation. Short-term measurements can roughly estimate the prevailing indoor radon concentration in a specific room under monitoring and are usually adopted to provide a crude indication of radon level for further analysis at a later stage [6].

In-situ measurements are essential to assess indoor radon concentration and are based on standardized protocols to ensure accurate and consistent results [6]. Although there are many published works focused on how, when, and where to assess [5], [7], a simple and straightforward methodology for sample selection based on a set of criteria with distinct weights that depend on their relevance – that can be integrated into clear and objective decision-making process, is, to the best of our knowledge, yet to be implemented. In short, the main goal of this study is to outline a methodology based on short-term measurements that aims to identify the most critical rooms to be instrumented in an extensive assessment campaign that needs further validation based on the instrumentation results [8], [9].

The structure of this paper is as follows. In Section 2, the materials and methods are described, presenting the proposed methodology for sample selection. Section 3 presents the results, discusses the advantages and disadvantages of sample characterization, and presents a multicriteria analysis matrix, based on the selected parameters. Finally, the conclusions and future work of this article are addressed in Section 4.

2 MATERIALS AND METHODS

Indoor radon concentration is prominent in the north region of Portugal, due to the soil lithology and to the use of granite blocks as a raw material in the construction industry [10]. Therefore, issues related to bad IAQ are particularly acute in this region, which is evidenced by a study carried out by Veloso et al. in 2011 that estimates radon to be associated with between 18% to 28% of lung cancer cases in the north region of Portugal, causing an average of around 215 deaths per year [11].

In scenarios of considerable diversity in the building stock for in-situ monitoring, a pre-selection procedure for sample choice is mandatory to ensure a representative and homogeneous sample selection process. Besides the geographic spread and the type of construction, other differences that influence in-situ monitoring are particularly relevant:

- Lithological characterization and soil type.
- Room occupancy (high occupancy rate versus vacant rooms).
- Type of ventilation (natural ventilation versus mechanical ventilation).

The case study for in-situ measurements must include a representative and homogeneous sample of the whole, so that experimental results can be used for data analysis and comparison, with a particular focus on rooms occupied daily during working time, namely administrative offices, and cabinets for staff [12]. For reasons related to increased exposure to radon gas, priority will be given to ground floor compartments. However, to check how indoor radon concentration is reduced with the ground clearance of the instrumented room, the analysis over a building vertical alignment will be implemented. This specific analysis allows checking how radon level is dissipating as it moves from one building floor to another building floor.

All buildings under monitoring hold many rooms that need to be assessed, however, due to the reduced time frame for instrumentation and the shortage of available radon detectors, only a few rooms will make part of the case study to be monitored. Given the constraints, an adequate procedure for sample selection can be a very effective operational tool, to allow the triage of the most determinant rooms to be instrumented based on a previous criteria analysis. A stage related to sample selection is a key process part of a straightforward methodology, whose first step is the evaluation of the most relevant criteria that influence indoor radon potential (Fig. 1), so that the quality of the experimental campaign can be assured. Fig. 1 depicts the methodology adopted for in-situ measurements implementation based on a set of five sequential steps that comprehend a range of tasks to be undertaken for each stage.

Sample selection is the first step to be carried out by adopting a multicriteria analysis for radon potential assessment. For this, several influencing criteria concerning indoor radon potential are plotted on a matrix linking them to a three-level scale: low, moderate, and high. Each risk level will be associated with a score allowing to design a grade scale used to rank the most relevant criteria to be selected. The model will be used to assess radon potential and applied to all buildings that make part of the case study. This stage implies a previous analysis to choose the most relevant criteria for sample selection. Criteria related to occupancy schedules, site geology and lithological characterization based on geological maps, room type, room size or floor location, air renovation systems and ventilation, prevalent building materials, etc. are of utmost importance to evaluate indoor radon potential for a further stage experimental campaign.

