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A pre-diagnosis model for radon potential evaluation in buildings: A tool for balancing ventilation, indoor air quality and energy efficiency

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Abstract

In a very early stage of implementation of a comprehensive experimental campaign for indoor radon assessment, a pre-evaluation selection of the variables that play a leading role in influencing expected results must be insightfully assessed, by stimulating compatibility between Indoor Air Quality (IAQ) and energy efficiency. Hence, a practical methodology for variable selection based on an analysis of historic data plays a key role concerning radon potential assessment, while never losing sight of the building energy performance. Given the circumstances, this work is focused on the design of a qualitative pre-diagnosis model for the evaluation of radon potential in indoor environments, for different energy efficiency scenarios, by considering a set of relevant variables carefully selected to characterize occupants' risk exposure. A prior survey was done to identify all relevant characteristics that most affect both Indoor Air Quality (IAQ) and building energy efficiency, mainly concerning local geology, thermal insulation, ventilation schemes, energy equipment, renewable energy assets, and occupancy schedules. The selected parameters will be afterward weighted and combined into performance indicators through an evidence-based literature review. In the current early stage, the requirements to drive the software development are presented, together with a software architecture proposal. Finally, it is expected that this pre-diagnosis model will allow a more refined sample selection for indoor radon assessment, by choosing the most susceptible variables that influence radon potential in a given scenario and making it compatible with the building energy efficiency.

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Keywords: Indoor radon assessment; Radon performance indicator; Radon potential; Energy efficiency; Energy performance; Energy equipment; Ventilation; Indoor air quality

1. Introduction

Radon is a noble radioactive gas found freely in the natural environment, odorless, colorless, and tasteless. It arises through the decay of uranium and is prominent on granite and schist soils and substrates, rocks, and even

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in borehole water. Though in smaller concentrations, radon is also present in some specific building materials such as concrete, brick, and aggregates [1]. In normal environmental conditions, such as those that exist on the earth's surface, radon exhalation from the soil occurs in the gas form, presenting in outdoor environments low concentrations of approximately 10 Bq.m-3 with reduced known impact on human health [2]. However, the accumulation of radon gas in indoor environments of high-energy performance buildings, often poorly ventilated, represents a known public health problem, extensively reported by the World Health Organization (WHO). Radon gas is approximately 8 times denser than air [3], and therefore in airtight high-energy performance buildings it seems to exist a relationship between significant indoor radon concentration levels and the prevalence of respiratory diseases, mainly lung cancer [1]. Previous research works have been carried out to highlight the correlation between high indoor radon concentration, and the lack of air renovation prevalent in high energy-efficient buildings [4]. However, an extensive analysis including other influencing parameters like the local geology, the implementation of new renewable energy equipment, the changing of ventilation schemes, is yet to be done.

Besides ventilation, the relationship between local geology (soil type, composition, and layers), all assets concerning energy efficiency refurbishment, and features (floors below ground level versus floors above ground level, applied building materials, and surface finishing, the existence of technical galleries, culverts, pipes or other infrastructures under buildings' floors, etc.), as well as building occupancy schedules, are additional parameters very relevant for determining the radon potential of a given room part of a critical building located in a specific risk location.

The main objectives of this research work are the following: (1) propose a methodology for radon potential assessment – Rn potential – based on historic data analysis, by considering a set of influencing variables previously selected, systematized, and categorized; (2) design a pre-diagnosis model for sample selection in a preliminary stage of an experimental campaign for indoor radon assessment, bearing in mind possible previous building rehabilitation for low-energy.

This pre-diagnosis model will incorporate the most influencing variables previously selected by the Rn potential methodology. A pre-diagnosis assessment is a form of pre-assessment where the radon potential of a certain site can evaluate a building's tendency concerning indoor radon exposure. With this form of assessment, a meaningful and efficient experimental campaign can be implemented, without spending unnecessary time and resources on measuring buildings with low radon indoor risk exposure, always having regard to previous energy retrofitting scenarios.

