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Multiple inspection modelling for decision making and management of jacket offshore platforms: effect of False Alarms

Franck SCHOEFS and Alexandre CLEMENT

GeM – Institut de Recherche en Génie Civil et Mécanique, Université de Nantes, Ecole Centrale de Nantes, 2 rue de la Houssinière, BP 92208, 44322 Nantes, cedex 3, France

Fax : + 33 251125499

E-mail : franck.schoefs@univ-nantes.fr

Abstract : Insertion of inspection results into decision scheme is still a challenge for structural analysis. Methods are generally named Risk Based Inspection. They aimed to provide aid tools to operators of marine structures which have to ensure that structural integrity is maintained at a sufficient level during in-service life or in case of reassessment. The objective is a global optimization of Inspection, Maintenance and Repair plans (IMR), particularly regarding inspections. In this context, original aid tools are presented keeping in mind that Probability of False Alarms must be introduced. Theoretical aspects and using of real data base are both treated. The benefit of multiple subsequent inspections is also discussed.

Keywords : Existing structures; Probability of detection; False alarm; Cost analysis; In-service inspections; Risk Based Inspections; Non destructive testing.

1 Introduction

Since 70's, thousands of fixed offshore platforms have been established in various sites and by using various design and technologies of building or launching. Some of them, called jackets offer harsh environmental conditions for in situ inspections and are submitted to extreme events. These steel framed structures are made up of cylinder which are welded together. Most of them currently reach or will reach soon their initial design lifetime and need structural integrity assessment from an economical point of view. Regarding fatigue effects on jackets platforms, cracks at the weld connection in tubular nodes are propagating. These are surface cracks, which reach the wall thickness with time: this is the

through cracks. Through crack is then considered as the critical size. It means that beyond this crack depth, repair is advocated whatever the consequence on the structural behaviour. Some recent works propose to analyze the structural effect of through crack before to decide a repair (Schoefs et al., 2001). To avoid such damages, the structure is managed using Inspection, Maintenance and Repair plans (Goyet, 2000, Guoyang, 1992, Moan, 1999, Bloch et al., 2000, Faber and Sorensen, 1999). In order to optimize costs induced by these plans, research have been carried out: optimization of inspection planning (Goyet, 2000, Faber, 2000, Rouhan and Schoefs, 2003), Risk-Based Maintenance/Inspections (Tanaka 1996, Madsen 1987, Jiao 1992, Onofriou 1999, Goyet 2000) and Reliability Centered Maintenance (Reicks 2000). They provide suitable models of inspections results in order to perform mechanical and fatigue computing as well as reliability updating. Definition of probability updating is devoted to this aim. Several challenges which may conflict have to be worked out :

- minimize inspections and maintenance costs,
- minimize uncertainty on inspection results,
- obtain the most complete information on structural integrity.

An optimal inspection is located where damages should be critical versus a risk criterion and is done with the right inspection tool in the sense of the cost/performance ratio. This can be achieved by minimization of a cost function including risk of good or bad decisions. This paper focus on probabilistic modeling of inspections results, including false alarms, in view to provide inputs in risk based decision cost models and to analyze the benefit of multiple inspections.

First, theoretical aspects coming from detection theory are reminded. Theoretical definitions of probability of detection (PoD), probability of false alarm (PFA) and receiver operating characteristic (ROC) are introduced.

Then, experimental approach are presented from results obtained in the ICON Project. Theoretical aspects coming from detection theory are reminded. Theoretical definitions of probability of detection (PoD), probability of false alarm (PFA) and receiver operating characteristic (ROC) are introduced.

An aid tool based on the description of the whole or a part of ROC curves is suggested. It allows to measure the benefit of multiple inspections which is then introduced for independent inspection. A cost analysis is then performed with sensitivity to dimensionless parameters which allows to discuss the relative weight of inspection, repair and failure cost. A more detailed cost analysis is finally proposed considering a realistic cost model.

2 Probabilistic modelling of inspection results based on detection theory

2.1 Need of a probabilistic modelling for inspection results

Inspection is an essential step in IMR plans, since it's the only way to achieve a partial view of the structural integrity. A complete overview can't be reached due to the size of monitored structures and hundreds of components which are concerned. On existing structures, non-destructive testing (abbreviated NDT) are widely used. Classically, there are two levels of analysing NDT performances: the sizing and the detection capacity. In this paper, the focus will be on the last one (i.e. crack detection) as crack is a very common damage in steel jacket platforms. All NDT tools have limitations and, in complex environment and harsh conditions, their capabilities and abilities to be well operated are different from those given by laboratories and/or factories (Barnouin et al., 1993, Hugues and Bond, 1989, Newton, 1990), even if a protocol is rigorously followed during inspection. This is the case for underwater inspections of offshore structures where accessibility is limited and conditions of use of the NDT tool are not optimal. This leads to lower performances than expected. In the offshore field, an important work of inter-calibration was made within the ICON project (Rudlin, 1996, Rudlin and Dover, 1996, Barnouin et al., 1993), in order to get an unified overview of several tool performances in realistic on site conditions. All the data performances were introduced into a single database. The decision-maker has then very powerful information to decide which best NDT tool to use, relatively to his performances, for a specific application, once he's able to provide a performance function. This allows an optimal choice of different tools in order to use them at their full capabilities. Specifying NDT tools ranking criteria is very difficult in this complex and multi-disciplinary context. It should be based on a detailed analysis of needs and performances.

2.2 Probability of detection and probability of false alarm: theoretical definitions based on detection theory

The most common concept which characterizes inspection tool performance is the probability of detection. Let a_d be the minimal crack size minimal crack size, under which it is assumed that no detection is done. a_d is called detection threshold in the following. Thus, the probability of detection is defined as:

$$PoD(a) = P(a \geq a_d) \quad (1)$$

where a is the measured crack length. a_d is deterministic parameter or random variable. This definition implies that PoD is a monotonic increasing function.

Detection theory gives a more complete definition and allows to define *PFA*, once given probability density functions f_{signal} and f_{noise} respectively of (signal+noise) and noise. Let's assume that noise and signal amplitude are independent random variables, then *PoD* and *PFA* have the following expression (2) and (3):

$$\text{PoD}(a) = \int_{a_d}^{+\infty} f_{\text{signal}}(\hat{a}_s, a) d\hat{a}_s \quad (2)$$

$$\text{PFA}(a) = \int_{a_d}^{+\infty} f_{\text{noise}}(\hat{a}_n, a) d\hat{a}_n \quad (3)$$

where \hat{a} is the measured response level of N.D.T tool and a the real size of crack. We assume in the following, for illustration objective, that (signal+noise) and noise amplitude are normally distributed with respective characteristics $N[\mu_s(a), \sigma_s(a)]$ and $N[\mu_n(a), \sigma_n(a)]$ (see figure 1). Then equations (2) and (3) take the form (4) and (5):

$$\text{PoD}(a) = \int_{a_d}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma_s(a)} e^{-\frac{(\hat{a}_s - \mu_s(a))^2}{2\sigma_s^2(a)}} d\hat{a}_s \quad (4)$$

$$\text{PFA}(a) = \int_{a_d}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma_n(a)} e^{-\frac{(\hat{a}_n - \mu_n(a))^2}{2\sigma_n^2(a)}} d\hat{a}_n \quad (5)$$

More details are given in Rouhan (2001).