After sample selection, the second stage to be implemented will be the so-called preliminary works. In this stage, preparatory activities for continuous in-situ measurements will be carried out by using a digital CRM instrument with an incorporated data logger, to register indoor air temperature, relative humidity, atmospheric pressure, and indoor radon concentration. To implement the experimental campaign, a certified digital CRM instrument with data logging capability must be selected for accurate and reliable average readings. Although long-term measurements are the most accurate procedure to assess potential radon health hazards, in this work short-term assessment will be used by applying a 1 week measurement to detect evidence of harmful radon levels. These 7 days represent a

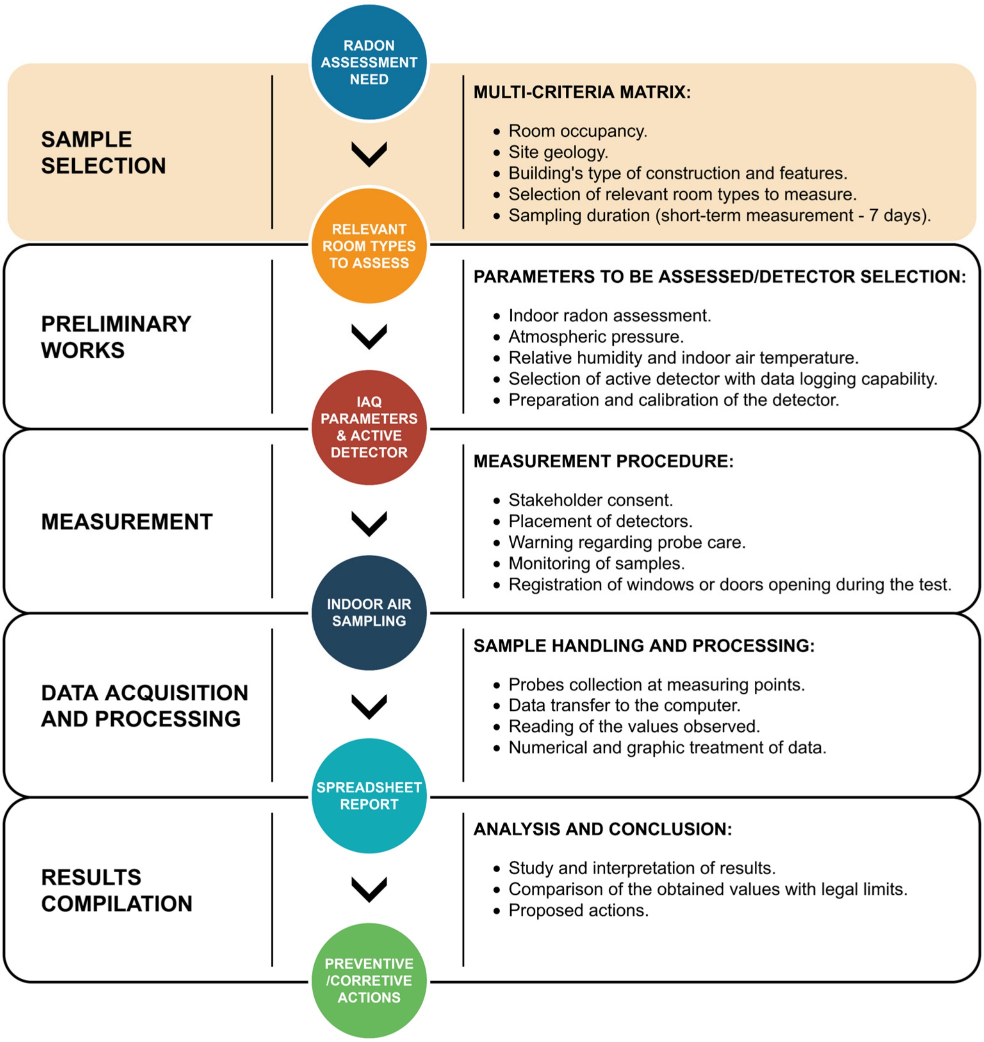

Figure 1: Proposed methodology for in-situ measurements.

cycle that allows us to see the radon concentration pattern in the period of occupation and out of occupation (labour days plus weekend). If by any means the detected levels are higher than initially expected, it will be necessary to reconsider the approach to long-term measurements.

