Optimal Plan for Inspection and Maintenance of Structural Components by Corrosion

Cesar Ortega-Estrada, Roobed Trejo, David De Leon and Dante Campos

***Abstract*—This paper studies the optimal plan for inspection and maintenance of steel structural components in tension by uniform corrosion, considering the following: A deteriorating model uncertain in time is considered, the probability to detect damage during the inspections is modeled, if damage is detected, the structural component is repaired, the failure probability of the component over time is considered supposing that the demands and capacities are random in time, the optimal plan will be the one in which the expected costs (costs of inspection, repair and failure) are minimum in the life cycle of the component, allowing to detect the number of inspections that minimize the expected costs; to determine the optimal plan, all the possibilities that are given of the tree diagram are studied, where each inspection has two existent possibilities: repair or not to repair, the occurrence possibility of each branch in the resulting tree diagram is calculated. In addition, the influence of the variables and parameters are calculated as: the net discount rate of money (r), uniform corrosion rate (ν), the mean load (μ_T), failure costs (C_f), repair cost (C_{rep}) inspection cost (C_{ins}) and quality of a nondestructive inspection ($\eta_{0.5}$). The results indicate that the optimal number of inspections in the life-cycle of the component is very sensible to each of the parameters involved. Every parameter in an optimization study needs to be carefully analyzed in order to proceed.**

***Index Terms*—Optimal Inspection, Risk-Based Maintenance, Corrosion Damage, Parametric Analysis**

I. INTRODUCTION

THE integrity of offshore platforms, oil ducts, gas ducts, electric power towers, bridges, etc., of steel when confronting corrosion depends strongly on the integrity of the components that form the structural systems [1], [2]. Therefore, it is of high relevance to study the deterioration in time and the means to reduce risks in these structural systems; there are very important contributions of optimal inspection and maintenance [3] – [6]. An optimal inspection plan involves several aspects such as: cost and quality of inspection, cost and quality of repair, failure costs, capacity and demand of the system, net discount rate, uniform corrosion rate, time for corrosion initiation, etc. The fundamental problem is to determine the optimal number of inspections in the lifetime of the component considering the indicated aspects, but also maintaining a certain level of reliability, which has been previously specified.

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In previous papers, repair has been considered flawless; this means that after the repair, the same initial properties are obtained, for example in [7], repair is considered to be perfect when accumulated damage by earthquakes in buildings is intervened. In other papers like [4], inspection and maintenance are considered imperfect, and for the specific case of damage by corrosion in steel rebars embedded in reinforced concrete elements, it is considered that after repair, the reliability of structural component increases, but the original conditions are not regained.

In the specific case of damage by uniform corrosion, the material is lost overtime, what produces a reduction in the transversal section of steel structural member. This paper considers the effect of uniform corrosion on a steel component, considering that the only option of repair is cleaning and applying an anticorrosive paint as indicated in the standards. Therefore, after repair, there is not a greater reliability of the component because the repair does not restore the material lost by corrosion.

II. LIFE CYCLE COST

In the last two decades, mathematical models that calculate the life cycle of members and structural systems have been proposed, for example, [4], [7] - [9]. This article follows the methodology proposed in [4] with two main differences: (1) Repair consists in cleaning the component and applying anticorrosive paint, therefore, after repair, the probability of failure does not decrease, This helps to model the real effect of repair. And (2) all the repair possibilities are evaluated in a tree diagram (based on a computer software), where the following aspects are considered explicitly: quality of inspection costs of inspection, repair and failure, the growing effect of uniform corrosion. It is considered in a realistic way the repair effect on the reliability of the component damaged by corrosion; and the effect of the value of money over time.