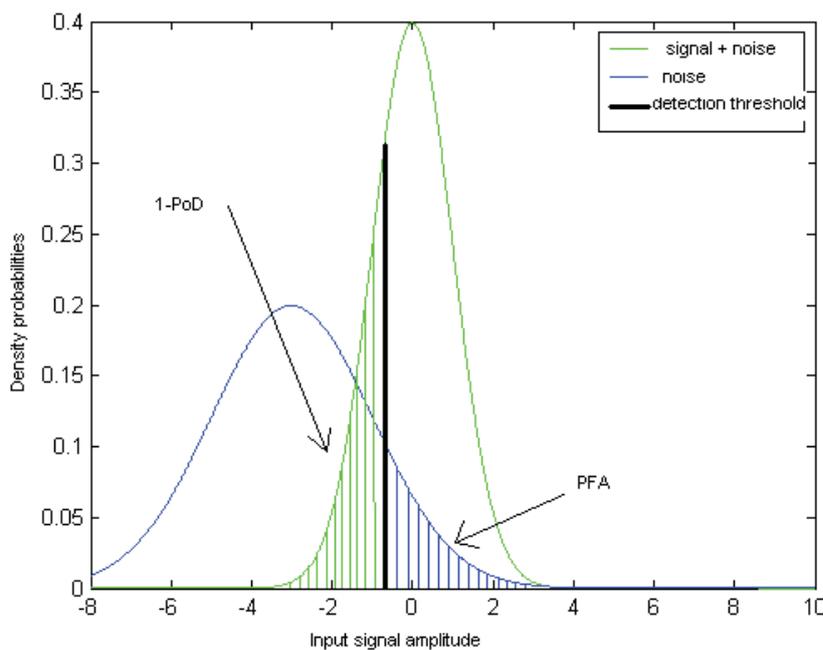


Figure 1. Illustration of PoD and PFA (signal and noise normally distributed).

For a given detection threshold there is a way to define N.D.T performance by the couple (PoD, PFA) ; this is the Receiver Operating Characteristic (abbreviated R.O.C.). This couple can be considered as coordinates of a point in (PoD, PFA) space. Let us consider that a_d takes values in the range $[-\infty; +\infty]$, it allows to plot a curve linking points of coordinates (PoD, PFA) ; this is the R.O.C curve. It is a parametric curve with equation:

$$\begin{cases} x(a_d) = \int_{a_d}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma_n} e^{-\frac{(\hat{a}_n - \mu_n)^2}{2\sigma_n^2}} d\hat{a}_n \\ y(a_d) = \int_{a_d}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma_s} e^{-\frac{(\hat{a}_s - \mu_s)^2}{2\sigma_s^2}} d\hat{a}_s \end{cases} \quad (6)$$

where x and y denote coordinates respectively along PFA and PoD axis. R.O.C. curve plotted on figure 2 is computed with p.d.f presented in figure 1.

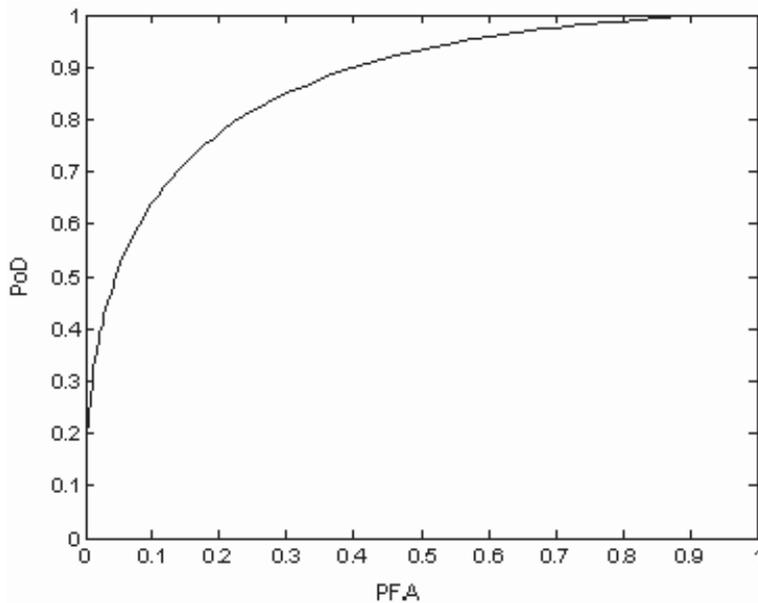


Figure 2. R.O.C. curve.

From a theoretical point of view, this is a convex, monotonically increasing function, always lying above 45° diagonal of the ROC space, and its first derivative is closely linked to the sensitivity of the receiver (see Arques, 1982 and Fücsök et al., 2000). The diagonal line running from lower left to upper right (curve "PoD=PFA") is the line of no "performance", since in that case the inspection result is the same, no matter what the observation is (see demonstration in Rouhan and Schoefs, 2003).

Looking for the best detection performances, the probability of detection should always take larger values than the probability of false alarm (low noise sensitivity). We have then $PoD \geq PFA$. When reading ROC curves, one must remind that the probability of false alarm depends on the noise and detection threshold only. It does not depend on crack size. Probability of detection is a function of the detection threshold, the crack size, and the noise. Thus, for a given detection threshold, the probability of false alarm is a constant, but the probability of detection is an increasing function of the crack size. ROC curve is a fundamental characteristic of the NDT tool performance for a given crack size. Perfect tool is represented by a ROC curve reduced to a single point whose coordinates in the (PoD, PFA) plane are: $(PoD, PFA)=(1,0)$. Different theoretical ROC curves, corresponding each one to different signal/noise ratio ($s/n=1.0$) of NDT tool are presented in Rouhan and Schoefs (2003).

3 Experimental data and linked definitions for PoD and PFA

3.1 Basic definitions from experimental data

There is actually no way to reach p.d.f of signal and (signal+noise) as presented above for inspections in harsh conditions where many factors affect inspection results. One way of modelling is to analyse the probabilistic structure of inspection results and to provide a model. That's why I.C.O.N project was dedicated to intercalibration of N.D.T tools with check done on-the-spot. A statistical analysis has been made from a set of tests which consider:

- various node typologies
- several inspection conditions (basin, sea)
- several inspector team coming from several countries

It leads to provide a set of R.O.C points or curves. First, as crack shape is hard to describe, there is a need to define crack classification. It is reminded in Rouhan (2001) and allows to know if we consider that a crack or a group of cracks has been detected. Then several intervals of crack size can be defined and corresponding range is $c = \{a \in \mathfrak{R}^+ \mid a \in [a_c; a_{c+1}]\}$. For calibration works, let us consider $n(c)$ tests inside a range c of real crack size. Several numbers are defined:

- $n_b(c)$ number of existing cracks which are detected ;
- $n_f(c)$ number of non-existing cracks which are detected ;
- $n_n(c)$ number of existing cracks which are not detected ;
- $n_r(c)$ number of un-cracked joints where no crack have been detected.

As the number of detected crack can exceed number of existing crack, the corresponding ration is not a probability. Two set of probabilities (eq. (7) and (8)) are defined:

The first one concerns good detections:

$$P_b(c) = \{p_b(c), p_r(c)\} \text{ où } \begin{cases} p_b(c) = \frac{n_b(c)}{n_b(c) + n_n(c)} = \frac{n_b(c)}{n_1(c)} \\ p_r(c) = \frac{n_r(c)}{n_f(c) + n_r(c)} = \frac{n_r(c)}{n_2(c)} \end{cases} \quad (7)$$

The second one deals with bad detections:

$$P_f(c) = \{p_f(c), p_n(c)\} \text{ où } \begin{cases} p_f(c) = \frac{n_f(c)}{n_2(c)} \\ p_n(c) = \frac{n_n(c)}{n_1(c)} \end{cases} \quad (8)$$

According to these definitions, $p_f(c)$ can be considered as *PFA* and $p_b(c)$ as *PoD*. It leads to build discrete *PoD* according to range which have been defined.

3.2 Analysis of PFA. Introduction of PFI definition

Definition of *PFA* is not normalized. As it has a great effect in Risk Based Inspection planning; it leads to investigate false scenario of failure and to repair a non-cracked joint. Moreover, there is a risk to affect it's integrity. In the ICON project, definition of PFA was different as one given upon:

$$PFA = \frac{n_f(c)}{n_b(c) + n_n(c)} \quad (9)$$

Figure 3 proposes three ROC points determined for three class of defects for a given tool and a given inspector.

