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Environmental assessment of several scenarios of active and passive radon control measures

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Abstract. In buildings, radon gas mainly enters through cracks in the floors and gaps around pipes and cables in contact with the soil, thereby increasing indoor radon levels. Like other building components or systems, the radon control measures have embodied and operational environmental impacts that have been neglected to a certain extent. While many actions have been taken recently to achieve carbon-neutral yet energy-efficient buildings, even radon control measures should be investigated not only for protecting human health since radon gas is the major source of ionising radiation for humans but also for the environment. This paper aims to undertake a comparative analysis of the embodied and operational impacts of variant radon-protective measures installed at the floor foundation level (both active and passive solutions) for new and existing buildings. In particular, this analysis includes four different measures based on radon venting from i) floor air gap created from plastic components, ii) flexible perforated pipes embedded in the gravel layer under the floor, iii) radon sump placed in the sub-floor layer, and iv) perforated tubes drilled horizontally into the subsoil under the house. In all cases, radon will be removed through a vertical exhaust pipe terminated above the roof or by a roof fan. The impacts are calculated for the life cycle assessment (LCA) stages A1-A3 (production phase) and B6 (operational energy) to determine whether future research should be focused on the reduction of environmental impacts on the production stages or the operational ones.

1. Introduction

The natural decay of uranium produces radon, which can enter buildings through cracks or openings in the foundation and accumulate in the air [1,2]. Radon is a naturally occurring radioactive gas present in the soil and the largest source of radioactivity in indoor air. Radon is invisible, odourless, and tasteless. The World Health Organization (WHO) estimates that lung cancers may be caused by radon in a range between 3 to 14 % [3]. Radon levels in indoor air must be effectively reduced because there is currently no documented lower limit for the health risks associated with radon. Preventive or remedial building practices may be adopted to mitigate the radon impact. Such practices include sealing cracks and other openings in foundations, improving ventilation systems, and installing gas-tight membranes [4]. The materials used and the energy consumed during the production, construction, and maintenance of buildings and their components have significant environmental implications. As Felicioni et al. [5] described, the environmental impacts of radon control technologies have not yet been sufficiently investigated. The study contributes to the growing body of research on the sustainability of radon control

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measures using the Life Cycle Assessment (LCA) methodology. The manuscript addresses in the environmental assessment the production stage (A1-A3 stages) and operational energy (B6 stage) for four floor foundation scenarios, which have implemented radon control technologies for venting both actively and passively. The production stage is related to the material production stream and, the operational energy accounts for the energy emissions during the use stage. This work aims to understand which floor scenario for radon venting is more environmentally friendly and to which extent operational emissions impact the overall assessment. The analysis is conducted by comparing the scenarios using a single score, which has been obtained by multiplying the environmental parameters results by using the Environmental Footprint Normalization and Weighting Method (EF 3.0) [6,7]. This method involves normalising and weighting the results to group them into midpoint categories that can be summed up into a single score [8]. Thus, using these single-score indicators derived from the EF 3.0 method allows to directly compare the performance of different scenarios to identify the most environmentally friendly solution.

2. Aim and scope

The current paper is part of a larger study of the EU RadoNORM project [9] under the EU Horizon 2020 Framework Program. This project aims to improve scientific evidence and address social concerns to provide effective radiation protection. The authors' task involved assessing the environmental impact of various types of radon preventive and remedial measures applied to buildings [4,5]. This project was conceived in response to the European Union's desire to reduce exposure to radon in buildings by adopting Directive 2013/59/Euratom [10]. In addition, this Directive is intended to promote awareness of radon risk indoors by implementing a rule in every European country since 2018 with a subsequent monitoring and mitigation plan [11]. Building design, construction, and retrofitting should include radon control technologies to reach radon indoor concentrations as low as feasible [12]. Still, it is equally significant not to overlook the energy and greenhouse gas emissions generated during the materials production (such as extraction and manufacturing of materials). Materials' life cycles should be considered to minimise environmental impact.

