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A Comparative Study of Indoor Radon Levels between Two Similar Dwellings Using CONTAM Software

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Abstract: Considered the second biggest risk factor for lung cancer in humans after smoking, indoor radon gas (^{222}Rn) is produced by the radioactive decay of ^{226}Ra, which is mainly present in building materials and soil. The current study proposes a methodology for estimating radon levels inside a dwelling using the multizone airflow and contaminant transport modeling software CONTAM, with the main purpose to improve indoor air quality by optimizing mechanical ventilation. The generation rate of indoor radon sources was investigated in relation to the total surface of each room and was subsequently used for identifying the rooms that require special attention. The methodology described should assist in modeling indoor radon contamination, which can be used to optimize the ventilation in a dwelling.

Keywords: radon; modeling; CONTAM; indoor air quality

1. Introduction

The radioactive isotope of radon, ^{222}Rn, having a 3.8-day half-life, is a member of the uranium (^{238}U) decay series and can be found in nature in its gaseous form. Radon is a noble gas that can move from the site of its formation through the process of diffusion, allowing it to reach the air that can be inhaled by humans. The average value of outdoor radon concentration is around 15 Bq/m^3 [1]. The inhalation of ^{222}Rn and its high-linear energy transfer alpha-emitting airborne progeny (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) have been associated with lung cancer due to the absorbed dose in the tracheobronchial epithelium.

In the general population, radon contributes to more than 50% of the natural radiation dose received, which occurs indoors, according to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [1]. Radon level fluctuations depend on many factors, like meteorology, radon exhalation rate from building materials, and even anthropogenic factors [2]. It is also known that radon varies significantly throughout the day and also depends on the season of the year [3]. The indoor radon concentration may be strongly affected by the nature of building materials and other sources, such as soil and water, and by building operations, such as ventilation. In specific cases, due to improper ventilation and the presence of more intense radon sources, the risk of exposure to natural radiation can be 5–10 times higher than normal.

In the European Union (EU), the legislation for radiation protection appears in the form of Commission Recommendations and Council Directives. The basic principles of protection against radon have recently been updated through the Council Directive 2013/59/EURATOM (European Atomic Energy Community) [4], also known as the new EURATOM Basic Safety Standards (or EURATOM BSS). Some countries outside the EU, for example, Croatia, have their regulation based on the International Atomic Energy Agency (IAEA) BSS [5]. EURATOM, since 20 February 1959, has adopted the Basic Safety Standards for the protection of the health of the general public and workers against the dangers

of ionizing radiation, and has regularly updated BSS in close cooperation with the development of international standards set by the IAEA. One of the novelties introduced by the 2013/59/EURATOM Directive is that member states must establish a national action plan addressing long-term risks from radon exposure in dwellings, buildings with public access, and workplaces for any source of radon ingress. Member states of the European Union needed to comply to the EURATOM guidelines by 6 February 2018. The International Commission on Radiological Protection (ICRP) recommends a new upper value of 300 Bq/m^3 for the reference level of radon gas in dwellings. This is half of the previous recommendation, and the World Health Organization (WHO) proposes a reference level of 100 Bq/m^3. Therefore, it is expected that the required national reference levels for indoor radon concentration will lower than, or equal to, 300 Bq/m^3. Lung cancer risk rises 16% per 100 Bq/m^3 increase in radon exposure, according to the WHO handbook [6]. Studies show that radon is the primary cause of lung cancer among people who have never smoked; however, the total number of radon-induced lung cancers is much larger in people who smoke, or who have smoked in the past, due to a strong combined effect of smoking and radon.

This paper reports a comparative study of indoor radon level in two similar dwellings based on simulation performed with the multizone modeling software CONTAM, version 3.2, developed by the National Institute of Standards and Technology (NIST) [7]. In a previous paper [8], a radon measurement campaign was carried out in both dwellings, located in the same building. More details about the building will be given in the Section 2. The results showed that the indoor radon level was similar in both dwellings, with an average of 62 ± 17 Bq/m^3 and 77 ± 20 Bq/m^3. Besides, the average radon level in both dwellings is the highest during August and September (summer). The radon level is significantly lower than the assumed maximum reference level of 300 Bq/m^3, as required by the new BSS.

