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Radon Risk Management in Public Buildings in Northwest Portugal: From Short-Term Characterization to the Design of Specific Mitigation Actions

António Curado, João P. Silva, Sérgio I. Lopes

ABSTRACT--- Portugal is a country with a considerable risk regarding natural radiation since in a considerable part of the territory the soil is mainly composed of granitic rocks, containing high uranium levels. Radon gas is currently classified by the International Agency for Research on Cancer (IARC) as a Group 1 carcinogen. To tackle the problem since the beginning of 2019 there is new legislation in force to regulate indoor occupational exposure to radon gas. An experimental study was carried out in a city in the Northwest of Portugal by taking short-term measurements in a set of 15 municipal buildings (schools, museums, galleries, theaters, and municipal bureaus and offices, etc.) differing not only on its architecture and its construction period, but also on the number of occupants, its habits, and occupancy schedules. The in situ characterization allowed highlighting radon risk to which buildings' occupants are subject to, and by results analysis to propose a radon management strategy aimed at minimizing the risk of occupant exposure.

Index Terms — Radon management strategy, Radon mitigation, Radon risk analysis.

I. INTRODUCTION

Radon is an inert gas found in nature formed from the successive radioactive decay of elements from uranium series. This gas is prevalent in granitic soils and in construction materials [1]. The radon concentration indoors depends on the characteristics of the foundation soil where the building lays, its permeability to radon diffusion, and its geo-morphological properties. Once in the building, radon propagation is directly related to ventilation schemes installed – buildings better ventilated assure a higher dilution of the contaminant [2][3]. Radon presence in the building cannot be felt since it has no color, no odor, and no taste. The gas presents a half-life of only 3.8 days however in the decaying process the gas emits alpha particles, responsible for lung cancer if inhaled during long periods of time, due to its radioactive nature [4].

A set of 15 public municipal buildings in a city in the Northwest of Portugal (Fig.1), Western Europe, were monitored under the scope of the R&D project RnMonitor. The monitoring campaign was carried out to characterize indoor radon gas concentration during 2 different periods of the year (winter and summer 2018). Buildings under study provide public services (schools, museums, galleries, theaters, and municipal bureaus and offices, etc.), differing on its architecture, period of construction, occupants number and habits, occupancy schedules and routines.

Fig.1. Region under study in Northwest of Portugal.

2 hygrothermal parameters (indoor air temperature and relative humidity) were additionally measured to assess thermal comfort. Collected data will be related to rooms' occupancy and linked to users' ventilation actions. Given sample extent, this study was based on short-term measurements assessed according to the new Portuguese radiation protection law, in force since the beginning of 2019. In the end, the study proposes a radon management

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António Curado, proMetheus - Instituto Politécnico de Viana do Castelo, Viana do Castelo, Portugal. CONSTRUCT LFC, Faculty of Engineering (FEUP), University of Porto, Portugal. (E-mail: acurado@estg.ipvc.pt)

João P. Silva, proMetheus - Instituto Politécnico de Viana do Castelo, Viana do Castelo, Portugal.

Sérgio I. Lopes, ARC4DigIT - Instituto Politécnico de Viana do Castelo, Viana do Castelo, Portugal. Instituto de Telecomunicações, Aveiro, Portugal.

strategy for minimizing the occupants' risk, supported not only on a set of buildings mitigation actions but also with other actions related to awareness-raising among buildings users.

II. RELATED WORKS

There have been some previous related works developed by this paper' authors regarding radon gas assessment in the Northwest region of Portugal. These studies underline the ventilation actions influence and rooms' occupancy importance on indoor radon concentration and define some active mitigation strategies based on online monitoring in order to reduce the radon risk of buildings users. The main previous contributions of the authors are the following:

