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Data Analysis for Radiological Characterisation: Geostatistical and Statistical Complementarity

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ABSTRACT

Radiological characterisation for decommissioning of nuclear sites and facilities a key issue for the global success of such industrial projects which imposes an efficient control of radiological hazards, cost estimation, planning and waste management.

Combined with historical information, in situ measurements and sampling are input data for the assessment of the initial radiological characterisation. The content and distribution complexity of contaminated materials is generally the stumbling block when using deterministic numerical models (overestimation or non-identification). The geostatistical framework provides probabilistic and reliable methods for activity estimation, uncertainty quantification and risk analysis, leading to a sound classification of radiological waste. Sampling optimisation is also addressed and largely depends on the spatial structure of the phenomenon and the evaluation objective.

Final radiological characterisation requires a final survey to demonstrate compliance with clearance levels. At this stage, statistical approaches enable the determination of the sample number to be collected. Classical statistical tests then allow validating that clearance levels are verified.

INTRODUCTION

Radiological characterisation may cover a large range of evaluation objectives during a decommissioning and dismantling (D&D) project: doubt removal, identification of hot spots, spatial extent of contaminated materials, dose rate estimation for workers, monitoring of the decontamination work and final survey. At each stage, collecting relevant data to be able to draw the conclusions needed is quite a big challenge.

Sampling design and data analysis are closely linked to the evaluation objective. From this point of view, setting up an appropriate evaluation methodology is of prime importance.

This contribution intends to compare and contrast geostatistical and statistical approaches, as for the optimisation of the sampling effort and the uncertainty quantification of the results.

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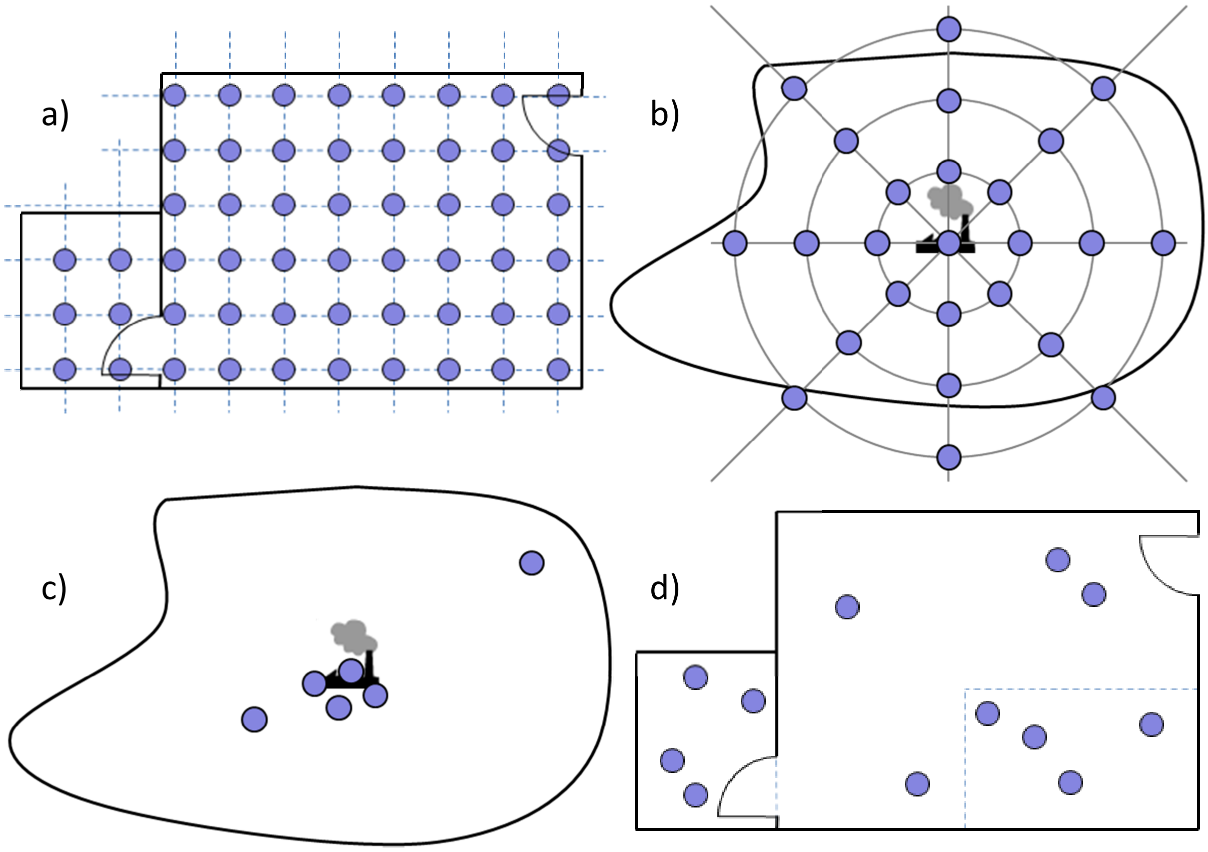
THE CHARACTERISATION TRIPTYCH

