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Limited applicability of cost–effectiveness and cost–benefit analyses for the optimization of radon remedial measures

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ABSTRACT

Ways of using different decision-aiding techniques for optimizing and evaluating radon remedial measures have been studied on a large set of data obtained from the remediation of 32 houses that had an original indoor radon level above 1000 Bq/m^3. Detailed information about radon concentrations before and after remediation, type of remedial measures and installation and operation costs were used as the input parameters for a comparison of costs and for determining the efficiencies, for a cost–benefit analysis and a cost–effectiveness analysis, in order to find out whether these criteria and techniques provide sufficient and relevant information for improving and optimizing remediation. Our study confirmed that the installation costs of remediation do not depend on the original indoor radon level, but on the technical state of the building. In addition, the study reveals that the efficiency of remediation does not depend on the installation costs. Cost–benefit analysis and cost–effectiveness analysis lead to the conclusion that remedial measures reducing the indoor radon concentration from values above 1000 Bq/m^3 are always acceptable and reasonable. On the other hand, these techniques can neither help the designer to choose the proper remedial measure nor provide information resulting in improved remediation.

1. Introduction

Radon in buildings is considered to be the most important indoor air pollutant, with harmful effects on the health of the general population. Inhalation of radon and its short-living decay products increases the risk of lung cancer. Therefore, exposure levels are regulated in many countries. The only way to decrease the radon dose in dwellings is to decrease the indoor radon concentration. Several types of radon remedial measures are available for such purposes [1]. However, people who have to make decisions on the type and the degree of remedial works have no effective tool for selecting the best solution.

It has not been clear how to optimize remedial measures in terms of a balance between costs of remediation and costs of the benefits, which include dose reduction and years of life gained by averting cases of radon-induced lung cancer. Standard straightforward decision-aiding techniques, such as cost–benefit analysis and cost–effectiveness analysis, which are commonly applied in the nuclear industry, have not been verified for practical implementation in the field of radon remediation. Latest research is devoted to the application of these techniques for verification of national strategies and policies for controlling radon levels in homes [2–4], but not to improving the design of countermeasures.

2. Materials and methods

2.1. Applied analyses

Ways of using various decision-aiding techniques for evaluating radon remedial measures are discussed in this paper. Our study is based on a large set of data obtained from the remediation of 32 houses with an indoor radon concentration above 1000 Bq/m^3 (around 3–4 thousands of all dwellings in the Czech Republic have a radon concentration higher than 1000 Bq/m^3). Detailed information about radon concentration levels before and after remediation, the type and the extent of remedial measures, the installation and operation costs were used as input parameters for a comparison of costs, for determining efficiencies, and for cost–benefit analysis and cost–effectiveness analysis in order to find out whether these criteria and techniques provide sufficient and relevant information for improving and optimizing the design of remedial measures.

2.2. Description of the studied houses and remedial measures

The houses under study were located throughout the territory of the Czech Republic. The age of the houses ranged from 20 to

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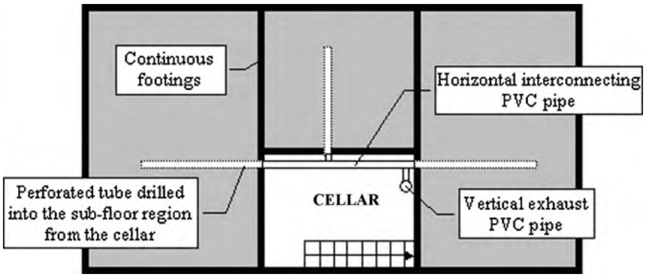

Fig. 1. Group S—Perforated tubes drilled into the sub-floor region from the cellar.

100 years. The houses had been remediated in the past 9 years. The selection included all types of substructures—houses with and without cellars, with timber floors placed directly on the soil or concrete slabs with or without dampproof insulation. The indoor radon concentration before remediation varied from 460 Bq/m^3 to 4177 Bq/m^3, with a mean value 1878 Bq/m^3, and it dropped to values between 43 Bq/m^3 and 410 Bq/m^3, with a mean value of 148 Bq/m^3 after the remedial measures had been installed. Concentrations were measured in all habitable rooms of a particular house under standard conditions (during the measurements, the houses were occupied, i.e. the indoor temperature and air exchange rate corresponded to the occupants' habits). The indoor radon concentration before remediation was measured by track detectors (Kodak LR 115) exposed for either 3 months (not in summer) or 1 year. Immediately after the installation of remedial measures had been completed, the indoor radon concentration was measured by electret detectors and continuous monitors with exposition time of 1 week. Continuous monitors helped to set the power of fans and the frequency of operating periods.

All types of remedial measures in recent use in the Czech Republic for remediation of houses with indoor concentrations above 1000 Bq/m^3 [5] are covered by this study. Such measures are based on various types of sub-slab depressurization (SSD) systems that lower the air pressure beneath the buildings and decrease the radon concentration in the soil gas. The air pressure is lowered by means of fans, which draw air from perforated tubes drilled beneath the existing floors or from flexible perforated pipes placed in the sub-floor gravel layer.