The research focused on newly built small dwellings and is justified by the adoption of Directive 2010/31/EU [9], which requires member states to apply minimum requirements, such as the energy performance of new and existing buildings. Following the introduction of efficiency requirements in building codes, new buildings consume half as much energy today as they did in the 1980s. In this framework, there is a growing interest about the impact of these requirements on indoor air quality (IAQ) that may result in increasing standards of insulation. Indoor radon concentration should be considered as a useful parameter to assess ambient air quality for a future update of the Spanish National Technical Building Code. For example, indoor radon concentration has been measured in newly built energy-efficient houses in France [10]. In this study, a simplified version of the dwellings and their relevant components were drawn into the software and, as a result, radon levels in the different rooms were determined.

The aims of this paper are: (a) to establish a methodology to estimate a radon level in the rooms of a dwelling using modeling software and (b) to compare the indoor radon levels in two similar dwellings. Results will be useful to design a radon measurement campaign in dwellings because the software allows one to find an order of magnitude of the radon level and, thus, to identify those rooms that require special attention.

2. Materials and Methods

The first subsection describes the main features of the building and its two dwellings, which are the subjects of the present paper. These dwellings were described and modeled via CONTAM, the software described in the second subsection. The last section explains the modeling approach that is proposed and adopted in this paper.

2.1. Building

The residential building is located in the neighborhood of Guindalera (district Barrio de Salamanca, Madrid) with the approximate coordinates of latitude 40°26′24″ N and longitude 3°40′12″ W, a location where new buildings have been built, mainly during the Spanish "construction boom" that collapsed

in 2008. Generally speaking, these buildings have similar features: each have three- or four-story brick buildings that contain small dwelling units (one or two bedrooms) and all were implemented with systems to achieve energy efficiency requirements according to European and Spanish regulations.

The building is located in a radon-prone area, which was identified, in part, from the information given by MARNA (it is an acronym in Spanish of "MApa de Radiación gamma Natural") [11] and "Radon Project 10 × 10" [12]. The survey was performed in a building constructed in 2012 that consists of three floors above the ground floor and two levels beneath. The Energy Performance Certificate gives the building a standard energy and carbon emission efficiency grade of 40.3 E, which is a typical rating for a home. A photograph of the building is shown in Figure 1a. The total built surface area of the building is 1459 m^2 over a parcel of 459 m^2. Each floor contains three dwelling units; two of them are one-bedroom dwellings of similar size and the other one is a two-bedroom dwelling. Figure 1b shows the floor plan of a one-bedroom dwelling, including a complete floor layout, the use of each area, the location of detector used in the previous study [8], and other relevant elements, such as doors and windows. Throughout this paper, the first dwelling will be labeled with the letter "A" and the other one with the letter "B".

(**a**) (**b**)
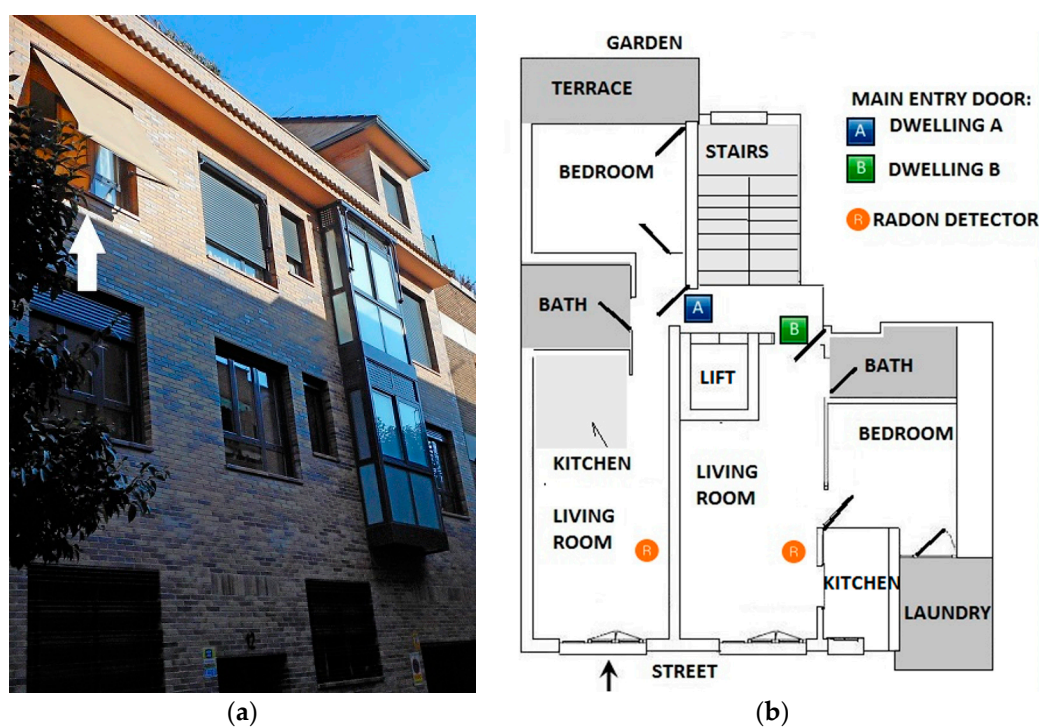
Figure 1. (**a**) Picture taken in the year 2018 showing the building's facade. A white arrow points to the location of the living room window of dwelling "A". This marker can be used as a visual reference point because it is also marked in the right diagram. (**b**) Floor plan of the dwelling units.