This paper assumes a circular cross-sectional tubular steel element with tension load under the following parameters:

1. Life-cycle Time (L) = 20 years
2. Exterior Diameter (D_0) = 102 mm
3. Interior Diameter (d_0) = 90.52 mm

4. Mean Tension Load (μ_T) = 43.74 t
5. Coefficient of Variation for Load (CV_T) = 0.25
6. Mean Yield Stress (μ_{fy}) = 4620 kg/cm^2
7. Coefficient of Variation for *fy* (CV_{fy}) = 0.1
8. Annual Increment for CV_{fy} = 0.02
9. Corrosion Initiation after applying the anticorrosive paint. (*Tic*) = 3 years
10. Corrosion Rate (ν) =0.0089 cm/year
11. Damage intensity at which the method of inspection has a 50% of detection probability ($\eta_{0.5}$) = 0.1
12. Coefficient of Variation for Inspection ($CV_{\eta 0.5}$) = 0.333
13. Annual discount rate (r) = 0.05
14. Inspection Cost (C_{ins}) = 500 ($USD)
15. Repair Cost (C_{rep}) = 3,000 ($USD)
16. Failure Cost (C_f) = 100,000 ($USD)
17. Number of inspections in the Life-cycle (m) = 2

The intensity of damage is evaluated as it is indicated as in (1), where $D(t)$ is the exterior diameter of the member over time t; before of the first repair, the exterior diameter is estimated as shown in (2a) and (2b), after the first repair occurs, it is calculated as shown in (3a) and (3b), where D_R is the exterior diameter of the member when repairing overtime t_R.

$$\eta(t) = \frac{D_0 - D(t)}{D_0 - d_0} \tag{1}$$

$$D(t) = D_0 \quad \text{for} \quad t \le Tic \tag{2a}$$
$$D(t) = D_0 - 2\nu(t - T_{ic}) \quad \text{for} \quad t > T_{ic} \tag{2b}$$

$$D(t) = D_R \quad \text{for} \quad t \le (t_R + T\text{ic}) \tag{3a}$$
$$D(t) = D_R - 2\nu\big(t - (t_R + T_{ic})\big) \quad \text{for} \quad t > (t_R + T_{ic}) \tag{3b}$$

In [4] the probability to detect damage $d(\eta)$ is calculated as in (4), where η_{min} is the minimum detectable intensity damage and η_{max} is the intensity of damage when the probability of detection is 1. Notice that the probability to detect damage depends on the mean and the standard deviation of the intensity of damage that a certain inspection method detects.

$$d(\eta) = 0 \quad \text{for} \quad 0 \le \eta \le \eta_{min} \tag{4a}$$
$$d(\eta) = \Phi\left(\frac{\eta - \eta_{0.5}}{\sigma_{\eta 0.5}}\right) \quad \text{for} \quad \eta_{min} \le \eta \le \eta_{max} \tag{4b}$$
$$d(\eta) = 1 \quad \text{for} \quad \eta > \eta_{max} \tag{4c}$$

To represent all the possible events associated with repair and non-repair actions, a tree event analysis is performed. From this moment on, Fig. 1 is considered to be the tree diagram for two uniformly distributed inspections in the life cycle of the component (m = 2), where 0 and 1 represent actions on repair and non-repair, respectively. T_i is the time of inspection; b^j_i represents the corresponding event of occurrence of the branch j overtime T_i; the probability of failure of the component before the first inspection is estimated with (5), where T represents the random variable of the tension load and R_{T1-} is the resistance of the component before the first inspection.

$$P_{f,T_{1-}} = P\left(\left(R_{T_{1-}} - T\right) \le 0\right) \tag{5}$$

According with [4], the probability of the event b^1_1 is calculated with (6) where η_{T1-} is calculated with (1).

$$P(b_1^1) = 1 - P(b_1^2) = \Phi\left(\frac{\eta_{T1-} - \eta_{0.5}}{\sigma_{\eta_{0.5}}}\right) \tag{6}$$

The probability of failure of the component before the second inspection, given the branch b^1_1, is calculated with (7a); and for the branch b^2_1, with (7b).

$$P^1_{f,T_{2-}} = P\left(\left(R^1_{T_{2-}} - T\right) \le 0\right) \tag{7a}$$
$$P^0_{f,T_{2-}} = P\left(\left(R^0_{T_{2-}} - T\right) \le 0\right) \tag{7b}$$