A total of 16 houses were remediated without damage to the existing floors: in the first group of 8 houses (Group S), the perforated tubes were drilled from the cellar (Fig. 1), and in the second group (Group E), the tubes were drilled from the trench excavated in the ground along one or two sides of the house (Fig. 2). In another 8 houses, the perforated tubes were installed from the

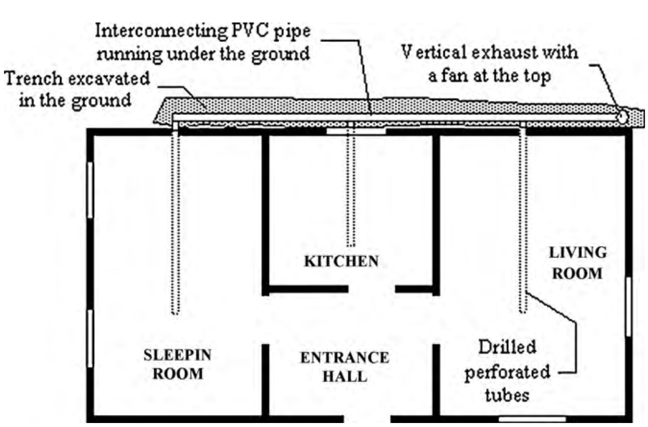

Fig. 2. Group E—Perforated tubes drilled into the sub-floor region from the trench excavated in the ground.

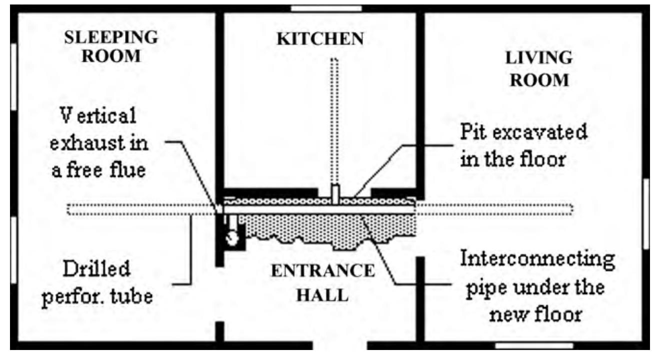

Fig. 3. Group K—Perforated tubes drilled into the sub-floor region from the floor pit. This solution requires a new floor in the room where the pit was excavated.

floor pit (Group K), usually excavated in one room (Fig. 3), where afterwards a new floor with a radon-proof membrane had to be placed. In the remaining 8 houses (Group P), the existing floors were replaced by new floors sealed with a radon-proof membrane [6] made of 1.5 mm thick HDPE foil. The soil ventilation was formed by a network of perforated pipes (Fig. 4) placed in the 150 mm thick sub-floor drainage layer of coarse gravel. Houses in group P therefore represent a combination of two techniques—sub-slab depressurization + a radon-proof membrane to increase the tightness of the floor slabs.

All important information about the surveyed houses is summarized in Table 1.

3. Analysis and results

3.1. Cost of remediation versus efficiency

The cost of pure remediation, presented in Table 1, covers not only the installation itself, but also the design costs and the costs of the measurements of indoor radon concentration to verify the efficiency of the implemented measures (CZK were converted into € at a rate of CZK 27 = €1). As can be seen from Fig. 5, which shows the mean costs of the types of SSD systems studied here, the cheapest measure consists of tubes drilled from the cellar. If the tubes are drilled from the exterior, the excavation work and rearranging the ground raises the price by about 30%. When tube drilling requires removal of a floor in one room, the new floor in this room raises the price approximately 2.1 times compared with the cheapest remediation discussed in this paper. Finally, as one might assume, a combination of new floors and soil depressurization is the most expensive measure. The ratio between the average costs of the most expensive type of measure and the cheapest type of measure is

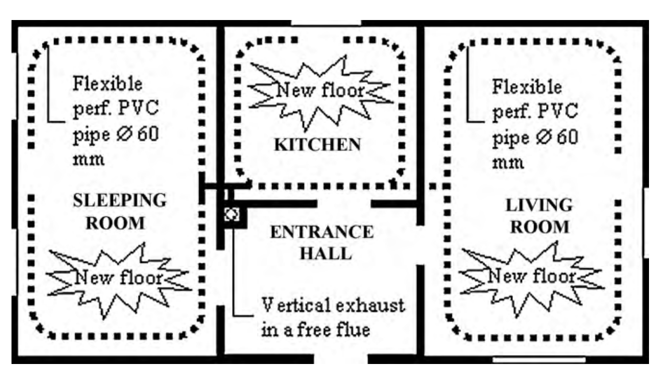

Fig. 4. Group P—Flexible perforated pipes inserted into the drainage layer placed under the new floors sealed with a radon-proof membrane. Pipes are laid along the walls in order to stop radon from entering the dwelling through the wall-floor joint.

Table 1
Extent of remedial works together with pure costs and efficiency of remediation for the groups of houses under study.