The third stage of the proposed methodology relates to the measurement stage. As described in Fig. 1, this study must be carried out with the informed consent of all staff involved. All of them were previously informed of the precautions to be taken during the sampling, namely, to not tamper or disconnect the CRM instrument to not compromise the results. During this stage, the correct CRM instrument placement is very important to get reliable measurements, since placement mistakes could lead to false-positive readings, like for instance placing a CRM instrument too close to a known radon source, or in a very small room of an area in an unoccupied basement. As buildings have multiple areas and floors, CRM instruments should be placed on the lowest occupied level of the building, and then go from there to other occupied floors [13]. The most important recommendations to follow in the CRM instrument placement are as follows [14]: it should not be exposed to direct sunlight or electromagnetic radiation; the probe should be on a shelf, or table positioned lying flat, against an interior wall that is free from ventilation sources like vents or air returns; it must be kept at least 150 cm away from all windows, doorways, ventilation devices, and exterior walls, to avoid fresh air: it should be at least 50 cm above the floor and below the ceiling and 25 cm away from other objects. Radon probes cannot be moved or touched during the measurement procedure.

The fourth stage concerns data acquisition and processing. In-situ assessment will take place under normal conditions of room "operation", i.e., people will use the room like they normally do during daily work time, within the regular conditions of use of the spaces, so opening windows or going in and out of the compartments is interpreted as normal usage behaviour and will be not valued. The statistical treatment of the measured parameters will be inferential statistics, and the parameters will be interpreted with caution and correlated with other relevant criteria. This will allow us to draw conclusions and make statements that will serve as a reference in similar future procedures of radon risk potential assessment.

The fifth stage is related to the results' presentation. After the testing period is complete, results are examined, and conclusions are extracted. Two possible actions can be then implemented: a first action regarding the decision on the need for mitigation must be undertaken by analysing short-term testing results. It will be possible to decide if long-term testing is advisable. The results will allow implementing a set of preventive or corrective actions, if necessary, and to decide how quickly to mitigate; a second action concerning retesting after implementing corrective actions. It is planned to retest all rooms yearly after renovation. In the future it will be important to define strategies for reviewing and maintaining the measures implemented based on the retesting results.

To implement the proposed methodology, a set of six schools spread through the north region of Portugal will be assessed to monitor rooms' IAQ, mainly related to radon concentration. Education institutions play a decisive responsibility in awakening the awareness regarding issues towards IAQ and a healthy indoor environment to create a safe and sustainable campus [15], [16]. The rooms to be monitored are occupied by staff members, administrative employees, grantees, researchers, and teaching staff, i.e., all enclosed space under in-situ monitoring share a permanent occupancy during working hours. The school buildings that make part of the case study to be instrumented are geographically dispersed throughout a large region, and differences in schools' characteristics are substantial, both in terms of building period, as in terms of building process, and in types of materials used for construction and finishing: for instance, the oldest school to be monitored is a public interest monument recently retrofitted, built with thick granite walls, and converted into a school building [17]. On the other hand, the most recent school building is a recent high-tech building equipped with several automation mechanisms and air conditioning centralized systems.

3 RESULTS AND DISCUSSION

Nowadays concerns with IAQ are directly linked to the time spent inside buildings, since today's society spends 80% to 90% of time indoors in homes, at workplaces or schools, in shopping and leisure, etc., where IAQ is two to five times worse than outdoor air [18]. Most of the contributions to a poor IAQ arise from construction materials, cladding and coating, furniture, cleaning products, and poor ventilation and air renewal, just to name a few [19].

Concerning radon, as is already well known, most of the contribution comes from the soil, and when radon enters an enclosed room, its accumulation can lead to high concentrations, representing a possible health harm that must be assessed by using a well-defined methodology [20].

