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Tools for planning large-scale measurement surveys for the assessment of indoor environmental pollutants: the case of radon

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Abstract

Risks from indoor pollutants require the implementation of effective policies to prevent and reduce exposure. To take decisions and actions, competent authorities need relevant information. In the case of indoor radon exposure, surveys are carried out by installing detectors in buildings (homes, workplaces) that measure radon concentration in rooms. Conducting national or large-scale surveys in buildings requires addressing both technical complexities of implementation and economic costs. In order to support the implementation of large-scale radon surveys, procedure and tools are described for defining the sample size of buildings to be measured according to available resources, for planning the sampling of buildings in relation to the specific objectives of the survey, and for obtaining a tool for management and control of sample recruitment and installation of radon detectors in buildings, reducing sources of bias. A particular application is shown for the case of the EU radon regulation.

Keywords: Indoor radon, measurement survey, sampling strategy, population

INTRODUCTION

Air pollution, both outdoor and indoor, represents the biggest environmental risk to health [1]. Despite people spending 80%-90% of their lives in indoor environments, and energy efficiency policies for buildings tend to increase the accumulation of indoor pollutants, indoor air pollution has traditionally received less attention than outdoor pollution [2].

The WHO guidelines for the protection of public health from risks from chemicals commonly found in indoor air [3] considers substances known to be hazardous to health, such as benzene, carbon monoxide, formaldehyde, naphthalene, nitrogen dioxide, polycyclic aromatic hydrocarbons, radon, trichloroethylene, and tetrachloroethylene. To prevent and reduce the concentration of these substances in indoor environments, authorities must implement appropriate policies and actions, as well as establish a framework of legally enforceable standards. This requires scientifically based information that enables authorities to objectively understand the situation in the country in order to make decisions.

In the case of radon, a naturally occurring radioactive natural gas derived from uranium in the soil, it penetrates from the ground and accumulates in buildings, so indoor radon concentrations can vary greatly depending on the geology. Building materials can also be an important source of radon in some cases. Because indoor radon concentration also has high temporal variability, the annual average indoor radon concentration is used as a fundamental parameter related to occupant exposure. The only way to know the indoor radon concentration is to take a measurement, so radon detectors are installed in homes and workplaces to determine the annual average indoor radon concentration.

Since radon is considered the second leading cause of lung cancer after smoking [4], competent authorities might conduct measurement surveys of annual average indoor radon concentrations in buildings to understand the spatial distribution of radon levels at the regional or national level [5,6] or to assess population exposure or to quantify the risk as the number of lung cancer cases attributable to radon [7–9]. All this information is essential to quantify the magnitude of health implications, to prepare actions to prevent (in new buildings) or reduce (in existing buildings) the risks from radon exposure, and to guide national policies or evaluate their long-term effectiveness.

The main objectives of a national radon survey are to estimate the population exposure to radon, to know the distribution of exposures, and to identify areas where significantly elevated indoor radon concentrations are most likely to be found [10]. In the first case it is necessary to plan a representative survey of the population in selected dwellings where measurements of the annual average radon concentration are to be made, in the second case to plan a combination of short-term screening and long-term measurements in selected dwellings [10].

In Europe, the European Council Directive 2013/59/Euratom stipulated that member states must establish national reference levels (RLs) not exceeding 300 Bq/m^3 annual average radon concentrations for homes and workplaces, must implement a national action plan addressing long-term risks from radon exposures in buildings, and must identify areas where indoor radon concentrations exceed the national RL in a significant number of buildings (art.103) [11]. In these areas, all workplaces on the ground and basement floors must compulsorily carry out radon measurements (art.54) [11].

National radon surveys require tens of thousands of indoor radon measurements and can raise many critical technical and practical issues that need to be addressed. A large number of detectors must be purchased, other materials may be needed for laboratory activities, detectors must be delivered and installed in buildings by trained personnel or sent by mail, occupants must be contacted and informed, and the return trip of detectors from buildings to the laboratory must also be managed to limit loss of information. Conducting the survey can be economically very costly, so it must be clearly established from the outset what the objectives and rationale for the survey are.

Primarily, it is important to assess what the expected output of the survey should be. Whether the goal is to know the spatial distribution of indoor radon levels, or to assess population exposure to radon, or to maximize the identification of dwellings with high radon concentrations, or additional needs determined by the state of knowledge. Each of these choices implies the need for different information and thus different sampling plans of buildings where to measure radon.

When no prior information is available, indoor radon measurement surveys are conducted to understand the country's average radon levels, so the goal is to estimate population exposure. Sample sizes used for surveys aimed at estimating the national average concentration or the average concentrations of major administrative districts typically ranges from a few to several thousand dwellings[12–15]. Such surveys can be repeated over time, years apart, to assess whether population exposure has remained constant or changed. Some environmental conditions, such as policies for energy efficiency in buildings, may have induced an increase in average radon levels and thus exposure[16,17].