Groups under study (each group was represented by 8 houses)	Cost of pure remediation (€)	Living area (m^2)	Length of drilled tubes (m)	Area of new floors (m^2)	C_{before} (Bq/m^3)	C_{after} (Bq/m^3)	Efficiency (%)
Average Group S	3200	91	12	0	1372	146	86
Std deviation Group S	1200	33	7.6	0	834	75	9
Average Group E	4190	114	16	0	1951	175	91
Std deviation Group E	600	41	3.6	0	829	114	5
Average Group K	6720	82	12	22	2285	136	94
Std deviation Group K	1980	25	4	15	836	61	3
Average Group P	10,840	68	1	60	1907	135	92
Std deviation Group P	2490	18	1	16	945	90	5
Total average	6240	89	14[a]	41[b]	1878	148	91
Std deviation of whole set of houses	2950	17	6	25	330	16	3

Note: the total average was calculated from all studied houses, not from the group averages. C_{before} – the mean value of indoor radon concentration measured by track detectors (Kodak LR 115) in all habitable rooms before installation of remedial measures; C_{after} – the mean value of indoor radon concentration measured by electret detectors or continuous monitors in all habitable rooms after installation of remedial measures.

[a] Only Groups S and E were considered.

[b] Only Groups K and P were considered.

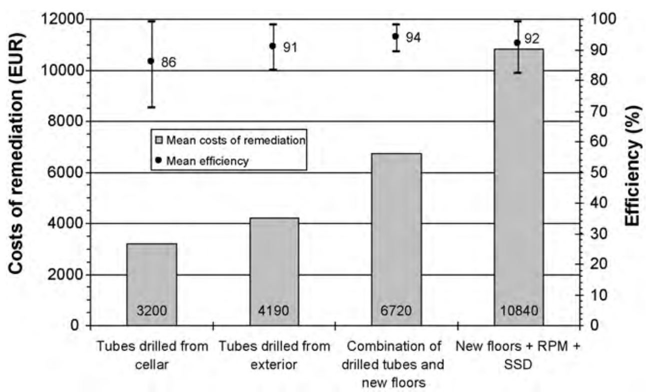

Fig. 5. Comparison between the mean pure cost values of various remedial measures and their efficiencies (SSD – sub-slab depressurization, RPM – radon-proof membrane).

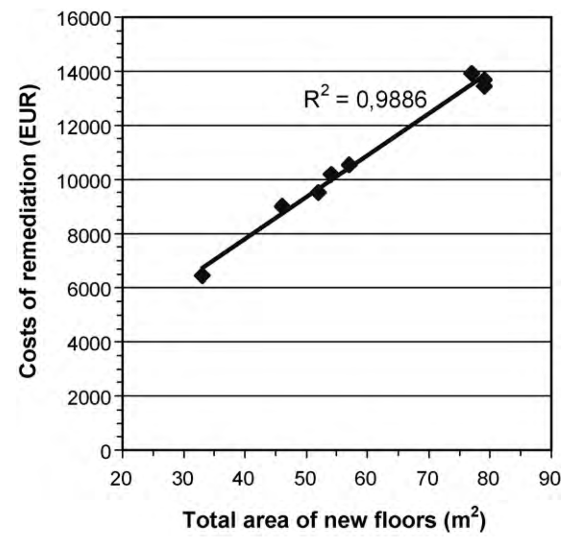

Fig. 7. Correlation between the costs of pure remediation and the area of new floors (Group P).

3.4. However, if particular houses are taken into consideration, the costs can differ more than sixfold. A very good correlation between remedial costs and the extent of remedial works is documented in Figs. 6 and 7, where the costs of pure remediation are plotted against the length of drilled tubes or the area of new floors.

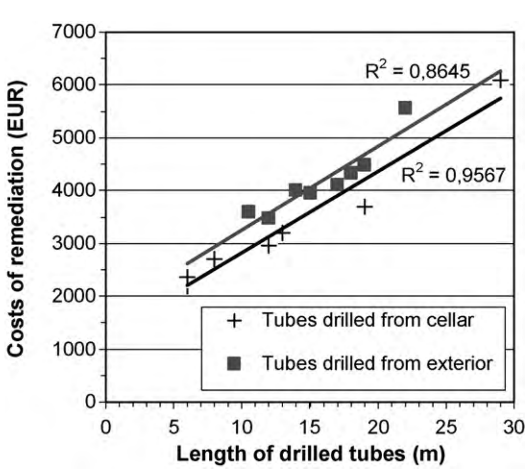

Fig. 6. Correlation between the costs of pure remediation and the length of drilled tubes (Groups S and E).

The fixed assumption that the costs of pure remediation depend on the original level of indoor radon concentration is rejected by our study. As shown in Fig. 8, there is no correlation between these two parameters. It is evident that the cost of remediation depends mainly on the technical state of the building (type and

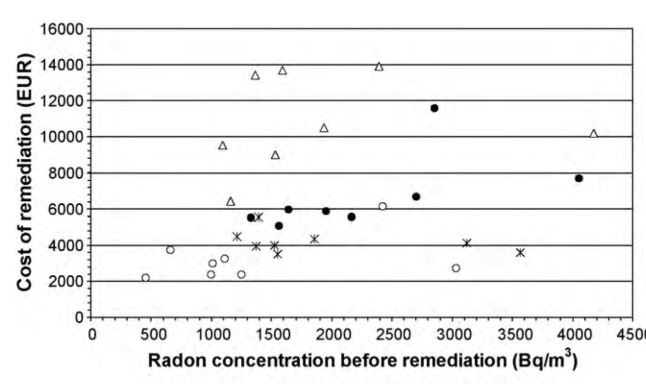

Fig. 8. Costs of pure remediation plotted in dependence on the original radon concentration.