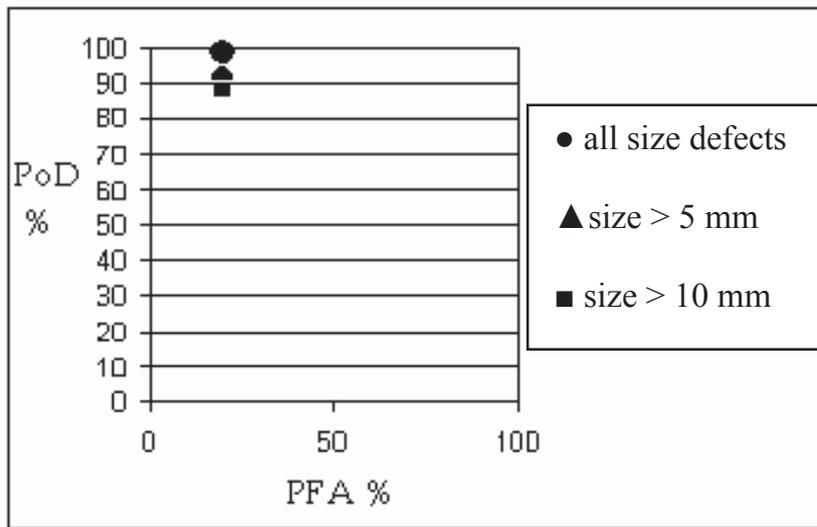


Figure 3. R.O.C points from experimental data.

Then it can lead to PFA upper than 1 which is not acceptable from probabilistic point of view. The most rigorous and helpful definition for RBI planning seems to link the probability of false alarm to an area e.g per meter of weld inspected (eq. 10). It is called Probability of False Indication (abbreviated *PFI*) in Straub (2002).

$$PFA = \frac{\sum_{i=1}^n s(n_i)}{m} \quad (10)$$

Where

- n_i is the i^{th} non-existing crack detected, $s(n_i)$ is its size (length or depth);
- m is the cumulated length of weld upon inspected joints.

In terms of risk analysis, this formulation allows to distinguish possible structural effects and the related policies according to this rate. It is to notice that this definition is based on the overall length or area of inspected weld and not only hot spot area: it is guided by results of ICON project where the simulated cracks by fatigue test were not only obtained on hot spot points due to initial defects, residual stresses ...

3.3 Enrichment of experimental data.

From a mathematical point of view, parametric equations of *ROC* curves (eq. 6) allows to compute parameters of distributions for noise and (signal+noise) amplitudes if we know coordinates of two points. It leads to assume that they follow normal distributions, that a_d is known for each point and that noise and (signal+noise) pdf are the same for the two points. From ICON data, two points of *ROC* curves have been introduced (see Fig. 4). Difference between these two points comes from inspection society and/or diver and top side operator.

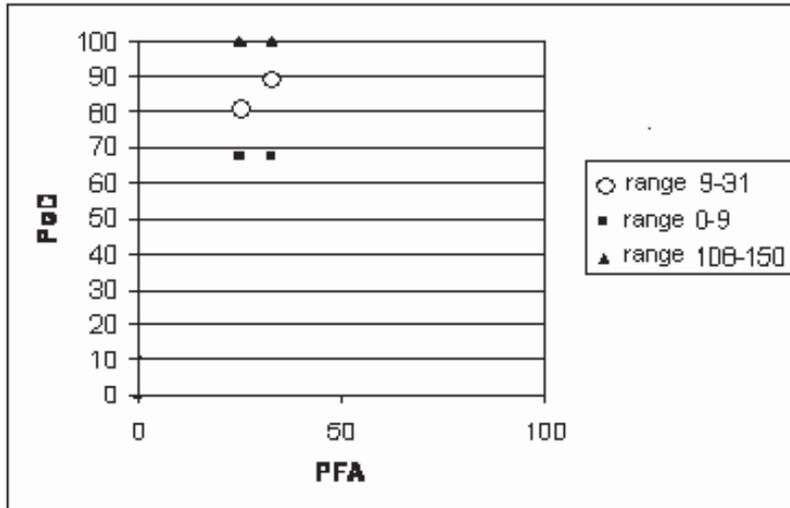


Figure 4. Simulation of R.O.C curves from two experimental data.

Such a theoretical approach is not convenient from expert judgment point of view. In fact, for a given N.D.T. tool, if (signal + noise) amplitude data are available, because they are the basis of PoD building, noise is more difficult to model because it contains mainly:

- inspector and top side operator performances;
- node typology and preparation (corrosion, cleaning, ...).

Moreover, for a given N.D.T. tool, detection threshold a_d can be evaluated from data obtained and is mainly dependent of:

- inspector and top side operator performances;
- node preparation.

Thus, noise amplitude and detection threshold are closely linked. It can be illustrate when analysing Magnetic Particle Inspection, which needs absence of corrosion residues: more inspector wants to detect small cracks, lower is detection threshold but more significant is the risk of false detections and consecutively noise amplitude increases. This problem is more dominant if corrosion residues still present.

4 Introduction of inspection results in IMR planning

4.1 Concepts of PoI and PFI

This concept is detailed in Staub and Faber (2003). It allows to link the Probability of Detection and of False Indication within a global term called Probability of Indication. As PFA depends of crack size, this definition will not be used in the following.

$$PoI(s) = PoD(s) + (1 - PoD(s))PFI \quad (11)$$

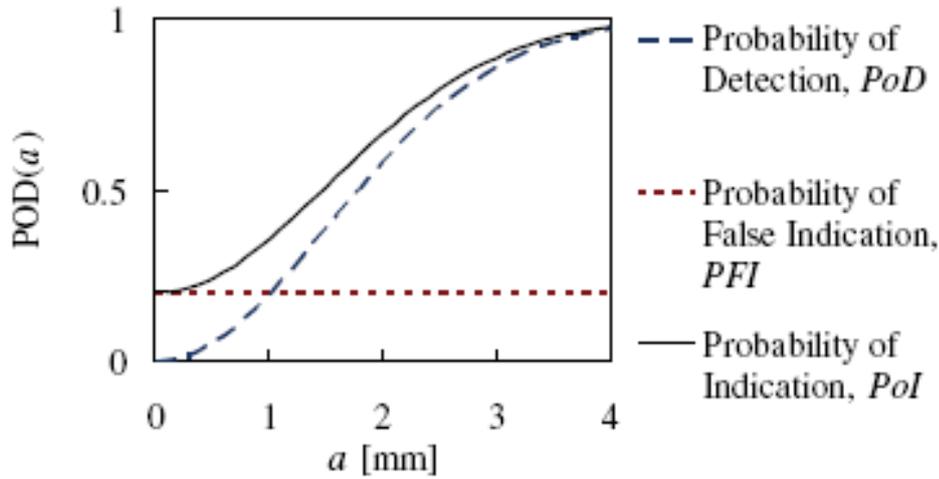


Figure 5. Definitions of PFI and PoI.

4.2 Bayesian modelling of inspection results

Another way for modelling inspections results for *RBI* objectives is to use a bayesian approach from decision theory (see Rouhan and Schoefs, 2003). An inspection is a decision problem: to make an inspection is equivalent to make a decision. Assume we have to detect an existing crack in a body (here a structural offshore tubular node), with a specific NDT tool. After inspection, the NDT result could be: no crack, or presence of crack (see section 3). In fact this primary result should be interpreted through a decision on the state of the body: cracked or not. The same scheme could be applied if the body is actually not cracked. As for in-service structures the state of the inspected area is not known, it is thus necessary to consider four inspections events:

- E_1 : no presence of crack, conditional to no crack detection;
- E_2 : no presence of crack, conditional to crack detection;
- E_3 : presence of crack, conditional to no crack detection; and
- E_4 : presence of crack, conditional to crack detection.

In these events definition, focus is on presence or absence of crack after an inspection: in a *RBI* objective, the aim is finally to know whether or not there is an existing crack. Let us consider the binary random variable “presence of a crack” X , whose value is 1 if a crack is present, 0 otherwise. We note $d()$, the random inspection decision function, whose value is 1 if a crack is detected (i.e. we decide that one crack is present), 0 otherwise.

Then four events are defined:

- $E_1 = [d(X)=0 / X=0]$;
- $E_2 = [d(X)=0 / X= 1]$;
- $E_3 = [d(X)=1 / X=0]$;
- $E_4 = [d(x)=1 / X=1]$.

By definition, these events are not independent and some of them are complementary. Thus, the probability of false alarm PFA and the probability of detection PoD could be written, according to Bayes' rule:

$$PoD = \text{proba}(E_4) = \text{proba}(d(X)=1/X=1) \quad (12)$$

$$PFA = \text{proba}(E_3) = \text{proba}(d(X)=1/X=0) \quad (13)$$

This gives the right definitions of PoD and PFA:

- PoD is the probability to decide crack presence (crack detection), conditional to an actual existing crack;
- PFA is the probability to decide crack presence (crack detection), conditional to no actual existing crack.