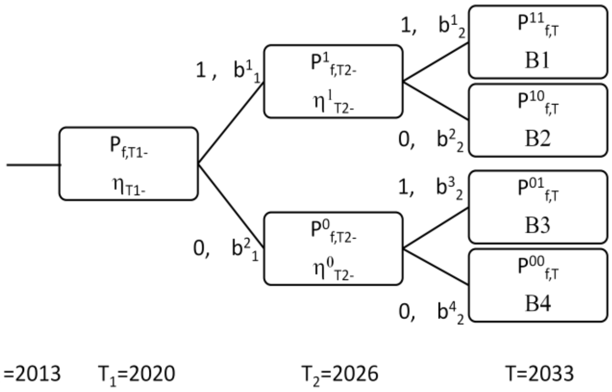

Fig. 1. Tree diagram for m = 2

After the second inspection, given the occurrence of the event b^1_1, there are two possibilities, b^1_2 and b^2_2, that indicate the action to repair or not to repair. In the same way, given the occurrence of the event b^2_1, there are two possibilities b^3_2 and b^4_2, which also indicate the action to repair or not to repair [4].

$$P(b_2^1) = 1 - P(b_2^2) = \Phi\left(\frac{\eta^1_{T2-} - \eta_{0.5}}{\sigma_{\eta_{0.5}}}\right) \tag{8a}$$
$$P(b_2^3) = 1 - P(b_2^4) = \Phi\left(\frac{\eta^0_{T2-} - \eta_{0.5}}{\sigma_{\eta_{0.5}}}\right) \tag{8b}$$

Each branch in the tree represents a sequence of events b^j_i. If all the events b^j_i are independent, see [4], the probability of occurrence of the trajectories B_1, B_2, B_3 and B_4 can be calculated with (9a), (9b), (9c) and (9d) respectively.

$$P(B_1) = P(b_1^1)P(b_2^1) \tag{9a}$$
$$P(B_2) = P(b_1^1)P(b_2^2) \tag{9b}$$
$$P(B_3) = P(b_1^2)P(b_2^3) \tag{9c}$$
$$P(B_4) = P(b_1^2)P(b_2^4) \tag{9d}$$

The probabilities of failure at the end of the life cycle, associated with the four possible trajectories, are calculated with (10a), (10b), (10c) and (10d), respectively. The Fig. 2 shows the evolution of the probabilities of failure for every possible case.

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$$P_{f,T}^{11} = P\left(\left(R_T^{11} - T\right) \leq 0\right) \quad (10a)$$
$$P_{f,T}^{10} = P\left(\left(R_T^{10} - T\right) \leq 0\right) \quad (10b)$$
$$P_{f,T}^{01} = P\left(\left(R_T^{01} - T\right) \leq 0\right) \quad (10c)$$
$$P_{f,T}^{00} = P\left(\left(R_T^{00} - T\right) \leq 0\right) \quad (10d)$$

Each branch has tree probabilities of failure (before the first inspection, before the second inspection, and at the end of its life time cycle); the probability of failure for each branch is calculated with (11a), (11b), (11c) and (11d).

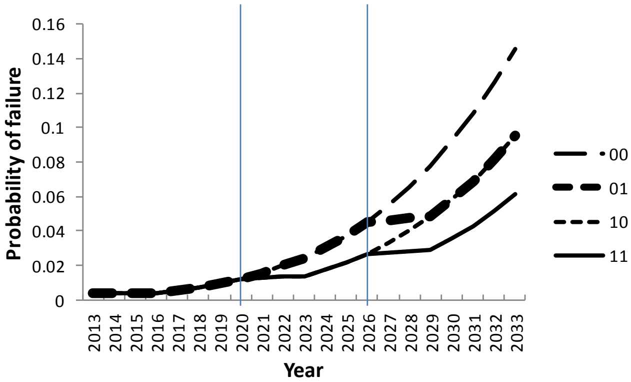

Fig. 2. Evolution of the probability of failure for all the possibilities of repair if $m = 2$

$$P_{f,life,1} = max\left(P_{f,T_1-}, P_{f,T_2-}^{1}, P_{f,T}^{11}\right) \quad (11a)$$
$$P_{f,life,2} = max\left(P_{f,T_1-}, P_{f,T_2-}^{1}, P_{f,T}^{10}\right) \quad (11b)$$
$$P_{f,life,3} = max\left(P_{f,T_1-}, P_{f,T_2-}^{0}, P_{f,T}^{01}\right) \quad (11c)$$
$$P_{f,life,4} = max\left(P_{f,T_1-}, P_{f,T_2-}^{0}, P_{f,T}^{00}\right) \quad (11d)$$