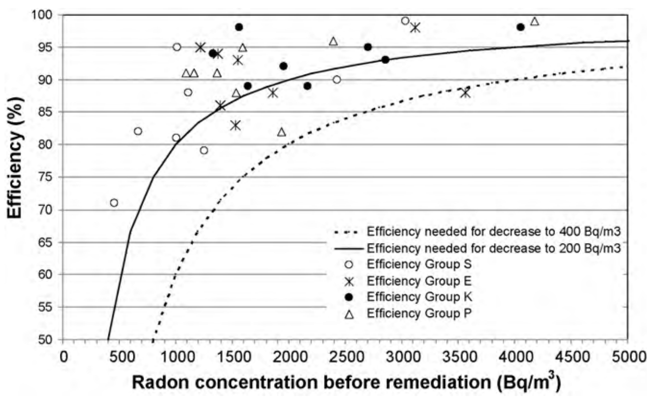

Fig. 9. Correlation between the obtained efficiencies and the required efficiencies.

air-tightness of floors resting on the ground, presence of internal foundations, permeability of sub-floor layers, built area, layout of the house, etc.) and on the applicability of a particular measure in a particular building. Especially for houses with an indoor radon concentration above 1000 Bq/m^3, which cannot be remediated by simple and cheap measures such as sealing the radon entry routes and enhanced natural basement or first floor ventilation, the indoor radon concentration plays only an advisory role in the design of remediation.

The efficiency e of remediation stated in Table 1 was calculated for each house, using the following formula:

$$e\ [\%] = \frac{C_{\text{before}} - C_{\text{after}}}{C_{\text{before}}} \times 100, \tag{1}$$

where C_{before} and C_{after} are indoor radon concentrations [Bq/m^3] before and after remediation.

As can be seen from Fig. 5, there are no substantial differences in efficiency between the types of remedial measures studied here [7] (the differences between the mean values are not greater than 5%). This is caused by the fact that the principle of mitigation is in all cases the same—soil depressurization. Increased tightness of floor slabs produced by placing a radon-proof membrane (Group P) had no substantial effect on the efficiency. The efficiency calculated for the whole group of 32 houses varies between 71% and 99%, with a mean value of 91%, which means that the indoor radon concentration decreases to between 29% and 1% of the initial values. Efficiency lower than 85% was discovered for only 6 houses, in which the initial indoor radon concentration values were below or slightly above 1000 Bq/m^3. Fig. 5 also illustrates quite clearly that the efficiency does not increase with increasing remedial costs (under the assumption that we exclude simple measures from consideration). Higher costs are usually associated with worse technical state of the building or complicated and difficult applicability of a particular measure. Therefore, expensive measures are not automatically the most effective measures.

Fig. 9 plots the obtained efficiencies for all houses in dependence on the radon concentration before remediation. The minimum efficiencies required for decreasing the indoor radon concentration below a reference level of 200 Bq/m^3 or 400 Bq/m^3 are presented by two curves. It can be seen that in most of the houses the radon concentration decreased below 200 Bq/m^3 after remediation. In six houses, the concentration was higher than 200 Bq/m^3, but there was only one house in which it slightly exceeded 400 Bq/m^3. Fig. 9 clearly shows that the efficiency itself says nothing about the resulting radon concentration, because this value also depends on the initial radon concentration. However, efficiency in combination with initial radon concentration is a powerful tool describing the differences in the ability of a particular measure to reduce the indoor radon concentration to a required level. This tool can be applied to any measure, not only to the types covered by this study.

It should be noted that the high efficiency of all active sub-slab depressurization systems is conditioned by the willingness of householders to pay the operational and maintenance costs. If an irresponsible person switches them off, the benefits are lost. Unfortunately, this is not a rare occurrence [8]. Scivyer and Noonan [8] shows that after significant house alteration works it is also necessary to retest the functionality of the SSD systems.

3.2. Cost–benefit analysis

Cost–benefit analysis is based on a comparison between the monetary value of an action (remediation) and the benefits (lives saved) produced by the action. For the purposes of this paper, the monetary value of the action is considered to be the sum of the costs of:

(a) design and installation of remedial measures,
(b) radon measurement after remediation (approx. €300),
(c) operation costs, covering the energy consumption of fans (based on the current energy retail price for general households, i.e. 1MWh costs €198 [9]),
(d) maintenance costs—fan replacement every 10 years (based on the average current price of a high-quality fan, including installation costs).

The cost of the initial measurement of radon ranges between €100 and €150. This amount is negligible in comparison with the other costs, and therefore it was not included in the total price of the remediation.

Table 2 shows the cost of pure remediation (covering expenses (a) and (b) from the above stated list) together with the total cost of remediation for 30-year operation (all expenses stated in the list are included). This time interval was chosen with respect to the average age of houses in the Czech Republic, which is 47 years [10], and also with respect to the average interval between two major reconstructions (based on good practice). The assumed interval for fan replacement (10 years) comes from practical experience, and it is also supported by the paper of Coskerkan et al. [11] and Petersen and Larsen [12]. Full-time fan operation is considered. However, in real conditions fans are usually switched to an intermittent mode, with the frequency of the operating periods depending on the rate of decrease and increase of indoor radon concentration after the fan is switched on and off. Savings in operation costs and prolonged life of the fans are advantages of intermittent fan operation. The real costs will therefore be lower than the total costs assumed in this paper. Due to lack of information about future economic developments, the authors do not take into consideration future values; all the calculations are made on the basis of current values.