Given the need to optimize resource usage, save time and to reduce costs, the in-situ assessment must include a representative sample of enclosed spaces in each of the 6 monitored schools, with a particular focus on rooms with long-term daily occupancy, namely administrative offices, professors' rooms, and staff cabinets. This strategy intentionally leaves classrooms out of assessment, given the fact that presential classes never last more than 2 hours for a particular group or class, then switching to another distinct group or class. Therefore, occupants' radon exposure risk is considerably lower than the risk in an administrative office, or a staff cabinet, where the occupation period is always considerably larger for the same people who work there.

After a thorough analysis of all schools that make part of the case study including buildings analysis for rooms' selection, based on the experience acquired in previous experimental campaigns conducted in the same geographic region, three main criteria were attended to build up the methodology for radon potential assessment:

- Room occupancy (occupancy schedule, number of occupants and room location).
- Site geology and lithological characterization based on official geological maps (soil type and layers structure).
- Building's type of construction and features (construction age, ventilation regime, heating and air conditioning systems installed).

Complementary to this criteria's choice, some main assumptions were taken previously to carry out the sample selection:

- Rooms for instrumentation are selected among enclosures occupied by school professors and staff over a period that can reach 35 hours per week, the total number of working hours for civil servants.
- Selected rooms must be representative of different working environments – administrative rooms or offices, professor, and staff cabinets, etc.
- Ground floor rooms are prioritized for indoor radon assessment.
- Measurements across a vertical alignment will be undertaken to assess radon variation in height throughout the building.

Table 1 shows among all occupied rooms, the selected rooms that will be used for in-situ monitoring. Tested rooms will be about 20% of all total rooms, involving the same percentage of employees, on average.

Table 1: Number of relevant rooms and staff by school (#1 to #6).

Rooms and staff	Schools					
	#1	#2	#3	#4	#5	#6
All rooms\Tested rooms	41/9	34/18	76/16	34/9	33/9	34/9
All staff\Tested staff	70/9	62/18	200/16	82/9	45/9	31/9

The implemented procedure for sample selection involves the analysis of the most influencing criteria to assess radon potential in a scenario of shortage of active radon detectors for in-situ assessment, bringing out the following achievable for future applications:

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- Allows selecting a representative sample for in-situ monitoring.
- Privilege rooms with an occupancy schedule for in-situ monitoring.
- Allows a broad evaluation of IAQ by assessing indoor radon concentration, atmospheric pressure, air temperature and relative humidity.
- Serves as a guide to help schools to assess radon potential.

Tables 2 and 3 present results concerning the use of a multicriteria analysis for sample selection. Both matrices relate the selected criteria and sub-criteria (in rows), with the relevant room types for the instrumented schools (in columns). The results derived from the cross-analysis of information will allow the selection of the critical rooms that should be measured in each school, by understanding whether a room located in a particular floor shows a higher radon potential when compared to others with a distinct location.

The quantification of the parameter "radon assessment need" for each criterion is divided into four levels within a score scale from 0 to 3, as follows: non-applicable (0 points), low (1 point), moderate (2 points), and high (3 points). Each score is attributed based on the sub-criteria analysis and related to the increasing level of radon potential exposure. All sub-criteria that do not have direct application to quantify the assessed parameter should be scored with 0 points or marked with "–" for a straightforward simplification of the results.

After scoring, the checksum for all relevant rooms is added. If the cross-sectional analysis of these criteria returns a checksum equal to or below 22 that indicates that the radon potential is moderate or low, therefore these room types should be ignored. On the other hand, if the value is above 22 it will be necessary to select those compartments for radon assessment according to these steps:

1. Checksum scores above 22 should be placed in descending order.
2. At least four room types with the highest scores should be chosen.
3. The number of available radon detectors should be evenly distributed among the selected room types.