The next section summarizes previous research works that identified the major factors contributing to high indoor radon concentration throughout several countries. Section 3 proposes a method to design a qualitative pre-diagnosis model for assessing indoor radon potential. Section 4 describes the expected outcomes of this model.

2. Related works

According to the literature, a pre-diagnosis model to assess radon potential must include a preliminary task consisting of gathering systematic information collected from previous experimental campaigns, creating in an inventory, a set of radon measurements carried out for different types of buildings: residential, school, kindergarten, administrative offices, historical buildings, etc.

High radon potential is consensually attributed to geosites underlying constructions [5], however previous building energy refurbishment or some other specific retrofitting actions undertaken to improve building energy performance must be taken into consideration since constructions itself play an important role in indoor radon exposure. Most authors emphasize that the territory is endowed with high geodiversity, namely: residual; granitic; tectonic; fluvial; wind, and geocultural geoforms, therefore increasing the tendency for increasing radon exposure. Beyond geologic issues, most instrumented buildings are operated with natural ventilation, mainly those that were retrofitted in order to reduce energy consumption, therefore indoor radon concentrations show daily and seasonal variations, floating throughout the day and over the year. Indoor radon concentration tends to be higher at night than during the day, and during winter when compared to other seasons, since buildings are densely occupied and airtight, due to strong energy-efficiency concerns, with the heating systems turned on, and so the heat flow tends to increase air pressure difference, acting as a radon soil "vacuum cleaner". On the other hand, in summer due to increased natural ventilation by windows opening in low energy consumption buildings, indoor concentration tends to reduce.

The following research state the importance of site geology, building energy efficiency, and ventilation on indoor radon potential:

- Barros-Dios et al. [6] conducted a cross-sectional study analyzing indoor radon concentration in a set of distinct 983 homes subject to different types of energetic rehabilitation of the constructive envelope. The bivariate analysis found that several factors influence indoor radon concentration, mainly the building age and its energy efficiency class, the location where in situ measurement took place, the building materials applied to improve energy efficiency, and all finishing coverings. In general, dwellings made of granite stone show higher radon concentrations. Additionally, the study revealed a positive correlation between indoor radon concentration and the altitude above sea level. Multivariate analysis found 4 variables with significant influence on radon concentration: the age of dwelling which is correlated to the building energy efficiency; the total number of floors; the building height, and the building finishing coats and construction materials applied for energy performance improvement. The model variability explained 10% of the studied cases. No significant differences between houses with and without cellars were detected.
- Regarding the same subject, Claus Andersen et al. [7] developed a linear regression model for indoor radon prediction in Danish houses. The model was calibrated against radon measurements in a set of 3116 single-family houses and apartments, by using an independent dataset with 788 house in-situ measurements concerning model performance assessment. Nine exploratory variables were tested, however, the most influencing variables concerning radon potential are the house type and the kind of rehabilitation the building was subjected to in order to improve its energy efficiency, and the local geology.
- To assess radon potential, Cortina et al. [8] performed a year-round study concerning indoor radon assessment in Santiago de Compostela, Galicia, Spain. A total of 233 samples at 59 different locations in 16 buildings were analyzed, showing a direct correlation between the indoor radon concentration and outdoor air temperature. No other correlation could be established with other climatic variables (wind direction, humidity, etc.). According to the authors, room ventilation which is directly related to the building energy efficiency, along with all human activities developed within the building, is the main factor influencing indoor radon concentration.
- Martins et al. [9] measured indoor radon concentration in a set of 73 dwellings in 3 different geological sites in Amarante, Portugal: soil in coarse-grained, porphyritic biotite granite (AT1), soil in medium-grained biotite granite (AT2), and soil in metasediments rocks of Paleozoic age (MTS). Average indoor radon concentrations in winter conditions are, respectively, 85, 220, and 430 Bq.m-3 for dwellings in MTS, AT1, and AT2 sites. Based on the results, the authors concluded that local geology is the most relevant factor concerning indoor radon concentration, nevertheless, the building characteristics, namely if it was subject to an energy efficiency refurbishment, can play an important role.
- Groves-Kirkby et al. [10], assessed indoor radon concentration and air temperature in an environmentally stable, rarely-visited basement in a public-service building, from June 2003 to March 2008. The authors detected a good correlation between indoor radon concentration and indoor–outdoor air temperature difference, suggesting that the principal driver for indoor radon potential is the atmospheric moisture content rather than indoor relative humidity. The authors did not study the impact of buildings' energy performance on radon potential.
- Martins et al. [11], in Vila Pouca de Aguiar, North of Portugal, stated that 62.6% of analyzed dwellings (n=57) present average indoor radon concentrations exceeding, by far, the national legal limit. The authors reported that the most problematic dwellings have less than 50 years old, are constructed with a basement, are low ventilated, well-insulated, and have been retrofitted to improve energy efficiency and thermal comfort. Recent buildings are more critical than the old ones, due to the lack of ventilation which derives from the necessity of reinforcing energy efficiency.
- Collignan et al. [12] conducted an indoor radon monitoring campaign evolving 3400 dwellings in Brittany, France from 2011 to 2014. Based on the study, the authors concluded that indoor radon potential is related to the total floor number, the sampling level, the type of foundation, the construction period which is directly related to the building energy performance, the construction material, the ventilation system, the use of wood heating, and the existence of a previous energy efficiency refurbishment.
- Under the scope of R&D Project Fundação Ilídio Pinho [4], a set of 9 buildings in Alto Minho region, Viana do Castelo, Portugal, was monitored continuously to assess indoor radon concentration. The authors state that all instrumented buildings share similar types of construction and energy efficiency, identical characteristics of the foundation soil, but different occupancy schemes and ventilation rates. As expected, rooms' occupancy and ventilation actions performed by the occupants played an important role in indoor radon concentration, and consequently on radon potential assessment.