These definitions are consistent with inspection calibration/inter-calibration aspects presented in section 3. Note that an inspection result can be entirely characterized by a set (PoD, PFA).

After calculations (see Rouhan and Schoefs, 2003), probability of events presented upon are deduced:

$$P(E_1) = P(X = 0 / d(X) = 0) = \frac{(1 - PFA(X))(1 - \gamma)}{(1 - PoD(X))\gamma + (1 - PFA(X))(1 - \gamma)} \quad (14)$$

$$P(E_2) = P(X = 0 / d(X) = 1) = \frac{PFA(X)(1 - \gamma)}{PoD(X)\gamma + PFA(X)(1 - \gamma)} \quad (15)$$

$$P(E_3) = P(X = 1 / d(X) = 0) = \frac{(1 - PoD(X))\gamma}{(1 - PoD(X))\gamma + (1 - PFA(X))(1 - \gamma)} \quad (16)$$

$$P(E_4) = P(X = 1 / d(X) = 1) = \frac{PoD(X)\gamma}{PoD(X)\gamma + PFA(X)(1 - \gamma)} \quad (17)$$

where γ is the probability of crack presence defined by $\gamma = P(X = 1)$. γ is a stochastic process: $\gamma_\tau(X, t)$ indexed by the position of the joint X and time t . τ denotes the joint typology. It can be deduced from statistics (see Moan et al., 1997) at given date and crack propagation law (Madsen, 1997). The historic of loading and extreme events or accidents are also helpful for crack size updating. Figure 6 gives an illustration of $P(E_2)$ as a function of PoD and PFA for two given probability of crack presence: $\gamma=0,1$ can be understood as probability of large crack presence and $\gamma=0,9$ probability of small crack presence.

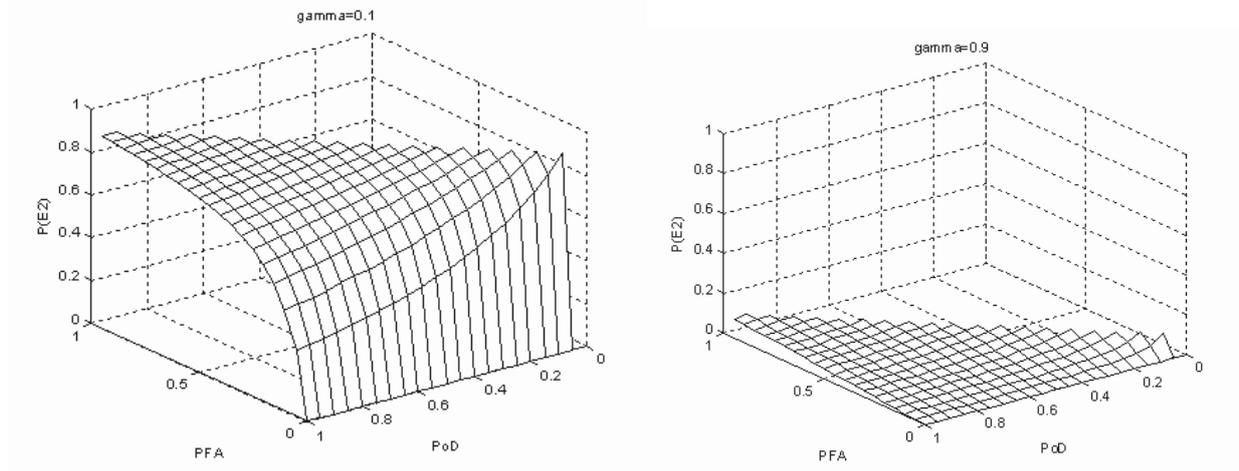


Figure 6. $P(E_2)$ for two level pf probability of crack presence ($\gamma=0,1$ and $\gamma=0,9$).

This figure shows that role of crack presence is dominant.

4.3 Projection of ROC curves on $P(E_i)$ surfaces

For a given N.D.T tool, only points of $P(E_i)$ surfaces being on a ROC curve have to be considered (see Rouhan and Schoefs, 2003). It leads to make a projection of R.O.C curves on $P(E_i)$ surfaces. Figure 7 presents such a projection for two R.O.C curves which can be interpreted as R.O.C curves plotted for two techniques and the same crack range or one technique and two crack ranges.

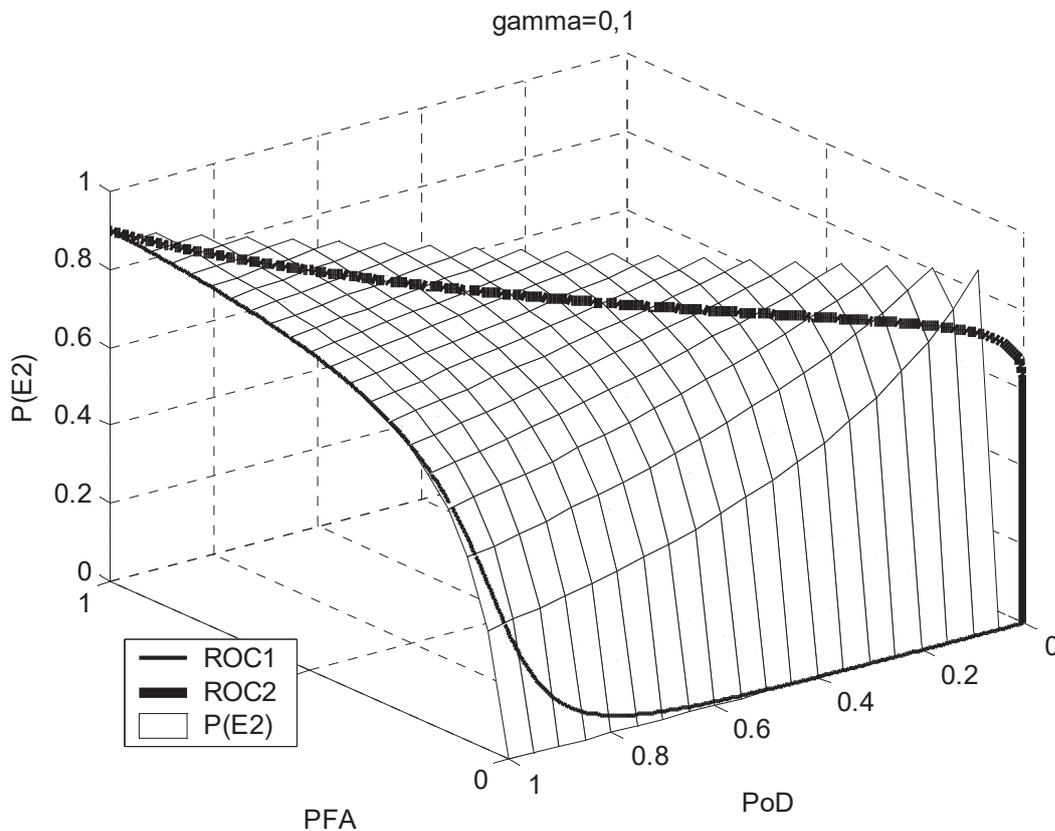


Figure 7. Projection of ROC curves on $P(E_2)$ for $\gamma=0,1$.

In view to perform a cost analysis, points of RoC curves can be considered (Rouhan and Schoefs, 2003). Two cost functions are considered: equation 18 suggest expression of cost overrun in case of detection $\overline{E(C)}_d$ and equation 19 the costs in case of no detection.

$$\begin{aligned}\overline{E(C)}_d &= (C_1 + \overline{C}_4)P(E_2) \\ &= (C_{inspection} + C_{repair})P(E_2)\end{aligned}\quad (18)$$

$$\begin{aligned}E(C)_{nd} &= C_1(1 - P(E_3)) + (C_1 + \overline{C}_1)P(E_3) \\ &= C_{inspection} + C_{failure}P(E_3)\end{aligned}\quad (19)$$

where $C_1 = C_{inspection}$, $C_2 = C_{inspection} + C_{repair}$, $C_4 = C_{inspection} + C_{repair}$, $\overline{C}_4 = C_{repair}$ given the inspection/repair policy:

- no crack detection leads to no action;
- crack detection leads to repair.