By the analysis of the results presented in Tables 2 and 3, it stands out, for all schools to be assessed, that the adoption of a score value of 22, referred to as the "border score", tends to favour monitored areas like receptions, offices, cabinets, and laboratories in comparison to libraries, canteens, bars, or workshops. This happens because the 6 schools have similar organizational profiles and layouts, except for the oldest school that differs from the other in many architectural characteristics, building materials, devices and equipment installed. Hence, the remaining 5 schools share similar scores on various sub-criteria, in terms of building features, layout, and occupancy patterns. This aspect is also verified regarding site geology, which is the most important main criteria, as schools are all located in the same region.

In overall terms, these results will trigger the following actions:

- Implement in-situ measurements by using a 7-day short-term procedure, starting with all frequently occupied rooms placed on the ground floor, during the same period.
- If the measurement results are higher than 300 Bq/m^3, a new follow-up procedure must be implemented for all monitored rooms. The new measurements should follow the same procedures as the previous ones, mainly regarding the locations, the conditions of the essays. If the new experimental results match with the initial, short-term measurements strategy seems to be enough.

Table 2: Multicriteria analysis matrix.

Main criteria	Sub-criteria	Assessment need (score)	School 1 – Relevant room types								School 2 – Relevant room types								School 3 – Relevant room types							
			Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops	Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops	Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops
Room occupancy	**Occupation profile:**																									
	Work time	Moderate (2)	–	2	2	2	–	2	2	–	–	2	2	2	–	2	2	–	–	2	2	2	–	2	2	–
	Full time (24 hours)	High (3)	3	–	–	–	–	–	–	–	3	–	–	–	–	–	–	–	3	–	–	–	–	–	–	–
	Partial time (morning/afternoon)	Low (1)	1	1	1	1	1	–	–	1	1	1	1	1	1	–	–	–	1	1	1	1	1	–	–	1
	Occupancy profile:																									
	Staff members	High (3)	3	3	3	–	–	3	3	3	3	3	3	–	–	3	3	–	3	3	3	–	–	3	3	3
	Grantee	Low (1)	–	–	–	–	1	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	1	–	–	–
	Professor/Researcher	High (3)	–	–	–	3	3	–	–	–	–	–	–	3	3	–	–	–	–	–	–	3	3	–	–	–
	Room occupancy:																									
	Low (1)	Low (1)	1	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–
	Medium (1–5)	Moderate (2)	–	2	2	2	2	2	–	2	–	2	2	2	2	2	2	–	–	2	2	2	2	2	–	2
	High (5+)	High (3)	–	–	–	–	–	–	3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3	–
	Room size (area):																									
	Below 100 m^2	High (3)	3	3	3	3	3	–	–	–	3	3	3	3	3	–	–		–	3	3	3	3	–	–	–
	Between 100–250 m^2	Moderate (2)	–	–	–	–	–	–	–	2	–	–	–	–	–	2	–	–	–	–	–	–	–	–	–	2
	Above 250 m^2	Low (1)	–	–	–	–	–	1	1	–	–	–	–	–	–	–	1	–	1	–	–	–	–	1	1	–
Site geology	**Lithological characterization:**																									
	Igneous	High (3)	–	–	–	–	–	–	–	–	3	3	3	3	3	3	3	–	3	3	3	3	3	3	3	3
	Metamorphic or sedimentary	Low (1)	1	1	1	1	1	1	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Soil type and layer's structure:																									
	Granitic/schist soils	High (3)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	–	3	3	3	3	3	3	3	3
	Non granitic/schist soils	Low (1)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Table 2: Continued.

