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Response surfaces and sensitivity analyses for an environmental model of dose calculations

Bertrand Iooss[a,*], François Van Dorpe[b], Nicolas Devictor[a]

[a]*CEA Cadarache, DEN/DER/SESI/LCFR, 13108 Saint Paul lez Durance, Cedex, France*
[b]*CEA Cadarache, DEN/DTN/SMTM/LMTE, 13108 Saint Paul lez Durance, Cedex, France*

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Abstract

A parametric sensitivity analysis is carried out on GASCON, a radiological impact software describing the radionuclides transfer to the man following a chronic gas release of a nuclear facility. An effective dose received by age group can thus be calculated according to a specific radionuclide and to the duration of the release. In this study, we are concerned by 18 output variables, each depending of approximately 50 uncertain input parameters. First, the generation of 1000 Monte-Carlo simulations allows us to calculate correlation coefficients between input parameters and output variables, which give a first overview of important factors. Response surfaces are then constructed in polynomial form, and used to predict system responses at reduced computation time cost; this response surface will be very useful for global sensitivity analysis where thousands of runs are required. Using the response surfaces, we calculate the total sensitivity indices of Sobol by the Monte-Carlo method. We demonstrate the application of this method to one site of study and to one reference group near the nuclear research Center of Cadarache (France), for two radionuclides: iodine 129 and uranium 238. It is thus shown that the most influential parameters are all related to the food chain of the goat's milk, in decreasing order of importance: dose coefficient "effective ingestion", goat's milk ration of the individuals of the reference group, grass ration of the goat, dry deposition velocity and transfer factor to the goat's milk.

Keywords: Radiological impact; Environmental transfer; Uncertainty analysis; Sensitivity analysis; Response surface

1. Introduction

The radiological impact evaluation of the nuclear facilities is one of the great challenge of the nuclear industry. Radiological exposure models due to severe nuclear accident or due to chronic releases have been extensively developed. In such complex models, it was recognized that many input variables are largely uncertain and that a rigorous procedure is required to arrive at realistic uncertainty distributions. Recently, uncertainty analysis techniques have been used in consequences investigation of different severe nuclear accident models [1–4].

This paper is devoted to the presentation of a global sensitivity analysis of a French radiological impact software called GASCON. GASCON is dedicated to chronic atmospheric releases and dosimetric impact, and is used for CEA facilities safety assessment. This software evaluates the doses received by a population (called reference group) exposed to the cloud of radionuclides and *via* the food ingestion pathways. It takes into account the interactions which exist between the man, the plant and the animal, the different pathways of transfer (wind, rain, ...), the distance between emission and observation, the time passed between emission and calculation, ...

Various stages in the analysis of a process (software, measurement, experiment, ...) introduce potential errors, in particular, in the construction of the various models: real phenomenon with the physical model, physical model with the mathematical model, and mathematical model with the numerical model. The principal sources of uncertainties are in the approximation made by the modeling of the physical phenomenon, the approximations made on the parameterization of the model, the input data and the input parameters. The uncertainty analysis is used to evaluate the confidence interval or the probability distribution of

*Corresponding author. Tel.: +33 4 4225 7273; fax: +33 4 4225 2408.
E-mail address: bertrand.iooss@cea.fr (B. Iooss).

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the result. The global sensitivity analysis is used to quantify the influence of the input parameters uncertainties on the output variables uncertainties [5,6]. Recent studies have applied different methods of uncertainty and sensitivity analysis to environmental models for the radioactive waste management problem [7,8].

The results provided by GASCON are in the form of annual effective doses (Sv/year) received by a reference group, divided into three age compartments: adult, child and baby. We also distinguish three operating cycles of the gas release: one year, 10 years, 50 years. In our study the reference group is a village near the nuclear facility, and we consider two radionuclides ^{129}I and ^{238}U. There is thus 18 output variables. The main ways of exposure taken into account in GASCON are:

- external exposures: radioactive cloud, soil deposits, groundshine;
- internal exposures: plume inhalation, ingestion of plants contaminated by direct pathway (foliar transfer by contact with the radioactive cloud) and indirect pathway (soil deposit then root transfer), ingestion of contaminated animal productions (animals having eaten plants contaminated by direct and indirect pathways).