$P(E_2)$ and $P(E_3)$ are called respectively in the following COWD (for Cost Overrun Weighting in case of Detection) and CWND (for Cost Weighting in Case of No Detection). The purpose here is to give an aid tool allowing to consider all the ROC curve or part of it. In fact, statistical ore other uncertainties on PoD curves (Straub and Faber 2003) and on PFA estimates leads to statistical uncertainty on R.O.C curves. Then a part of a R.O.C. curve can be considered around a point (see Fig. 8). It allows to compare techniques with various statistical uncertainty.

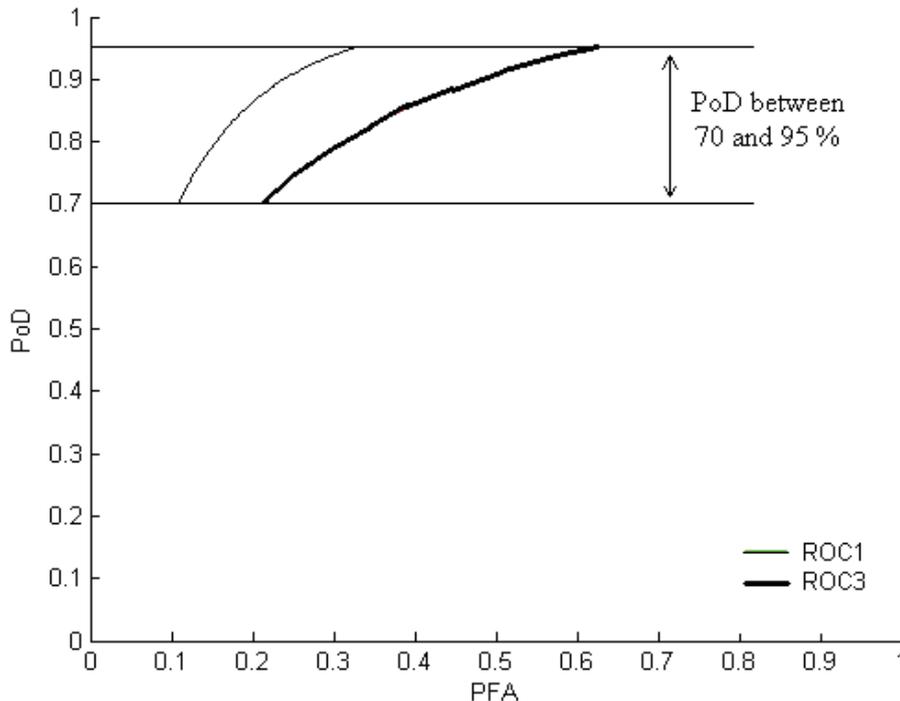


Figure 8. Uncertainty on ROC curves.

Then $P(E_i)$ are replaced in eq. 19 and 20 by their expected value (Eq. 20):

$$m(P(E_i))|_{ROC} = \frac{1}{L_{ROC}} \int_{ROC} P(E_i)|_{ROC} dl_{ROC} \quad (20)$$

where l_{ROC} is the curvilinear abscissa along the projected R.O.C curve on $P(E_i)$ surface, L_{ROC} the length of R.O.CC curve in (PoD, PFA) plane and $P(E_i)|_{ROC}$ value of $P(E_i)$ at this abscissa. This expected value can be interpreted as the ratio of the area under the projected R.O.C and the length of this curve in (PoD, PFA) plane (see Fig 9).

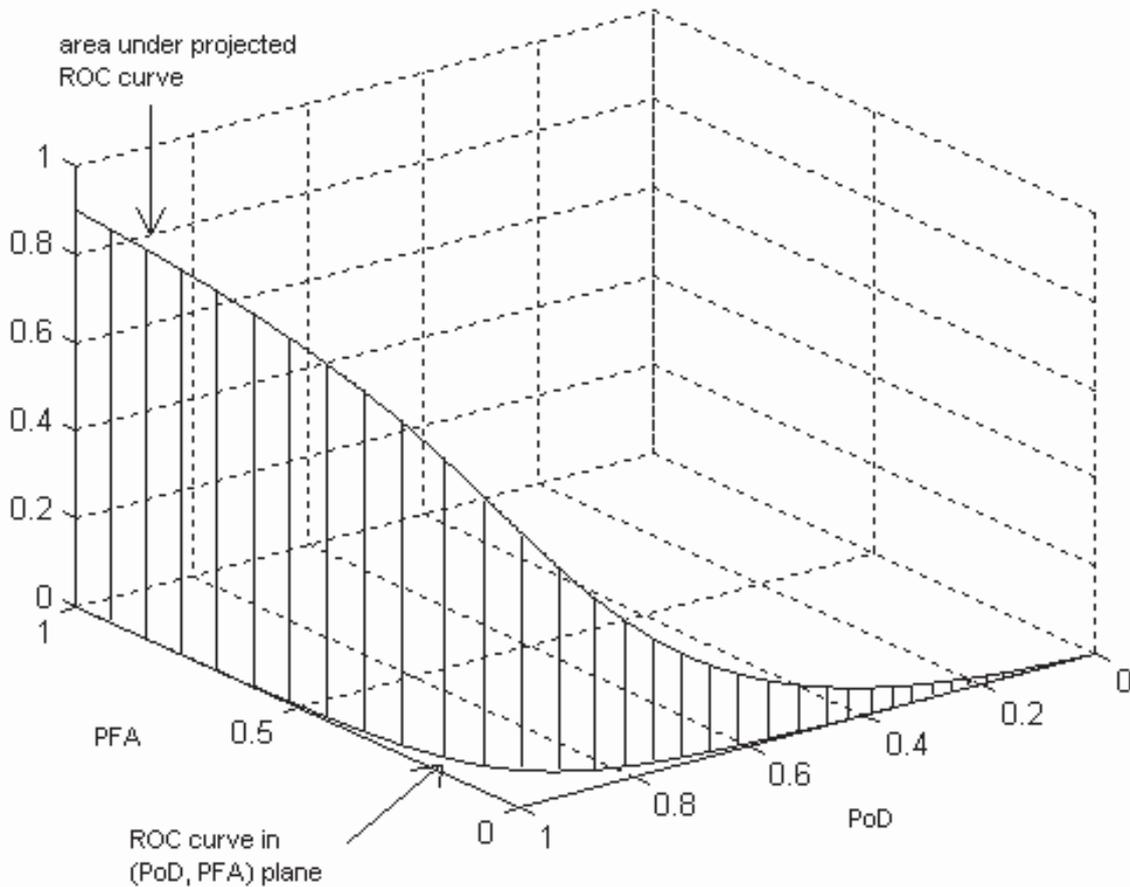


Figure 9. Area under the projected ROC curve.

5 Case of multiple inspection

5.1 Basic concept

Several techniques allow to obtain P.o.D result after multiple inspections. Horn and Mayo (1999) suggest three methods, mean based one, Bayesian one and one base on Dempster-Shafer theory. Straub and Faber (2003) suggest a technique based on dependence probabilistic structure between

inspections. We use here intersection and union methods given by Yang and Donath (1984). In this technique, inspection are supposed to be independent. This hypothesis can be followed if techniques, diver and top-side operator are different and in the case of simple joint typology where access is easy. We adopt condensed expressions presented in equations (21) for union method and (22) for intersection method.

$$\text{ROC}(E_i;1 \cup 2) = \text{ROC}(E_i;1) + \text{ROC}(E_i;2) - \text{ROC}(E_i;1) \cdot \text{ROC}(E_i;2) \quad (21)$$

$$\text{ROC}(E_i;1 \cap 2) = \text{ROC}(E_i;1) \cdot \text{ROC}(E_i;2) \quad (22)$$

5.1 Illustration according to $m(P(E_i))$

Thus, curves presented in figure 10 can be obtained. This technique allows to introduce interest of repeat the same inspection but independence hypothesis is not suitable in this case. The dash area represents the position of alternative hypothesis which are between the two boundaries given by equations 21 and 22.