Main criteria	Sub-criteria	Assessment need (score)	School 1 – Relevant room types								School 2 – Relevant room types								School 3 – Relevant room types							
			Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops	Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops	Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops
Building's type of construction and features	**Buildings constructive typology:**																									
	Stone masonry construction	High (3)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Concrete construction	Moderate (2)	–	–	–	–	–	–	–	–	2	2	2	2	2	2	2	–	2	2	2	2	2	2	2	2
	Prefabrication	Low (1)	1	1	1	1	1	1	1	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Compartment location:																									
	Basement/Cellar	High (3)	–	–	–	–	–	–	–	3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Ground/Main floor	Moderate (2)	2	–	2	2	2	2	2	–	–	–	–	–	–	–	–	–	2	2	2	2	2	2	2	2
	Any Upper floor	Low (1)	–	1	–	1	1	–	–	–	1	1	1	1	1	1	1	–	–	–	–	1	1	–	–	–
	Prevalent buildings materials:																									
	Granite/schist, solid rock, concrete	High (3)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Stone coverings	Moderate (2)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Others	Low (1)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	–	1	1	1	1	1	1	1	1
	Type of ventilation:																									
	Natural	High (3)	3	3	3	3	3	–	–	3	3	3	3	3	3	–	–	–	3	3	3	3	3	–	–	–
	Mechanical/Air conditioning	Low (1)	–	–	–	–	–	1	1	–	–	–	–	–	–	1	1	–	–	–	–	–	–	1	1	1
	Heating system:																									
	Yes	Low (1)	1	1	1	1	1	1	1	–	1	1	1	1	1	1	1	–	1	1	1	1	1	1	1	–
	No	Moderate (2)	–	–	–	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2
Checksum (Border score = 22)			23	22	23	24	23	18	19	22	25	25	25	25	24	21	20	–	24	26	26	27	26	21	22	22

Table 3: Multicriteria analysis matrix.

Main criteria	Sub-criteria	Assessment need (score)	School 4 – Relevant room types								School 5 – Relevant room types								School 6 – Relevant room types							
			Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops	Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops	Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops
Room occupancy	**Occupation profile:**																									
	Work time	Moderate (2)	–	2	2	2	–	2	2	–	–	2	2	2	–	2	2	–	–	2	2	2	–	2	2	–
	Full time (24 hours)	High (3)	3	–	–	–	–	–	–	–	3	–	–	–	–	–	–	–	3	–	–	–	–	–	–	–
	Partial time (morning/afternoon)	Low (1)	1	1	1	1	1	–	–	–	1	1	1	1	–	–	–	–	1	1	1	1	1	–	–	1
	Occupancy profile:																									
	Staff members	High (3)	3	3	3	–	–	3	3	3	3	3	3	–	–	3	3	–	3	3	3	–	–	3	3	3
	Grantee	Low (1)	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–
	Professor/Researcher	High (3)	–	–	–	3	3	–	–	–	–	–	–	3	–	–	–	–	–	–	–	3	3	–	–	–
	Room occupancy:																									
	Low (1)	Low (1)	1	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–
	Medium (1–5)	Moderate (2)	–	2	2	2	2	2	–	2	–	2	2	2	–	2	–	–	–	2	2	2	2	2	–	2
	High (5+)	High (3)	–	–	–	–	–	–	3	–	–	–	–	–	–	–	3	–	–	–	–	–	–	–	3	–
	Room size (area):																									
	Below 100 m^2	High (3)	3	3	3	3	3	–	–	3	3	3	3	3	–	–	–	–	3	3	3	3	3	–	–	3
	Between 100–250 m^2	Moderate (2)	–	–	–	–	–	2	2	–	–	–	–	–	–	–	2	–	–	–	–	–	–	2	2	–
	Above 250 m^2	Low (1)	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–
Site geology	**Lithological characterization:**																									
	Igneous	High (3)	3	3	3	3	3	3	3	3	–	–	–	–	–	–	–	–	3	3	3	3	3	3	3	3
	Metamorphic or sedimentary	Low (1)	–	–	–	–	–	–	–	–	1	1	1	1	–	1	1	–	–	–	–	–	–	–	–	–
	Soil type and layer's structure:																									
	Granitic/schist soils	High (3)	3	3	3	3	3	3	3	3	3	3	3	3	–	3	3	–	3	3	3	3	3	3	3	3
	Non granitic/schist soils	Low (1)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Table 3: Continued.