The probability of failure in the life on the component is:

$$P_{f,life} = \sum_{i=1}^{2m} P_{f,life,i} P(B_i) \quad (12)$$

The optimal maintenance plan is that in, which the costs of inspection, repair, and failure are minimum. The costs of inspection are calculated with (13), where C_{ins} is the cost of inspection based on the employed technique. The costs of repair are calculated with (14a), where C_{rep} is the cost of repair based on the method used. The costs of failure are estimated with (15), where C_f are the consequences of failure. The total cost is calculated with (16).

$$C_I = \sum_{i=1}^{m} C_{ins} \frac{1}{(1+r)^{T_i}} \quad (13)$$
$$C_R = \sum_{i=1}^{2m} C_{rep,i} P(B_i) \quad (14a)$$
$$C_{rep,i} = \sum_{i=1}^{m} C_{rep} \frac{1}{(1+r)^{T_i}} \quad (14b)$$
$$C_F = C_f P_{f,life} \quad (15)$$
$$C_T = C_I + C_R + C_F \quad (16)$$

III. Optimal Inspection Program

To calculate the life cycle costs, great effort is required; therefore, a computer software was developed OIMS v01 [10] and [11]. The method was followed for the data presented considering a variation in the number of inspections (m = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10), the results are presented in Fig. 3. The optimal number of inspections resulted to be m = 5, and the branch with the greatest probability of occurrence is 00011; Fig. 4 shows the evolution of the probability of failure of that branch.

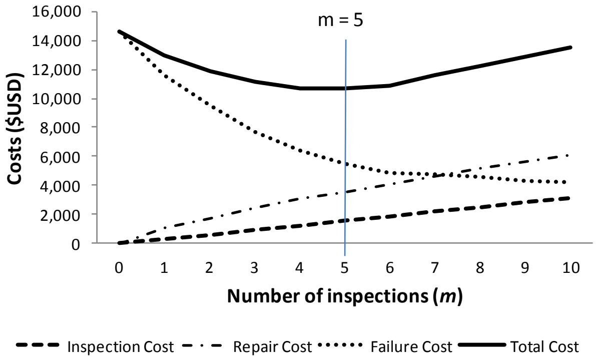

Fig. 3. Optimization Costs in function of the number of inspections with uniform intervals in the life time cycle.

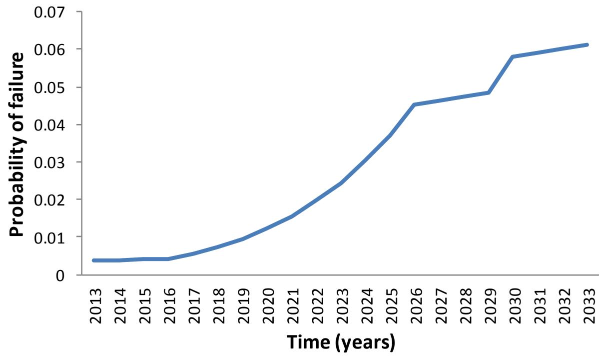

Fig. 4. Evolution of the probability of failure for the trajectory 00011 if $m = 5$

IV. Parametric Analysis

It is of major interest, to evaluate the importance that each variable has in the determination of the optimal number of inspections in the life time cycle of the component at issue. The variables analyzed are presented in Table 1.

TABLE I
VARIABLES CONSIDERED IN THE PARAMETRIC STUDY

Variable Studied	Considered Values
Corrosion Rate (ν) cm/year	0.005, 0.007, 0.0089, 0.011, 0.013, 0.015 and 0.02
Mean Tension Load (μ_T) t	10, 30, 43.74 and 70
Failure Costs (C_f) $USD	10,000, 50,000, 100,000 and 500,000
Repair Cost (C_{rep}) $USD	500, 1,000, 3,000 and 10,000
Inspection Cost (C_{ins}) $USD	100, 500, 1,000 and 5,000
Annual Discount Rate (r)	0.01, 0.02, 0.05 and 0.1

The effect of the Corrosion Rate (ν) is shown in Fig. 5; if ν increases, the optimal number of inspections in the life-cycle of the component increases too. Notice that the optimal number of inspections is very sensible between ν = 0.005 and 0.0089 cm/year. In real cases, corrosion rates between these intervals have been found [12]. The tags shown in Fig. 5 represent $P_{f,life}$, calculated for each case.

