MALFUNCTIONS IN RADIOACTIVITY SENSORS' NETWORKS

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ABSTRACT[1]

The capacity to promptly and efficiently detect any source of contamination of the environment (a radioactive cloud) at a local and a country scale is mandatory to a safe and secure exploitation of civil nuclear energy. This capacity must rely upon a robust network of measurement devices which is to be optimized vs. several main parameters including the overall reliability, the investment, the operation and maintenance costs.

The evaluation of the reliability of such a network needs the identification of the all effects and consequences of the malfunctions which are likely to affect the measurement devices individually, the propagation of the consequences of these malfunctions at the scale of the reconstruction of the overall signal which is to be used to provide with alarms to officials and population. These alarms are likely to actuate actions of protection, sheltering, and, in extreme cases, evacuation.

Moreover, even though the sensors are operating continuously, it is practically impossible to store all the data they provide, thus it is necessary to discretize the measurements which limit the detection capacity at the cloud arrival and later on.

Three types of malfunctions of measurement devices can be identified:

- Failure: the sensor stops sending information and needs to be fixed. If a radioactive cloud appears, it will not be able to detect it;
- False alarm: the sensor detects a radioactive cloud whereas it does not exist;
- Uncertainty upon the measurement. When the radioactivity level is close to the alert threshold, the measurement errors can make the sensors gauge incorrectly the situation: a false alarm may then be sent or, conversely, the sensors may underestimate the radioactivity and do not monitor it.

The sensitivity of the efficiency vs. cost of the network has been evaluated to several parameters, including density, lay-out, etc…

The network can be arranged in different ways, many of which are inadequate. Accordingly, the efficiency of four configurations of sensors has been tested through simulations. The denser arrangement turns out the more efficient; moreover its efficiency is increased when sensors are non-uniformly distributed over the country, with accumulation at the borders. In the case of France, as radioactive threats are most likely to come from the East, having more sensors only on the eastern border is the best solution.

But the cost of the network increases with the number of sensors and a compromise solution with a limited number of well-placed sensors can turn out more efficient and cost-effective than regular many-sensor ones.

Moreover, adopting a stationary network of sensors is not the best solution to detect a radioactive threat, because of the false alarms and the maintenance cost. In this paper, two solutions are investigated and proposed:

- Displaying a limited number of stationary sensors at the borders only. When a threat is detected, mobile units are dispatched to characterize it more precisely ;
- Adopting a modern version of "Archimedes' method", which relies upon systematic comparisons among results of simulations of the radioactive clouds stored in databases and the measurements. When the presence of a cloud is detected, it is possible to forecast its evolution (because it has been already simulated). Meteorological parameters are used to identify the cloud, which are far more affordable than radioactivity sensors.

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1. INTRODUCTION

Nowadays, nuclear plants are an important source of electricity worldwide and their contribution to the overall sharing is ever increasing, despite decision of some countries to drop nuclear energy off[2].

Many countries (including France and Ukraine) perform a constant monitoring of radioactivity in the atmosphere, through a network of sensors which are able to provide with alarms for actions of protection, sheltering, and, in extreme case, evacuation of populations, see [4], [5].

Our research program "Malfunctions in Sensors' Networks" [6] deals with the propagation of radionuclides in the atmosphere and their likelihood of detection by a suitable network of sensors, accounting for the features of the network and its possible malfunctions originating from uncertainties, failures, false alarms.

The objectives of the ongoing research are:

1. Checking the effectiveness of a given network of sensors: is it possible to reconstruct the shape of a radioactive cloud relying upon the indications provided by a given network of sensors? And how accurately?
2. Optimizing the design of the networks of sensors: is it possible to increase their robustness (vs. uncertainties, failures and false alarms) keeping the investment and exploitation costs at a reasonable level?

To answer these questions, the problem will be addressed through a graduate step by step approach, adopting time by time various assumptions upon the type of cloud, its direction, speed, and so on.

2. FEATURES OF THE MODELING

2.1 Theory

First of all, the cloud is "pixellised". In such an approach, no precise geometrical shape is attributed to the cloud. A radioactivity level, which is a real number, is attributed to each pixel of the domain. Certainly, this assumption engenders a loss in terms of precision, because the cloud has no specific boundaries anymore, moreover the usual difficulties connected with pixels hold: all points inside a given pixel are addressed the same way.

Compared to the presentation of the cloud as a collection of geometrical shapes with different levels of radioactivity, our approach is closer to reality. In fact, there is always a natural level of radioactivity (which may differ from one zone to another) and radioactive clouds do not have precise boundaries. A pixel of 1 x 1 km seems reasonable, in terms of precision.

Also, the administrator of the network of sensors has no knowledge at all about the shape of the cloud. He has at his disposal only the information given by the sensors, plus some meteorological information (speed and direction of wind).

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[2] France presently has 58 reactors in operation, distributed over 19 sites.