When the goal is to estimate population exposure to indoor radon in a country, indoor radon measurements are made in dwellings, and surveys are generally designed with house sampling plans aimed at obtaining a representative sample of the population, thus with a population density-based survey (PD-based survey). As a result, only major population centers will be well represented[18] and dwellings should be sampled in all floors of buildings. Although concentrations in upper floors often do not have significant values in comparison with ground floors (the main source of indoor radon is soil), performing measurements exclusively or predominantly in dwellings on the ground floors would overestimate the average radon levels in the national housing stock.

Once the average radon levels of the country or major administrative districts have been estimated, there may be a need to assess radon levels in smaller districts, or to know the spatial distribution of radon levels with a more detailed spatial resolution to identify areas with average indoor radon levels higher than the national or administrative district levels. Outlining these areas allows the authorities to identify the vast majority of homes that exceed the RL in the country and focus actions to reduce the concentration in these areas. However, radon enters all buildings and high levels of radon can be found everywhere, although much less frequently than in radon areas, so the national radon strategy needs to deal more extensively with reducing the average concentrations of radon in dwellings (e.g., introduction of national building codes to limit radon ingress into new buildings) to achieve a long-term public health benefit[19]. Identifying dwellings with radon concentrations above the RL and implementing concentration reduction are two objectives that should be achieved by the national radon strategy[19]. The EU radon regulation, in addition to the obligation to identify radon areas, requires member states to promote actions, by technical or other means, to achieve these objectives (art.74)[11].

When the objective is to know the spatial distribution of radon levels, surveys can be designed with household sampling plans aimed at obtaining a spatially distributed sample to obtain information in all zones of the area of interest, thus based on the spatial distibution of the population-based survey (SD-based survey). The resulting sample of dwellings will not only be located in the most populated centers but will also reach out to less densely populated areas until, depending on the sample size, it covers areas with scattered houses. In this case, one could choose to make radon measurements only in dwellings on the ground floors to more directly identify the spatial variability of indoor radon and thus identify with greater spatial detail the areas with high indoor radon concentrations. The results of the SD-based survey may be useful for mapping areas with high probability of indoor radon concentrations exceeding the RL[20–22].

A radon measurement survey can be designed with a sampling plan that combines both PD-based survey and SD-based survey approaches simultaneously[19].

With the aim of supporting the planning phase of home sampling in carrying out a radon survey over large geographical areas, the methodological procedure is illustrated through a Sampling Plan Tool (SPT). Considering the resources allocated for the survey (number of measurements available) the procedure calculates the size of the sample of homes to be measured within each administrative area. Then, considering the objectives of the survey (type of sampling) an IT tool assigns the spatial location of the number of dwellings to be measured within a 1 km grid square using population data. The final result is a detailed digital map of the spatial distribution of the sample of homes to be measured in the survey. In order to show the results of the application, the case of a hypothetical national indoor radon surveys in Italy is considered. The SPT is a tool to control and manage the sampling of homes, the recruitment of participants and the placement of radon detectors in homes, as part of a radon concentration measurement survey. Some specific applications aimed at supporting the achievement of the objectives set by European regulations are shown.

MATERIALS AND METHODS

Once the objectives of an indoor radon measurement survey have been defined, in order to design the sampling plan for the homes where radon detectors are to be installed, it is necessary to consider the economic costs arising from both the measurements and the management of the survey. The available budget is the key parameter in determining how many radon measurements can be made and thus how many homes will need to be sampled. In addition, the type and size of the spatial sampling unit and the number of dwellings to be sampled within will have to be chosen.

Using grid squares as spatial sampling units is advantageous because they have regular size, and within 1 or 2 km grid squares the expected variability of geological parameters and building types can reasonably be considered moderate. However, it is often preferred to provide survey results using administrative units, because any decisions and actions can be taken directly by the relevant district administration. In addition, population data, which are needed to plan housing sampling, are usually available in administrative area such as municipality or census areas.

Sample size

One of the first steps in planning a national, regional or large-area radon measurement survey is to calculate how many homes will need to be measured within the administrative districts. A simple way to define the total number of dwellings to be measured in the survey is to use an algorithm based on population[23] or based on number of dwellings N_M^{dw} in municipalities provided by the National Institute of Statistics. For each municipality M, the sample size K_M^{dw} of dwellings to be measured can be calculated with the algorithm:

$$\begin{aligned} K_M^{dw} &= \left(N_M^{dw}\right)^p, \text{ if } \left(N_M^{dw}\right)^p > m \\ K_M^{dw} &= m, \text{ if } \left(N_M^{dw}\right)^p \leq m \end{aligned} \tag{1}$$

The parameter p depends on the survey resources, and is chosen according to the maximum total number of indoor radon measurements that can be made in the survey. The parameter m is set as the minimum sample size to ensure that the parameter error estimated from radon concentrations is less than a certain value. In SD-based surveys it may be preferable to consider only dwellings on the ground floors so, using the number $N_M^{dw}(f_0)$ of dwellings on the ground floors, the sample $K_M^{dw}(f_0)$ of dwellings on the ground floors to be measured is given by:

$$\begin{aligned} K_M^{dw}(f_0) &= \left(N_M^{dw}(f_0)\right)^p, \text{ if } \left(N_M^{dw}(f_0)\right)^p > m \\ K_M^{dw}(f_0) &= m, \text{ if } \left(N_M^{dw}(f_0)\right)^p \leq m \end{aligned} \tag{2}$$

