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A dynamic multi-criteria decision-making model for the maintenance planning of reinforced concrete structures

Pablo Benítez[a,b,*], Eugénio Rocha[c], Humberto Varum[d], Fernanda Rodrigues[b]

[a]*FIUNI, Facultad de Ingeniera, Universidad Nacional de Itapa, Paraguay*
[b]*RISCO, Department of Civil Engineering, University of Aveiro, Portugal*
[c]*Center for Research and Development in Mathematics and Applications, Department of Mathematics, University of Aveiro, Portugal*
[d]*CONSTRUCT-LESE, FEUP, Faculty of Engineering University of Porto, Porto, Portugal*

Abstract

Decision-making is essential in buildings management process playing a decisive role in the maintenance planning design. Multi-Criteria Decision Making (MCDM) methods can be applied as a support tool to fulfil a set of requirements that arise during the scheduling of maintenance activities of these structures. The Analytic Hierarchy Process (AHP) is a broadly recognised methodology applied to model subjectively decision problems based on multi attributes analysis. This paper applies the AHP method under an objective approach, where the weight assignments are stochastically calculated instead of defining it based on the judgement of experts. The main objective of this study is to propose a dynamic decision model based on AHP for the maintenance planning of reinforced concrete structures under corrosion risk. This methodology provides the best maintenance alternative (inspection/repair) to be performed in these structures for a given intervention time. The best solution for the intervention is chosen regarding the Global Priority Vector of the final pairwise comparison matrix. After an illustrative application, the new dynamic decision model developed proven be a helpful tool for decisions-making regarding the most suitable intervention alternative within the maintenance planning of these structures.

Keywords: Decision-Making, Inspections, Corrosion, Repair, Concrete Structures, Analytic Hierarchy Process

1. Introduction

Performing structures' maintenance is meaningful to ensure their safety and durability. Nonetheless, the choice of the best maintenance strategy is usually established based on a set of criteria, i.e., safety, cost, available resources, accessibility of the structure, and so on. To properly address the study of maintenance management, it is important to establish decision-making methods based on multiple criteria analysis. A maintenance strategy should be oriented to reduce the amount and frequency of maintenance, improving maintenance operations, decreasing the complexity effect, reducing the skills required for maintenance, among others [1]. The choice of an option among a set of alternatives based on some criteria is what is considered as decision-making. This

*Corresponding author
Email address: pablo.benitez@ua.pt (Pablo Benítez)

decision can be based on multiple criteria instead of a single one, where the main objective is to obtain a relative ranking of alternatives regarding a decision problem. The decision-making based on a simple criterion or requirement used in the past has allowed current investigation of highly complex decision problems that include a multitude of variables that are usually stochastic [2].

Maintenance must be carefully designed to be adapted to existing technical, geographical and personnel situations. An essential preventive maintenance program includes the periodic evaluation of critical elements to detect potential problems and immediately schedule maintenance activities that will prevent any severe degradation. Likewise, preventive maintenance must be designed to anticipate the need for corrective maintenance and prolong the service life of the structure. Furthermore, a poor maintenance or repair task often results in more damage to the structure [3].

The maintenance of existing buildings has become meaningful since the cost of new construction has been increased in the last decades. The efficiency of the building's maintenance is highly relevant concerning its durability and functionality, which requires a precise method for planning the different intervention tasks involved [4]. Hence, the maintenance strategies should be suitable and cost-effective to allow the best allocation of budgets and minimise the deterioration of the building over its whole life cycle [5]. Appropriate knowledge of the degradation process and measurement techniques are essential to improve the durability of structures as well as the monitoring, evaluation and repair procedures. All these considerations should be an integral part of any durability strategy, incorporating the planning into the design phase [6].

The maintenance can be established in three large groups: the preventive, the corrective and the predictive. The main difference among them lies in the time at which the repair or maintenance task is implemented [3]. Preventive maintenance includes scheduled actions to reduce the probability of failure or an unacceptable level of degradation. It usually comprises the most significant proportion of the total maintenance effort. Corrective maintenance, instead, includes unscheduled actions that are carried out once the deficiencies are detected and whose purpose is to return the damaged element to a defined state. Predictive maintenance is associated with the continuous monitoring and processing of damages that allow diagnosing the condition of the structure during the service [1].