- Curado A. and Lopes S.I. [5] performed an *in situ* measurement campaign in 2016 to assess radon concentration in residential buildings in Alto Minho region, North of Portugal. The study highlights a strong correlation between radon concentration and the ventilation actions implemented by occupants. The undertaken short-term measurements revealed that buildings with higher occupation and stronger air renovation have lower indoor radon concentrations.
- António Curado, João Silva, Lúcia Carvalho and Sérgio I. Lopes [6] analyzed the radon concentration in 3 housing buildings with granitic construction in Barcelos, North of Portugal, a critical area towards radon risk due to the nature of the soil. The experimental study showed the air renovation influence on the reduction of indoor radon and other air pollutants. Moreover, the study suggested that most part or radon gas emission arises through the buildings´ foundations.
- Sérgio I. Lopes, João Silva, Ana Antão and António Curado [7] developed an experimental study in a centenary monastery recently converted to a polytechnic school building in an inner village in the Northwest region of Portugal, named Ponte de Lima. The *in situ* campaign ran during spring and summer 2017 and involved a set of radon concentration short-term measurements in 17 rooms during 2 different time periods. The study reinforced the ventilation influence on the radon concentration reduction and stressed the year season influence in which the monitoring campaign is carried out, on the radon concentration performance.
- Sérgio I. Lopes et al. [8] developed a methodology to design a Human-in-the-Loop Cyber-Physical System for online monitoring and active mitigation of the indoor radon gas concentration in public buildings. This technology allows not only a continuous and online monitoring of the radon gas concentration but also the implementation on time of active mitigation strategies to reduce the indoor radon gas concentration.

III. INDOOR AIR QUALITY – RADON PROTECTION

Buildings ventilation lack helps to increment indoor air pollutants coming from external and interior sources (furniture, construction materials, people and air conditioning systems) [9].

AHSRAE 62.1 [10] defines Indoor Air Quality (IAQ) as the air where there are no known contaminants at hazardous concentrations, determined by recognized authorities and where the majority (at least 80%) of the exposed occupants, do not express dissatisfaction.

In 1984, a World Health Organization (WHO) study reported 30% of new or retrofitted scholar buildings subject to excessive levels of pollutants affecting IAQ [3]. The main symptoms of the occupants were related to problems with headaches, nasal irritation, irritation of the throat, eye irritation, cough, allergies, asthma, nausea, lack of concentration and fatigue. The study stated that most complaints ceased when students leave buildings.

One of the dangerous contaminants in buildings indoor air is radon gas, representing after smoking the second most important risk factor for lung cancer [4] [5]. Nowadays, in Europe, mortality derived from indoor radon gas exposure represents 9% of all annual deaths from lung cancer [4]. Hence, the new legislation publication to tackle the radon risk in buildings and workplaces is an important safeguard measure.

2013/59/Euratom Directive [11], relative to protection against the dangers arising from exposure to ionizing radiation was transposed into Portuguese legislation on December 3, 2018 [12]. The new Portuguese law is now the legal regime for radiological protection, specifying the national authorities' responsibilities on the subject.

The new Portuguese law in force imposes the obligation of protection against radon gas by analyzing the workers or members of the public to radon gas exposure and to radiation exposure derived from construction materials (Articles 2.3 and 133) [6]. The exposure limit to radon gas concentration (reference level for annual average concentration) is 300 Bq/m^3. This limit is valid for dwellings, public buildings, and workplaces (Article 145) [12].

In buildings displaying radon gas concentration above the so-called reference level, the building owner or manager must define a strategy for occupant protection with the aim of reducing radon concentrations to an optimal level (Article 149) [12].

According to the law, a National Radon Plan (Article 150) [12] is planned. The Plan responsibility lies with the Portuguese Environment Agency (APA), a public institute, in charge of taking a set of actions for indoor radon occupational exposure reduction, namely: i) to draw a radon risk map; ii) to identify higher radon concentration buildings; iii) to study preventive measures for new buildings to monitor underground workplaces and schools; iv) to implement post-construction corrective measures; v) to define remediation techniques and tools to prevent radon penetration in new buildings; vi) to raise public awareness; and vii) to alert employers and employees for radon risks, mainly combined with tobacco risks in case of smokers.