3. Materials and method

3.1. Variants

As the common practice suggests, the easiest and most economical solution for reducing the ingress of gas radon in the building would be to insert a radonproof membrane into the floor structure resting on the ground; different kinds of membranes can have different performances in terms of radon proofing and embodied emission as presented by Felicioni et al. [5]. This study focused on situations where the soil gas radon concentration was considered so high that other solutions were required to ensure a healthy indoor environment. Four different protective measures installed at the building's floor foundation level (active and passive solutions) are investigated, as summarised in Table 1. In all cases, a polymeric radonproof membrane is installed at the foundation level, from which radon will be removed either through a vertical exhaust pipe terminating above the roof or a roof fan. In this LCA case study, the functional unit was a set of radon protective measures for venting floor foundations installed for a two-story single-family house for a 50 years service life as it could be seen as representative and easily replicable. The theoretical building footprint is 72.5 m^2, and the standard floor height is 2.7 m. The footprint represents only the area within the building that interfaces with the ground. There is no basement. This is a theoretical case study in which various floor scenarios are installed individually and compared to each other.

Table 1. Scenarios of floor foundation radon control technologies.

Variant	Description	Control	Suitability
A	Floor air gap created from preformed plastic components	Passive	New building

B	Flexible perforated pipes embedded in the gravel layer under the floor	Passive	New building
C	Radon sumps placed in the gravel layer under the floor	Active	New building
D	Perforated tubes drilled horizontally into the subsoil under the house	Active	Building Renovation

These variant sets of protective measures were compared to each other to understand which solution was the most environmentally friendly in terms of impacts that are described in Section 3.2. Figure 1 graphically describes the variant sets. In all four scenarios, the exterior walls of the single-family house are constructed with brick blocks with reinforced concrete structures and external insulation. Due to the design of these four variants, they would all result in the same reduction in radon concentration (same effectiveness) otherwise, the comparison of their environmental impacts would not be feasible.

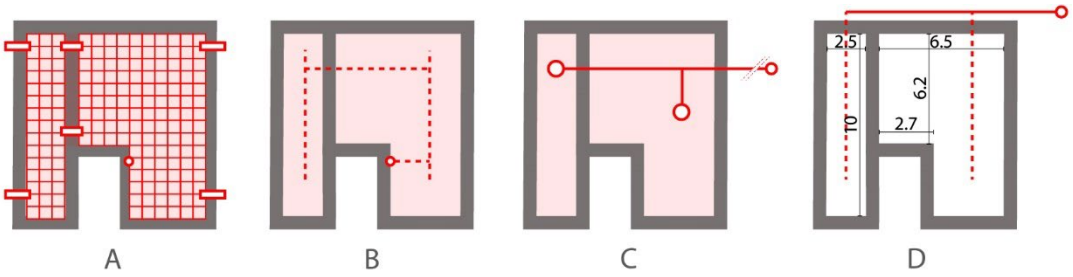

Figure 1. Schematic representation of foundation variants considered in the study. Variants A presents preformed plastic components, air inlets and a vertical exhaust pipe terminating above the roof. Variant B presents perforated pipes (dotted line) and a vertical exhaust pipe. Variant C present two radon sums connected with plastic pipes (solid line) to a roof fan. Variant D presents a combination of solid and perforated tubes; each pipe is drilled from the outside, and the connection to the fan must be outside the house.

3.1.1. Variant A. This variant consists of a floor air gap made from preformed plastic components (500x500 mm) with a vertical exhaust polyvinyl chloride (PVC) pipe (125 mm in diameter) terminating above the roof, which draws air naturally. Plastic components create an air gap of 200 mm in height. Usually, this solution is adopted for new buildings. The floor layers, including floor tiles, concrete screed, double thermal insulation in expanded polystyrene insulation boards (EPS), and a 50 mm concrete slab reinforced with steel mesh, were not included in the environmental calculation because they are typical layers regardless of radon protection. Instead, a PVC membrane of 1.5 mm thickness between two geotextile foils and a 5 cm gravel layer has been considered. The total foundation height is 67 cm, but excavations have not considered the volume of the non-considered layers. This variant includes six PVC inlets placed in between the foundation stripe, allowing outdoor air to enter the air gap and, with the principle of cross ventilation, diluting the radon concentration through the exhaust pipe that works as an outlet [4]. The excavation machine's impact has also been considered as part of calculating the environmental impacts.