Main criteria	Sub-criteria	Assessment need (score)	School 4 – Relevant room types								School 5 – Relevant room types								School 6 – Relevant room types							
			Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops	Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops	Reception	Management board offices	Administrative offices	Professors and researchers cabinets	Laboratories	Library	Canteen/Bar	Workshops
Building's type of construction and features	**Buildings constructive typology:**																									
	Stone masonry construction	High (3)	3	3	3	3	3	3	–	3	–	3	3	–	–	–	–	–	–	–	–	–	–	–	–	–
	Concrete construction	Moderate (2)	–	–	–	–	–	–	2	–	2	–	–	2	–	2	2	–	2	2	2	2	2	2	2	2
	Prefabrication	Low (1)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Compartment location:																									
	Basement/Cellar	High (3)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3	–	–	3
	Ground/Main floor	Moderate (2)	2	2	2	–	–	–	2	2	2	2	2	–	–	2	2	–	–	–	–	–	–	–	–	–
	Any Upper floor	Low (1)	–	–	–	1	1	1	–	–	–	–	–	1	–	–	–	–	1	1	1	1	–	1	1	–
	Prevalent buildings materials:																									
	Granite/schist, solid rock, concrete	High (3)	3	3	3	3	3	3	3	3	–	3	3	–	–	–	–	–	–	–	–	–	–	–	–	–
	Stone coverings	Moderate (2)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Others	Low (1)	–	–	–	–	–	–	–	–	1	–	–	1	–	1	1	–	1	1	1	1	1	1	1	1
	Type of ventilation:																									
	Natural	High (3)	3	3	3	3	3	–	–	3	3	3	3	3	–	–	–	–	3	3	3	3	3	–	–	3
	Mechanical/Air conditioning	Low (1)	–	–	–	–	–	1	1	–	–	–	–	–	–	1	1	–	–	–	–	–	–	1	1	–
	Heating system:																									
	Yes	Low (1)	1	1	1	1	1	1	1	–	1	1	1	1	–	1	1	–	1	1	1	1	1	1	1	–
	No	Moderate (2)	–	–	–	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2
Checksum (Border score = 22)			29	29	29	28	27	24	25	27	24	27	27	23	–	19	21	–	25	25	25	25	26	21	22	26

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When these actions are done, it is time to analyse the collected data and decide if a follow-up long-term assessment is better to understand the average radon concentrations for the entire school year. If after a long-term assessment the results are still critical then mitigation actions should be considered. When major renovations are implemented in buildings it is essential to retest all previous rooms to check the effectiveness of mitigation measures.

4 CONCLUSIONS AND FUTURE WORK

The implemented methodology for sample selection is a preliminary tool concerning radon potential evaluation, designed to be replicated in similar experimental scenarios towards indoor radon testing, as well as for other IAQ parameters.

Particularly designed for school buildings, the methodology relies on a multicriteria analysis matrix designed for selecting the most relevant spaces to be tested in an indoor radon campaign. The focus is set on rooms with high occupancy, typically occupied by staff in regular working periods where the likelihood of being exposed to indoor radon gas increases. The scenario with extended occupancy is mostly relevant for school staff in a 5-day workweek, mainly for people working in administrative offices, or researchers and professors in laboratory rooms or cabinets.

To develop the multicriteria analysis matrix, the most relevant criteria, sub-criteria, and room types were selected, case by case, for each monitored room for the six instrumented schools. In-situ monitoring will consider short-term assessment based on a 1-week monitoring cycle, including weekend days.

The experimental campaign selected during the presented case study is ongoing during the spring of 2021 and its experimental results will be applied in future radon mitigation studies, where applicable.

Lastly, the proposed methodology, relying on a multicriteria matrix, is meant to be a decision-making tool for complex monitoring scenarios, holding many criteria to deal with and where a multicriteria analysis can help to solve problems related to criteria selection.

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