Dwellings "A" and "B" have similar features, such as an almost identical useful surface area whose values are, respectively, 39 and 37 m^2. As can be observed from Figure 1a, there are two differences between the dwellings. First, dwelling "A" has a double frontage, whereas dwelling "B" has only one. The second difference concerns the kitchen; dwelling "A" has an open kitchen-living room, unlike dwelling "B", whose kitchen is completely separate from the living room.

2.2. The CONTAM Software

This paper shows the effect of a ventilation system on the indoor radon level within two similar dwellings, as assessed by a multizone modeling software for airflow and contaminant transport. The software used is CONTAM version 3.2 [7], developed by NIST, the first version being released in

the year 2000 [13,14]. In the present study, it was used mainly to model natural and mechanical airflow and to determine the radon concentrations based on predefined indoor sources.

Air change rates can be affected by a variety of driving forces, including weather (wind and indoor–outdoor temperature difference) and mechanical ventilation. CONTAM performs a simultaneous mass balance of air in all zones to determine zonal pressures and airflow rates through each airflow path (in CONTAM, a zone is a volume of air separated from other volumes of air by walls, floors, and the ceiling). The ability to calculate building airflow rates and relative pressures between zones of the building is useful for assessing the adequacy of ventilation rates, for determining the variation in ventilation rates over time, depending on certain schedules, for determining the distribution of ventilation air within a building, for estimating the impact of envelope air-tightening efforts on infiltration rates, and for evaluating the energy impact of building airflow.

Once the mass flow rates are computed, contaminant concentrations can be determined based on conservation of mass for every contaminant in each zone. The program takes into account the dispersal of airborne contaminants transported by the airflow and transformed by a variety of processes, including chemical and radiochemical transformations. A contaminant can be added to a zone by inward airflow, generation at a constant rate, or reactions with other contaminants. The same contaminant can be removed by outward airflow, removal at a specific rate, or first-order chemical reactions with other contaminants.

Airflow and contaminant information are then used to determine contaminant concentrations within the zones. The mass flow rate from one zone to another along a given airflow path is a function of the pressure difference between the zones (assumed to be governed by the Bernoulli equation, which accounts for static pressure on each side of the flow path), pressure differences due to density, and height differences and pressure differences due to wind. Conservation of mass is applied for all zones, leading to a set of nonlinear algebraic equations that must be solved interactively.

The prediction of contaminant concentrations can be used to determine the IAQ performance of buildings before they are constructed and occupied, to investigate the impacts of various design decisions related to ventilation systems and building material selection, to evaluate IAQ control technologies, and to assess the IAQ performance of existing buildings. Predicted contaminant concentrations can also be used to estimate personal exposure based on occupancy [15].

The following tasks are required in order to get realistic results: develop a building idealization, draw a schematic representation, define building components, perform simulations, and review results. These steps are treated jointly in the next section.