IV. EXPERIMENTAL CAMPAIGN

The experimental campaign focused on the indoor radon concentration assessment in a set of 15 public buildings in the Northwest of Portugal during winter and summer 2018. Along with radon assessment, the campaign measured indoor air temperature and relative humidity in all monitored rooms. The buildings' selection depended on its type of construction (granite walls, partitions, and floors) and on the nature of its foundation made of granitic soil, quite prevalent in the Northwest region of Iberian Peninsula. The rooms picked for instrumentation show different occupants' number and distinct occupation schedules. The occupation profile for each building is related to the work schedule of the employees. The monitoring campaign was divided in 2 periods - the winter and summer period, both lasting a week and involving 15 buildings:

- The 1st instrumentation period (winter) ran from January 9 to February 28, 2018. Some specific conditions for winter period assessment can be listed: rooms heating systems were on during the monitoring period; no ventilation actions were undertaken by the occupants in order to keep thermal comfort in the heated rooms.
- The 2nd instrumentation period (summer) ran from June 26 to September 19, 2018. Some specific conditions for summer period assessment can be listed: rooms cooling systems were off during the monitoring period; ventilation actions were undertaken by the occupants mostly by daily windows opening. The air renovation contributed to increasing occupants' summer thermal comfort.

Rooms' occupancy was the key variable for sample selection. Monitoring priority was given to rooms occupied by a different number of people to evaluate its effect of the on radon concentration performance. Hence, it was possible to study occupation influence on all monitoring parameters performance, also including indoor air temperature and relative humidity).

Particular attention was given to some particular rooms - classrooms in the school building, office rooms in services buildings and exhibition halls in museums, art centers, and galleries were chosen given the number of occupants and its occupancy rate.

According to Table 1, each instrumented building (sample) was identified by an alphabetic letter from A to O. Each sample was divided into *subsamples* numbered from A1 to O2. 2 different rooms per building were monitored, exception made for buildings with 1 floor, where both rooms were monitored at the same level.

In situ measurements were taken continuously using digital radon probes (1-hour resolution) with incorporated data log. Indoor air temperature, relative humidity, and radon concentration were monitored with the same probe. Probes location was done away from doors and windows and far from radiation sources and electronic equipment.

Probes specification for data logging (Airthings) can be found in [13]. Through a survey, the ventilation actions undertaken by the occupants of the monitored rooms were registered and afterward analyzed. The same survey allowed the occupants to register the operating time for the heating systems, as well as the occupancy schedules of monitored rooms. Table 1 summarizes the instrumentation plan.

Table 1. Synthesis of the monitoring campaign

Period	Sample		Public building	Room	Floor
1st – 09 to 16/01	A	A1	Tourism office	Help desk	Ground
2nd – 12 to 19/09		A2		Help desk	High
1st – 09 to 16/01	B	B1	Museum 1	Exhibition hall	Ground
2nd - 26/06 to 03/07		B2		Exhibition hall	High
1st – 09 to 16/01	C	C1	Cultural center	Office	Ground
2nd - 26/06 to 03/07		C2		Office	High
1st – 16 to 23/01	D	D1	School 1	Classroom	Ground
2nd - 03/07 to 10/07		D2		Classroom	High
1st – 16 to 23/01	E	E1	Museum 2	Exhibition hall	Ground
2nd - 03/07 to 10/07		E2		Technical room	High
1st – 16 to 23/01	F	F1	Municipal theater	Ticket office	Ground
2nd - 03/07 to 10/07		F2		Office	High
1st – 23 to 30/01	G	G1	Municipal facilities	Technical office	Ground
2nd - 10/07 to 17/07		G2		Technical office	High
1st – 23 to 30/01	H	H1	Environmental monitoring center	Technical office	Ground
2nd - 10/07 to 17/07		H2		Technical room	Ground
1st – 30/1 to 06/02	I	I1	City Hall	Technical office	Ground
2nd - 10/07 to 17/07		I2		Technical office	High
1st – 30/1 to 06/02	J	J1	School 2	Classroom	Ground
2nd - 17/07 to 24/07		J2		Classroom	High
1st – 14/2 to 21/02	K	K1	Teachers´ association	Office	Ground
2nd - 19/09 to 26/09		K2		Office	High
1st – 14/2 to 21/02	L	L1	School 3	Classroom	Ground
2nd - 17/07 to 24/07		L2		Classroom	High
1st – 21/2 to 28/02	M	M1	School 4	Classroom	Ground
2nd - 24/07 to 31/07		M2		Classroom	High
1st – 21/2 to 28/02	N	N1	School 5	Classroom	Ground
2nd - 24/07 to 31/07		N2		Classroom	High
1st – 21/2 to 28/02	O	O1	Kindergarten	Classroom	Ground
2nd - 12/09 to 19/09		O2		Classroom	Ground