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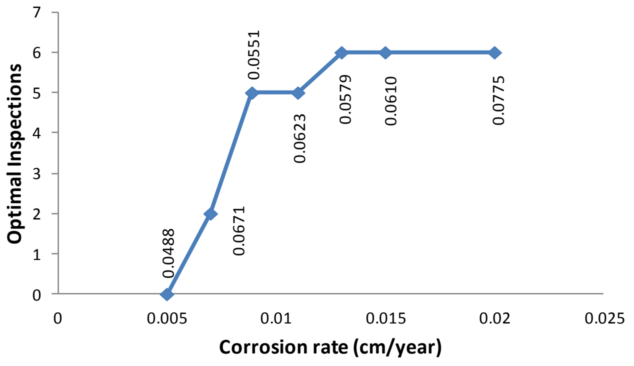

Fig. 5. Optimal number of inspections in function of the corrosion rate (cm/year).

The Mean Tension Load (μ_T), in the optimal number of inspections is shown in Fig. 6. The allowed tension for the studied member is 43.74 t and the optimal number of inspections is 5. If the mean tension load is reduced to 30 t (an approximate reduction of 31%), the optimal number of inspections is 0; therefore, the optimal number of inspections is very sensible to the load level in the system.

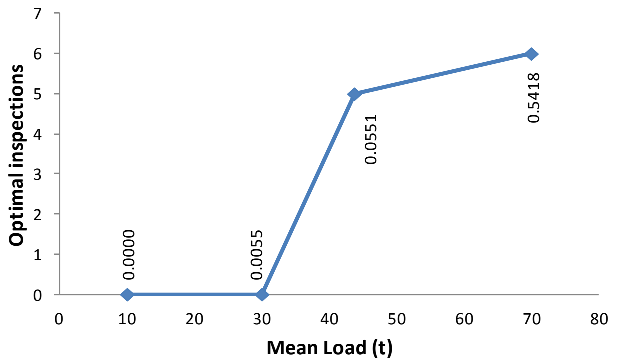

Fig. 6. Optimal number of inspections in function of the mean load (t).

The consequences of failure also have great influence in the determination of the optimal number of inspections in the life time cycle, Fig. 7 presents the results of the parametric analysis, where it can be observed that it is very important to determine in detail the consequences of failure, where direct loss must be considered (production loss, installation damage, environment damage, injury or loss of human life) and also indirect loss (other industrial sectors will have lost because the sector that provides the goods or services are out of service); in this topic, very few studies have been done so it is justifiable to deepen into the determination of the failure consequences.

The costs of repair also have a great influence in the determination of the optimal number of inspections. Fig. 8 shows that if the cost of repair reduces, then the optimal number of inspections increases, in other way, if the cost of repair increases, then the number of inspections reduces.

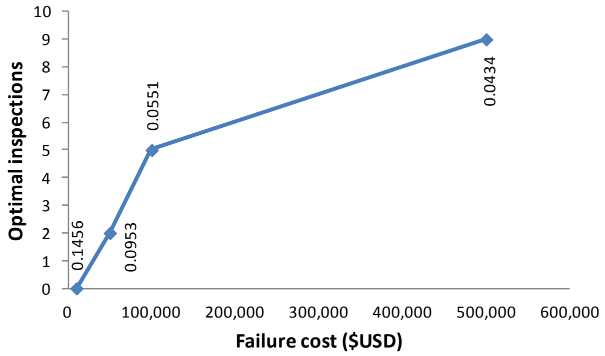

Fig. 7. Optimal Number of inspections in function of the failure costs.

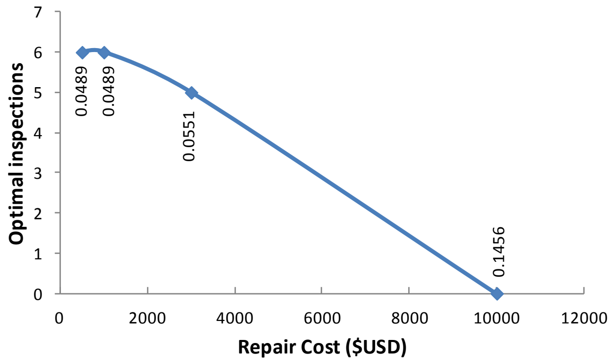

Fig. 8. Optimal Number of inspections in function of the repair costs.