Table 2 shows great differences between pure and total costs of remediation. Whilst the average cost of pure remediation is €6240 only, the total cost of remediation covering installation, maintenance and operation costs is €10,150. Almost 40% of the total cost of remediation is for operation and maintenance costs.

As can be seen from Table 1, the average indoor radon concentration before the application of remedial measures was 1878 Bq/m^3, and after remediation it was only 148 Bq/m^3. As a result of this significant reduction in radon concentration, the average effective dose has decreased from 32 mSv/y to only 2.5 mSv/y (Table 2). The annual effective dose E was calculated using formula (2):

$$E\ [\text{mSv}] = h_P \cdot C \cdot T, \tag{2}$$

where $h_P = 2.4\text{E}^{-6}$ mSv m^3/Bq h is the conversion convention according to ICRP Recommendation 65 [13], C is the radon con-

Table 2
Average costs of remediation for 30-year operation and effective doses before and after remediation for the studied groups of remedial actions (the values are for one house).

Groups under study (each group was represented by 8 houses)	Cost of pure remediation (€)	Total cost of remediation (€)	E_{before} (mSv/y)	E_{after} (mSv/y)	Averted collective dose (manSv)
Average Group S	3200	6220	23.1	2.5	1.60
Std deviation Group S	1200	1930	14.0	1.3	1.10
Average Group E	4190	8730	32.8	2.9	2.32
Std deviation Group E	600	1880	13.9	1.9	1.02
Average Group K	6720	11,260	38.4	2.3	2.80
Std deviation Group K	1980	2580	14.1	1.0	1.10
Average Group P	10,840	14,380	32.0	2.3	2.31
Std deviation Group P	2490	2510	15.9	1.5	1.26
Total average	6240	10,150	32	2.5	2.26
Std deviation of whole set of houses	2950	3020	5	0.27	0.43

Note: the total average was calculated from all studied houses, not from group averages.

centration [Bq/m^3], and T is the exposition time spent at home [h] that was considered by a value of 7000 hours per year [13].

Eq. (2) can also be used for calculating the averted dose due to the application of remedial measures in the studied group of houses. In this case, C is replaced by the difference $C_{before} - C_{after}$.

The collective dose S [manSv] per one house was calculated by multiplying Eq. (2) by a factor of 2.59, which is the average number of persons living in one household in the Czech Republic [10]. The averted collective dose is obtained by the same procedure as in the case of the averted effective dose. The total averted collective dose due to the remediation of 32 houses is 2.4 manSv per year.

The ICRP [23] commission has recently re-evaluated the "detriment-adjusted nominal risk coefficients for stochastic effects after exposure at low dose rate", which are about two times the values adopted in Publication 65. On the one hand, the effective dose will increase about two times due to this change; on the other hand this will not influence either the cost–benefit or the cost–effectiveness analysis, which are based on saved lives not on the effective dose. It should be mentioned that UNSCEAR also uses different coefficients.

The second integral part of the cost–benefit analysis is an evaluation of the cost of the benefits. The cost of saved lives or, better to say, the cost of saved years due to the averted dose from radon and its decay products is the main benefit of radon concentration reduction in the houses.

Estimating the cost of a saved life is not a simple task. One approach that is often used is connected with *Willingness to pay* (*WTP*), which is the amount that an individual is ready to pay for extra protection. No general analysis of *WTP* in the Czech Republic is available, but data from the study carried out for the State Office for Nuclear Safety (SONS) can be used as provisional *WTP* results [14]. Various approaches to evaluate the cost of a life have also been studied in the literature, as summarized in the following list.

- The preliminary results of the public opinion research stated in the report of SONS [14] indicate that Czech people are ready to pay €7800 per one saved year.
- Poffijn et al. [15] indicates that Swedish society is willing to pay 1–10 times the average national gross domestic product per person for a year's postponement of death. The average national gross domestic product per person in the Czech Republic was €13,000 in 2008 [16]. If the *WTP* of Czech and Swedish society were the same, the cost per one saved year would be at least €13,000.
- In the field of road transportation science, a value of €355,555 per saved life is used for optimization of safety measures in the Czech Republic [14]. Due to the lack of other values for the cost of a life, this value was also used in this study for deaths due to radon.
- An EU DG workshop [17] which dealt with statistical fatality values recommends a statistical fatality value of €1.4 million.
- Petersen and Larsen [12] published a value of €47,785 per hospital admission and loss of production per one case of lung cancer. The cost of lung cancer treatment is approximately €11,000 in the Czech Republic (Personal communication).
- The value of €18,520 per averted manSv, which is set in Czech legislation [18], serves as the upper limit of reasonable costs of remedial action in the field of natural radioactive sources.