Any sampling campaign aims to collect data in order to answer a precise evaluation objective i.e. the final goal of the characterisation. This may look simplistic but before collecting data, a key issue is to correctly identify what the expected results are. That way, evaluation objective, sampling design and data processing are closely interrelated.

These are the three legs of a stool. If one is missing, the characterisation fails. Indeed data collection requires a sampling design that identifies the number and location of samples. Besides, this sampling design has to be suited to the evaluation objective. Once the analytical results available (in situ measurements or laboratory results) data processing intends to answer the evaluation objective in an adequate way. In case of an inaccurate answer (not precise enough for example) additional sampling may be decided to complete the initial sampling design.

We can mention the Data Quality Objectives (DQO) process recommended by EPA policy in order to implement systematic planning process to develop acceptance or performance criteria for the collection, evaluation, or use of data. Choosing the appropriate sampling design requires stating the problem, identifying the decision (and its inputs), defining the boundaries of the study, developing the decision rule, specifying tolerable limits on decision errors and finally optimising the design for obtaining data [1].

Sampling strategies can be divided in two main categories: probability-based designs and judgmental designs. Probabilistic inferences, statistical for example, are available when using probability-based design, while professional judgment or expertise knowledge is mainly involved for judgmental design. On the next figure, subfigures a) and d) stand for systematic and random designs (probability-based) while subfigure c) is a case of judgmental design (a few samples collected according to the site knowledge). But sampling is not that Manichean as Subfigure b) is a perfect mix between judgmental design (the circle centre is located close to the emission point) and probability-based design (regular mesh for the circular grid).



In addition, sampling designs may be combined to get all required information. An iterative sampling strategy is a very efficient alternative to optimise the number of samples for a given evaluation objective: large systematic mesh at first then additional samples decided on criteria to complete the dataset. These improved sampling approaches generally give better results but are more sophisticated to implement.

RADIOLOGICAL CHARACTERISATION AND DATA PROCESSING

At each stage of a decommissioning programme or project, adequate radiological characterisation is of crucial importance. But it represents an even major issue before and after the decontamination works. During the decontamination phase itself, the monitoring of the area and the packaged waste characterisation does not imply sophisticated sampling strategies. On the contrary, the two other radiological characterisation stages require an advanced sampling process and data analysis. They concern (i) the initial categorisation and optimisation of the materials to be removed and (ii) the final survey to demonstrate compliance with clearance levels for decommissioning. Other evaluation objectives generally imply a simpler sampling strategy and data analysis; they may also be a secondary result ensuing from answering the main objective.