- R&D Project RnMonitor (2021) monitored two sets of 15 public buildings made with granite blocks, in 2 different regions in the Northwest of Portugal. The monitored buildings diverged on construction period, energy efficiency, occupancy, ventilation schemes, and devices. The results showed the influence of local geology, room ventilation, and energy efficiency on indoor radon potential. Rooms in basements and ground-floor levels low ventilated and highly insulated, show higher indoor radon concentration [13,14].

Based on the related research works, a pre-diagnosis model concerning radon potential assessment must include the analysis of variables like site geology, construction materials, energy systems and equipment, ventilation schemes, occupancy rates, and heating devices. Previous research found a correlation between the indoor radon concentration and several factors, that can be external or internal to the building. The external factors are related to the building localization and the climate conditions: geology and lithology, region, elevation above sea level, location on a hill or slope, air pressure difference, outdoor temperature, and total atmospheric moisture. The internal factors are composed of the foundation type, the existence of a basement, the construction materials and the building energy efficiency, the story (distance from the ground), ventilation system, heating devices, and energy systems, previous energy retrofitting, and indoor relative humidity. Table 1 shows the list of factors and respective research that found the correlation of each factor with the radon gas concentration.

Table 1. List of factors correlated with indoor radon concentration.

Category	Factor	References
External factors	Geology and Lithology	[7,9,11,15]
	Region	[7]
	Elevation above sea level	[6]
	Location on a hill or slope	[15]
	Air pressure difference	[15–18]
	Outdoor temperature	[8,16,17]
	Total atmospheric moisture	[10]
Internal factors	Foundation type	[6,7,12,15]
	Existence of basement	[6,7,11,15,19]
	Building materials and thermal insulation	[6,7,12,15]
	Story (distance from the ground)	[6,7,12,19]
	Ventilation system	[12,19]
	Heating systems	[12,16,19]
	Thermal retrofit	[12]
	Indoor relative humidity	[17]

3. Materials and methods

Based on the evidence presented in the literature, the first step in the design of a qualitative pre-diagnosis model for indoor radon potential evaluation is the selection of a set of relevant variables correlated with indoor concentration level. These variables consist of a set of characteristics that will be selected from the work developed in the scope of previous Indoor Air Quality (IAQ) and Energy Efficiency research, according to three categories: local geology, building energy performance, and occupancy schedules.