In this simulation, the radioactive cloud is assumed moving along a straight line from East to West: entrance point A and exit point B. It is assumed that the cloud has the shape of a disk of radius r: this is the simulation point of view; as we said earlier, the sensors only see pixels. We denote by V the speed of propagation; in the numerical examples below, we will take $V = 10$ km/h. Let Δ be the length of the segment AB and let C be the center of the disk representing the radioactive cloud. The equation of the movement of C is:

$$\overrightarrow{AC} = Vt\,\frac{\overrightarrow{AB}}{\Delta} \tag{1}$$

assuming the origin of time ($t = 0$) at the moment C was in A.

2.2 The domain

Since the shape of the domain does not matter, we take a simplified domain, namely a square. The dimensions of the square will be comparable to the dimensions of continental France, namely 750 x 750 km. The domain is thus divided into 562 500 pixels, each of them being 1 x 1 km. The origin of the axes is the point left bottom of the square.

2.3 Pixel representation of the radioactive cloud

Radioactivity may be located anywhere in the domain, so each pixel has its own level of measurement, represented by a matrix $ral(x, y)$, which characterizes the radioactivity level in this pixel. To start with, we take a simplified representation of the radioactivity; real values will be introduced later in the paper: if there is no radioactivity, its value is 0 (no radioactivity); in the other case, it is 1 (high level).

2.4 Case of a unique sensor

A unique sensor, denoted by U, is put somewhere in the square area and its coordinates are (x_U, y_U); it measures the radioactivity level in the pixel where it is located, that is the value of $ral(x_U, y_U)$.

2.5 Time units

The sensor monitors the environment continuously, but transmits the information every ten minutes only. In other words, all motions are discretized and viewed every 10 minutes. The time unit (TU) is denoted by τ; it may be modified in the simulator.

The program represents the radioactive cloud as a collection of pixels. The coordinates of its center x_C, y_C are determined from the law of uniform linear motion. We denote by n the number of time units; at each TU, n is increased by 1. The time will be written as:

$$T = \tau \cdot n \tag{2}$$

3. CONSEQUENCES OF CHANGES IN THE SHAPE OF THE CLOUD

3.1 Introduction

We know from the Fukushima and Chernobyl accidents ([2], [10]) that a radioactive cloud spreads far from the initial emission point and gets larger and less radioactive with time. Therefore, it can be assumed that, on the average and at least in a first approximation[3], areas which are far from the nuclear power plant are likely to be less contaminated than the nearby ones.

Let's consider situations where the shape of the radioactive cloud changes: the radius increases and radioactivity decreases at each time step. The increase of the radius is likely to allow an earlier detection of the cloud compared to the simpler case (cloud detected after 30 hours). If we assume an increase of 0.2 km per time unit, the sensor will detect the cloud earlier (26.78 hours), and after 24.19 hours if the radius increase is 0.4 km per time unit.

When the radioactivity decreases, the results will be different, depending on the initial radioactivity value of the cloud. Assuming a radioactivity decrease of 0.01 µSv/h per time unit, we can consider three bounding cases:

- A cloud with an initial concentration of contaminants generating 29 µSv/h: even with the decrease, the cloud will remain dangerous, with a minimum value of 25.6 µSv/h at the last time of detection by the sensor;
- A cloud with an initial concentration of contaminants generating 27 µSv/h: with the decrease, the radioactivity will go from 25.4 µSv/h (first time of detection by the sensor) to 23.6 µSv/h (last time of detection);
- A cloud with an initial concentration of contaminants generating 25 µSv/h: with the decrease, the radioactivity will never be above the threshold of 25 µSv/h.

Besides, the false alarms, failures and the uncertainty of measurement can modify the detection, mainly in the last two cases: the sensor can miss the cloud or send a false alarm. However, the increase of the radius, if the cloud is radioactive enough, can improve the likelihood of detection. For instance, if we assume an increase of 0.4 km per time unit, as the cloud increases in radius (average radius 207.4 km at the time of first detection), it becomes almost twice bigger compared to the previous case.

Assuming a repair-time of 24 h in the case with increased radius, part of the cloud can be detected before the failure appears and the last part the sensor has been repaired. This situation cannot happen in the case of constant radius, since the diameter is less than 240 km. In the situation with an increasing radius, we can calculate the true radius of the cloud even if the failure occurs.

3.2 General description

Assuming a linear increase of the cloud radius with (α [km] at each time unit), the radius increase can be expressed as follow:

$$r(n) = r(n-1) + \alpha \tag{3}$$

The cloud is likely to reach the sensor faster compared to the constant-radius case. Let us denote by l the distance spanned by the cloud with fixed shape from the entrance point to the point of the first detection. Then the first announced time of the cloud detection is:

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[3] This assumption is to be checked vs. the configuration of the region around the detector and the actual weather conditions (see § 5)

$$T_1 = \frac{l}{\frac{\alpha \cdot 60}{10} + V} \tag{4}$$

If n_1 is the number of time units that corresponds to the first detection of the cloud, then the last announced time of the cloud detection is:

$$T_2 = T_1 + \frac{r(n_1) \cdot 2}{V - \frac{\alpha \cdot 60}{10}} \tag{5}$$

The radioactivity of the cloud decreases by β [μSv/h] each time unit. We assume in our simulations that the radioactivity level of the cloud decreases linearly:

$$radioactivity(n) = radioactivity(n-1) - \beta \tag{6}$$

3.3 Numerical simulation

Let us consider different couples of changes in radius and radioactivity of the cloud.
We postulate the values:

x_A=750 km, y_A= 500km, x_B= 0 km, y_B=100 km, x_U= 400km, y_U= 310 km, V=10 km/h, $\tau = 10$ min.