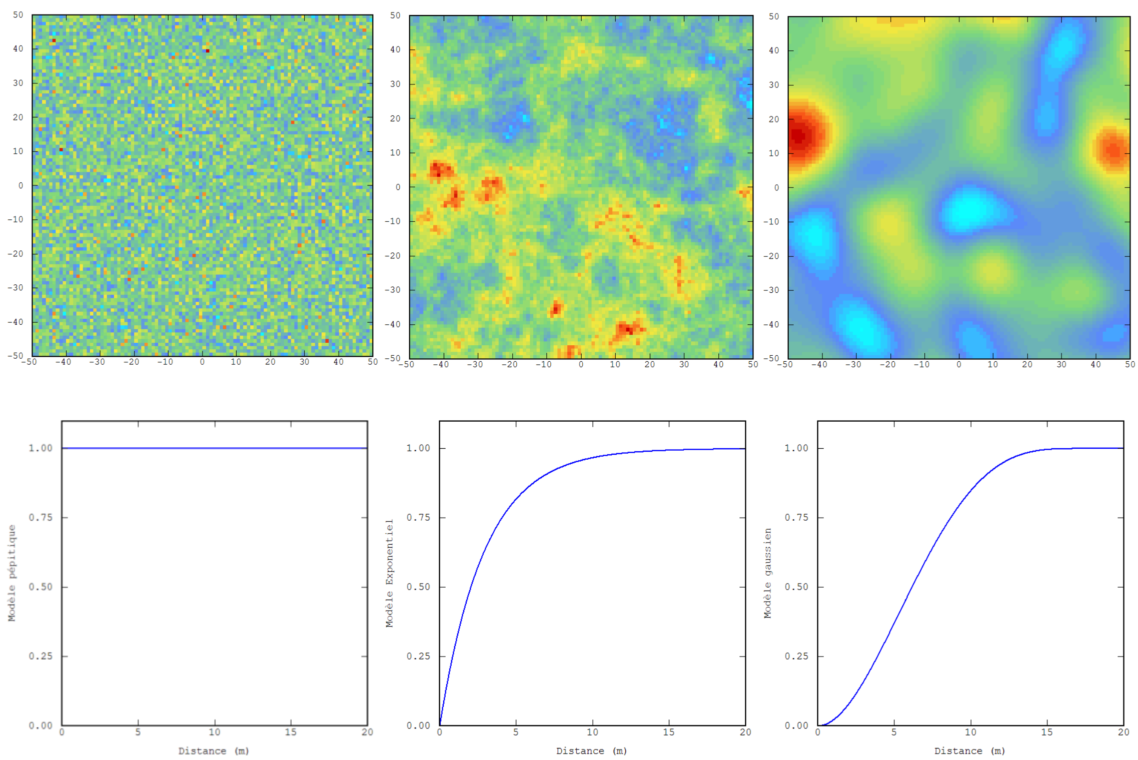
Initial Radiological Characterisation

D&D projects are largely impacted by the contaminated state of the facility. Initial characterisation stage is then a crucial issue for project management: radiological hazards, cost estimation, planning and waste management.

Deterministic numerical models are generally used to describe the contamination distribution in simple cases. They deal with activation, migration, dispersion, etc. But most of the time, they fail to represent accurately the reality due to its complexity. Model parameters and hypotheses become too numerous to be handled correctly.