3.1.2. Variant B. In this variant, flexible perforated PVC pipes (60 mm diameter) are embedded beneath the floor in a gravel layer (150 mm thick). The system operates passively by installing a vertical exhaust PVC pipe (125 mm in diameter) from the foundation level to the roof. Typically, this solution is adopted in the case of new buildings. The floor layers consisting of floor tiles, concrete screed, single thermal insulation in an EPS board, and a 100 mm concrete slab reinforced with steel mesh were not included in the environmental calculation because they are typical layers regardless of radon protection. Instead, a PVC membrane of 1.5 mm thickness between two foils of geotextile has been considered. In addition, the impact of the excavation machine has also been accounted for in the environmental assessment. The

total foundation height is 45 cm, but excavations have not considered the volume of the non-considered layers.

3.1.3. Variant C. In this variant, two PVC radon sumps are placed below the floor layers into the gravel (150 mm thickness). Indeed, each section of the foundation level surrounded by foundation strips must contain at least one radon sump. In order for the system to function actively, a polypropylene (PP) roof fan is installed at the end of a PVC pipe (100 mm in diameter), which runs from the farther place in the house's garden to the radon sump. The solution is ideally suited for use in both new and existing buildings; however, in this study, a new building is considered. Floor tiles, concrete screed with an EPS board, and a 100-mm concrete slab reinforced with steel mesh were not included in the environmental calculation because they are typical layers regardless of radon protection. Instead, a PVC membrane of 1.5 mm thickness between two foils of geotextile has been considered. In addition to the environmental impact calculation, the impact of the excavation machine has also been accounted. The total foundation height is 45 cm, but excavations have not considered the volume of the non-considered floor layers.

3.1.4. Variant D. As part of this variant, perforated tubes are drilled horizontally into the subsoil underneath an existing house (for ease of calculation, the design of the existing house has been considered equal to the design of the new building used for the other variants). PVC tubes (60 mm diameter) are usually drilled through the perimeter foundation strip from the external trench. Each section of the foundation level surrounded by foundation strips must contain at least one perforated tube. In this case, since two perforated tubes are designed, they must be connected to one fan through an underground PVC pipe. The PP roof fan is mounted at a suitable height above the ground, preferably as far away from the house as possible. Passive ventilation is not used because it is ineffective in this case. Since variant D is installed in an existing building, the floor layers are not required to be considered in the environmental impact calculations; only the additional elements introduced to reduce the impact of radon on the indoor environment are included. For the excavation process, the volume of the tubes was considered.

3.2. Environmental impact categories and assessment

After designing the floor foundation variants, the bill of quantity for each was calculated based on the single-family house case study. Indeed, the foundation system was considered as the sum in kilograms of each building element, the excavation volume and the potential energy consumption. The quantity of each element was then inserted in the LCA tool. The fan's operational energy's impact in scenarios C and D (E_f, expressed in kWh) was calculated according to Equation (1).

$$E_f = P * n_w * a \quad (1)$$

where P is fan power consumption (40 W was assumed); n_w is the number of operating hours (24 hours of operation was considered); a is the number of operating days (365 days were considered). In this study, the fan was assumed to be powered by a medium-voltage electricity mix from Czechia (the Simapro data are from 2017). At that time, the Czech energy mix was made up of 54.03 % fossil fuels (43.89 % lignite, 9.89 % natural gas, etc.), 40.41 % nuclear power, and 5.56 % renewables (3.31 % biomass, 1.65 % solar, 0.61 % water, etc.).

All floor foundation scenarios were modelled in SimaPro v9.4.0.2 [13], one of the most widely-known software for conducting LCA based on the Ecoinvent v3.9.1 Life Cycle Inventory (LCI) database [14], considering the EN 15804+A2:2019 standard [15], and the four impact categories among the most thoroughly investigated impact categories in the construction industry. These are Global Warming Potential (GWP – expressed in kg-CO2 eq.), Ozone Layer Depletion Potential (ODP – expressed in kg-CFC11 eq.), Acidification Potential (AP – expressed in mol H+ eq.), and Eutrophication Potential (EP – expressed in kg-Phosphate eq.). Also, EF 3.0 method [6,7] was used to compare the results of the floor foundations, which allows the four impact categories to be combined into a single score.