Figure 9 shows the influence of the inspection costs with the optimal number of inspections. In this case, there is a direct relation between the costs of inspection and the quality of inspection. This work supposes that when the cost of inspection increases, the detectable intensity of damage decreases (represented by a 50% probability of detection $\eta_{0.5}$).

Figure 10 presents the costs associated to different alternatives of cost and quality of inspection, so the alternative with the minimal cost can be visualized. This type of analysis helps to determine when to inspection and with what inspection technique, minimizing the costs.

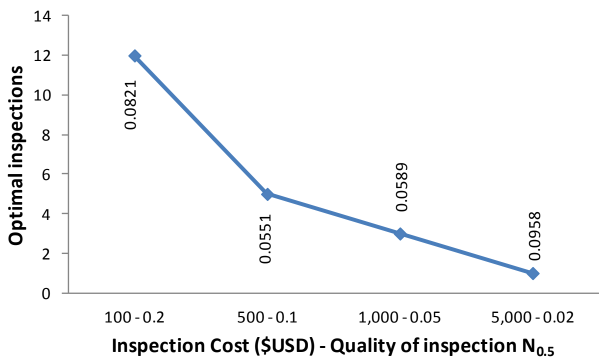

Fig. 9. Optimal Number of inspections in function of the costs and quality of inspection.

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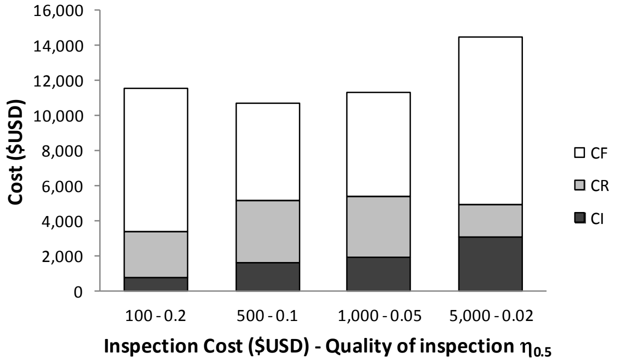

Fig. 10. Associated costs to the Optimal Number of Inspections in function of the costs and quality of inspection.

Fig. 11 presents the optimal number of inspections in function of the annual discount rate (r). The obtained results agree with [8]. The annual discount rate must be a realistic factor in an optimization study, because it also influences in the determination of the optimal number of inspections in the life cycle of the component.

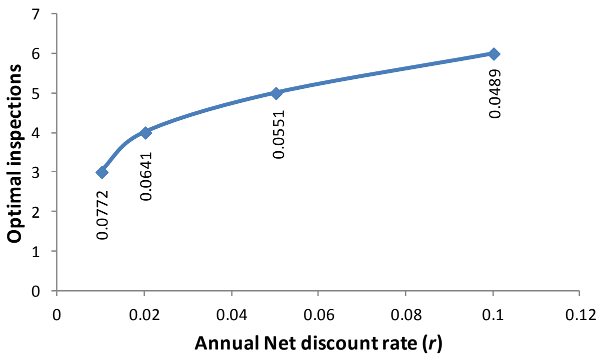

Fig. 11. Optimal number of inspections in function of the annual net discount rate.

V. Conclusions

This article presents the methodology to calculate the optimal number of inspections in a steel member with cross-sectional tubular circular subject to tension load, under the effect of uniform corrosion. When calculating the optimal number of inspections, all the possible events associated with actions of repair and non-repair are considered; the following aspects are explicitly considered: cost and quality of inspection, failure consequences, demand and capacity of the system, net discount rate, deterioration rate and initiation of damage overtime. The type of repair-maintenance considered is only the replacement of the anticorrosive paint, so after repair, there is no decrease in the probability of failure.

Also, a parametric study on the following variables was preformed: Corrosion Rate (v), Mean Tension Load (μ_T), Failure Cost (C_f), Repair Cost (C_{rep}), Inspection Cost (C_{ins}) and Annual Discount Rate (r). Important results were obtained, because the optimal number of inspections in fact is sensible to the values adopted by each one of the variables, therefore, the optimization studies must justify in a realistic way each one of the adopted values.

The methodology presented helps to determine when to inspection and with what inspection technique, minimizing the costs on the life-cycle.

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