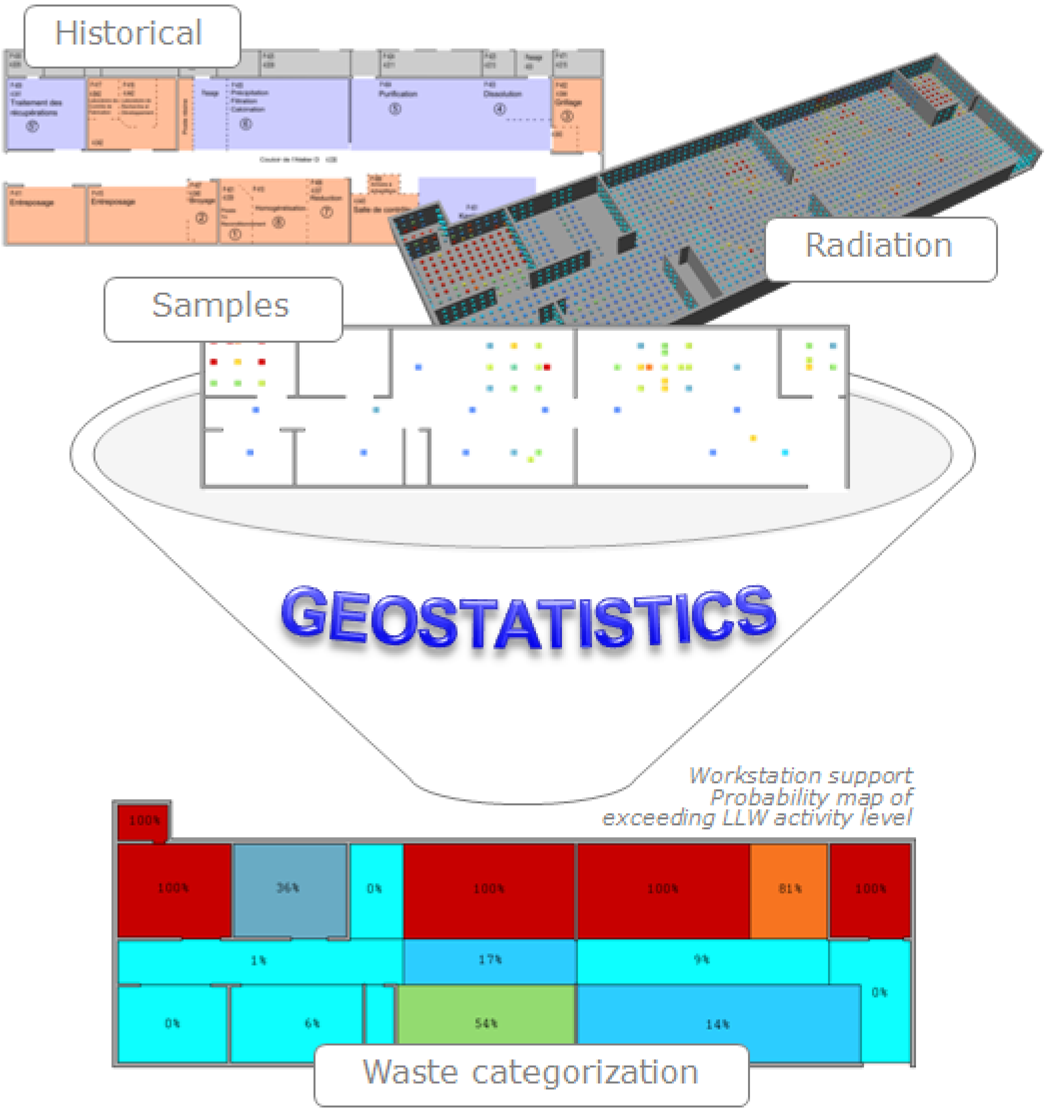
As a consequence, a more appropriate evaluation methodology has to be implemented for the initial radiological characterisation for building structures (and for lands), using a probabilistic approach.

The geostatistical framework is an efficient way to satisfy the radiological characterisation requirements providing a sound decision-making approach for the decommissioning and dismantling of nuclear premises. The relevance of the geostatistical methodology relies on the presence of a spatial continuity for radiological contamination. The phenomenon variability is analysed through the variogram which estimates the variance contribution between data points [2]. Generally, for a structured phenomenon, the spatial variability increases with distance and tends to stabilize ("sill") at a distance named "range" (last two examples on the next figure). Data separated by a distance larger than the range are no longer spatially correlated. In the case of a spatial random phenomenon, the variability keeps the same value whatever the distance between points; white noise is analysed as a pure nugget effect on the variogram (first example on the figure).

