Cost-effectiveness analysis of radon control actions

E. Nissi[1], A. Sarra[2*]

[1] *Department of Economics, University "G.d'Annunzio" of Pescara; nissi@unich.it,*
[2] *Department of Economics, University "G.d'Annunzio" of Pescara; asarra@unich.it*
[*] *Corresponding author*

Abstract. *Radon is a naturally occurring radioactive noble gas belonging to the decay chain of uranium. In confined spaces, high concentration of radon can become a serious health concern. Experts widely agree that prolonged exposure to this gas can significantly increase the risk of lung cancer. Over the last decades, finding the appropriate measurement and remediation strategies for the problem of radon at home has been the subject of intense debate in literature. An important step in deciding which policies to implement regards the comparison of the proposed radon actions along two dimensions of interest: benefits and costs. In this paper, we examine the decision problems associated with a hypothetical domestic radon control programme in target areas of a region of interest. The main focus is on showing how the cost-effectiveness analysis can be enhanced by exploiting the advantages of a Bayesian hierarchical modeling.*

Keywords. *Radon; Cost-effectiveness; Hierarchical modeling; Bayesian analysis.*

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1 Introduction

Radon ^{222} is a naturally occurring carcinogen gas which can accumulate in built environment where it mixes with indoor air, with harmful effects on the health of the occupants. Knowledge on threat posed to health by the radon gas exposure has considerably increased in the last years, providing evidence of the statistical association between radon and lung cancer in domestic properties ([2]). Even if the exact risk of developing lung cancer from domestic radon levels is very doubtful, depending on several factors which might complicate the causality such as gender, age and smoking status, direct evidence has confirmed that there is an increased risk of lung cancer also in the range of 100 to 200 Bq/m^3 . Given that, in general, less people are exposed to high indoor radon concentrations, the majority of radon-induced lung cancers are thus caused by low and moderate radon concentrations rather than by high radon levels. Responding to the risk to health raised by the presence of radon in domestic properties many developed countries already have policies to control radon. These countries have established a regulatory background and implemented different strategies for radon remediation in existing, affected buildings and prevention in new and reconstructed houses. Various remediation measure can be undertaken to decrease the radon dose in dwellings, including the installations of a gas membrane or mat, improvements in ventilations and repairing cracks in the construction or combinations of these. In this paper we focus on the economic implications and trade-offs involved in radon gas mitigation. A well-recognized way of examining the resources allocation issues present in radon control policies is to carry out a cost-effectiveness analysis (CEA). The CEA is an evaluative technique, traditionally employed in health economics, which allows to establish whether a radon control measure is justified, compared to other interventions that could improve the health status of the inhabitants of radon affected houses. To deal with the decision problems associated with indoor radon mitigation strategies, we propose a methodological framework to evaluate the incremental cost-effectiveness of a hypothetical radon control programme against some alternative. In this preliminary paper, we draw attention to the method rather than to a particular case study whose results will be likely to vary in different settings and countries. The next Section details the main steps in conducting a cost-effectiveness analysis. Particular emphasis is given to the influence that input parameters might have on results. One crucial parameter refers to the proportion of homes likely to be above a specified reference level. To this end, in Section 3, we describe how a Bayesian hierarchical analysis offers opportunities to identify the houses that are likely to have high radon concentrations, given information at geographical and house level.

2 The cost-effectiveness framework

Over the last years there have been different economic evaluations of radon reduction programmes (see, among others, [6], [3], [5]). The cost-effectiveness analysis provides a useful framework within which it is possible to compare the costs and effects of a new radon prevention policy against some alternative. The cost-effectiveness is calculated as the ratio of the net change in cost to net change in outcome, taking the form of difference in costs divided by the difference in effects. There are some different ways to include the health benefits into the cost-effectiveness model. Researchers working in that field adopted as an overall measure of effectiveness the number of lung cancer deaths averted, expressed in terms of Quality Adjusted Life Years (QALYs) gained. The QALYs is a composite outcome measure which considers how a given policy both adds years to individual's life and enhances the quality of those lives, allowing comparisons across actions intended to improve health. In establishing the presumed improvement in quality of life arising from a remediation or a basic prevention radon strategy, estimates of quality of life in presence or absence of a radon control measure are compulsory. With this regard, a suitable approach can be found in [3]. To estimate the expected number of lung cancer deaths information on population data, life-tables and lung-cancer incidence for different age-intervals are typically necessary. In general, the CEA model requires to specify a number of input parameters and the results of analysis depend on the perspective adopted. For instance, comprehensive analyses adopt a "societal" perspective in which all costs are included. Since costs and benefits of a program such as radon prevention is spread over time, it is necessary to express them in present values, using an approved annual discount rate. Further, the cost-effectiveness analysis should adopt a time horizon long enough to capture all the main costs and benefits of the program being evaluated. For radon reduction measures this is likely to be the lifetime. Also, calculations of health benefits require information on the number of occupants in each building. These data are often unavailable and the figure conventionally employed is an average of residents for buildings, derived from the population census. A crucial parameter in performing the cost-effectiveness analysis of a radon measure is the mean radon level in the area because the CEA improves as the average radon concentrations in the area increases. The standard practice adopted in radon policies of classifying areas according to the percentage of measurements exceeding a specified value, typically known as "the action level" or "reference level", such 100 Bq/m^3 or 200 Bq/m^3 , presents a number of disadvantages. One of the most important drawback of estimating the proportion of measurements above any given high value is the major uncertainty characterizing it compared to a central measure of the radon distribution. Various monitoring efforts demonstrate that, after subtracting the outdoor radon concentration, the indoor radon measures are well represented by a lognormal distribution (see, among others, [8]), fully described by the geometric mean (GM) and the geometric standard deviation (GSD) parameters. The knowledge of GM and GSD allows to easily estimate the percentage of dwellings exceeding any reference level by using statistical table of the area under the standardized normal curve. However, providing that radon concentrations in home are conform to a log-normal distribution, the estimates of the GM and GSD may be characterized by an elevated uncertainty, as a consequence of a limited number of data in many geographic units. To minimize the effect of small sample size and make, accordingly, the GM estimates more accurate and less variable, some authors ([9], [1]) suggest to employ a Bayesian approach.