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V. RESULTS & DISCUSSION

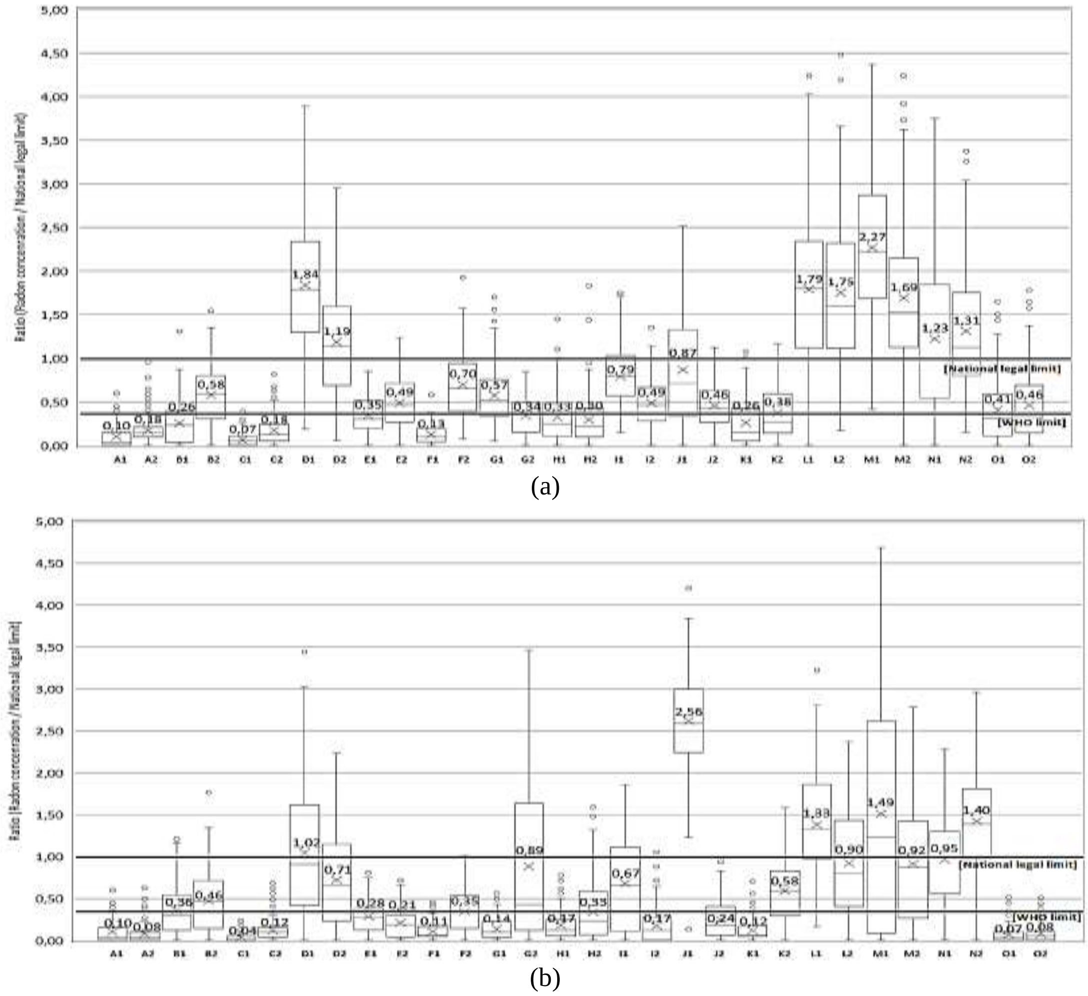
Figure 2 a) and b) synthesize the experimental results gathered during the experimental campaign of 2018, by using a boxplot representation. Boxplot diagrams depict data variation along the monitoring period for a set of 15 public buildings in a city in the Northwest of Portugal, both for winter and summer instrumentation. Buildings were monitored in 2 different rooms - Figure a) and b) show 30 boxplot diagrams corresponding to 30 monitored rooms.