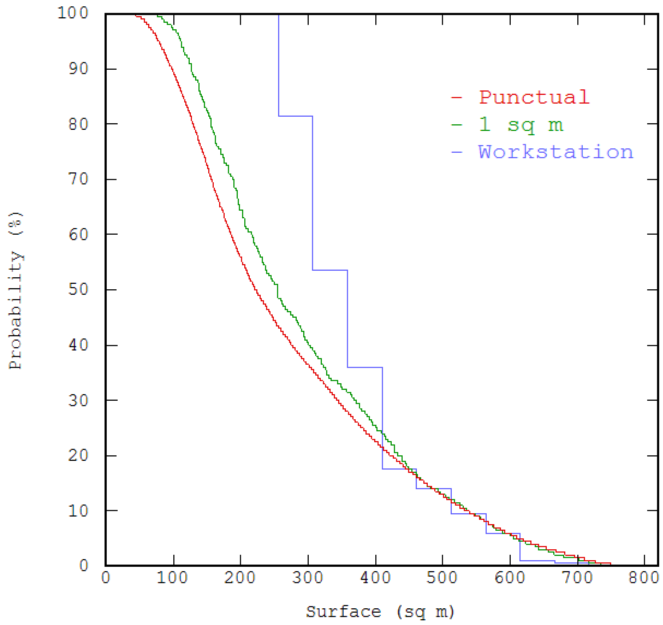


Thus geostatistics provides reliable methods for activity estimation, uncertainty quantification and risk analysis, leading to a sound classification of radiological waste (for surfaces and volumes, as change-of-support problem is correctly addressed) [3].

This way, the radiological characterisation of contaminated premises can be divided into three steps. First, the most exhaustive facility analysis provides historical and qualitative information. Then, a systematic (exhaustive or not) surface survey of the contamination is implemented on a regular grid. Finally, in order to assess activity levels and contamination depths, destructive samples are collected at several locations within the premises (based on the surface survey results) and analysed. Combined with historical information and radiation maps, such data improve and reinforce the preliminary waste zoning.



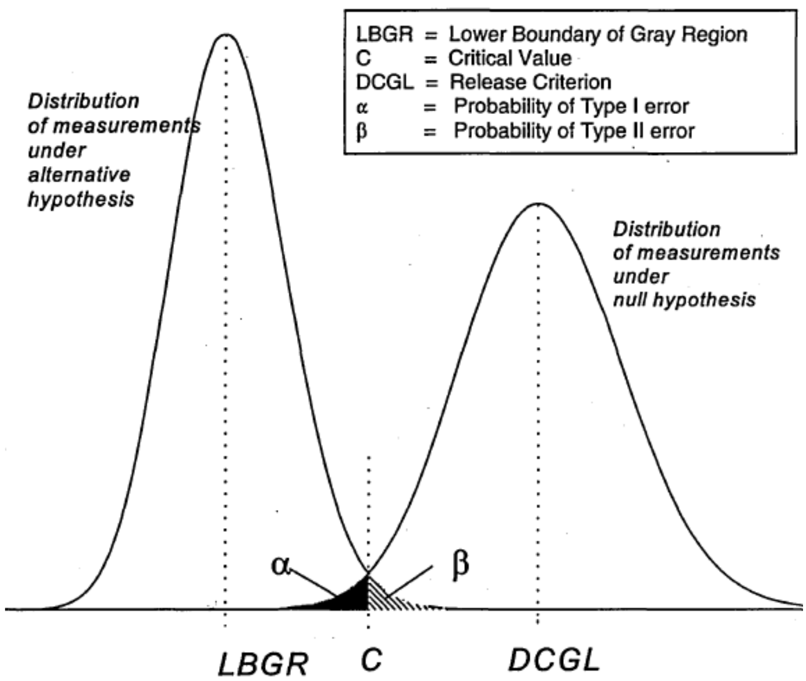
Cost-benefit analyses may be presented by comparing the risk threshold and the corresponding waste surfaces. For a given radiological threshold, surface classification is performed according to the tolerated risk (probability of exceeding) and the remediation support (punctual, 1 m² or workstation area).



Final Radiological Characterisation

On the other hand the methodology for sampling strategy at final stage is well developed in international and national guides and norms (for example MARSSIM [4]).