In parallel, the research team is gathering systematic data on radon concentration measurements and enriching this data with these three categories of characteristics. The inventory of our previous studies comprises radon measurements carried out in different types of buildings: dwellings, schools, and administrative offices. This list includes several heritage buildings in the historic center of cities of North of Portugal. Then, it will be assessed the correlation and relative weight of each variable concerning the radon to select the set of the most relevant characteristics or factors. Based on that set of variables, it will be developed a qualitative pre-diagnosis model for the evaluation of radon concentration potential in indoor environments through the possible use of classification and regression trees.

A pre-diagnosis model is an interactive tool where the user can verify the need to carry out a radon assessment study, starting from a set of variables. This approach allows the determination of the level of radon occurrence potential in a building, be it for housing or as the workplace. The pre-diagnosis model aims to measure the level of risk so that the necessary measures can be taken, after confirmation by assessment, to mitigate the problem and consequent monitoring. Thus, the pre-diagnosis model is based on the determination of the potential of radon concentration, assuming a set of variables, namely the location, the type of occupancy of the building, and the type of construction which is strongly related to the building energy performance, as shown in the flowchart of Fig. 1.

In the specific case of the location, which is a critical variable because it is directly related to the geology of the place, is decisive for the occurrence of radon. However, also for the other variables, the user must provide indications so that the pre-diagnosis model can determine the potential occurrence of the radon. In this way, the user must enter information about the variable's location, occupation schedules, ventilation schemes, and the building energy performance. For example, is the building subject to permanent occupation or is it occasional? Is the building constructed with a crawl space, a slab-on-grade, or a basement with a slab foundation? What is the most prevailing building material and which are the applied windows? There was the introduction of energy efficiency measures when the building was subject to major renovation? Is the room under monitoring placed in the building basement, on the ground floor, or the 1st or upper floor? Does the room have any kind of ventilation system applied, or is it operated with natural ventilation? Is the building operated with heating and air conditioning equipment or other similar solutions?

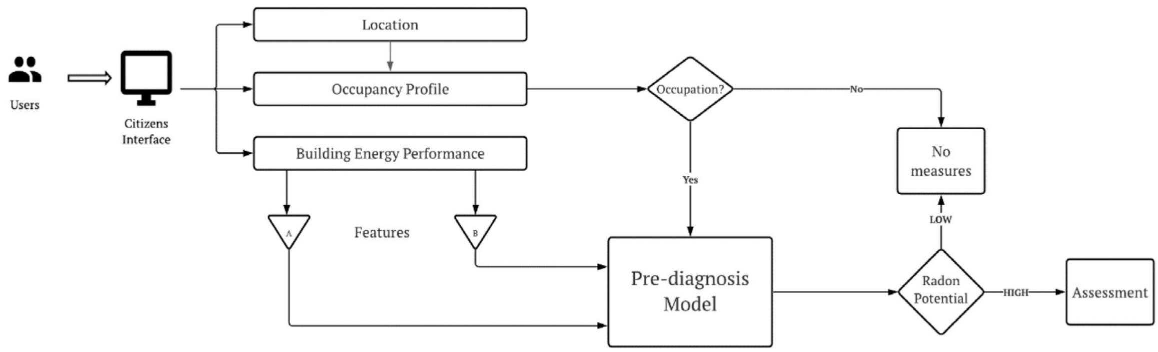

Fig. 1. Pre-diagnosis model.

After assigning a weight to each variable, these are the characteristics that will allow building a pre-diagnosis model to assess the potential for radon occurrence inside the building. When the result points to a low potential, it is not necessary to implement radon mitigation procedures. However, if the pre-diagnosis model points towards the verification of high potential, in situ assessment measures should be taken to quantify radon concentrations and to be able to calculate the doses to which the building's occupants may be exposed.