A Boxplot diagram is a statistical tool which summarizes collected data over the monitoring periods — each boxplot includes five statistical parameters: the minimum, the first quartile (Q1), the median, the third quartile (Q3) and the maximum. Some isolated points (outliers) without statistical relevance are also represented. On each boxplot is inscribed the arithmetical mean value for indoor radon concentration during the monitoring period, 2 horizontal lines parallel to the abscissa axis represent, respectively, the WHO limit and the national limit for indoor radon concentration. Values represented in the ordinate axis are dimensionless — the base reference is the National legal limit of 300 Bq/m^3.

The graph in Figure 2 a) (winter) allows concluding that in 8 out of 30 samples (27%) stay above the National legal limit of 300 Bq/m^3 for radon concentration. When the considered limit is the WHO action level of 100 Bq/m^3, samples number rise to 22 (73%). The graph in Figure 2 b) (summer) show improved results — only 5 out of 30 (17%) samples exceed the National legal limit of 300 Bq/m^3 and 16 out 30 (53%) are above the WHO limit.

The 5 most problematic samples both for winter and summer measurements are samples D1, J1, L1, M1, and N2. Samples labeled with "1" correspond to rooms placed in the ground floor, hence there´s strong evidence for higher radon concentrations in rooms placed in the ground and underground floors.

The graphs in Figure 3 a) and b) represent the variation over time of the indoor radon concentration, air temperature and relative humidity for sample D1 (classroom in ground floor). Sample D1 was chosen due to the high radon concentrations both for winter and summer measurements. Both graphs were plotted for an observation period of 1 complete week. The time periods for human occupancy and ventilation actions undertaken by the users are directly identified on the plots. Ventilation actions were only performed during the summer by windows opening.



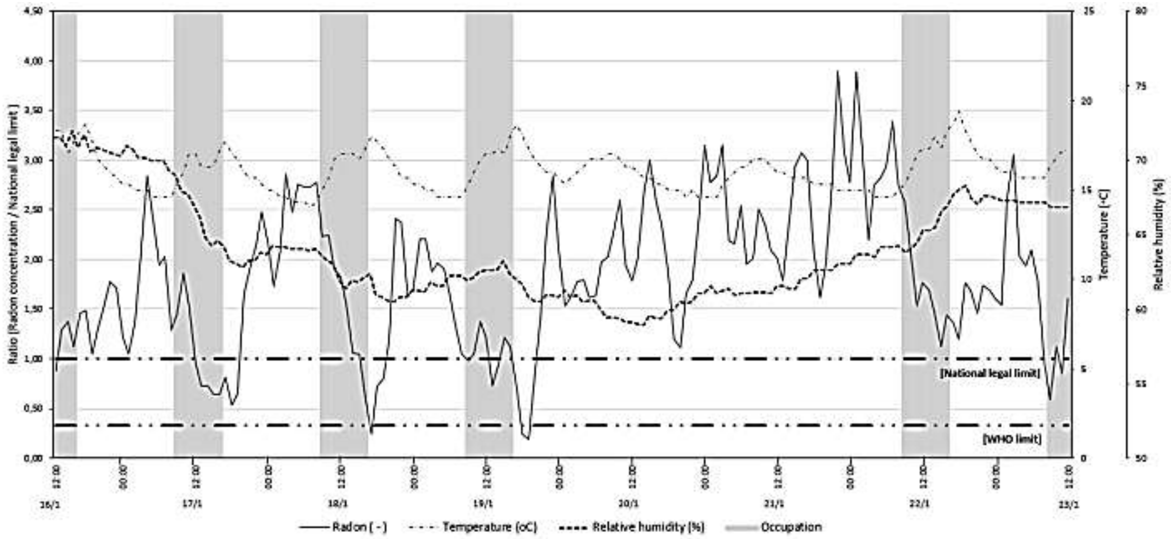
(a)

(b)