4. Results and discussion

The four variants were processed using SimaPro to calculate the environmental impacts. Figure 2a displays the single score indicators for the scenarios (A to D) calculated using the EF 3.0 method and specifies the percentage share between embodied impacts (I_e) and operational impacts (I_o). Variant D (drilled tubes - active control) presents the lowest single score value because this radon control technique is installed on an existing building; that is to say, all the emissions associated with manufacturing the building's floor materials are not considered. Among the three other variants for new buildings, variant B (perforated pipes - passive control) presents the lowest single score value - 0.056; however, variant C (radon sumps – active control) presents the lowest embodied impact - 0.052. It is worth noting, however, that variant C's total single score results in 72% of embodied impacts and 28% of operational impacts. Figure 2b shows the GWP impact. A, B, and C demonstrate similar results (around 20 kg CO_2eq/m^2 over a 50-year service life); however, variant C includes both stages A1-A3 (product stage) and B6 (operational stage). Nevertheless, the energy required for the fan function is not very high, so it is not very impactful. The total impact analysis includes the impacts resulting from the excavation process using a skid-steer loader which requires 0,13 kg of diesel to excavate 1 m^3. For this reason, scenario A presents the highest embodied GWP since it requires a soil excavation volume 65% greater than scenario B or C.

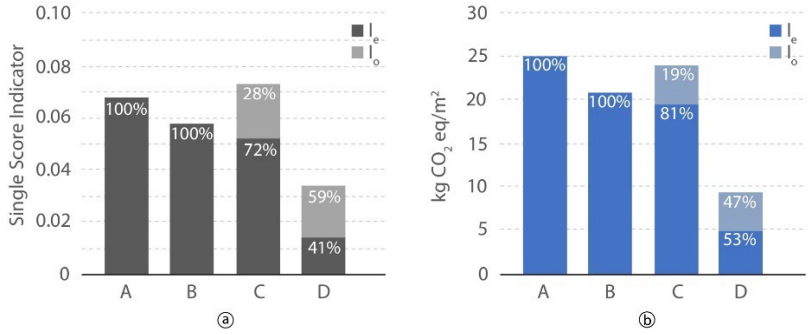

Figure 2. a) Single score indicator for each scenario. b) GWP expressed in kg CO_2 eq./m^2 for 50 years of building service life. In both graphs, scenarios A and B consider A1-A3 stages while scenarios C and D consider A1-A3 and B6 for accounting fan's operation. Percentages indicate the share between embodied and operational impacts.

Figure 3 shows pie charts that illustrate the share of the four environmental impacts on the single score value for each variant. For example, in variant A, 70% of the total score is generated by GWP, followed by EP with 14.5%; variants B and C have quite similar results. By contrast, variant D's single score is accounted for by GWP and EP, respectively, 55% and 33%, respectively.

Figure 3. Environmental impact ratios for each scenario based on their single score.

5. Conclusion

This paper was developed as part of the EU RadoNORM project under the Horizon 2020 framework program to calculate the environmental impacts of radon protective measures for buildings. This study examines the environmental impacts of four radon control techniques for venting at the floor foundations (active and passive solutions) on a single-family house case study since it is the most manageable and replicable solution. In the environmental calculations, the standard floor layers were not considered since they are common elements of all houses regardless of radon. In new buildings, radon protective measures include additional gravel layers, plastic components, fans, and larger excavations.

Implementing anti-radon measures in existing buildings can be less environmentally impacting because the existing floor layers are not accounted for in the assessment. Based on the results, adding a roof fan (active solution) to ventilate the subsoil/gravel significantly affects the score in the case of an existing building (Variant D – ca 60% on the overall single score); however, the impact is lower in the case of a new building (Variant C – ca 30%) since production stages have a greater impact. Future studies will examine more scenarios of radon control measures to identify their environmental impact and provide a comprehensive analysis of the less environmental impact measures available for radon mitigation.

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