Some input data are specific of the studied radionuclide or of the studied site (meteorological conditions, soils nature, feed rations, ...). We have deduced from the literature the variation ranges of parameters considered for the sensitivity analysis, which are:

- dose factors for external irradiation, effective ingestion, effective inhalation;
- transfer factors to animal productions (milk, meat of cow, ewe, goat, pig, ...);
- factors of soil–plant transfer (vegetables, cereals, fodder, ...);
- translocation factors (fruits, vegetables, cereals, ...);
- sorption coefficients K_d (sands, silts, clays and organic matter);
- dry deposition velocity for each radionuclide;
- local feed rations of the reference group for the various age compartments (vegetables, fruits, cereals, milk, meat, egg, ...), and animal feed rations (grass, hay, corn) related to the products eaten by the reference group.

The following section presents the four steps of our methodology: uncertainty analysis *via* Monte-Carlo calculations, sensitivity analysis by computations of correlation coefficients between input and output variables, construction of response surfaces requiring negligible computation times, final sensitivity analysis by calculations of Sobol sensitivity indices. In the third section this methodology is applied to the GASCON software using specific nuclear facility and reference group. We conclude this study with a summary in the last section.

2. Methodology

2.1. Uncertainty analysis

The general objective of an uncertainty analysis is to evaluate uncertainty on a computation result Y taking into account uncertainties on the input parameters X_j ($j = 1, \ldots, N_p$). To do so, it is necessary to evaluate a probability density function for each input parameter (by expert opinion or by data statistical analysis). The results of the uncertainty analysis is conditioned with the choices of these probability densities. To propagate uncertainties, we use a simple Monte-Carlo strategy [9,10]: random generation of N samples of input parameters, then software calculation for each sample. Therefore, we deduce output uncertainties by a statistical analysis of all software results.

The only information on the input parameters given by the experts of environmental radiological transfer are their variation bounds and their nominal values. There are no available measurements, nor complementary information on the input parameters. Therefore, for the distribution of each input parameter, we choose the uniform law which requires only the bounds of the parameter variation ranges. However, for the majority of the GASCON parameters, an order of magnitude separates the minimal and nominal values (min $\sim$nominal/10) and the nominal and maximal values (max $\sim$nominal $\times$ 10). Thus, if we choose the uniform function on [min; max], the majority of the simulated values will be included in the interval [nominal; max]. The triangular, log-normal or log-uniform laws would resolve this problem. However, because of their total lack of knowledge on the parameter distributions, the experts insist on the fact that all the values inside the variation ranges [min; nominal] and [nominal; max] have to be equiprobable (which is not the case for log-normal, log-uniform or triangular laws). Therefore, we find an heuristic (and arbitrary) way to respect such constraints. Each simulation proceeds in the following way:

- we simulate a uniform random variable u on [0; 1];
- if $u \leqslant 0.5$: the simulation value is $2u(\text{nominal} - \text{min}) + \text{min} \in [\text{min}; \text{nominal}]$;
- if $u > 0.5$: the value is $(2u - 1)(\text{max} - \text{nominal}) + \text{nominal} \in]\text{nominal}; \text{max}]$.

This procedure creates equiprobable random sampling on the intervals [min; nominal] and]nominal; max].

From the Monte-Carlo simulations, we obtain for each output variable its elementary statistical parameters (average, minimum, maximum, standard deviation, variation coefficient, skewness and Kurtosis coefficients) and its probability distribution. From the distributions, we can observe the spreading out of the output variables, the confidence intervals, the multiplicity of modes, ... Statistical comparison tests between output variables can also be made. In our study, we analyze nine output variables for each radionuclide, and we deduce by the Kolmogorov–Smirnov test