Decision to consider compliance with clearance level is based on a statistical test and requires values to be collected using random sampling designs. More advanced strategies can be employed such as two-phase sampling designs when some initial parameters are missing to implement a simple random sampling. A large number of statistical tests are available: compare average to a fixed threshold (as shown on the next figure), compare proportions, estimate the mean, construct a confidence interval on the mean, etc. Attention should be paid to the underlying hypotheses of these statistical tests: spatial randomness of values most of the time, type of statistical distribution, etc.



SAMPLING OPTIMISATION

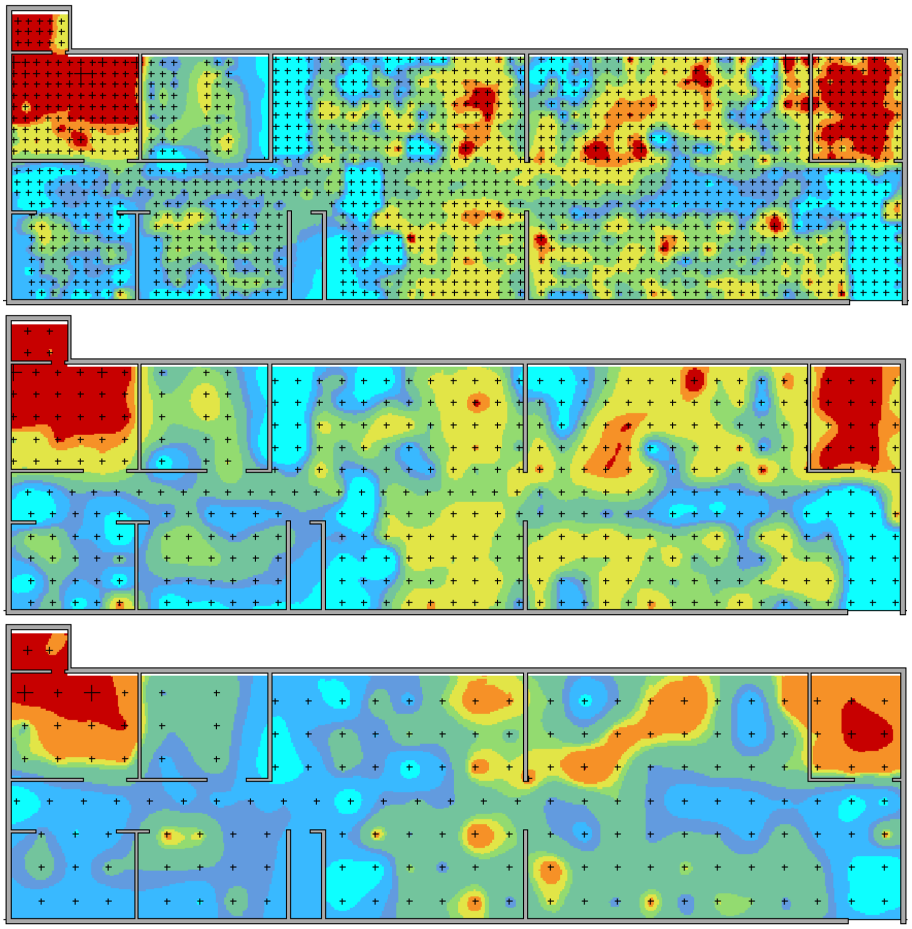
Once evaluation objectives, sampling strategy and data analysis are correctly identified, optimising the sampling effort is the remaining question. Both statistics and geostatistics offer suited answers strongly linked with the expected precision of the results.

Geostatistical Optimisation

For the initial radiological characterisation the geostatistical framework is not only a sound data processing technique but also an efficient way to optimise the sampling strategy.

First, the initial mesh for the radiation map is determined thanks to the historical and functional analysis and to the experience feedback on geostatistical analysis of similar contaminations: indeed spatial structure ranges (maximum autocorrelation distance) show similarities on the various case studies. To be more precise, radiological contamination ranges for concrete structures classically vary from 1 meter to 5 meters. In other words, on the one hand a 5m mesh is useless for geostatistical processing as the spatial structure is not going to be identified; on the other hand a 10cm mesh implies redundancy between collected values as well as time and money wasting.