When the number $N_M^{dw}(f_0)$ in municipalities is not provided by the National Institute of Statistics, it can be

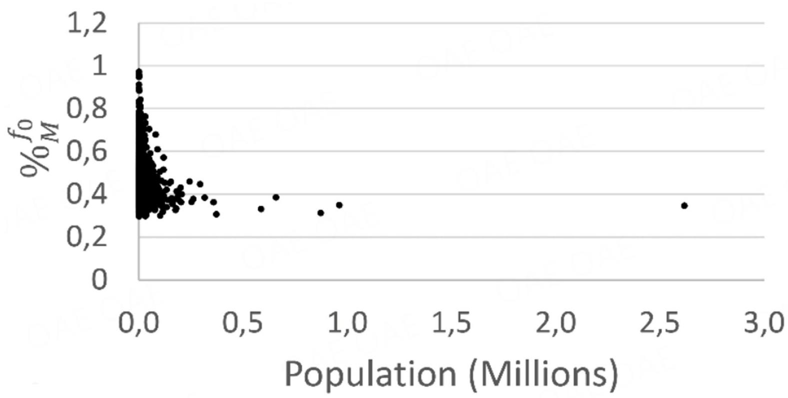

Figure 1. Fraction of ground floors in the municipalities as a function of the population.

estimated in a municipality M from data on the number of residential buildings by number of above-ground storeys (ags). Buildings with $ags = 1$ have only ground floor f_0, buildings with $ags = 2$ have ground floor f_0 and first floor f_1, and so on. The total number of ground floors of buildings, $N_M^{f_0}$, in municipality M corresponds to the number of buildings, because all buildings have the ground floor. The total number of i-th floor in the municipality M, is given by:

$$N_M^{f_i} = \sum_{j=1+i}^{Z} N_M^{ags_j}$$

where i=0,1, …Z-1 is the floor level in the building.

The total number N_M^f of floors in buildings in municipality M is given by:

$$N_M^f = \sum_{i=0}^{z-1} N_M^{f_i}$$

The fraction of ground floor $\%_M^{f_0}$ in municipality M is given by:

$$\%_M^{f_0} = N_M^{f_0} / N_M^f$$

Assuming that dwellings are evenly distributed on the floors of buildings, the total number $N_M^{dw}(f_0)$ of dwellings on the ground floor in municipality M is given by:

$$N_M^{dw}(f_0) = \%_M^{f_0} \cdot N_M^{dw} \tag{3}$$

In the case of Italy, where the population of about 60 million is distributed in about 8,000 municipalities, the data show that 43% of the dwellings are on the ground floor and that in the most populated cities the $\%_M^{f_0}$ is lower because the buildings are taller on average. Municipalities with populations above 300,000 have $\%_M^{f_0} < 40\%$, while municipalities with populations below 300,000 can reach $\%_M^{f_0} \sim 100\%$ [Figure 1].

Given $N_M^{dw}(f_0)$, it is possible to use expression (2) to calculate $K_M^{dw}(f_0)$.

Choosing $p = 0.4$ and $m = 10$, and considering all N_{IT}^{dw} dwellings in Italy, Equation (1) allows us to calculate the nationwide sample of dwellings, which would equal 173,253 dwellings. Considering only ground-floor dwellings, Equation (2) and Equation (3) allow estimating the total sample of dwellings to be measured nationwide, $K_{IT}^{dw}(f_0)$, equal to 128,432. To decrease the cost of the survey by giving up part of the information, lower values of the p and m parameters can be chosen Table 1.

Table 1. Sample size of dwellings to be measured in a national survey by selecting the K_M^{dw} sample of dwellings on all floors in buildings for a PD-based survey and by selecting the $K_M^{dw}(f_0)$ of dwellings on ground floors for an SD-based survey, obtained by varying the parameters p and m in equations (1) and (2). The results are referred to the case of Italy where there are about 31,000,000 dwellings

N_{IT}^{dw}	$N_{IT}^{dw}(f_0)$	p	m	K_{IT}^{dw}	$K_{IT}^{dw}(f_0)$
31,067,523	13,299,409	0.40	10	173,253	128,432
31,067,523	13,299,409	0.30	10	90,241	83,572
31,067,523	13,299,409	0.3	5	78,333	62,078

PD: Population density; SD: spatial distibution.

Samplig plan tool

The Sampling Plans Tool (SPT) is a computer tool that supports the planning of house sampling when designing an indoor radon measurement survey. Having defined the type of sampling, which depends on the objectives of the survey, the tool identifies the number of dwellings to be measured within each 1 km grid square based on the population, considering the average number of occupants per dwelling in municipality M provided by the National Institute of Statistics. The spatial distribution of the sample of dwellings is then represented on a map. The JRC GEOSTAT, a regular grid map of 1 km × 1 km grid squares, developed by European Commission Joint Research Centre with the collaboration of Eurostat, reporting the number of residents for the year 2018 for Europe, was used for the population data [24].