2.3. Modeling Approach

This section presents a methodology for modeling indoor radon concentration using CONTAM. The building chosen to carry out the simulation, described in Section 2.1, was selected because the radon level was known from the measurement campaign performed between 2014 and 2015 [8]. Furthermore, it is a type of building that is very common in the last period in Spain, so the results have a more significant contribution to the general population.

The floor is divided into two dwellings, identified in this study by the letters "A" and "B". The dwellings are connected by a common hallway made of granite, in which the stairs and the elevator are placed. Each dwelling is divided into rooms, with each room constituting one zone. Besides, it is required to define the building components, airflow elements, and sources (or sinks) of contaminants that are represented in the code through mathematical models. The CONTAM SketchPad representations of dwellings A and B are shown in Figure 2, including the elements defined earlier: fans, windows, doors, and sources of radon. The simulation was performed separately for each dwelling. The same hallway is shown in both sketches.
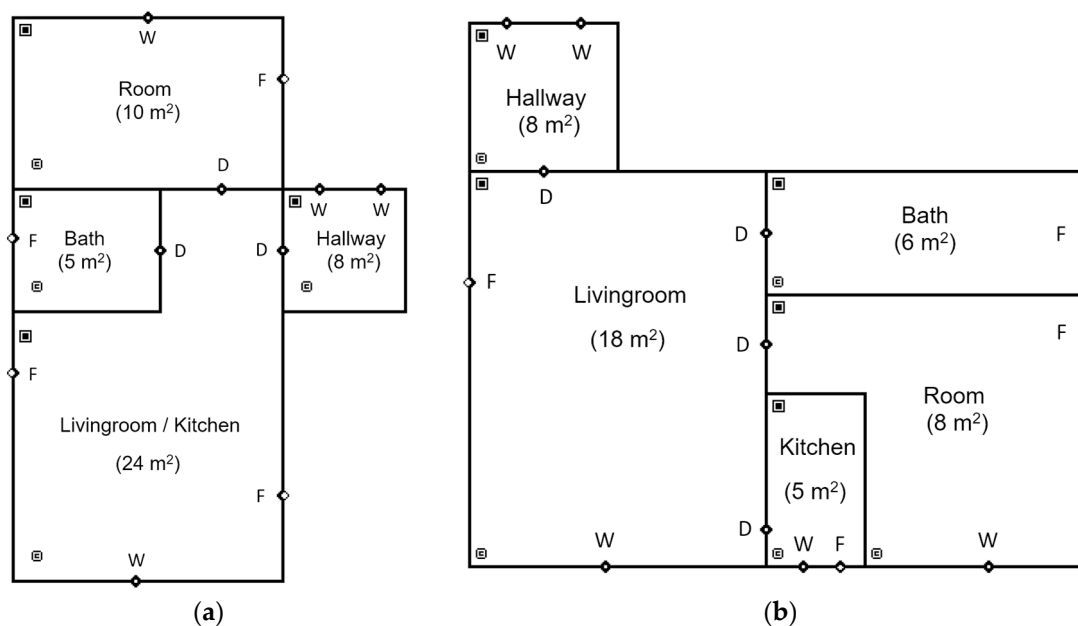
Figure 2. CONTAM SketchPad representation of (**a**) dwelling "A" and (**b**) dwelling "B", including the surface of each room. The open diamonds represent the fans (denoted with letter F), windows (W), and doors (D). The filled squares indicate the individual zones. The open squares with the letter "C" inside indicate the sources of the radon contaminant.

The characteristics of the elements chosen in Figure 2 are given in Table 1, which shows the room identification code that was formed by the ID of the dwelling ("A" or "B") and the brief description of the room, surface, and, finally, the number and type of airflow path. Not all parameters are specified in the table, such as the volume, which can be determined from the surface and the room height. In particular, the height of the room was modified to 2.5 m from the default value given by the software (3 m). Furthermore, it is not necessary to indicate the building level in the table because all rooms are located on the first floor.