We will keep these values in all examples.

3.3.1 First simulation

The initial value of radioactivity is $radioactivity(1) = 29\,\mu Sv/h$ and $\beta = 0.01\,\mu Sv/h$. The initial value of the radius is $r(1) = 100\,km$ and $\alpha = 0.2\,km$.

The average radius is 150 km. The radius of the cloud, taking into account the uncertainty due to the delay in detection, is:

$$r_{b_1} = 149.17 \le r \le r_{b_2} = 150.83 \text{ (km)}$$

The first and last announced times of the cloud detection are $T_1 = 26.83$ (h) and $T_2 = 57.33$ (h). The uncertainty does not influence much, so the sensor sees one cloud.
The size of the cloud is:

$$r_{b_1} = 151.67 \le r \le r_{b_2} = 153.33 \text{ (km)}$$

That is bigger by 2.5 km compared to the numerical simulation, where the values of the estimated radius are in the range r_{C_1} =149.17 km, r_{C_2} =150.83 km. We overestimate the size of the cloud because of the condition where we wait 4 time units for the high level of the radioactivity.

3.3.2 Second simulation

The initial value of radioactivity is $radioactivity(1) = 27$ μSv/h and $\beta = 0.01$ μSv/h. The initial value of the radius is $r(1) = 100$ km and $\alpha = 0.2$ km.

The average radius is 135.9 km. The radius, taking into account the uncertainty due to the delay in detection, is:

$$r_{b_1} = 138.97 \leq r \leq r_{b_2} = 140.63 \text{ (km)}$$

First, the sensor sees two clouds as it underestimates the value of radioactivity: the first cloud has times of the detection $T_1 = 26.833$ (h) and $T_2 = 32.33$ (h) and the second has times of the detection $T_1 = 32.666$ (h) and $T_2 = 34.666$ (h).

The sensor can overestimate the value of radioactivity and send a false alarm from the time $T = 33.33$ h. Therefore the sensor gave false alarm from 33.33 h to 34.66 h. Then the sensor sees five false clouds.

The size of the big circle, containing all small clouds, is:

$$r_{b_1} = 151.17 \leq r \leq r_{b_2} = 153.33 \text{ (km)}$$

That is bigger by 12,2 km compared to the case in the numerical simulation, where the values of the estimated radius are between $r_{C_1} = 138.97$ km, $r_{C_2} = 140.63$ km. We overestimate the size of the cloud because of the false alarms that occur due to the uncertainty of measurements.

3.3.3 Third simulation

The initial value of radioactivity is $radioactivity(1) = 25$ μSv/h and $\beta = 0.01$ μSv/h. The initial value of the radius is $r(1) = 100$ km and $\alpha = 0.2$ km.

Since the radioactivity of the cloud is less than the threshold, during all the time of possible detection, then the sensor may not detect the cloud but can send a false alarm.

In this case the sensor sees three false clouds during the detection. The size of the big circle, containing all small false clouds, is:

$$r_{b_1} = 41.67 \leq r \leq r_{b_2} = 43.33 \text{ (km)}$$

Therefore, due to the false alarms, we find a non-zero value for the radius.

3.3.4 Fourth simulation

The initial value of radioactivity is $radioactivity(1) = 29$ μSv/h and $\beta = 0.01$ μSv/h. The initial value of the radius is $r(1) = 100$ km and $\alpha = 0.4$ km.

The average radius is 207.4 km. The radius, taking into account the uncertainty due to the delay in detection, is:

$$r_{b_1} = 206.57 \leq r \leq r_{b_2} = 208.23 \text{ (km)}$$

In this case, the sensor underestimates the value of radioactivity only once during the detection and it sees two clouds.

The size of the big circle, containing all small clouds, is:

$$r_{b_1} = 209.17 \le r \le r_{b_2} = 210.83 \ \text{(km)}$$

That is bigger by 2,6 km compared to the case in the numerical simulation, where the values of the estimated radius are between r_{C_1} =206.57 km, r_{C_2} =208.23 km. We overestimate the size of the cloud, because of the condition where we wait 4 time units for the high level of the radioactivity.