Intersecting the 1 km grid squares S_i with the polygons of the municipalities we obtain fractions F_{ij} of the grid squares:

$$A(S_i) = \sum_{j=1}^{N_i} A(F_{ij})$$

where $A(S_i)$ is the area of the grid square S_i; and N_i is the number of F_{ij} that form S_i.

Each F_{ij} has:
$A(F_{ij})$, area in sqkm of the fraction F_{ij};
$Pop(F_{ij}) = Pop(S_i)/A(F_{ij})/1000000$, population within the F_{ij} proportional to its area $A(F_{ij})$.

If S_i is entirely within a municipality, then:
$A(S_i) = A(F_{ii})$, for $j = i$.

When the S_i intersects the municipal boundary, one of the F_{ij} will be larger than the others, so suppose that:
$A(F_{ik}) = \text{Max}\left[A(F_{ij})\right]$, when $j = k$.

The SPT selects the F_{ij} in which dwellings are to be sampled ($sampling = 1$) in the following way:

$$\text{if } j = i \text{ or } j = k \text{ then } sampling = 1 \tag{4}$$

$$\text{if } j <> i, k \text{ then } sampling = 0 \tag{5}$$

this allows for the exclusion of smaller F_{ij} that fall outside municipal boundaries;

$$\text{if } Pop(F_{ij}) < Pop_{\min}, \text{for any } j, \text{then } sampling = 0 \tag{6}$$

this makes it possible to exclude F_{ij} with a small number of inhabitants. In this application, the threshold $Pop_{\min} = 20$ was chosen to exclude F_{ij} with less than 20 inhabitants.

Sample of dwellings from a spatial distribution of the population-based survey

When the objective of the measurement survey is to know the spatial distribution of indoor radon levels, a sample of ground-floor dwellings uniformly distributed over the area of interest can be selected. First the SPT sorts the F_{ij} by increasing municipality code and then by decreasing $Pop(F_{ij})$ in order to identify the F_{ij} where

Table 2. Number of dwellings $K^{dw}_{M,ij}\ (f_0)$ to be selected in the F_{ij} according to the $K^{dw}_{M}\ (f_0)$ and $N_{M,ij}$ values of municipality M

Value of $K^{dw}_{M}\ (f_0)\ (x = 0, 1, 2, 3, \ldots)$	Number of F_{ij} with $K^{dw}_{M,ij}\ (f_0) = x$	Number of $K^{dw}_{M,ij}\ (f_0) = x + 1$
$x \cdot N_{M,ij} < K^{dw}_{M}\ (f_0) \leq (x+1) \cdot N_{M,ij}$	$(x+1) \cdot N_{M,ij} - K^{dw}_{M}\ (f_0)$	$K^{dw}_{M}\ (f_0) - x \cdot N_{M,ij}$

the dwellings to be measured are to be sampled, according to Equation (4), Equation (5) and Equation (6). In each municipality M we have a number $K^{dw}_{M}\ (f_0)$ of ground-floor dwellings to be sampled and a number $N_{M,ij}$ of F_{ij} in which $K^{dw}_{M,ij}\ (f_0)$ dwellings are to be sampled.

In each municipality M we have [Table 2]:
$K^{dw}_{M}\ (f_0)$, number of dwellings on the ground floor to be sampled, given by (2); $N_{M,ij}$, number of F_{ij} in which $K^{dw}_{M}\ (f_0)$ dwellings are to be sampled, identified according to Equation (4), Equation (5) and Equation (6); $K^{dw}_{M,ij}\ (f_0)$, number of ground-floor dwellings to be sampled attributed to each F_{ij}, such that:

$$K^{dw}_{M}\ (f_0) = \sum_{i,j}^{N_{M,ij}} K^{dw}_{M,ij}\ (f_0)$$

The resulting number of ground-floor dwellings $K^{dw}_{M,ij}\ (f_0)$ to be selected in the F_{ij} is calculated by the SPT and varies as a function of $K^{dw}_{M}\ (f_0)$ and $N_{M,ij}$ of municipality M [Table 2].

The SPT provides the spatial distribution map of the sample $K^{dw}_{M,ij}\ (f_0)$ indicating the number of ground-floor dwellings to be measured for each 1 km grid square [Figure 2A]. The resulting sampling plan includes radon measurements at ground floors in both major population centers and less densely populated areas, resulting in more accurate information on the spatial distribution of radon levels.

Sample of dwellings from a population density-based survey

When the objective of the radon measurement survey is to assess population exposure, the sample must be representative of the population, so it is necessary to select a sample of dwellings in all floors of buildings proportional to the population.