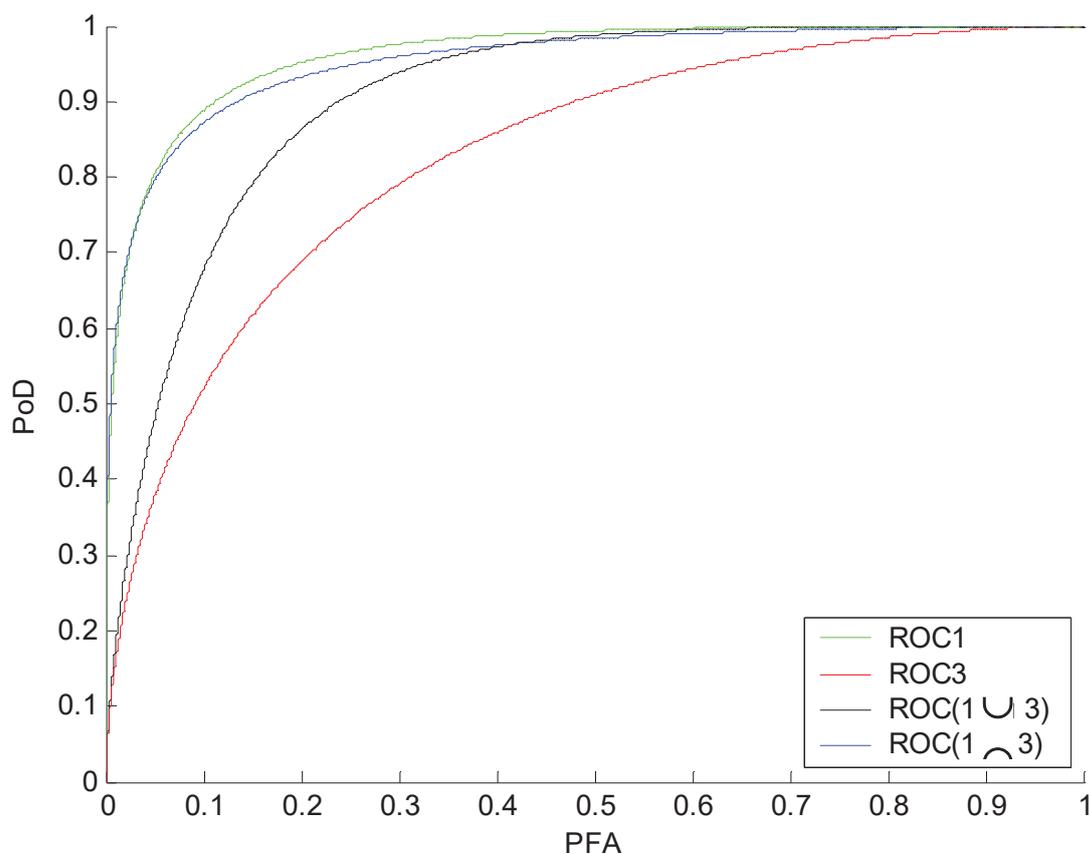


Figure 10. R.O.C. curves resulting from intersection and union techniques in case of combination of two techniques. Combination at given a_d .

This technique is used for combining three techniques with R.O.C. curves plotted on figure 11 and global aid tool given in equation 20 is used for comparison.

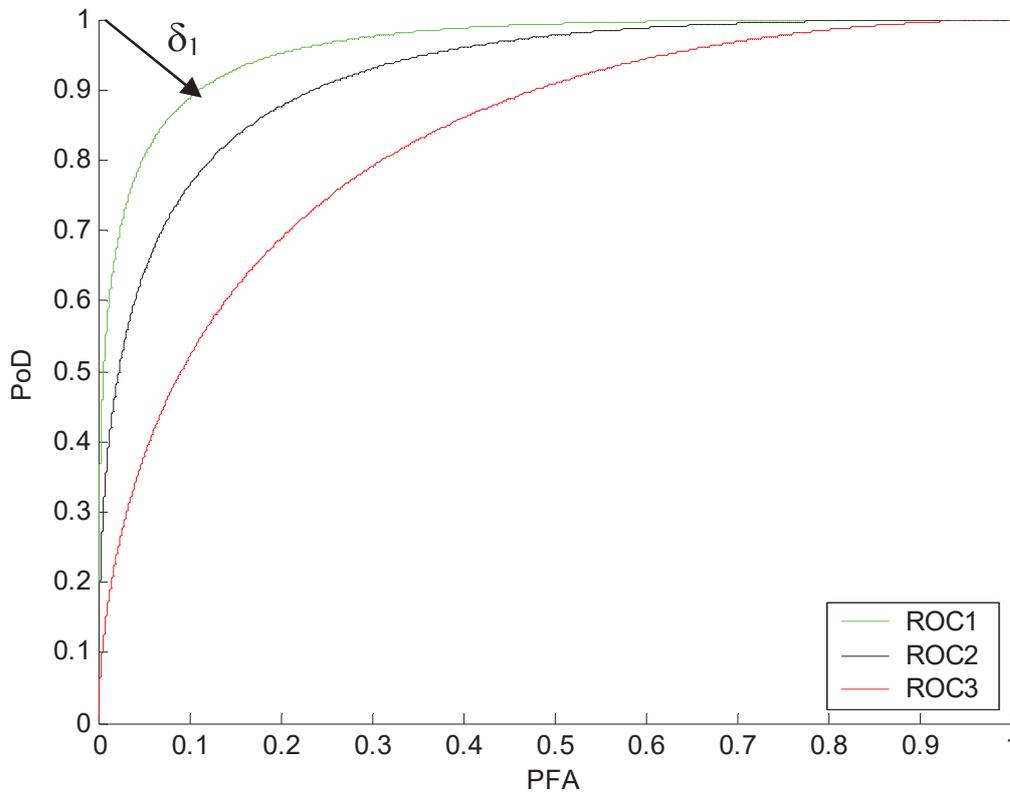


Figure 11. R.O.C. curves used for illustration.

Results for COWD are presented in table 1 for two levels of γ .

Techniques combination	L_{ROC}	$m(P(E_2))$ $\gamma=0,1$	$m(P(E_2))$ $\gamma=0,9$
1 or 2	1,8647	0,4494	0,0287
1 or 3	1,7328	0,6313	0,0355
2 or 3	1,6677	0,6695	0,039
1 and 2	1,8329	0,4515	0,0294
1 and 3	1,8159	0,4802	0,0299
2 and 3	1,7694	0,5204	0,0318

Table 1. COWD values in case of two techniques combination.

It confirms the dominant role of the probability of crack presence γ . The benefit when mixing technique 1 and 3 appears to be very interested. Graphs presented on figure 12 and 13 gives respectively results for $m(P(E_2))$ and $m(P(E_3))$ in percent compared to technique T1.

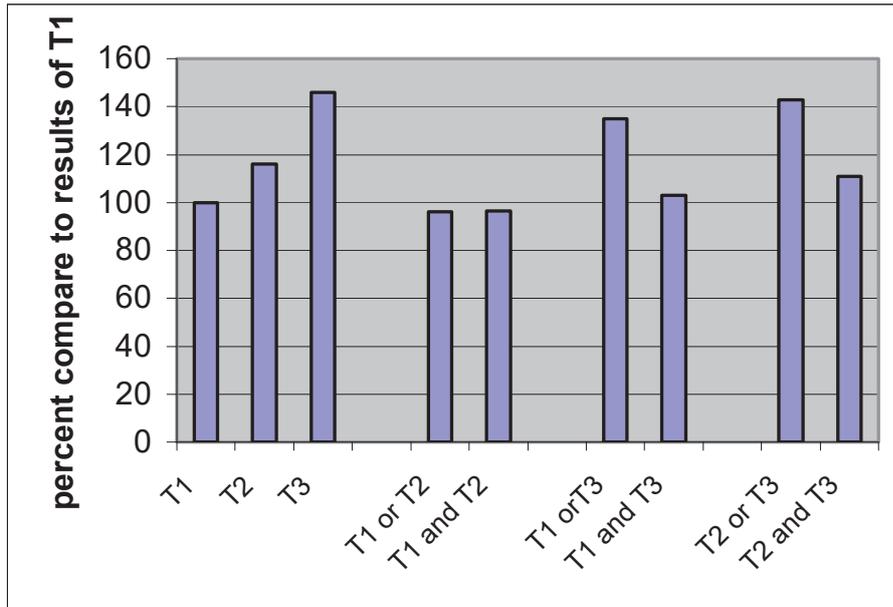


Figure 12. Results of combination for $m(P(E_2))$ compared to technique T1 ($\gamma = 0.1$).