3.3.5   Fifth simulation

The sensor presents a failure. The repair lasts for 24 h and we can miss 240 km of the cloud. Since the radius increases each time unit and the average radius for this case is 414.8 km, we can see one part of the cloud before the failure and the other after the repair of the sensor. We take the values: $r(1) = 100 \ \text{km}$, $\alpha = 0.4$ km, $radioactivity(1) = 29 \ \mu\text{Sv/h}$, $\beta = 0.01 \ \mu\text{Sv/h}$.
The sensor detects the radioactive cloud at 24.333 h and then, from 38.666 h to 63.333 h, it presents a failure. After the failure, the sensor sees the last part of the cloud.
The size of the big circle, containing all small clouds, is:

$$r_{b_1} = 208.335 \le r \le r_{b_2} = 209.99 \ \text{(km)}$$

That is bigger by 1,765 km compared to the case in the numerical simulation, where the values of the estimated radius are between r_{C_1} =206.57 km, r_{C_2} =208.23 km. We overestimate the size of the cloud because of the condition where we wait 4 time units for the high level of the radioactivity. In this situation, the sensor presents a failure but we can calculate the size of the cloud, since we see a part after the failure.

4.   COMPARISON AMONG SEVERAL TYPES OF NETWORKS

4.1   Introduction

In this paragraph, we assume that the cloud enters a region where it can be detected by several sensors. The information about the radioactive cloud is more reliable when we have several sensors[4], see [3].
We consider that each sensor provides with information upon a circle of radius 20 km around it. We do not actually know the real shape of the cloud, so that, in a first approximation, for the simulations, we attribute it a circular shape.

Therefore the area spanned by each sensor and the area of radioactive cloud form two circles, generating different situations:

- The circle of the cloud contains the circle spanned by the sensor;
- The circle of the cloud contains only a part of the circle spanned by the sensor;
- The circle of the cloud does not contain the circle around the sensor.

We introduce a ratio of "efficient detection": it is the area spanned by the network divided by the area of the radioactive cloud. If the ratio is 1, then the network is able to completely detect the cloud. We can find the maximum ratio for a given simulation at the time when the detection is the best. If we have the appropriate position of the sensors in the network and enough sensors, we could detect almost all the radioactive cloud.

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[4] The French network of sensors TELERAY monitors the radioactivity in the environment. There are 400 sensors located on French territory mainly in the vicinity of nuclear sites and major cities, see [9].

An "efficient" network has to:

- Detect the radioactive cloud as soon as possible (time of first detection);
- Detect the cloud as long as possible (detection duration);
- Span the greatest possible area (ratio of detection).

We consider different cases modifying the location of the sensors, their number, and assuming different trajectories for the cloud. We determine the maximum ratio of efficient detection, the first time of detection and the duration of the detection in the simulations.

Our conclusions, based on the results of the simulations are as follows:

- The first time of the cloud detection and the duration of the detection are different for the networks of 20,40, 60 sensors and equal for all types of networks with 100, 200 sensors;
- The maximum ratio increases with the number of sensors. In the case of France, the more interesting network is the one with more sensors at the East border (see footnote 3). In most cases, it has a good ratio and an earlier detection of the cloud;
- We can take into account only the detection of the cloud (then the value of ratio does not matter). Almost always, the networks with 60 sensors are as good in the time detection of the cloud as the networks with more sensors. The fourth type of network (more sensors on the borders) has early detection (0.333 h) and the maximum duration of the detection when it has 60 or more sensors;
- If we want to detect and reconstruct the cloud intensity and size, we must consider the ratio. It is bigger than 0.5 (50%) for almost all types of networks with 200 sensors.

We compute the average costs of the networks per year, taking into account the casual maintenance, false alarms and failures of the sensors. For each network, we calculate the efficiency (that is the ratio of detection divided by the cost of the network).

Our conclusions about the costs of the networks are as follows:

- The average cost of the network per year increases linearly with the number of sensors;
- The third type of network (sensors on the East border) with 20 sensors has the best efficiency;
- The third type of network with 40 sensors has almost the same efficiency as the first type of network with 20 sensors, so we can use more sensors for the detection of the cloud and the efficiency will remain the same;
- The third type of network with 20, 40, 200 sensors has the best efficiency compared to other types of networks with the same number of sensors, therefore it is better to use the network with more sensors at the East border;
- The networks with 20, 40, 60 sensors have better combination of detection ratio and cost than the networks with 100, 200, 400 sensors.

4.2   General description

The area that the sensor sees is limited by a circle of radius R. The area seen by the sensor can be in, partially in, or outside the radioactive cloud each time unit. When the sensor sees the cloud, its area can be into the cloud or partially in it.