In this case, the SPT sorts the F_{ij} by increasing municipality code and then by decreasing $Pop\ (F_{ij})$ in order to identify the F_{ij} in which the $K^{dw}_{M,ij}$ dwellings to be measured are to be sampled. In each F_{ij} the fraction of $Pop\ (F_{ij})$ of the total population of the municipality $Pop(M)$ is calculated:

$$\%\ [Pop\ (F_{ij})] = Pop\ (F_{ij})\ / Pop(M)$$

Then the number $K^{dw}_{M,ij}$ of dwellings to be sampled in F_{ij} is given by:

$$K^{dw}_{M,ij} = K^{dw}_{M} \cdot \%\ [Pop\ (F_{ij})] \tag{7}$$

The SPT provides the spatial distribution map of the sample $K^{dw}_{M,ij}$ indicating the number of dwellings to be measured per 1 km grid square. This sampling plan includes radon measurements in dwellings in major population centers, resulting in more representative information of the population; however, less populated areas are not well represented. Expression (7) can also be applied by considering only ground-floor dwellings $K^{dw}_{M}\ (f_0)$ in order to obtain a sample proportional to the population but referring to ground floors [Figure 2B]. This salmple, while not representative of population exposure, will better represent the major population centers and could be used for the identification of areas with high radon levels.

An additional parameter h can be included in Equation (7) to obtain a sample of $K^{dw}_{M,ij}$ dwellings that retains more information in the most densely populated centers but extended to more F_{ij} to characterize smaller

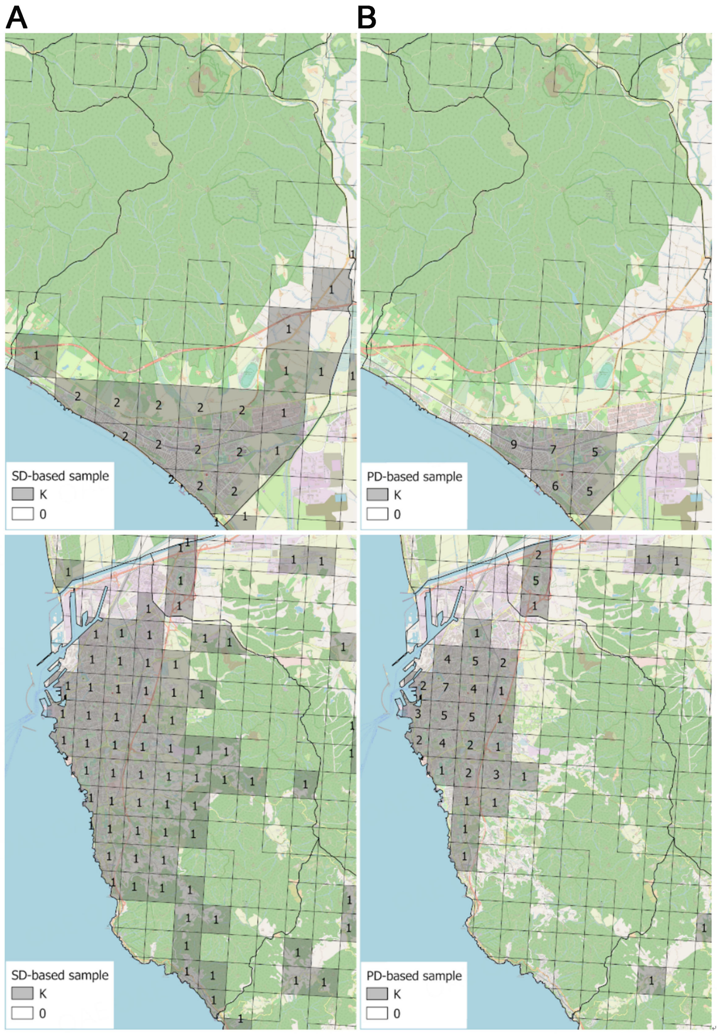

Figure 2. (A) Detail of sampling plans of an SD-based survey and (B) a PD-based survey obtained by SPT considering ground-floor dwellings and parameters $p = 0.4, m = 10$, $Pop_{min} = 20$. PD: population density; SD: spatial distibution; SPT: sampling plan tool.

population centers as well: $K^{dw}_{M,ij} = K^{dw}_{M} \cdot \% \left[Pop\left(F_{ij}\right)\right]/h$, with $h = 1$ the sample is proportional to the population as in (7).

The procedure allows obtaining national sampling plans based on the survey objectives and defined criteria [Figure 3]. The sampling plan obtained for the SD-based survey [Figure 3A] reaches a larger portion of the country, with about 24,000 S_i 1 km grid squares more [Table 3] than the sampling plan of the PD-based survey [Figure 3B], because in the former case the dwellings selected for indoor radon measurement are more spatially distributed, while in the latter case they are concentrated in the major population centers. This can be appreciated from the larger dark areas that result in the map of the national sampling plan of the SD-based survey compared to the map of the PD-based survey [Figure 3].