This paper focuses its study on a preventive maintenance strategy. The advantages and shortcomings of a preventive maintenance strategy depend on the performance knowledge, decision criteria, economic and technical characteristics of each intervention technique, and the structured data [5]. Among the advantages of preventive maintenance, it is possible to identify the improvement of safety, the efficiency in the use of time and economic resources, and the cost/benefit optimisation during maintenance [1]. Therefore, in building life cycle management, the most advantageous strategy for the extension of its service life is the application of preventive maintenance throughout all the life cycle of the structure. In other words, preventive maintenance is the cheapest alternative and it is the only one that enhances the durability of materials and constructive elements [7].

The process of multiple-criteria decision-making (MCDM) may comprise the solution of the problem referred as how to derive weights or rankings of importance for a set of alternatives/criteria according to their effect on the objective of the decision taken [2]. Thus, the MCDM problems may be classified into two main groups: multiple attribute decision-making (MADM) and multiple objective decision-making (MODM). The MADM method is applied to decision problems with a limited number of predetermined alternatives and discrete preference ratings, and the MODM aims to achieve the optimal goals by considering several interactions within the given constraints [8]. Hence, in the management of maintenance strategies, the possible answers for a decision problem are finite and MADM is the category which must be chosen for the study [9].

Considering the complexity of classifying alternatives in multiple individual criteria, a common practice is to take a weighted average of the satisfaction of an alternative for the individual criteria, i.e., the importance of the individual criteria [10]. This is the main approach of the well-know MADM method called the Analytic Hierarchy Process (AHP). However, as such analysis involves some subjectivity in the final results, this paper proposes a new perspective for the traditional AHP model that includes a stochastic analysis for the weight assignments of criteria and alternatives.

One of the primary causes of concern among buildings and infrastructure owners is the corrosion of steel rebar in reinforced concrete (RC) structures, which represents a billionaire expense concerning repair and maintenance actions. The degradation of RC structures is characterised by the general or localised loss of the cross-section of the rebar caused by the corrosion phenomenon [11]. The expenditures associated with maintenance and repair are estimated at around USD 100 billion per annum worldwide [12]. Hence, the purpose of this study is to provide a useful tool to the decision maker so that they can schedule the best maintenance strategy in RC structures subject to corrosion degradation. The support tool comprises a dynamic decision model based on the AHP method. It has been proven that AHP is a useful tool to solve complex decision problems on which some controversy can be expected among the different judgements of experts regarding which one is the best alternative to achieve a specific objective.

Therefore, considering the above, this research has two main contributions to knowledge. On the one hand, this paper examines the viability of the application of the AHP method (applied in other fields of science) in the study of the maintenance management of structures. On the other hand, and considering that the AHP method has been initially established for discrete variables, this research proposes applying the same process from a stochastic approach for continuous variables, which try to decreases the subjectivity of the original method. In the AHP method, the attributes of the decision model are evaluated based on the criterion of the stakeholders (subjective approach). In the proposed model, the weight of each criterion is calculated with a formula based on stochastic equations that are proposed in this paper. This new approach enables a better dealing with the uncertainty of the degradation process and reduces the subjectivity in decision-making for the maintenance of structures.

The remainder of this paper is structured as follows. This section has a brief description of the traditional AHP method that will be the base of the study. Then in Section 2 is presented step-by-step the methodology for the dynamic decision model as a support tool for the maintenance planning. The functionality of the decision-making model has been tested after applying it in a hypothetical case study for maintenance planning in Section 3. Discussion concerning the main results of the research and the applicability of the model is carried

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out in Section 4. In the end, some conclusions are remarked.

1.1. Analytic Hierarchy Process approach

The Analytic Hierarchy Process (AHP) was developed by Thomas L. Saaty [13], and since then it has been widely studied and applied for decision-making in several fields of science. AHP is a general theory of measurement that is used to derive ratio scales from the discrete paired comparison. It consists in a nonlinear framework for developing both deductive and inductive thinking by taking several factors in considerations without the use of syllogism [14]. The AHP method is a useful tool to deal with complex decisions about the most general structures encountered in real life that involve dependency and feedback analysed in the context of costs, risks, benefits and opportunities. Thus, a quality of the AHP method is that it produces results that consider the external risks concerning the decision and not only the values of the decision maker [15].