Let us consider different cases of the radioactive cloud area and the area seen by the sensor location:

1. The circles do not intersect, when the distance between them l satisfies the relationship $l > R + r(n)$. The area inside the cloud is $S_{in} = 0$:
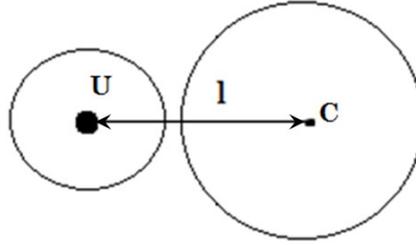
Figure 1 – The cloud and the area spanned by the sensor do not intersect

2. The area seen by the sensor is inside the area of the radioactive cloud, when $l \leq r(n) - R$. The area inside the cloud is: $S_{in} = \pi R^2$.
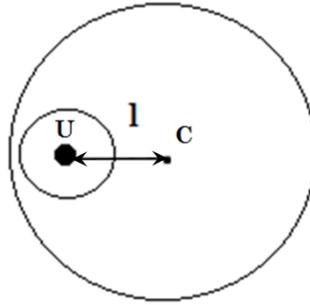
Figure 2 – The area spanned by the sensor is inside the cloud

3. The area spanned by the sensor is partially inside the radioactive cloud, when $r(n) - R \leq l \leq r(n)$. The distances are given by the formulas:

$$l_1 = \frac{r^2(n) - R^2 - l^2}{2 \cdot l}, \quad l_2 = l + l_1$$
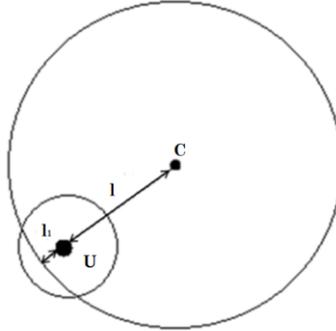
The angles are given by the formulas:

$$\alpha_1 = 2 \cdot \arcsin(\frac{\sqrt{R^2 - l_1^2}}{R}), \quad \alpha_2 = 2 \cdot \arcsin(\frac{\sqrt{r^2(n) - l_2^2}}{r(n)})$$

The areas are given by the formulas:

$$S_1 = \frac{\alpha_1 \cdot R^2 \cdot \pi}{360} - \frac{R^2 \sin(\alpha_1)}{2}, \quad S_2 = \frac{\alpha_2 \cdot r^2(n) \cdot \pi}{360} - \frac{r^2(n) \sin(\alpha_2)}{2}$$
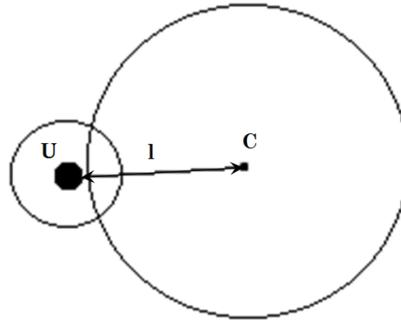
Then the area inside the cloud is:

$$S_{in} = \pi R^2 - S_1 + S_2$$

Figure 3 – The area seen by the sensor is partially inside the cloud

4. The circles intersect but the sensor does not detect the radioactivity level because it is located outside the cloud:

$$r(n) < l \leq r(n) + R$$

Fig. 4 The sensor is not able to detect the cloud

Since the sensor does not detect the cloud in this case, the part of its area in the cloud is not considered:

$$S_{in} = 0$$

If several sensors are able located in the region spanned by the cloud, their influence areas will cover only part of it. It is possible to evaluate the ratio of the cloud the sensors are able to detect over its actual size. If N is the number of sensors, this ratio is:

$$ratio(n) = \frac{\sum_{k=1}^{N} S_{in_k}}{\pi \cdot r^2(n)} *$$

4.3   Numerical simulation

We consider networks with different number of sensors and different positions. At each time, we record the status of each sensor, whether it detected the cloud (D) or not (N).