Sample recruitment

The sampling plan indicates the number of dwellings to be measured in each 1 km grid square calculated with the criteria and parameters established according to the objectives of the survey [Figure 2]. After that, the dwellings must be physically identified in order to ask the owners or occupants to join the survey, i.e., to obtain the opportunity to install radon detectors to carry out the indoor radon concentration measurement. If in a grid square the SPT has indicated 3 dwellings to be measured [Figure 4], it is preferable to triple the

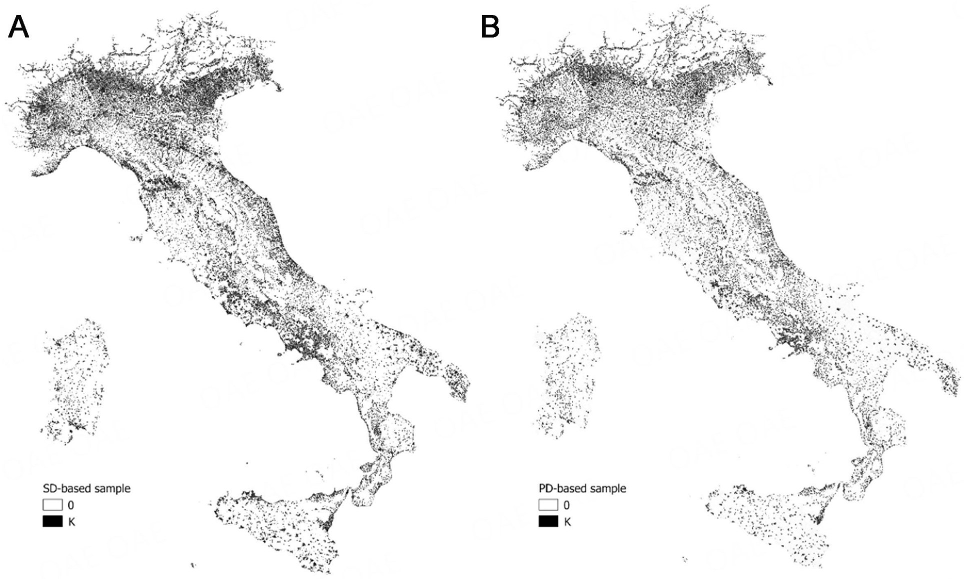

Figure 3. National sampling plan maps of dwellings in Italy for (A) SD-based survey and (B) PD-based survey obtained from SPT considering ground floor dwellings and parameters $p = 0.4, m = 10, Pop_{min} = 20$. PD: population density; SD: spatial distibution; SPT: sampling plan tool.

Table 3. Geographic coverages (sqkm) of the SD-based survey and PD-based survey sampling plans shown in Figure 3

Type of survey	Number of S_i considered for sampling of **dwellings**$^{(1)}$	Total sample size of dwellings to be selected in $S_i^{(2)}$	Number of S_i with at least one dwelling sampled
PD-based survey	278,111	127,262	57,161
SD-based survey	278,111	127,262	81,088

$^{(1)}$Using the parameter $Pop_{min} = 20$; $^{(2)}$Defining the parameters $p = 0.4, m = 10$. PD: Population density; SD: spatial distibution.

number of dwellings to be selected in the grid square to account for refusals by homeowners or occupants to participate in the survey.

To locate a $K^{dw}_{M,ij}$ number of dwellings to be measured in an F_{ij}, a number $K^{dw}_{M,ij}$ of dwelling addresses must be selected in the F_{ij}. To obtain a random location of dwellings in the F_{ij}, one must generate random values of coordinate pairs that have values internal to the F_{ij} and obtain the addresses of those locations (or the nearest addresses within the grid square) from a geocoding system.

These addresses can be searched in registry office lists and will correspond to as many names of residents. People can be contacted by telephone, by retrieving the phone from telephone utility databases, or by letter to be delivered by the municipal government or a central institution that is organizing the survey, or even door-to-door, in order to obtain consent to participate in the indoor radon measurement survey.

Passive radon detectors used in extended measurement surveys are small and lightweight, so they can be mailed to survey participants, or they can be delivered door-to-door to selected homes and installed by operational teams. In most municipalities, which are small in size, radon detectors can be delivered to homes by municipal government contact persons.

In this way, the sample of homes where indoor radon measurements are to be made has been selected from an exhaustive set of addresses within each sampling unit[25].