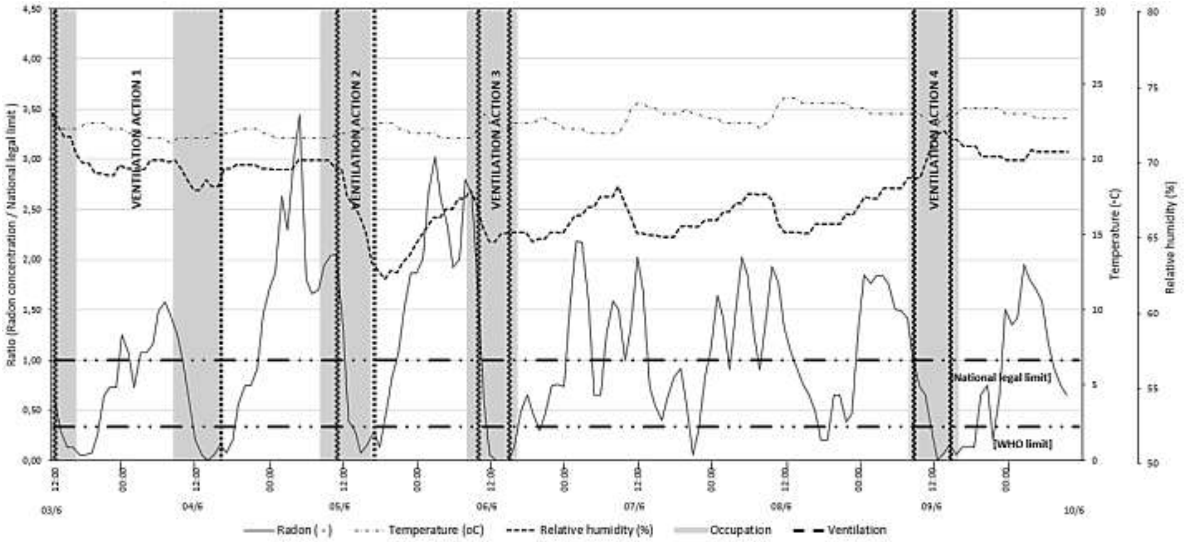
Fig. 2. Statistical results for the monitoring campaign (winter and summer seasons)

Data variation in graphs of Figure 3 a) and b) show a significant reduction on indoor radon concentration as a result of the occupancy of the classroom. The reduction is more evident in summer, where the occupancy comes combined with ventilation actions performed by the users. During summer in accordance with the ventilation periods, it´s evident a reduction on the indoor relative humidity and a steady variation on the air temperature. On the other hand, in winter it´s evident an increasing of indoor air temperature along the periods of occupation of the classroom, and no substantial variation on relative humidity due to room occupation and ventilation. The variation on relative humidity is related to outdoor environmental changes.

In short, it´s possible to identify with the observation of graphs in Figure 3 a) and b) a direct correlation between indoor radon concentration reduction and the increment of summer ventilation rates. In winter it´s evident an indirect correlation between radon concentration and indoor air temperature — when the radon concentration decreases the indoor air temperature rises due to the presence of occupants in the room. No evident correlation between radon concentration and relative humidity is shown, both in winter and summer.



(a)



(b)

Fig. 3. Variation over 1 week time for radon concentration, air temperature and relative humidity (winter and summer seasons)

VI. RADON MANAGEMENT

Health risk associated with radon gas exposure in enclosed rooms with low ventilation rates, where people pass a considerable amount of time, cannot be negligible.

World Health Organization (WHO) introduced in 2005 the International Radon Project (IRP) [14]. IRP aimed to aid member states to develop strategies regarding not only radon risk analysis and remediation but also radon risk communication to the public. In 2009, WHO published a handbook oriented to health risks reduction derived from radon exposure in residential houses from a public health perspective [15].

WHO agenda have hugely contributed to improving people awareness about radon risk, since IRP and WHO handbook [15] strongly encouraged buildings´ owners and managers to carry out radon mitigation actions when necessary.

However, a radon management strategy is a much broader project than simple radon mitigation or risk communication. When we are discussing radon management, we refer to a comprehensive strategy involving a diversity of actions undertaken to reduce radon risk. Radon management involves not only public education by promoting awareness campaigns, but also actions, such as the development of extensive radon monitoring campaigns for public buildings and homes in high-risk regions followed with the implementation of mitigation actions, development of technical *capacitation* actions for radon remediation oriented to local companies, development of work together with construction companies making radon a part of the training program to increment companies awareness and skills to developed new technologies focused on radon mitigation, and implementation of programs of subsidies for residential houses remediation.