Assume first that the cloud keeps constant shape and radioactivity. The cloud may move along different trajectories, starting from the East border of France. In the simulations, the radioactivity of the cloud is assumed 35 µSv/h, not accounting for the uncertainty of the measurements.
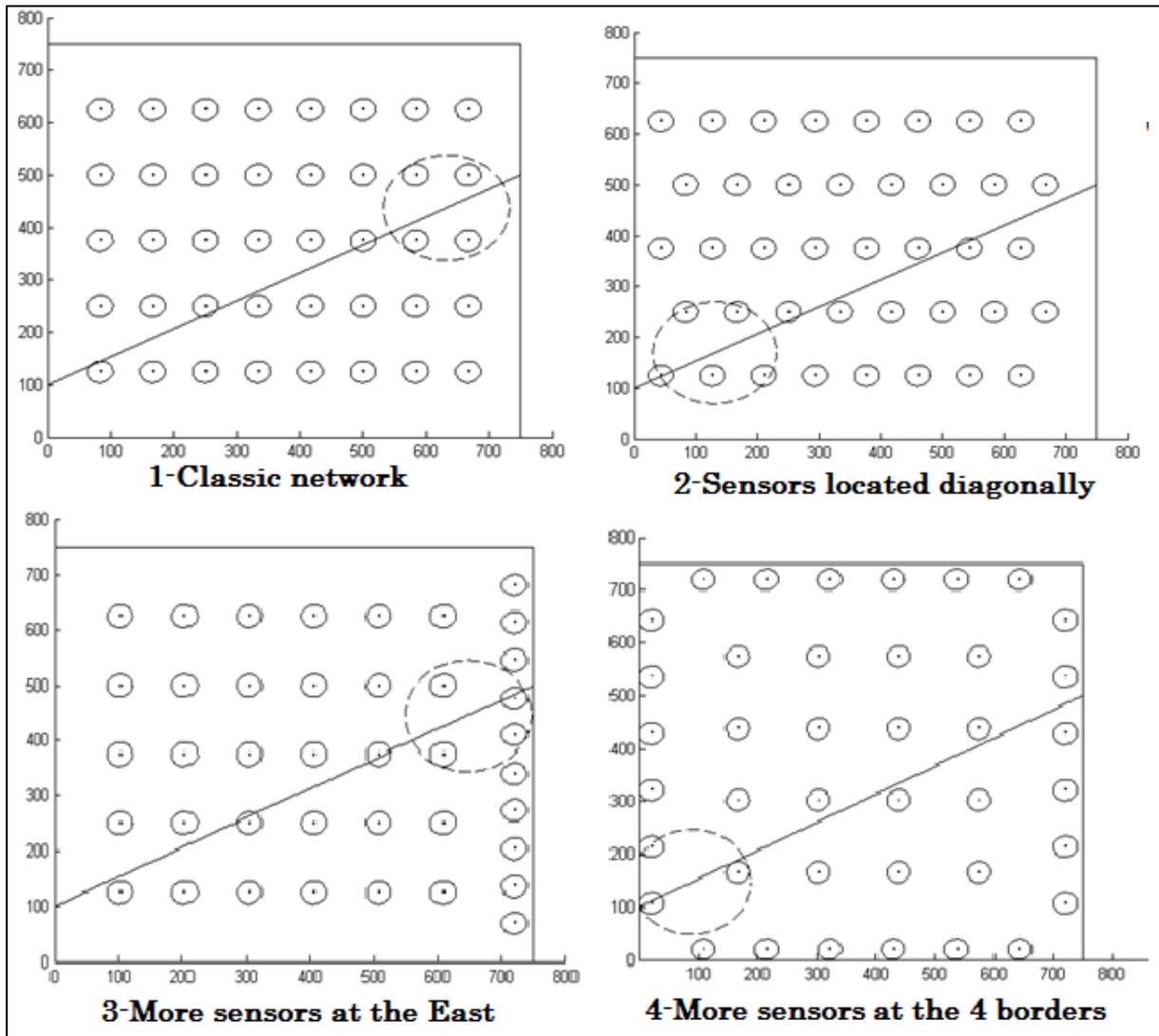

Figure 5 – The 4 types of networks

The software simulates the movement of the radioactive cloud and calculates the *ratio*(*n*) each time unit. We can find the maximum among the values of the *ratio*(*n*) in each simulation (*ratio*), when the radioactive cloud was better detected.

We consider four types of networks.

The maximum ratio increases with the number of sensors for all types of networks:

- For the networks with 20 sensors, the maximum ratio is bigger for the third network, *ratio* = 0.120. The first time of detection is smaller (0.333 h) for the third network, but the duration of detection is not as long as for the first or second networks.
- For the networks with 40 sensors, the maximum ratio is bigger for the second network, *ratio* = 0.1622. The time of the first detection is 0.333 h for the third network for all

the trajectories of the cloud, the duration of detection at some trajectories is less than what the first and second networks require.

- For the networks with 60 sensors, the maximum ratio is bigger for the third network, $ratio = 0.2217$. The time of the first detection is 0.333 for the third and fourth networks for all the trajectories of the cloud, and the duration of detection is bigger for the fourth network.
- For the networks with 100 sensors, the maximum ratio is bigger for the first network, $ratio = 0.3028$.
- For the networks of 200 sensors, the maximum ratio is bigger for the third network, $ratio = 0.5375$.
- For all the networks with 100, 200 sensors, the time of the first detection is 0.333 h and the duration of detection is maximal for all the trajectories of the cloud.

The network with 400 sensors has a maximum ratio 0.9523.

- The mathematical expectations and standard deviations of the maximum ratio for each network are the following:
- The mathematical expectation is bigger for the third type of network, among the networks with 20 sensors (M = 0.013), but the standard deviation is $\sigma = 0.016$.
- The mathematical expectation is bigger for the third type of network, among the networks with 40 sensors (M = 0.158), the standard deviation is $\sigma = 2.585 \cdot 10^{-3}$.
- The mathematical expectation is bigger for the first network, among the networks with 60 sensors (M = 0.213), but the standard deviation is $\sigma = 0.016$.
- The mathematical expectation is bigger for the first network, among the networks with 100 sensors (M = 0.296), the standard deviation is $\sigma = 6.396 \cdot 10^{-3}$.
- The mathematical expectation is bigger for the third network, among the networks with 200 sensors (M = 0.532), the standard deviation is $\sigma = 5.574 \cdot 10^{-3}$.
- The network with 400 sensors covers almost all the area and the mathematical expectation is 0.946.