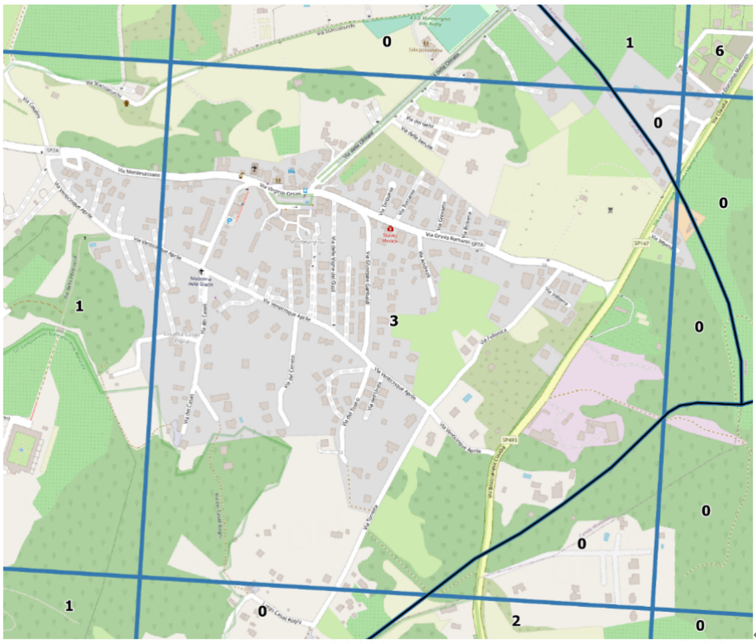

Figure 4. Grid square (1 sqkm) in which SPT indicates a sample of 3 dwellings to be selected for making indoor radon measurement. The background map shows building polygons and addresses. From the attribute tables of the open-source vector data, residential buildings can be distinguished. SPT: Sampling Plan Tool.

REGULATORY APPLICATIONS

National strategy for the identification of radon areas

A national radon protection strategy is a programme of actions that must include indoor radon measurement surveys, radon risk information campaigns for the population and workers, financial support for radon measurements and remedial actions, and much more. National authorities have to take decisions because implementing these actions is very complex and costly. High radon levels can be found anywhere in the country but, for mainly geological reasons, there are areas where buildings with high radon levels are much more likely to be found. The radon action programme may be implemented preferentially in these areas, and in buildings that are heavily occupied [10].

The European regulation requires Member States to identify areas where the annual average radon concentration in a significant number of buildings is expected to exceed the relevant national RL (art.103) [11].

Since both the radon concentration and the population vary spatially, there will be areas in which both variables take on high values. These areas, which are likely to be small compared to the entire country, contain a large fraction of the total risk. By carrying out radon measurement surveys in these areas it will be much more likely to identify buildings that exceed the RL than outside, obtaining a great advantage in terms of cost effectiveness. National authorities should carry out national radon measurement surveys in order to identify radon areas in a relevant way, because this means optimising available resources. The SPT can support this task by enabling the planning of household sampling according to the set objectives, providing the tools to control the survey by helping to reduce possible sources of bias and providing the expected results in a form suitable for regulators.

By substituting $K_M^{dw}(f_0)$ in expression (7), we consider only ground floor housing to be conservative. The resulting sampling plan outlines a national PD-based survey representative of the ground floor housing stock in each municipality M [Figure 3B]. Using the data measured in the PD-based survey, it will be possible to estimate the parameters of the log-normal distribution of radon concentrations and calculate the fraction of the distribution that exceeds the RL[26], corresponding to the fraction of ground floor dwellings that exceed the RL, $\%_M^{dw>RL}(f_0)$.

Without a proper sampling plan, if the sample of dwellings to be measured were based on scattered measurement surveys or derived from citizens' requests stimulated by information campaigns, we would have no guarantee that the $\%_M^{dw>RL}(f_0)$ estimated for the municipality is correct. An overestimation would lead us to invest resources where it is not justified, an underestimation to neglect the problem by shifting resources to other areas. To avoid these biases, we would need such a large number of measures (sample size) to be able to represent the real situation of the municipality in each case.

In municipality M, the number of dwellings on ground floors where the radon concentration is above the RL is given by:

$$N_M^{dw>RL}(f_0) = N_M^{dw}(f_0) \cdot \%_M^{dw>RL}(f_0)$$

Where $N_M^{dw}(f_0)$ is the total number of ground floor dwellings in municipality M, estimated using Equation (3).

By defining the value of $N_M^{dw>RL}(f_0)$ that is considered significant, it is possible to decide whether municipality M is identified as a radon area in accordance with European regulations[11]. Identified radon areas can be provided to the EU Member state regulators in the form of a list of administrative districts, such as municipalities[27]. It would be more useful to identify radon areas with 1 km grid squares but regulators often prefer to use administrative areas, such as municipalities, because they are more directly related to the responsibilities and decisions of the competent authorities. In these areas, remedial actions to reduce the radon concentration of buildings above the RL will allow to reduce the exposure of residents by prioritizing situations above the RL (EC 2013[11]), and to reduce average concentrations of radon in dwellings (IAEA 2015[19]). Achieving the same result by acting outside the areas would require much greater effort.

Radon areas must be used to prioritize the most important situations, without neglecting the rest. To act on the remaining part of the risk in the country, which is located outside the areas, it is necessary to implement a national radon strategy that impacts exposure in the long term, introducing appropriate practices in the construction of new buildings and regulations on building materials, identifying the typologies of workplaces, work activities and buildings with public access that have greater risk, training health and safety professionals and establishing synergies with national strategies against tobacco smoking and those for energy efficiency in buildings. Continuing radon surveys is equally important and the radon areas can be updated over time by incorporating additional municipalities.