4. Results and discussion

In order to implement the Pre-diagnosis model, a platform for indoor radon potential evaluation will be implemented accordingly to Fig. 2. The platform combines geologic information gathered from external entities with data inserted by the user to evaluate the assessment, concerning building occupancy, ventilation schemes, and building energy performance. The result is made available through a web server accessible to users via a web browser or a mobile device.

For assessing radon potential based on geographical location, the platform gathers Gamma radiation data from the Portuguese National Energy and Geology Laboratory (LNEG). This data is used to estimate the geogenic radon potential in the location of the building [20]. The user should provide relevant building characteristics, including energy performance parameters, and the room occupation schedule. The entered data will be stored in the database server which contains the corresponding radon measurements. The radon potential engine will use these data

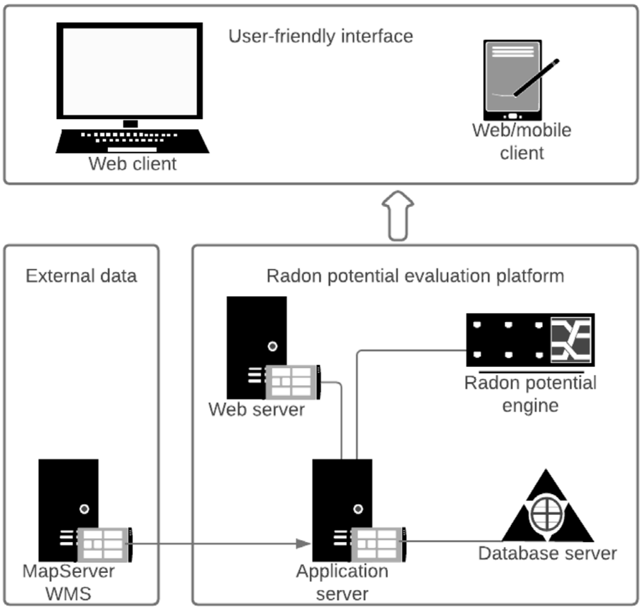

Fig. 2. High-level architecture for the radon potential evaluation platform.

combined with indoor radon concentration historic data, enhanced with the occupancy schedules, the ventilation profiles, and with the building energy efficiency characteristics to estimate the radon potential level.

The platform user interface of the platform is very friendly and easy to use, keeping in mind that it is designed for the general public, therefore it must be avoided unnecessary technicalities that will only increase the complexity for the final user. In the first step, the user will insert data about the building location, the room occupancy schedules, and the building characteristics, according to Fig. 3 (type of building foundation, building construction, type of ventilation, and other building energy efficiency data). In the second step, the platform will inform the user about the radon potential estimated level. These measurements should be later introduced in the platform associated with the data inserted by the user in the first step. The in situ measurements and the corresponding building characteristics are stored in the database and will be used to continuously tune the radon potential evaluation.

In case of high potential results, as previously referred, the user will be recommended to proceed to a detailed indoor radon concentration assessment and afterward to implement remediation measures to reduce radon risk exposure. Based on the in-situ radon measurements, a specific mitigation strategy should be proposed and implemented. In most cases, ventilation-based approaches will be used due to their easy and inexpensive implementation, as well as some other specific energy efficiency measures designed to reduce radon risk exposure. In-situ active ventilation, automatic or manual, despite improving Indoor Air Quality, can have a negative impact on the building energy efficiency by increasing heat losses. This way, ventilation actions should be implemented carefully to avoid boosting energy consumption, both for heating and cooling.