Table 1. Description of the parameters used as input for the simulation. The hallway is the same for both dwelling "A" and dwelling "B".

| | ID room | Surface (m^2) | Sources (Bq/h) | Airflow Elements (Maximum Flow Rate (Number of Elements)) | | |
				Window	Door	Fan
A (39 m^2)	Bedroom	10	8000	(1)	(1)	50 L/s * (1)
	Living room (includes kitchen)	24	19,200	(1)	(1)	Kitchen: 10 L/s (1) Living room: 72 L/s (1)
	Bath	5	4000	(1)	(0)	10 L/s (1)
	Hallway	8	12,800	(2)	(1)	(0)
B (37 m^2)	Bedroom	8	6400	(1)	(1)	40 L/s (1)
	Living room	18	14,400	(1)	(3)	54 L/s (1)
	Bath	6	4800	(1)	(0)	12 L/s (1)
	Kitchen	5	4000	(1)	(1)	10 L/s (1)
	Hallway	8	12,800	(2)	(1)	(0)

* L/s is the abbreviation for liters/second.

The technical specifications of the previous elements that were necessary as input are shown in Table 2. The mathematical model employed in the present CONTAM simulation that provides the relationship between airflow and pressure difference of airflow paths, such as windows and doors, is a one-way flow type using a classical power law model named "orifice area data". This simplified, one-way flow approach was suggested by a previous study [15] that used a similar model for the doors because of constant indoor temperatures. A two-way flow model was also investigated for the present simulations and the final results concerning radon concentrations were unchanged, therefore confirming the simplified approach.

Table 2. Model summary of parameters for windows and doors in both dwellings.

	Window	Door
Type of model	One-way flow using power law	
Formula	Orifice area data	
Cross-sectional data (cm^2)	5	80
Hydraulic diameter (cm)	2.52	10.09
Transition Reynolds number	30	30
Discharge coefficient	0.6	0.6
Flow exponent	0.5	0.5

Fresh air is supplied through paths through the building envelope, which is the physical separator between the interior and exterior of a building. In addition, a mechanical ventilation was set up in the kitchens, bathrooms, living rooms, and bedrooms. The fan model chosen in the CONTAM simulation is the "constant volume flow fan". A constant flow rate was set for each fan according to its room designation; therefore, the flow values are proportional to the surface of each room, as summarized in Table 3. The flow rates were chosen following the recommendations given by Spanish regulation.

Table 3. Flow rates of each fan corresponding to a specific room type.

Room Type	Flow Rates (L/s/m^2)
Kitchen/bath	2
Bedroom	5
Living room	3

CONTAM allows addition of many contaminants (CO$_2$, NOX, PM, etc.), but, in the present simulation, only radon was added. The main characteristics of radon are a molecular weight of 222 kg/kmol, diffusion coefficient of 5.91 mm^2/s, and decay half-life of 3.8 days. Radon is considered a trace contaminant, because its very low concentration level does not affect the density of air within a zone. The contribution of building materials towards indoor radon depends upon the radium content and exhalation rates, and can be used as a primary index for radon levels in the dwellings. Building materials are the second major source of indoor radon, after soil. Both types of sources can be defined using the constant coefficient model described through the following equation:

$$S(t) = G - D \times C(t) \tag{1}$$

G = Generation rate [mass of contaminant/time]
D = Effective removal rate [mass of air/time]
C = Current concentration [mass of contaminant/mass of air]

Setting realistic intensities for the indoor radon sinks was the most challenging step of the present simulation because there are not many details about this in literature [16–18]. In Reference [16], the authors placed a ^{222}Rn source having a generation rate of 12,000 Bq/h; however, they did not

explain why they selected that particular value. In Reference [17], a more appropriate and general model was selected among available models in literature for the prediction of indoor radon by determining the exhalation rates of building materials. They reported average values of ~50 Bq/m^2/h for the building surfaces of mud dwellings. Reference [18] interpreted the lithology and building effects, suggesting that radon accumulation in indoor environments is quite a complex phenomenon which can only really be explained by measurable architectonic or other factors.

With the previous considerations in mind, in the present study, we provide a more realistic approximation in CONTAM of indoor radon sinks that accurately reproduce previously measured values [8] by defining a radon generation rate proportional with the room surface. This value is expected to be of the same order of magnitude as the ones in References [16,17]; however, it heavily depends on the geographic region and building materials used. A detailed discussion will be provided in the next section.

Before running the simulation, the last step was setting the type of analysis that is needed (steady-state, transient, or cyclical) along with many other simulation parameters that were discussed earlier. For simulating airflow and contaminant transport, the transient mode was used. The transient integration method selected was the default solver. Initial contaminant concentration was set to zero. The simulation ran for 24 h, using constant weather conditions.