To carry out a radon management strategy for the 15 public buildings instrumented under the scope of the research project RnMonitor it is important to have in mind that the studied buildings are municipal buildings providing public services. This corresponds to a big difference between buildings occupancy schedules and occupants profile — the case study included schools, museums, galleries, theaters, municipal bureaus, and offices, etc. The action plan designed for a radon management strategy should include:

1) Long-term monitoring campaign over a period not less than 3 months, focused on buildings in which radon concentrations were above the National legal limit. The monitoring campaign should include all rooms occupied for a time period of more than 4 hours a day.
2) Radon risk analysis by using a dosimetric approach validated by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and based on the indoor annual effective doses calculation from radon exposure [16] [17] for a predefined building occupation schedule.
3) To implement specific remediation actions designed for buildings with increased radon risk for occupants, after a dosimetric assessment for radon risk analysis according to 2). The mitigation actions should include typical ventilation actions by windows opening or mechanical air extractors' activation, for a time period enough to reduce indoor radon concentration below a safe level. If mitigation actions fail to reduce to radon risk in critical compartments, a solution for the problem must involve removing people working in rooms radon-exposed.
4) To develop awareness-raising actions among building users and occupants. The campaigns must increase radon awareness as a health issue and translate it into mitigation actions developed by the occupants, mainly by adopting predefined ventilation procedures according to programmed schedules. The awareness-raising campaigns must be focused on prevention by avoiding unnecessary panic towards radon risk subject.
5) Design a web-based platform for integrated radon risk management that will enable real-time radon gas monitoring and specific mitigation actions control, cf. Fig. 4. It includes specific hardware designed to collect and communicate data to a cloud-based server. The collected data are then reasoned by a cloud engine to trigger specific mitigation actions using two distinct approaches: i) automatic ventilation actions (closed-loop control) and ii) manual ventilation actions (human-in-the-loop control).

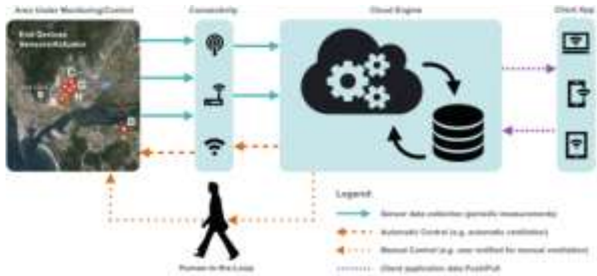


Fig.4 – Conceptual RnMonitor system architecture.

VII. CONCLUSIONS

An experimental campaign was carried out in winter and summer of 2018 to assess radon indoor concentration in 15 public buildings in a medium-sized city in the Northwest of Portugal, Western Europe, under the scope of the R&D project RnMonitor, by taking short-term measurements for all instrumented rooms. The case study included municipal buildings (schools, museums, galleries, theaters, and municipal bureaus and offices) providing public services. Monitored buildings differed not only on its architecture and its construction period, but also on the number of occupants, its habits, and occupancy schedules. The experimental results allow the following conclusions:

1) Radon gas concentration is generally higher in ground floor rooms. In fact, radon gas propagation derives mainly from the buildings' foundation soil. Walls and pavements building materials effect on radon gas propagation is reduced when compared to the effect produced by the soil.
2) Radon gas concentration tends to reduce with the time period of rooms occupation. This reduction is more evident in summer when ventilation actions undertaken by the occupants became more frequent. In fact, poorly ventilated rooms in radon risk areas lead to higher radon gas concentration.
3) A radon management strategy for the 15 public buildings part of the case study is mandatory. Short-term characterization results recommend the adoption of a long-term analysis over a time period, not less

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than 3 months. The long-term monitoring campaign should be particularly focused on buildings with higher indoor radon concentration according to National regulation in force.

4) Radon risk analysis should be assessed according to dosimetric approach validated by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Afterward, an action plan for buildings with higher risk impact is strongly recommended.
5) To implement effective mitigation actions for critical buildings regarding occupants radon risk. If mitigation actions fail to reduce radon risk, the solution must involve a rooms' occupation redefinition by avoiding people presence for a large time period in order to reduce radon gas exposure.
6) To develop awareness-raising actions among building users and occupants.
7) To create an integrated platform for radon gas real-time visualization in the monitored buildings.

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