5. Conclusions

The goal of this work is to design a qualitative pre-diagnosis model for indoor radon potential risk evaluation, by considering a set of relevant variables carefully selected to characterize occupants' radon risk exposure. To select the referred variables, a list of relevant factors that most affect indoor radon concentration was chosen and divided into external and internal factors. The external factors are mainly related to climatic, geological, or other physical variables, and the internal factors are related to the building's energy efficiency variables (insulation, energy equipment, ventilation), and occupancy schemes. The designed platform integrates radon measurements data sets and related with the selected factors that most affect the obtained results for a particular building. By using this methodology, a radon potential analysis can be adopted as the first approach for indoor radon concentration assessment.

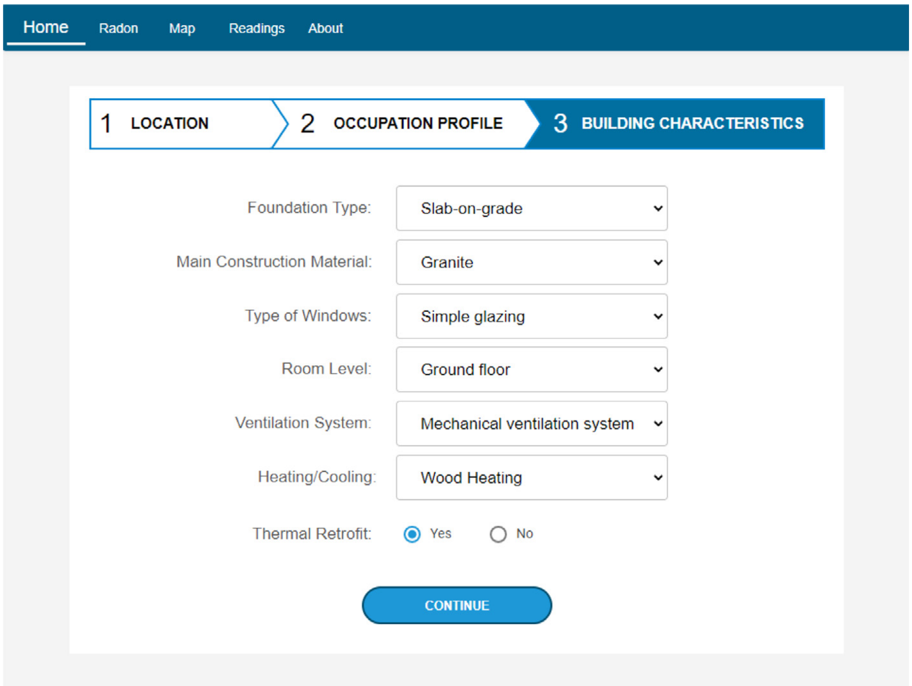

Fig. 3. Interface example for the radon potential evaluation platform.

The final goal is to provide a tool for general public access so that a pre-diagnosis analysis concerning indoor radon potential can be implemented. This tool can be understood as a software tool to support the first step of a broader approach to public health problems.

After this stage is concluded, a short-term radon concentration assessment must be implemented whenever a user gets a high-risk estimate. Moreover, if the short-term assessment confirms the high-risk prediction, a further long-term radon concentration measurement should be carried out. At last, after the long-term measurement confirms the high-risk initial prediction, an in-situ remediation program will be implemented to reduce indoor radon exposure.

Recently retrofitted buildings play an important role in the current model development since well-insulated walls, windows, and roofs with high energy efficiency performance can lead to an air renovation reduction, designed to optimize winter thermal comfort. Nevertheless, the ventilation strategies are essential to improve Indoor Air Quality and reduce indoor radon potential without compromising the building energy efficiency. Radon mitigation strategies should accomplish a good trade-off between Indoor Air Quality and energy efficiency in order to improve indoor air quality with low impact on energy efficiency.

CRediT authorship contribution statement

Joaquim Silva: Investigation, Conceptualization, Supervision, Validation, Formal analysis, Validation, Writing – original draft. **Nuno Lopes:** Conceptualization, Supervision, Writing – review & editing. **António Curado:** Conceptualization, Validation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Leonel J.R. Nunes:** Data curation, Writing – review & editing. **Sérgio I. Lopes:** Conceptualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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