3. Results and Discussion

The results obtained following the methodology described above are presented in the following section. The main focus is showing the impact of ventilation on the radon concentration in the two dwellings studied.

3.1. Realistic Generation Rates for Indoor Radon Sources

Thanks to the previous measurement campaign [8], we were able to fix the parameters related to the ventilation and find the generation rates of radon normalized to the unit surface (Bq/m^2/h), which is required in order to reproduce the average measurements of 62 ± 17 Bq/m^3 and 77 ± 20 Bq/m^3 in the living rooms of dwellings A and B, respectively. Given the large uncertainties, for simplicity, we chose an average radon source of 800 Bq/m^2/h for each room of the two dwellings for the rest of the simulation. A 2-fold more intense source of 1600 Bq/m^2/h was considered for the hallway due to the contribution of soil and the presence of the elevator that communicates directly with the lower floors and basement, where a higher radon level is expected.

The generation rates of the radon sources corresponding to each room are summarized in Table 1. This approach provides radon concentration values having realistic orders of magnitude, similar to the values measured experimentally; however, it is not expected to reproduce them exactly.

3.2. Comparison between Two Dwellings with Similar Radon Sources

Figure 3 shows the indoor radon concentration in both dwellings as it builds up in time, considering that the starting concentration is zero. It should be noted that the radon generation rate and airflow reach equilibrium after roughly 2 h. In the rest of the paper, only the equilibrium concentration is reported. The simulated values obtained for the living rooms in dwellings "A" and "B" are 66 Bq/m^3 and 74 Bq/m^3, respectively. These are similar to the measured values, which validates the methodology for choosing the indoor radon sources.

It should be noted that the radon concentration in all rooms is well below the recommended upper limit of the reference level of 300 Bq/m^3 recommended by the ICRP and comparable to the 100 Bq/m^3 recommended by the WHO. In the European Union, these limits are enforced through the Council Directive 2013/59/EURATOM of 5 December 2013 [4], which lays down basic safety standards for protection against the dangers arising from exposure to ionizing radiation. The bedroom and living rooms are both below 80 Bq/m^3, which is desirable because these are the places where people spend the most time. Special attention must be directed towards the ventilation in the bathroom and