Detection of RL exceedances within radon areas

The large-scale survey made it possible to identify radon areas by taking a few annual average radon concentration measurements in selected dwellings in each municipality. Now it is necessary to carry out dense measurement surveys with many measurements in a few selected municipalities (radon areas).

A comprehensive radon measurement survey within the radon areas will identify many RL exceedances, but not all buildings in these municipalities exceed the RL, and measuring all dwellings would be too expensive. Information indicating where RL exceedances are most likely to be found is needed in order to make the ratio of detected exceedances to radon measurements made efficient.

Previously made indoor radon measurements for the identification of radon areas already provide some indications to guide the dense survey but further information is needed.

Since the main source of indoor radon concentration is soil, many authors have focused on investigating geological factors. European regulators have taken these aspects into account in the Council Directive (Annex

XVIII)[11]. The strategy for conducting surveys to measure indoor radon concentration could be supplemented with additional parameters, such as soil and rock types, permeability and radium-226 content of rock or soil. By overlaying appropriate digital geological maps[28,29], each F_{ij} can include a set of parameters that allow its geogenic radon weight to be calculated. Each F_{ij} would be characterized by its area $A(F_{ij})$, population $Pop(F_{ij})$, and geogenic weight $W(F_{ij})$. The new $W(F_{ij})$ parameter gives sampling priority in areas with higher geogenic potential. The SPT can sort the F_{ij} by increasing municipality code and then by decreasing $W(F_{ij})$ and decreasing $Pop(F_{ij})$, resulting in a SD-based survey sampling plan spatially targeted to the inhabited areas with higher geogenic potential. Similar to the exclusion threshold Pop_{min} used for population, a threshold W_{min} can be introduced in order to exclude F_{ij} with lower geogenic weights. The resulting sampling plan would include radon measurements in ground-floor dwellings in the most densely populated areas selected from those with the highest radon geogenic potential, resulting in the opportunity to identify more dwellings exceeding the reference level.

Since European legislation imposes compulsory radon measurements in workplaces on ground floors and basements within radon areas (art.54)[11], national authorities can also use these measures to improve the orientation of the dense survey.

CONCLUSIONS

In order to define and implement a national radon protection strategy, the national authorities must carry out a characterisation of the situation in the country. Relevant information is needed to make decisions on public health priorities taking into account social and economic factors.

A national population-weighted radon survey must be carried out to assess the radon exposure of the population in the country[10]. A national radon survey is also needed to identify areas where significantly high indoor radon concentrations are more likely to be found[10] in order to focus resources on measuring and reducing radon concentrations.

Designing a geographically extensive indoor radon measurement survey is a complex task that requires carefully defining the objectives of the survey and considering the technical and economic aspects for implementation. Based on these preliminary assessments, it is necessary to make an appropriate sampling plan of the dwellings where radon detectors are to be installed to measure the indoor radon concentration. Sampling of dwellings is an important step in a radon survey because if the data acquired do not meet the requirements defined by the objectives of the survey, bias may be introduced into the results, and thus incorrect decisions or policies may be undertaken.

In the case of population density-based surveys, once the addresses of the sampled dwellings and the names of their occupants have been obtained, it is complex to manage and control the installation of detectors in dwellings by teams of operators. In case of refusal by occupants, operators could introduce arbitrary choices, such as installing detectors in homes occupied by volunteers or unintentionally favoring installation, and thus radon measurements, on ground floors. This is one of the possible reasons for bias in the survey results. Having the detailed map of the sample of dwellings makes it possible to monitor and control that radon measurements reflect the desired sample, helping to reduce sources of bias.

In the case of the spatial distribution of the population-based survey, SPT allows random selection of dwellings in the 1 km grid squares, because it is known how many dwellings there are and where they are, producing a spatially distributed sample. By selecting dwellings from the registry lists of municipalities, this is not possible. The results of the spatial distribution of the population-based survey can be used effectively for mapping areas where radon concentration exceeds the reference level. In such cases, having the radon concentration measurements unclustered and distributed in a regular grid allow data from adjacent squares to be used to estimate the geometric mean and the geometric standard deviation if results of measurements are insufficient for any particular square[26,30].

A particular application of the SPT is shown for the case of the objectives set by the EU regulation, which provides a definition of radon area (art.103), indicates the geological parameters to be taken into account (Annex XVIII) and requires specific obligations for workplaces within the areas (art.54)[11]. The procedure and tools described are adaptable to different indoor radon measurement surveys, whatever the size of the survey, national or local. They make it possible to plan the survey taking into account the expected objectives and available resources, and to control and manage all phases of the survey in order to obtain results that comply with the established requirements. The procedure can support the national authorities in the task of implementing the instructions of the competent international bodies and achieving the objectives set by the regulations.

DECLARATIONS

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Authors' contributions

The author contributed solely to the article.

Availability of data and materials

The JRC-GEOSTAT 2018 gridded population estimates are available from the Eurostat, GISCO webpage: https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/geostat.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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