The third type of network shows good results in achieving maximum ratio and early detection of the cloud. When it has 200 sensors, it shows a maximum duration of radioactive cloud detection and maximum ratio is $ratio = 0.5375$.

4.4 Average cost of the network per year

Let's consider the average cost of the network with N sensors per year. It should have not only good ratio and time characteristics of detection, but also acceptable expenses. The network with high number of sensors is good for the detection but has a high cost.

Assuming that the probability to provide with a false alarm is $p_{FA} = 0.28 \cdot 10^{-3}$, failure is $p_{BR} = 0.014$ for all the sensors at some time unit. The probability for each sensor to have at least one failure per year, without false alarms is:

Proba (failure per year) $= 0.9804$

The probability that each sensor provides at least with one false alarm per year, without accounting for failures is:

Proba (false alarm per year) = 0.01961 [5]

The average cost of the network per year consists of:

- The casual maintenance cost; the sensors must be inspected all the time in order to keep operating ability. The casual maintenance cost for one sensor per year is K_{CM}, then for N sensors the cost will be $K_{CM} \cdot N$;
- The cost of a false alarm, which mobilizes services. Experts will visit the place where the sensor is located. The cost of one false alarm is K_{FA}. We consider that all sensors present malfunctions independently. With the number of false alarms, therefore with the number of sensors, this cost increases. The false alarm occurs with some probability, then for N sensors the cost will be $K_{FA} \cdot N \cdot Proba(false\ alarm\ per\ year)$;
- The cost of the failure, as the device must be repaired or replaced. The cost of one failure is K_{BR}. With the number of failures, therefore with the number of sensors, this cost increases, but failure occurs with some probability, then for N sensors the cost will be $K_{BR} \cdot N \cdot Proba(failure\ per\ year)$.

Therefore, the average cost of the network per year is:

$$K_A = K_{CM} \cdot N + K_{FA} \cdot N \cdot Proba(false\ alarm\ per\ year) + K_{BR} \cdot N \cdot Proba(failure\ per\ year)$$

We take the values: K_{CM} =500 €, K_{FA} =5000 €, K_{BR} =1000 €.

The cost function of the number of sensors increases linearly with the number of sensors.

Let us denote the mathematical expectation of the maximum detection ratio for each network as $M(ratio)$, then the efficiency of the network is:

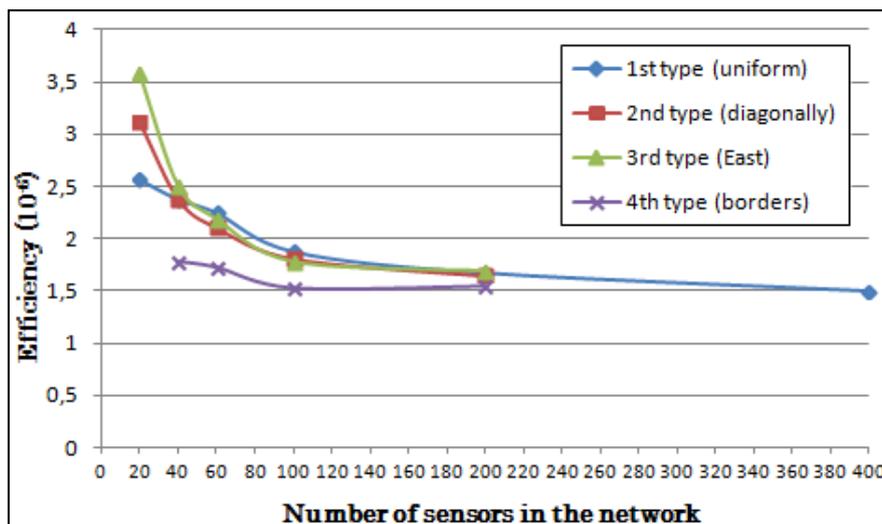$$Ef = \frac{M(ratio)}{K_A}$$

Figure 6 – Efficiency of the 4 types of networks, depending on the number of sensors

[5]Data used here are originating from the Teleray Network, [9].

Let us find which of the networks has greater efficiency, therefore a better combination of cost and ratio of detection. The efficiency of each network is shown in Fig. 6.

The greatest efficiency $(3.579 \cdot 10^{-6})$ is met with the third network with 20 sensors (that has more sensors at the East border). We can use the first, the second and the third type of networks with 20, 40, 60 sensors as they have better efficiency than the networks with 100, 200, 400 sensors.

The third type of network shows better results in efficiency almost for all numbers of sensors.

5. ARCHIMEDES' METHOD OR HOW TO USE A DATABASE OF CLOUDS

In the previous chapters of the paper, we have addressed and investigated the effect on detection capacity of a network of sensors considering several sources imprecisions: failures, false alarms, uncertainties of measurement.

Increasing the number of sensors in the network is not necessarily appropriate, because of the cost of each flaw (failures and false alarms). An alternative solution is based on a model identified as "Archimedes' method", see [1]. It is based on the capacity to reconstruct the information not through calculations or propagation of data, but through suitable comparisons with pre-existing information stored in database.