Table 3 presents the number of saved lives and gained years, summarized together with the appropriate costs for the studied groups of houses. The number of lung cancers caused by the elevated radon concentration C was estimated using formula (3), which was proposed by Thomas et al. [19]:

$$N_{Rn} = N \cdot R_0 \cdot \beta \cdot C, \quad (3)$$

where N_{Rn} is the approximate number of radon-induced lung cancers in the exposed population of size N in a demographical steady state, R_0 is the spontaneous occurrence of lung cancers in the Czech Republic $R_0 = 0.0436$ [19], $\beta = 0.0016\,\text{Bq/m}^3$ is the excess relative risk of lung cancer for 30-year exposure to an average radon concentration of 1 Bq/m^3 [19,20], C is the radon concentration in Bq/m^3.

A reduction in radon-induced lung cancers ΔN_{Rn} (in other words, the number of saved lives) caused by the decrease in indoor radon concentration after the implementation of remedial measures was approximated by Eq. (3), in which C was replaced by the difference $C_{before} - C_{after}$.

The years of life gained ΔY were estimated as the product of ΔN_{Rn} and the mean time $\tau = 13.7$ years [21] for the difference in length of life without and with lung cancer:

$$\Delta Y \ [\text{y}] = \Delta N_{Rn} \cdot \tau \quad (4)$$

Another useful indicator that can also be found in Table 3 is the cost of 1 year of life gained by the implementation of countermeasures. This was calculated as the ratio between the total cost of remediation and the number of gained years ΔY. The cost of a saved life is assessed as the ratio of the total cost of remediation and the number of saved lives. The cost of averted manSv is obtained in the same way as the ratio of the total cost and the averted collective dose.

The average number of saved lives per one house is 0.31, and the total number of saved lives due to remediation of the whole group of 32 houses is 10. The cost of averted manSv for 30-year operation of remediation is on an average €5350, while the cost of a saved life is on an average €38,550. This value is 4 times greater

Table 3
Summary of cost-benefit analysis for 30-year operation (the values are per one house).

Groups under study (each group was represented by 8 houses)	Total cost of remediation (€)	Gained years (y)	Saved lives	Cost of one gained year (€)	Cost of averted manSv (€)	Cost of saved life (€)
Average Group S	6220	3.04	0.22	2810	5330	38,430
Std deviation Group S	1930	2.09	0.15	1430	2720	19,640
Average Group E	8730	4.40	0.32	2350	4470	32,220
Std deviation Group E	1880	1.93	0.14	1060	2020	14,540
Average Group K	11,260	5.33	0.39	2260	4290	30,960
Std deviation Group K	2580	2.08	0.15	470	900	6480
Average Group P	14,380	4.39	0.32	3840	7290	52,590
Std deviation Group P	2510	2.40	0.18	1160	2200	15,860
Total average	10,150	4.29	0.31	2820	5350	38,550
Std deviation of whole set of houses	3020	0.82	0.06	630	1190	8590

Note: the total average was calculated from all studied houses, not from group averages.

than the average total cost of remediation by the types of remedial measures studied here.

Fig. 10 compares the total costs of remedial actions in 32 houses with the maximum permissible value according to the cost of the benefit (the cost of a life multiplied by the number of lives saved by the application of remedial measures). Three different approaches were used for evaluating the cost per life saved:

- the conversion factor of €18,520 per averted manSv according to Czech legislation [18] (solid line),
- the sum of the cost of lung cancer treatment and the cost of a life [14], equal to €366,555 per life saved (squares),
- the average cost of lung cancer treatment summed with the national gross domestic product per person (according to [15]) multiplied by the number of saved years (dashed line).

As shown by the graph, all of the applied remedial measures meet the criterion that the cost is lower than the benefit.

3.3. Cost–effectiveness analysis

The aim of cost–effectiveness analysis is to compare the costs of the actions and the residual collective dose. This comparison was made for all types of remedial measures studied here. As shown in Fig. 11, there is no correlation between the type of measure and the remaining dose level. On the other hand, the figure confirms that the most expensive measure is to replace existing floors by new floors, and the cheapest measure is sub-slab depressurization installed from the cellar.

Since cost–effectiveness analysis is more powerful and more useful when applied to quite different measures, we decided to compare the set of studied remedial measures with a completely different remedial action. After detailed consideration, we chose the simplest remedial action – natural ventilation – for the comparison (also used by Katona et al. [22]). To be as effective as the original measures studied here, natural ventilation must ensure a ventilation rate that decreases the indoor radon concentration to the same level as the studied measures or at least to the action level of 400 Bq/m^3. Because of lack of information about the ventilation habits of the householders, we assumed that the original ventilation rate in all of the studied houses was 0.6 h^{-1}. This value is twice greater than the recommended minimum ventilation value according to Czech legislation. The required air exchange rate that must be ensured by natural ventilation was calculated for each of the studied houses for a typical room with dimensions of 5 m × 5 m × 2.7 m and interior air volume of 67.5 m^3.

The average annual cost for heating the incoming air that replaces the warm air exhausted by ventilation from the house was calculated with the following assumptions: average annual outdoor temperature, 10 °C; average annual indoor temperature, 22 °C; heat transfer through building materials, not taken into account; cost of 1 MWh for electric heating panels, €104 [9]. The average annual cost of heating to eliminate the heat losses caused by enhanced natural ventilation is then €262 × k, where k is the ventilation rate in h^{-1}.