In essence, the AHP method gives as an outcome a plan of preferences and alternatives based on the level of importance obtained for the different criteria where the comparative judgements of experts are taken into account [16]. Some studies in construction and engineering maintenance are found in the literature [17–20] concerning the application of the AHP method to solve decision problems. Its success lies in its easy of implementation and understanding as well as in its almost universal adoption as a new paradigm for decision-making. Furthermore, it has been found to be a methodology capable of determining results that are in agreement with general perceptions and expectations [2].

The simplest way to structure a decision-making problem is through a hierarchy of three levels as is depicted in Figure 1. The three levels comprise the goals, criteria, and alternatives. The organization of the problem in hierarchies allows a better understanding regarding the decision that must be achieved, the criteria that will be used and the alternatives that will be assessed. The participation of experts is crucial at this stage of the method since they ensure that all criteria and alternatives are considered properly [16]. Thus, once the problem is structured, the AHP method is simple to apply to solve decision problems [21]. The existence of a relation of hierarchical dependence between elements of the structure is marked by the line that connects them [22].

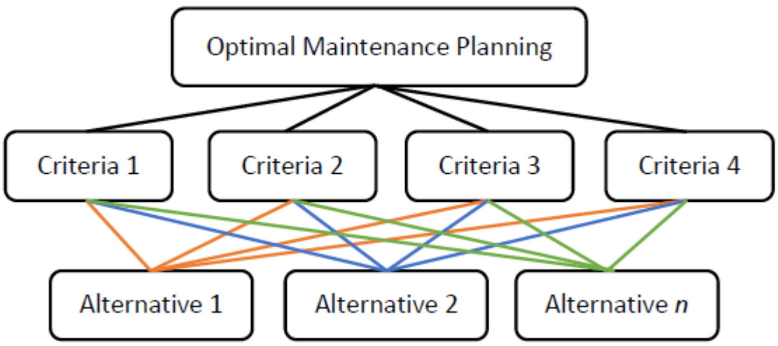

Figure 1: Hierarchical structure for decision-making [21]

Once the problem is structured, the method continues with the construction of a pairwise comparison matrixes to solve the decision problem. The best option to concentrate the weights judgement of each criterion is to take a couple of the elements and compare them concerning a simple property or attribute. In this way, the comparison by pairs in combination with the hierarchical structure is quite useful in deriving measurements. A pairwise comparison matrix of criteria is built and the weights assignment of each criterion is given by experts or decision makers. These weights will determine which criterion has the highest priority or importance in the decision problem to achieve the goal. The unification of the multidimensionality of the problem in a unified dimension from the perspective of the final result is given through the use of a ratio scale of comparisons [2].

Some linguistic expressions have been proposed in the AHP to help the decision maker assign values to the judgments of criteria/alternatives. That is, the decision maker can express opinions in pairs through linguistic terms that are then associated with real numbers [22]. The importance scale is represented by the numbers 1, 3, 5, 7 and 9 that establish the verbal judgements "equal importance", "moderate importance", "strong importance", "very strong importance" and "extreme importance" respectively. The values 2, 4, 6 and 8 are used to represent intermediate values [23]. Subjective bias may be created by the use of semantic labels. To compensate for such a handicap, it is convenient to analyse, compare and, eventually, modify the resultant weights [24].

Considering that the numerical values (importance scale) are derived from the subjective preferences of the experts, it is impossible to avoid some inconsistencies in the final matrix of comparison. Therefore, the method calculates a consistency ratio (CR) from the relation between the consistency index (CI) of the comparison matrix and the consistency index of a random-like matrix (RI). A consistency ratio of 0.10 or less is permissible to validate the AHP analysis [16]. Therefore, to calculate the CR is necessary to calculate first the CI and RI. The CI can be obtained from Eq. (1) and the RI is a fixed index obtained from Table 1 which depends on the number of elements (n) of the comparison matrix [23], having the expression

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{1}$$

where λ_{max} is the eigenvalue and n the number of comparisons. The eigenvector is a particular vector associated with a linear system of equation that is widely used for subjective assessments by researchers [9]. Subsequently, the analysis continues with the calculation of the priority vector of the comparison matrix. The best-known method for estimating a priority vector is considering that this vector should be the principal eigenvector of the comparison matrix. Thus, the priority vector may be obtained by summing each row in the matrix and dividing each by the total sum of all the rows, or approximately by adding each row of the matrix and dividing by their total [25]. The priority vector is important for the process since it influences the final ranking of importance of alternatives formulated for the decision problem.

Table 1: Values of Random Index.