6. CREATION OF A DATABASE OF RADIOACTIVE CLOUDS

Our knowledge of the propagation of radioactive clouds in the environment relies upon the past experience of major nuclear accidents, the information of which has been recorded in database [2]. However these cases are quite rare (Chernobyl, Fukushima, Kychtym, Three Miles Island) and we have got good recordings for Chernobyl and Fukushima only, see [2], [7], [8], [10].

A recording of a radioactive cloud is the evolution of the contamination in function of time. To create a database of radioactive clouds, we will need computer simulations. These simulations will take into account meteorological parameters, such as temperature, the direction and strength of the wind, humidity… As said here above (see footnote 2) for a given radioactivity source (intensity and location), the propagation will depend on the characteristics of the wind:

- Strong wind: great size for the cloud, the particles will take a long time before reaching the ground, the radioactivity will be low;
- Weak wind: small size for the cloud, the particles will quickly reach the ground, the radioactivity will be high.
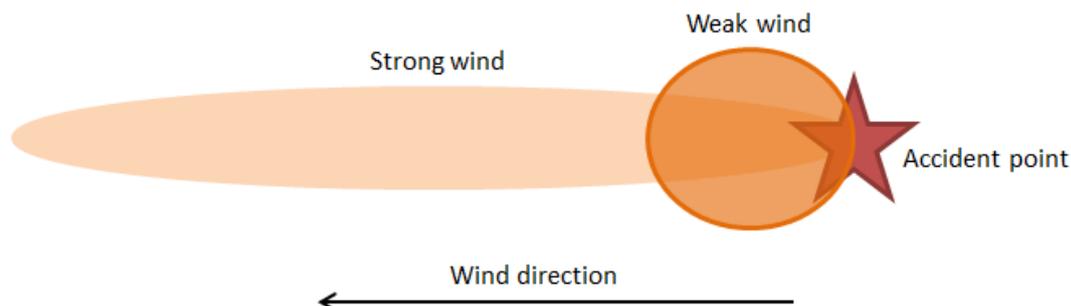

Figure 7 – Propagation of radioactivity depending on the wind

So, for a given radioactivity and starting point, there will be a great number of possible evolutions, depending on the wind map, the temperature map…

The creation of a good database relies on taking into account all these parameters. Of course, each meteorological parameter will also be simulated: this requires a joint work between weather experts and nuclear safety institutions, the first ones will give data and knowledge to the second ones.

6.1   How to use this database

Archimedes used comparison methods to determine properties of an unknown object by comparing it to a known object, for instance a cylinder and a sphere, see [1]. These methods are already used when all other methods fail, because the quality of the data is too bad to allow a standard analysis. For example:

- Pattern recognition, for instance hand writing recognition, uses a dictionary, that is a list of predefined letters, and tries to find which one is the closest to the letter under investigation;
- GPS positioning uses signals sent by satellites, but these signals are extremely weak. So the receiver emits similar signals, and tries to find which "translation" of the signal matches the one emitted by the satellites (the question is to measure a distance, which corresponds to a delay in the signal).

The main characteristic of Archimedes' method is the robustness: the main drawback of the analytic formulas often used is that they produce a precise result from precise data, but in practice data are not precise and the laws to be put inside the formulas are not correctly known.

In our case, it is not the formulas that are put aside, but the sensors. We saw that having a great number of sensors is not always a good idea, because of the costs and flaws. With a database of clouds at our disposition, we will just need several radioactive sensors. The values of radioactivity they will send will be compared with the radioactivity of the simulated clouds. We will keep only the clouds whose radioactivity is close to the real value. Then, we will keep the clouds that have the same meteorological parameters as the ones observed in the real environment (using a set of meteorological sensors).

This method is cheaper than using only radioactive sensors. We need only a few sensors and we use also meteorological stations (basic stations are really cheap) to determine the exact environment of the cloud. When we have selected a simulated cloud, we have an idea of how the real radioactivity will evolve (in space and time). The results can be refreshed within a period, so we can take into account brutal variations of wind, humidity, etc., and in that case we switch into another simulated cloud.

7. CONCLUSION

The capacity to promptly and efficiently detect any source of contamination to the environment at a local and a country scale is mandatory to a safe and secure exploitation of civil nuclear energy worldwide.

This capacity must rely upon a robust network of measurement devices which is to be optimized vs. several main parameters including its overall reliability, the investment, the operation and maintenance cost.

The present paper investigates the efficiency vs. cost of such network of detectors to several parameters, including their density, lay-out, etc., also considering the major failure modes which may affect them.

Eventually, a modern version of "Archimedes' method" is proposed for optimization. It relies upon systematic comparisons among the results of simulations stored in suitable databases and the actual measurements on-site. In our approach, the best network would be made of three items:

- A few radioactivity sensors, preferably put on the East border;
- Several mobile units, to be sent where detection is supposed to occur;
- A database of simulations, to be used for comparisons.

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