hallway, as they are the places prone to having increased radon concentration. In the next subsection, the influence of ventilation on the radon concentrations is discussed.
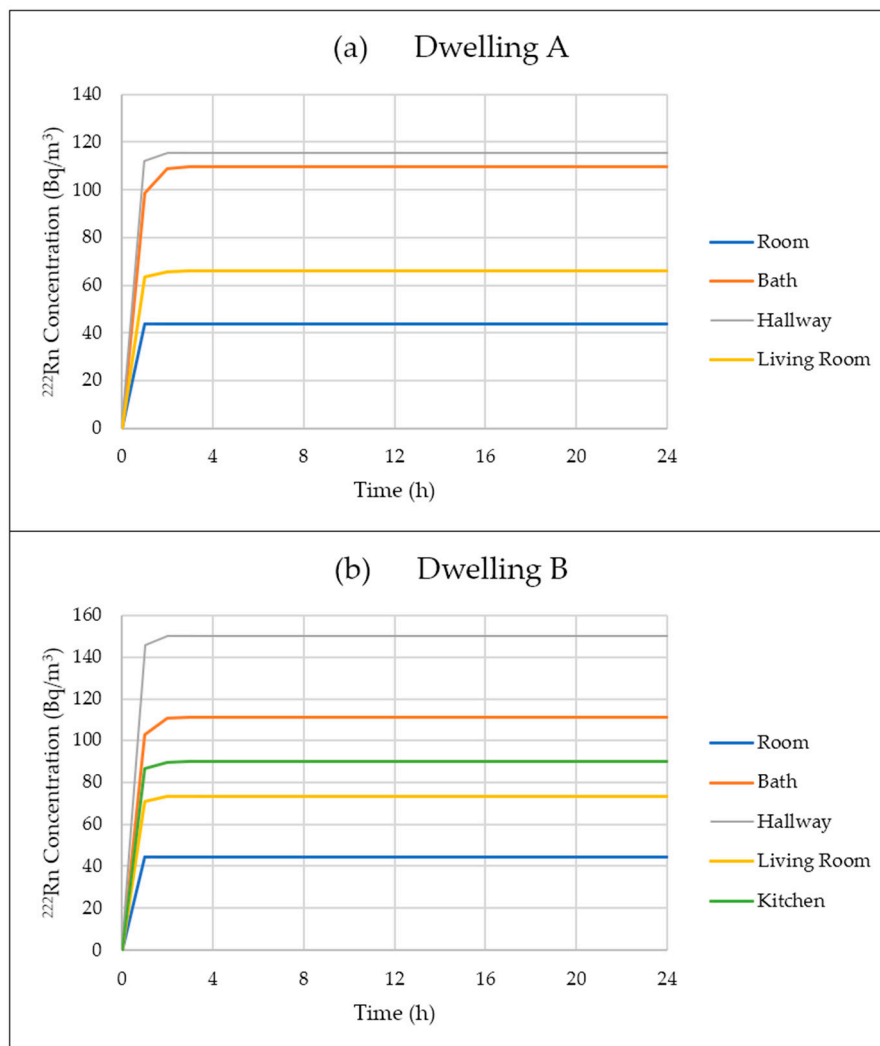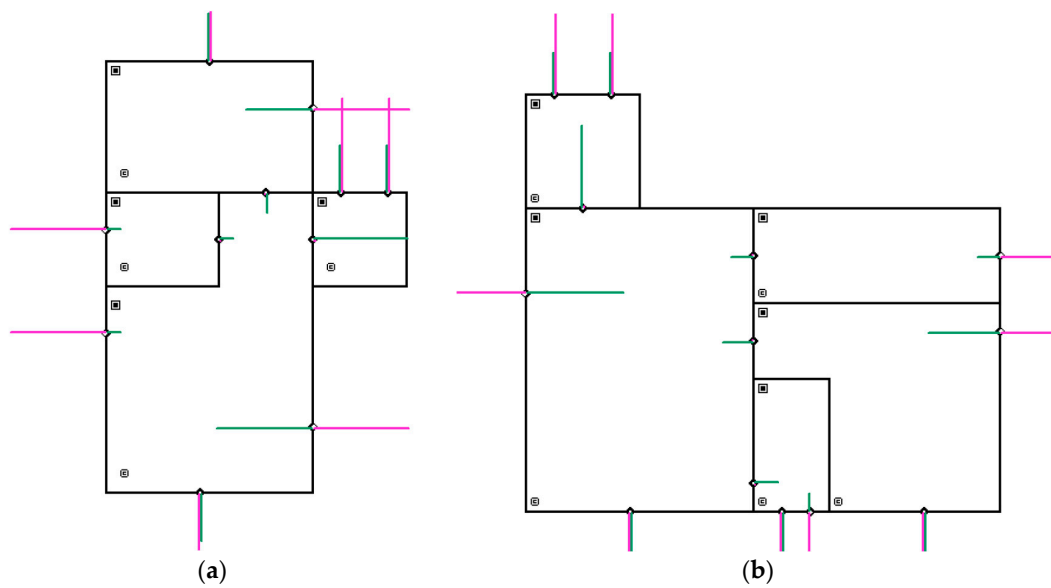

Figure 3. Evolution of radon concentration in (**a**) dwelling "A" and (**b**) dwelling "B", considering the parameters from Table 1. The results were obtained from simulations using the CONTAM software following the methodology described in the paper.

### 3.3. Impact of Ventilation on Radon Concentration

As explained above, the ventilation of the dwellings is both natural and mechanical. The results of the ventilation simulation are shown in Figure 4.

Considering that the bathroom is the area most prone to high radon concentration values, we increased the flow rate of the fan from 2 L/s/m^2 to 3 L/s/m^2 and 4 L/s/m^2 successively, and the results are shown below in Figure 5. It should be noted that by doubling the fan flow rate of the bathroom, the radon concentration is reduced by ~50%. This increase in the fan flow rate will also influence the radon concentration in the other rooms, but only slightly, to around 5%. The radon concentration in the bedroom appears to not be affected at all, most probably due to the "one-way flow using power law" model that was used for the doors.