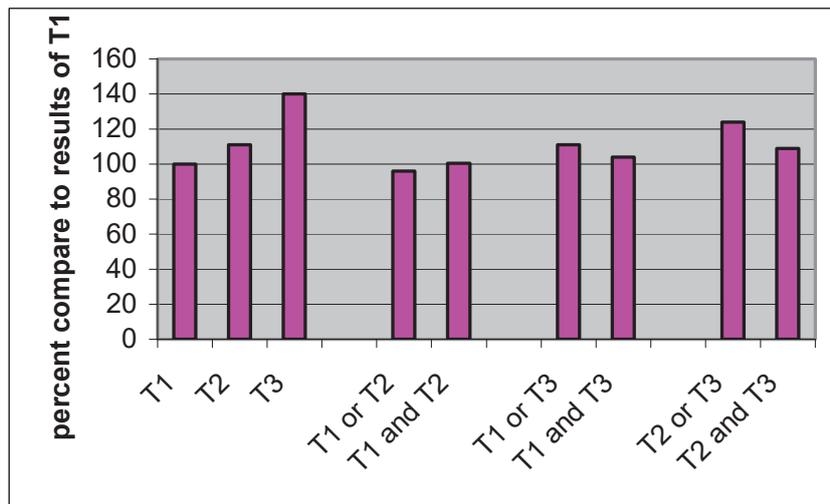


Figure 13. Results of combination for $m(P(E_3))$ compared to technique T1 ($\gamma = 0.1$).

Results appear to be various between $m(P(E_3))$ and $m(P(E_2))$: effect on combination is observed on $m(P(E_2))$ value mainly and according to equation 18 and 19 affects mainly $\overline{E(C)}_d$. If we consider the detailed uncertainty analysis presented in figure 8, in the range [70%-95%] for PoD, we obtain results presented in table 3.

gamma	M(P(E ₂)) (1 or 3)	M(P(E ₂)) (1 and 3)
0,1	0,6411	0,3942
0,9	0,0219	0,0085

Table 3. P(E₂) values in case of two techniques combination and detailed analysis on the range [70%-95%] for PoD..

6 Cost analysis

6.1 Sensitivity to cost model

First a parametric analysis is performed considering two dimensionless parameters : $c_1 = \frac{c_i}{c_r}$ and $c_2 = \frac{c_f}{c_r}$. It allows to introduce the relative cost of inspection compared to repair and repair compared to failure. Only effect of COWD is analysed for two values of γ : $\gamma = 0.1$ for figures 14 (a) and (b) and $\gamma = 0.9$ for figures 15 (c) and (d). Cost are calculated considering ROC 1 (figures 14 (a) and 15 (c)) and 3 (figures 14 (b) and 15 (d)). The policy has been presented in section 4.

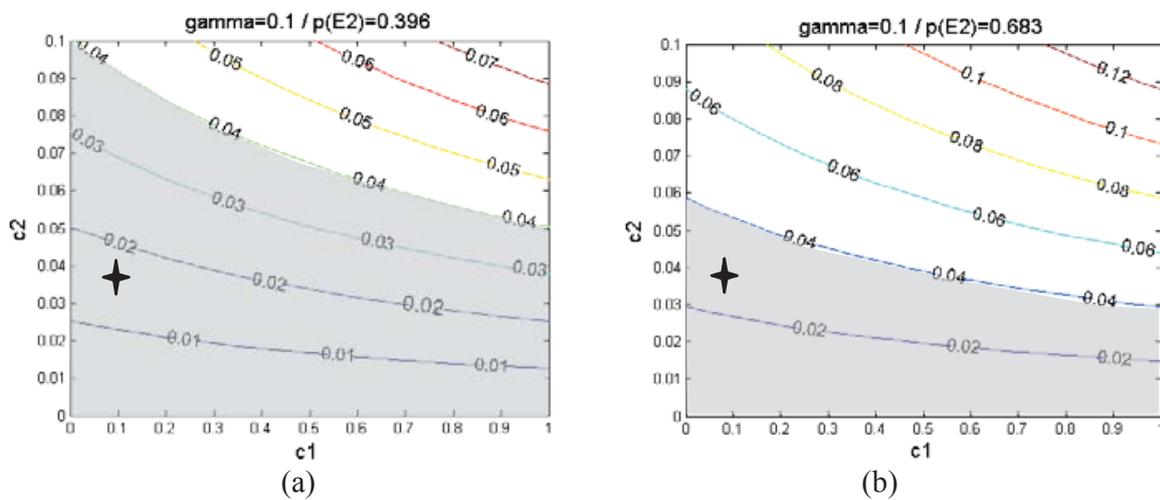


Figure 14. Cost expectation in case of detection for ROC 1 (a) and 3 (b) and $\gamma = 0.1$.

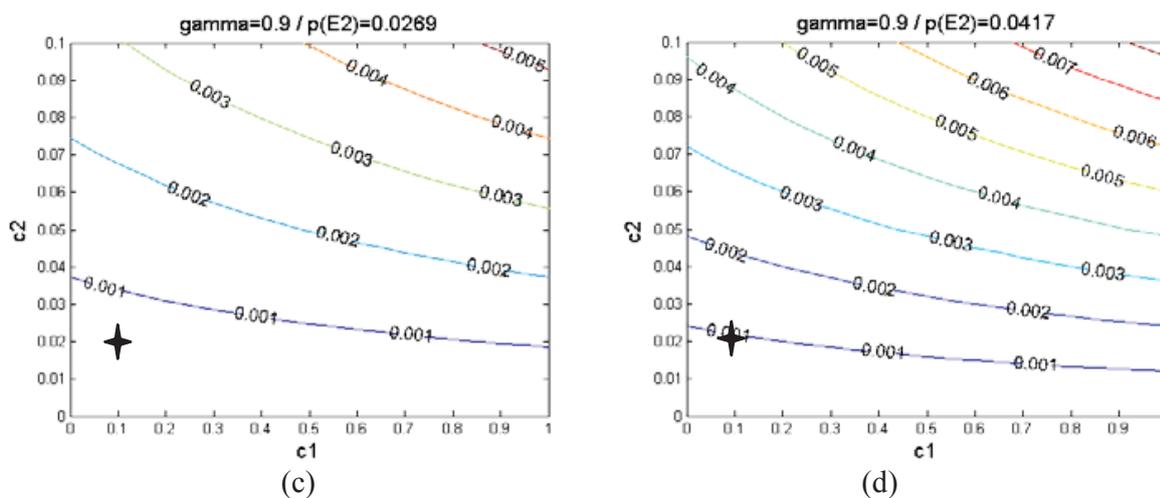


Figure 15. Cost expectation in case of detection for ROC 1 (c) and 3 (d) and $\gamma = 0.9$.

Several remarks can be pointed out. First, these graphs confirm that the expected cost overrun in case of detection is mainly dependent to c_2 , the

relative level of repair and failure costs. Second, higher is the probability of crack presence, lower is cost overrun induced by bad detections. Finally, a technique with good performances (figures (a) and (c) for ROC₁ where $\delta_1 = 0.0567$) leads to a lower gradient of cost overrun than a technique with less performances (figures (a) and (c) for ROC₃ where $\delta_3 = 0.3571$). The grey area on figure (a) and (b) denotes a range of cost overrun from 0 to 0.04. Consequently, the cost overrun in case of a technique with lower performances is more sensitive to the cost model, especially the ratio between repair and failure costs.

6.2 Basic assumptions

In the following, the focus is mainly on effect of cost model on COWD level. Cost model selected for failure, inspection and repair costs is given in table 4. It amounts to fix the parameters defined in section 6.1 $c_1 = 0.1$ and $c_2 = 0.02$ (see stars plotted on figures 14 and 15).

Cost of failure	$C_f=1,0$
Cost of repair	$C_r=0,02$
Cost of inspection	$C_i=0,002$

Table 4. Cost model selected for illustration.