3 Bayesian inference

In this section we give details of Bayesian procedure to be implemented to perform inference and decision analysis of cost-effectiveness of a radon control measure in a given region of interest. In what follow we adopt the following notation. Let Y_{ij} be the measure of radon concentration (after subtraction of outdoor concentration and application of normalization procedure) for the i-th dwelling within the j-th unit (municipality area). The application of Bayesian inference is based on the assumption that the Y_{ij} values follow a log-normal distribution. Accordingly, the log (Y_{ij}) are normally distributed within each geographic unit, with mean and variance of the distribution being, respectively, log(GM_j) and $\sigma^2{}_y$ (assumed the same for all the units). We also assume that the observed GM_j are log-normally distributed, thus GM_j distribution is normal, with mean μ_α and variance $\sigma^2{}_\alpha$ to be estimated from the data. A simple result for the estimate for log(GM_j) comes down from the application of Bayes's theorem and it is known as Bayesian point or empirical Bayes estimate ([4]):

$$\hat{\alpha} = \frac{(1/\sigma^2{}_\alpha)\mu_\alpha + (n_j/\sigma^2{}_y)log(GM_y{}^{obs})}{(1/\sigma^2{}_\alpha) + (n_j/\sigma^2{}_y)}, \quad V^2{}_j = (1/\sigma^2{}_\alpha + n_j/\sigma^2{}_y)^{-1} \tag{1}$$

In Equation 1 the estimate for log (GM_j), denoted as $\hat{\alpha}$, is a weighted average with weights depending on the sample size in the municipality and the variance at the data and group levels, such that sample means from municipalities with smaller sample size convey less information whereas sample means from municipalities with larger sample sizes loads more information. The parameters $\sigma^2{}_\alpha$ and $\sigma^2{}_y$ are the variance components, respectively, between and within geographic units, and can be determined from an analysis of variance (ANOVA). The proper ANOVA method is based on a hierarchical nested model with random factor effects ([7]). The choice of multilevel approach is suggested by the hierarchical structure of the radon data which involve components at different levels: the first level units are represented by dwellings, while the second level are represented by the municipalities, assumed to be different in some respect (geology, climate or prevailing building characteristics). At the beginning a simple two-level model with group (municipality)-level effects α_j can be specified. The empirical Bayes method is easy to implement and represents an appealing alternative to purely classical approach, leading to reasonable estimates of the municipalities GMs. However, that method does not include the uncertainties in the model parameters themselves. As a result, unrealistically low standard errors for municipality-level estimates are often observed. This argument support the adoption of a fully bayesian inference, which, implemented via multilevel hierarchical models, has many advantages over the Empirical Bayes approach. In a full Bayesian analysis all uncertainty are accounted for in the analyses and accurate estimate, with more realistic standard errors, can be obtained. In the bayesian framework posterior inference is facilitated by MCMC methods. For a simple multilevel model without predictors the Gibbs updating steps can be summarized as follows ([4]):

Update α_j : For j=1,...,J , compute $\hat{\alpha_j}$ and V_j from Eq.1 and then draw α_j from N($\hat{\alpha}_j, V$)
Update μ_α: First compute $\hat{\mu_\alpha}$ as average of municipality intercepts α_j and then draw from N($\hat{\mu_\alpha}, \sigma^2{}_\alpha/J$)
Update $\sigma^2{}_j$: First compute $\hat{\sigma^2}_j$ as residual variance $\hat{\sigma^2}_j = \frac{1}{n}\sum_{i=1}^{n}(y_i - \alpha_{j[i]})^2$ and then draw $\sigma^2{}_j = \hat{\sigma}^2{}_y/X^2{}_{n-1}$ where $X^2{}_{n-1}$ is a random draw from $\chi^2(_{n-1})$
Update $\sigma^2{}_\alpha$:First compute $\hat{\sigma^2}_\alpha$ from $\hat{\sigma^2}_\alpha = \frac{1}{J}\sum_{j=1}^{J}(\alpha_{j[i]} - \mu_\alpha)^2$ and then draw $\sigma^2{}_\alpha = \hat{\sigma}^2{}_\alpha/X^2{}_{J-1}$ where $X^2{}_{J-1}$ is a random draw from $\chi^2(_{J-1})$.

This algorithm uses random simulations rather than point estimates allowing to capture the inferential uncertainty about the parameters. The Bayesian inference is completed with the definition of the prior distributions to the model parameters. For the parameters α_j a Normal distribution $N(\mu_\alpha, \sigma^2{}_\alpha)$ is elicited while for the hyperparameters of the model non-informative priors distributions are assigned which are Normal for μ_α $N(0, 1000)$ with a very wide variance and Uniform on the range [0,100] for the variance components $\sigma^2{}_\alpha$ and $\sigma^2{}_j$.

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