The minimum ventilation rates and the corresponding costs for additional heating are summarized in Table 4.

As shown in Table 4, the cost for additional heating is too high to be acceptable. If the enhanced natural ventilation decreases the indoor radon concentration only to 400 Bq/m^3, the cost of additional heating is on an average nearly twice as high as the total cost of remediation by soil depressurization. If natural ventilation were made as effective as soil ventilation, the cost for additional

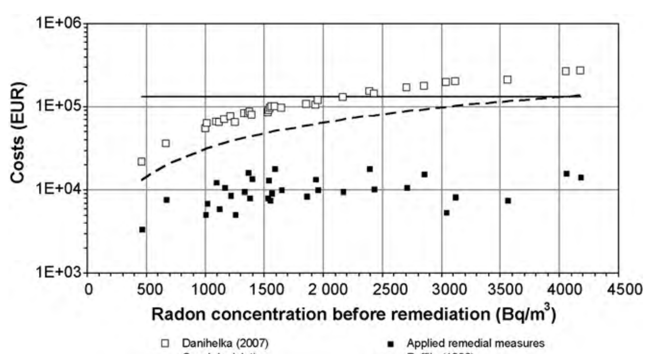

Fig. 10. Total costs of remediation for 30-year operation versus costs of lives saved, plotted as a function of the radon concentration before remediation.

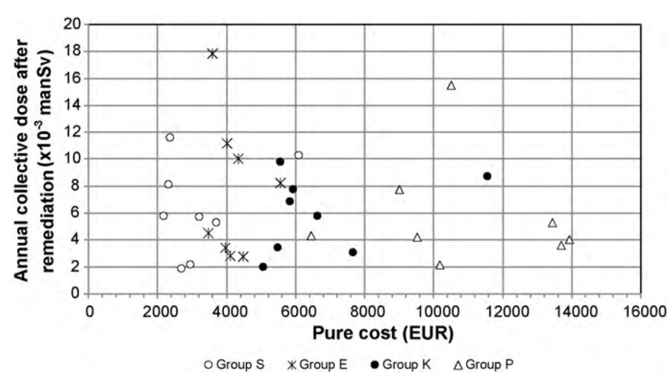

Fig. 11. Annual collective dose after remediation in terms of pure costs of the types of remedial measures studied here.

Table 4
Minimum ventilation rates ensuring a decrease in indoor radon concentration to the same level as with the remedial action, or to the action level of 400 Bq/m^3, and the corresponding costs for additional heating (the values are per one house and for 30-year operation).

Groups under study (each group was represented by 8 houses)	Total cost of remediation (€)	Ventilation needed for 400 Bq/m^3 (h^{-1})	Cost of additional heating for ventilation to 400 Bq/m^3 (€)	Necessary ventilation providing the same radon concentration as the remedial measure (h^{-1})	Cost of additional heating for the same conc. as the remedial measure (€)
Average Group S	6220	2.06	11,442	9.66	71,060
Average Group E	8730	2.93	18,249	9.72	71,570
Average Group K	11,260	3.43	22,181	13.17	98,630
Average Group P	14,380	2.86	17,734	13.25	99,280
Total average	10,150	2.82	17,400	11.45	85,140

Note: the total average was calculated from all studied houses, not from group averages.

heating would exceed the total costs of remediation by soil depressurization eightfold. This analysis illustrates quite clearly that the application of any type of sub-slab depressurization system is a cost-effective solution.

We can also compare the residual exposure after the same amount of money is spent for different remedial actions. In our case, we compared residual exposures in particular houses after the application of sub-slab depressurization systems with the exposures resulting from enhanced ventilation if the cost of additional heating is equal to the total cost of remediation by soil depressurization. The comparison is presented in Fig. 12 in terms of the residual collective effective dose plotted against the total cost covering the installation of sub-slab depressurization systems and operating them for 30 years. The horizontal lines correspond to the collective doses for radon concentration equal to 400 Bq/m^3 and 1000 Bq/m^3, respectively.

Fig. 13 compares the total cost of remediation by soil depressurization, the cost of additional heating due to enhanced natural ventilation, and the Czech legislation recommendation for optimization of irradiation from natural sources of radiation, which is equal to €18,520 per manSv [18], up to which the remedial measures should be cost-effective.

As shown in the graph in Fig. 13, all remedial measures applied for reducing indoor radon concentrations higher than 1000 Bq/m^3 are reasonable and cost-effective in comparison with the recommended value of €18,520 per averted manSv [18]. However, when we compare the total cost of remediation by soil depressurization with the cost of additional heating due to enhanced natural ventilation, the above statement is not fully valid. The total cost of soil depressurization applied in combination with replacing existing floors by new floors is acceptable only for concentrations higher than 1500 Bq/m^3. This is not a complication, since this type of remedial measure is applied only if required by the technical state of the house, when no other effective measure exists.