Performance on NDT tool is represented by the minimal distance δ_i between the optimal point of ROC (coordinates [0,1] in (PFA, PoD) plane) and R.O.C. curve number i (see Fig. 11). Figure 16 and 17 give results obtained respectively for COWD and COWND as function of δ .

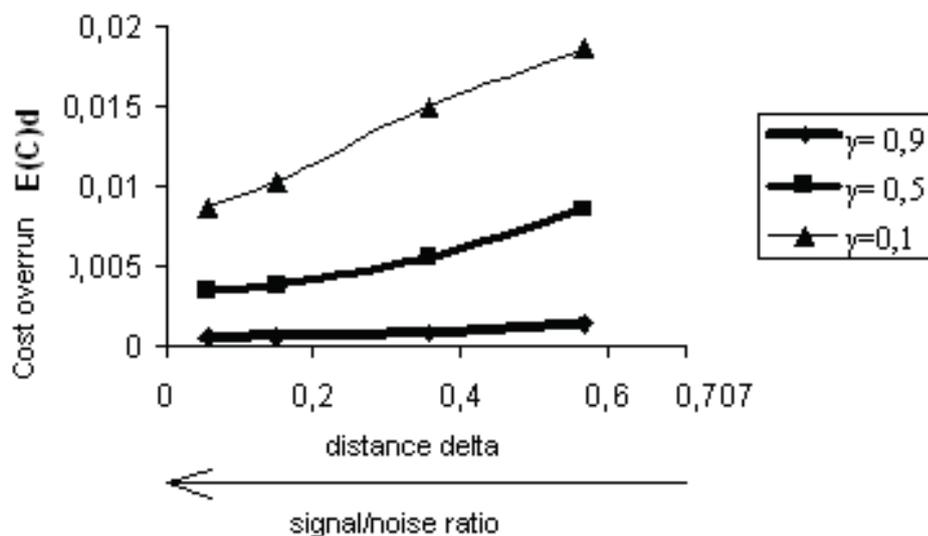


Figure 16. COWD as a function of performance.

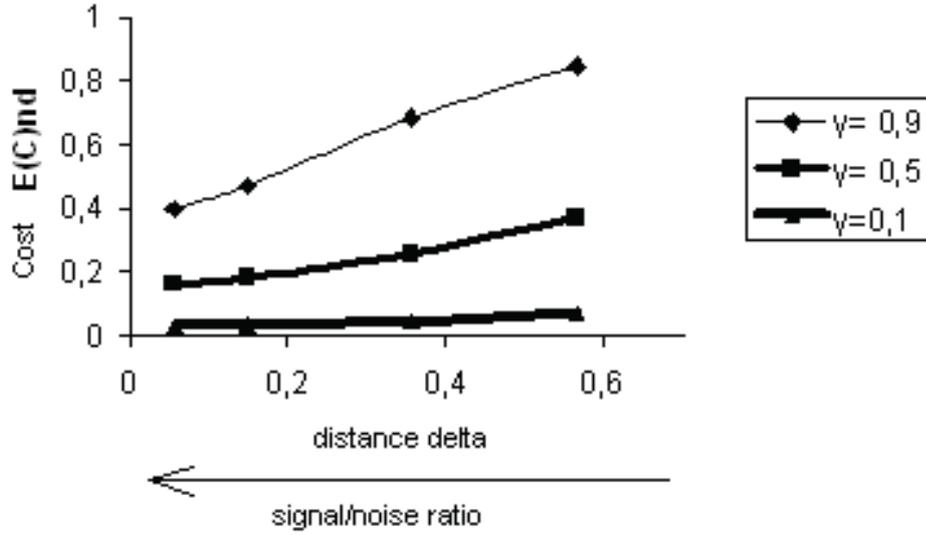


Figure 17. CWND as a function of performance.

These results show that cost in case of no detection is much larger and increases when performance decreases. This variation is much larger for small cracks (high γ) than for large cracks : worse is the technique performance more is the difference between costs among γ .

A comparison of this two figures leads to conclude that probability of crack presence acts in a opposite way for COWD and CWND. It comes from property of the transformation \mathcal{J} defined by equation 23.

$$\left. \begin{array}{l} \gamma \\ \text{PoD} \\ \text{PFA} \end{array} \right\} \rightarrow \mathcal{J} \left\{ \begin{array}{l} 1 - \gamma \\ 1 - \text{PFA} \\ 1 - \text{PoD} \end{array} \right. \quad (23)$$

which allows to demonstrate that $\mathcal{J}(P(E_2)) = P(E_3)$.

If the probability density function of crack size is known (generally, exponentially distributed), then γ is a function of crack size or class. We note γ_i the probability of crack presence inside the class c_i . Then overall costs $\tilde{E}(C)_{nd}$ and $\tilde{E}(C)_d$ are obtained from equations 24 and 25.

$$\tilde{E}(C)_{nd} = \sum_{i=1}^n E(C)_{nd,i} \gamma_i \quad (24)$$

$$\tilde{E}(C)_d = \sum_{i=1}^n E(C)_{d,i} \gamma_i \quad (25)$$

where $E(C)_{nd,i}$ and $E(C)_{d,i}$ are deduced from equation (18) and (19) for a given crack size, that means a given ROC curve or point.

In case of detection, analysis can be completed in taking into account PFA result (see eq. 23). Then, the cost overrun takes the form (eq. 26) with the property describe in equation 27:

$$E(C)_d=C_4(1-P(E_2/s \geq d))+(C_1+\overline{C_4})P(E_2/s \geq d)+C_1P(E_2/s < d)+C_1P(E_2/s < d) \quad (26)$$

$$P(E_i)=P(E_i/s \geq d)+P(E_i/s < d) \quad i=2,4 \quad (27)$$

6.3 Realistic assumptions

Figures 16 and 17 show that the optimal technique in terms of cost impact is the best one in terms of performance. This is due to the fact that the cost of inspection is constant whatever NDT performance. Let us now consider a more realistic cost model for inspection $C_{i,\delta}$, other costs being unchanged. It is linked to the performance δ by the formula (eq. 26):

$$C_{i,\delta}=(1+\lambda_\delta)C_i \quad (26)$$

where λ_δ is a increasing function of δ .

Figure 18 presents results obtained for COWD and $\gamma = 0.9$ with the function :

$$\lambda_\delta = \frac{0.01}{\delta} \quad \text{for } \delta \neq 0 ; \lambda_0 = 1$$

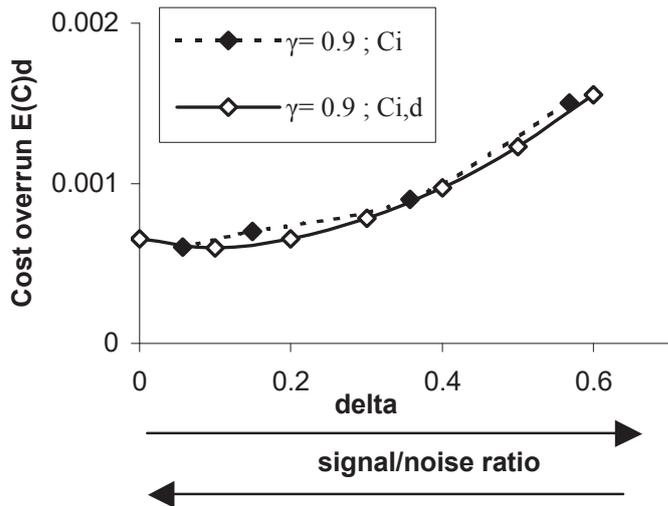


Figure 18. COWD for cost of inspection function of the performance.

Then COWD has an optimum value (minimum) for values of δ around 0.08.

7 Conclusion

This paper underlines the role of PFA and the need to best define and assess this quantity when introducing inspection results in RBI planning. A bayesian modelling is suggested and leads to the definition of two functions varying with PoD, PFA and probability of crack presence. They are introduced in two cost functions, given a maintenance policy; the cost overrun in case of detection and the cost in case of no detection. An aid

tool based on the description of the whole ROC curve projected on surfaces of probability is then suggested. It allows to discuss the case of multiple inspection for independent inspections. A cost analysis is then suggested for illustration with parametric studies. It allows to point out the sensitivity to probability of crack presence and ratio between costs of inspection, repair and failure.

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