Figure 4. CONTAM SketchPad representation of pressure and flow in (**a**) dwelling "A" and (**b**) dwelling "B". The airflow rates are denoted as green lines and pressure differences as pink lines.
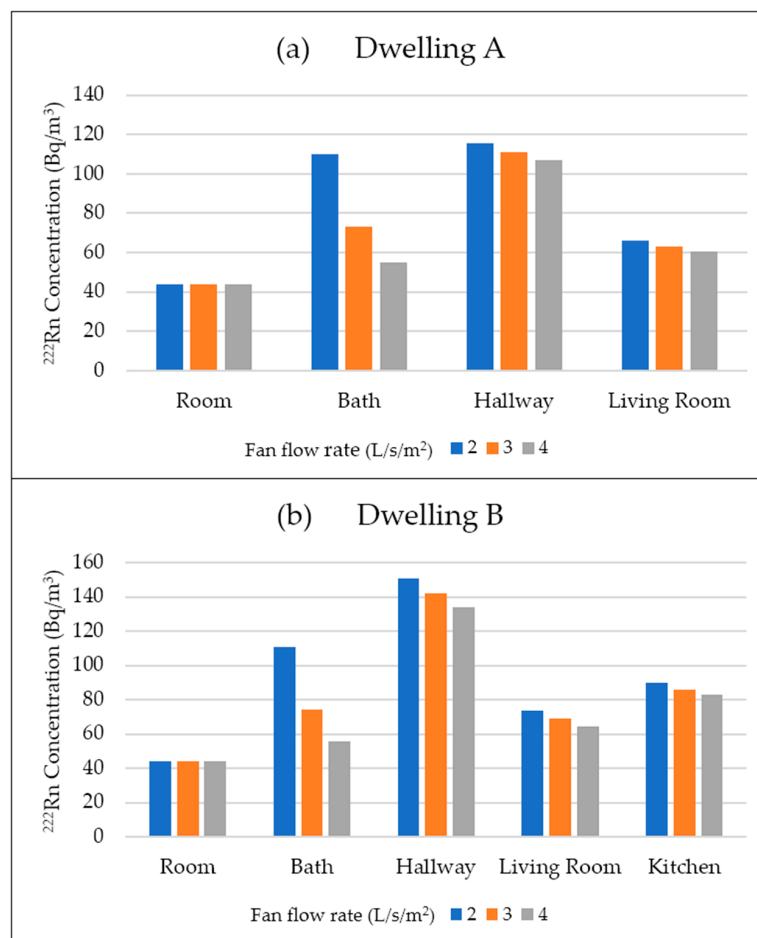
Figure 5. Evolution of radon concentration in (**a**) dwelling "A" and (**b**) dwelling "B", considering the variation of the bathroom fan flow rate. The results were obtained from simulations using the CONTAM software following the methodology described in the paper.

4. Conclusions

The present study presented a methodology for estimating radon levels in the different rooms of two dwellings using the CONTAM modeling software. The generation rate of indoor radon sources was investigated relative to the total surface of each room. A comparison of the simulated indoor radon levels helped identify the rooms that required special attention. Simulations for different fan airflow levels were performed for a specific room, and the impact on the radon concentrations was analyzed.

The CONTAM software and methodology presented should help in accomplishing the requirements from the Council Directive 2013/59/EURATOM [4], as part of arranging for the establishment of strategies. This is to ensure the appropriate management of existing exposure situations commensurate with the risks, and with the effectiveness of protective measures required in Article 101, together with Article 103. These articles state that the member states should ensure that appropriate measures are in place to prevent radon ingress into new buildings and identify radon-prone areas, where the radon concentration (as an annual average) in a significant number of buildings is expected to exceed the relevant national reference level.

As a final remark, more research is needed to extend these results to other buildings with a major complexity. It should be noted that the two dwellings studied in the present paper are not representative for all the dwellings in Spain, being a special case of newly built small dwellings with a high efficiency following the requirements of Directive 2010/31/EU [9]. It is proposed to more thoroughly investigate radon concentrations through measurements in different rooms at the same time, and to compare with simulations in CONTAM following the methodology described in this study. This should assist in modeling more realistic indoor radon sources that can afterwards be used to optimize the ventilation in a dwelling.

Conflicts of Interest: The author declares no conflict of interest.

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