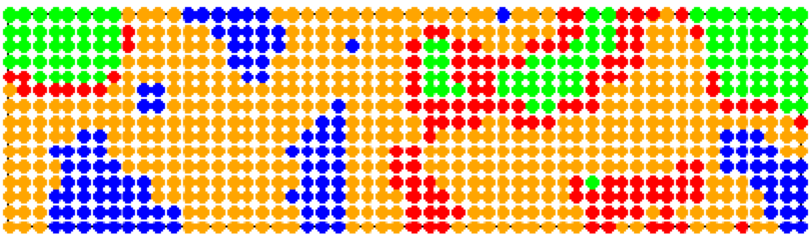
Next figure underlines the impact of the sampling mesh (dose rate for radiation mapping) on the estimated map (kriging interpolation): 66cm, 1.3m and 2.0m. Hot spots are better recognised with the densest design but global trends are correctly estimated with the largest mesh. The correct map (and the corresponding sampling mesh) still depends on the evaluation objective and the expected results.



As for external soils, spatial structure ranges typically varies between 10 and 30 meters for contaminations around or under nuclear facilities. It may increase up to dozen of kilometres for major incidents on regional scale, such as Fukushima event. In that case of post-incident monitoring, geostatistics correctly addresses the anisotropy issue using directional variograms and suitable neighbourhood for interpolation.

Then as the added value of geostatistics lies in the uncertainty quantification of the prediction (kriging), it is very powerful to identify areas where the confidence interval is too large. Similarly probability of exceeding a fixed threshold may conduct to perform additional measurements. The quick update of the geostatistical results is proven to be relevant for an iterative and optimised sampling strategy.

The false negative risk, namely estimating as clean a contaminated area, is also an interesting indicator for risk analysis. On the next figure, green points are declared to be above the radiological threshold, red points have the highest risk to be misclassified while this risk decreases in orange areas and is very low in green ones.



For the third investigation phase, destructive samples are basically located according to the radiation map results. This is the judgmental part of the methodology. Additional sampling points might then be located using the same approach than for the surface radiation mapping (reduction of uncertainty, intermediate probability validation…). The vertical variability of the phenomenon is significantly higher than in the horizontal plane. Sampling resolution in the vertical direction has to be denser as a consequence (typically a few centimetres or less for building structures and a few dozens of centimetres for soils).

Statistical Optimisation

Determining the right number of samples for the final radiological characterisation naturally relies on the statistical test to be performed at the end. Again, suited formulas are widely known and quite easy to implement to get the required confidence level for decision making.

CONCLUSIONS

Radiological characterisation may cover a large range of evaluation objectives during a decommissioning and dismantling (D&D) project: doubt removal, delineation of contaminated materials, monitoring of the decontamination work and final survey. At each stage, collecting relevant data to be able to draw the conclusions needed is quite a big challenge.

Two radiological characterisation stages require an advanced sampling process and data analysis, namely the initial categorisation of the materials to be removed and the final survey to demonstrate compliance with clearance levels. On the one hand the latter is widely used and well developed in national guides and norms, using random sampling designs and statistical data analysis. On the other hand a more complex evaluation methodology has to be implemented for the initial radiological characterisation, both for sampling design and for data analysis.

The geostatistical framework is an efficient way to satisfy the radiological characterisation requirements providing a sound decision-making approach for the decommissioning and dismantling of nuclear premises. The relevance of the geostatistical methodology relies on the presence of a spatial continuity for radiological contamination. Thus geostatistics provides reliable methods for activity estimation, uncertainty quantification and risk analysis, leading to a sound classification of radiological waste (surfaces and volumes).

Finally geostatistical and statistical data analyses are complementary rather than in opposition because they are not used at the same radiological characterisation stage of a D&D project.

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