4. Discussion

Standard decision-aiding techniques widely used in the field of optimization of radiation protection, such as cost–benefit analysis and cost–effectiveness analysis, have had limited application in the field of radon remediation. When applied to houses with concentrations above 1000 Bq/m^3, they do not produce information that could contribute to the optimization and improvement of remedial actions. All measures that are able to mitigate houses with higher concentrations than 1000 Bq/m^3 will be considered by these analyses as acceptable and reasonable. Therefore, it seems to us that such analyses have sense only if they are applied to houses with indoor radon concentrations below 1000 Bq/m^3, where there is a substantially larger number and range of applicable remedial measures, technical solutions, installation costs and efficiencies.

No substantial differences in efficiency were observed between the types of soil depressurization systems studied here. The mean efficiency of all measures was 91%. This quite high value demonstrates the fact that only powerful remedial action can succeed in reducing high indoor radon concentrations. Our study shows that the efficiency of remediation does not depend on the installation costs.

Assuming 30-year operation, each of the studied remedial measures will on an average avert a collective dose of 2.26 manSv, and it will save on an average 0.31 lives or gain 4.3 years of life. Remediation of all 32 houses will result in 10 saved lives and 137.2 gained years. Since the sum of the total costs for 30-year operation of all measures is €325,000, it requires on an average €38,550 to save one life by radon remediation, and it costs €2820 to save 1 year of life.

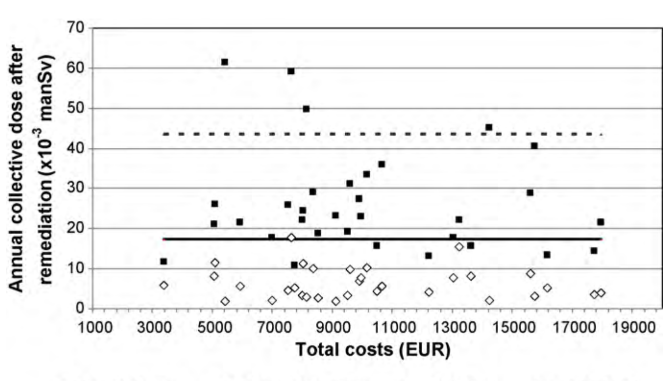

Fig. 12. The residual collective effective dose in individual houses remediated either by sub-slab ventilation systems or by enhanced natural ventilation, if the cost of both actions is the same.

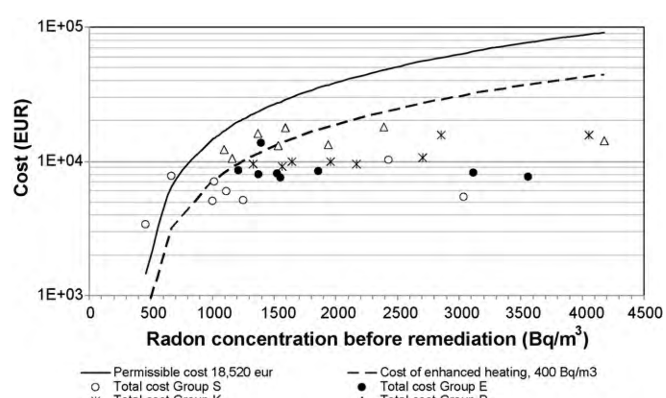

Fig. 13. Comparison between the total cost of remediation by soil ventilation, the cost of additional heating due to enhanced natural ventilation (for a decrease to 400 Bq/m^3), and the recommended value of €18,520 per averted manSv.

The results of a cost–benefit analysis, which compares the cost of the remedial action with the benefits provided by it, indicate that all measures reducing indoor radon concentration from values above 1000 Bq/m^3 to values below the action level of 400 Bq/m^3 provide benefits greater than the cost. This is documented by comparing the average cost of a life, calculated via the total cost of the applied remedial measures divided by the number of lives saved due to the decreased concentration. The total cost of a life is €38,550, while the permissible cost of a life calculated via the conversion factor of €18,520 per averted manSv according to Czech legislation and number of saved lives is on an average €133,620.

The cost–effectiveness analysis comparing the costs of actions and the residual collective dose shows that there is no significant difference between the types of soil depressurization systems studied here and the remaining dose level. In comparison with enhanced natural ventilation of houses, the cost of additional heating to eliminate the heat losses would exceed the total costs of remediation by soil ventilation eightfold. We can therefore conclude that the application of any type of sub-slab depressurization system is a cost–effective solution.

Our finding in this field differs considerably from results of Gray et al. [4], whose studies indicate that remediation of existing homes with high radon concentrations are unlikely to be cost–effective.

5. Conclusions

Our study, in which two important criteria (the cost and efficiency of remediation) and two decision-aiding techniques (cost–benefit analysis and cost–effectiveness analysis) were investigated in order to find out whether they can provide sufficient and relevant information for the optimization of remedial measures, yields quite new findings. On the basis of data from 32 houses with indoor radon concentration above 1000 Bq/m^3, it is confirmed that the installation costs of remedial measures do not depend on the original level of indoor radon concentration. The study revealed that these costs depend mainly on the technical state of the building and on the applicability of a particular measure in a particular case.

We have found that efficiency in combination with initial radon concentration is a powerful tool describing the differences in the ability of a particular measure to reduce indoor radon concentration to a required level. After eliminating measures with insufficient efficiency, the second important parameter affecting the decision-aiding process is installation cost.

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