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

The next stage comprises the derivation of local priorities for the alternatives in the lower level of the hierarchy. For this, once again is performed the pairwise comparison matrix but, in this case, between alternatives.

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However, each criterion is considered in the matrix. So, the set of alternatives are analysed for each criterion in the decision problem following a similar process as in the previous stage. Likewise, in this stage shall be verified the consistency of weights before to derive the priority vector on each matrix [16].

Lastly, after having elaborated the comparison matrices for each level and after having calculated the priority vectors, it is then possible to establish the global priority of the elements of these matrices. The global priority vector is calculated through the elaboration of an overall matrix that includes the local priorities of each alternative concerning each criterion. Then, each column of vectors is multiplied by the priority corresponding to each criterion and add across each row which results in the desired vector of best alternatives ordered in a ranking of importance or preference [26].

In summary, the AHP is a methodology for relative measurements. Relative measurements theory adapts suitably some decision problems where the best alternative has to be chosen. Thus, the ultimate scope of the AHP is to apply pairwise comparisons between alternatives as inputs, to produce a rating of alternatives, compatible with the theory of relative measurements [22]. Further details regarding the traditional AHP method can be found in the literature [14, 15, 26]. Nevertheless, the methodology described in the next section of this paper follows the same process of the AHP method but some changes are introduced to adapt it to the context of the study.

2. Dynamic decision-making model

As previously referred, decision-making is meaningful in the maintenance management process of buildings, structures and infrastructures. The intervention planning is directed by a set of multi-criteria which generally diverge from each other concerning the objective sought by the decision-making process. In this section, a decision-making model based on the AHP method is developed. The proposed model has two main advantages. One is that the weights assignment for the alternatives concerning each criterion is carried out through a probability formulation instead of experts' judgement. This leaves aside the subjectivity of the traditional AHP method by taking into account the uncertainty of the deterioration process, which is stochastically addressed. The other advantage consist on development of a dynamic model since all the mathematical formulations are in function of time, which allows evaluating the decision-making for any moment of the service life of the structure. Furthermore, it is possible to consider any number of inspection and repair techniques available permitting maintenance planning to be suitable to each particular case.

Hereafter, the dynamic model for decision-making is systematically explained and this methodology will then be applied to a hypothetical case study in order to illustrate the applicability and usefulness of the proposed model. The model has been developed considering the capabilities of damage detection of each inspection technique and the capabilities of reduce the damage degree in the structure that each repair method has. Then, a set of criteria and alternatives related to the capabilities of these inspection/repair techniques and the cost associated with the application of them in a intervention have been formulated. Lastly, this study proposes a new method for the evaluation of criteria based on a formulation of probabilistic indexes. These equations allow to obtain the final comparison matrix of the AHP method from a stochastic approach that enable leading with the uncertainty of structures degradation in a more proper way.

2.1. Step 1: Structure of the MCDM model

§2.1.1 *Hierarchical structure of the problem.* Implementing the traditional AHP, the decision problem is hierarchically structured. For the problem under study, the goal is to find the best intervention alternative for the maintenance planning of RC structures with corrosion risk. At the next level, the criteria that are decisive to attain the objective are established. Four criteria are adopted in this study. For the model, two criteria are formulated regarding the inspection of the structure, namely the probability of damage detection and the inspection technique cost. Furthermore, other two criteria taking into account the repair action of the structure are also considered, namely, the effectiveness of the repair action and the repair cost.

In the last level of the hierarchical structure, the available alternatives are set. In this paper, the range of alternatives is established combining different inspection techniques and repair methods available to perform the intervention in the structure allowing to know the best way to perform the intervention in the structure for a specific time.

§2.1.2 *Inspections and repair methods.* Knowing the inspection and repair methods available to perform maintenance is essential to address the decision problem since the final result of the study will depend on the capabilities of these methods. There are several inspection techniques to detect the corrosion risk in the structure, namely half-cell potential, linear polarisation resistance, resistivity, among others. Likewise, there are several repair methods for structures damaged by corrosion, such as cleaning the corroded rebar, cathodic protection, realkalisation, and so on [27]. Nonetheless, the main objective of this work is not to prove the effectiveness of each method but to propose a decision-making model that allows, once it is known the characteristics of each technique/method, to select which one is the most suitable way to perform the intervention. Furthermore, to establish the quality of a technique or method is extremely complex since it does not only depend on the equipment used but also on the damage degree of the structure and of the technician's experience in charge of performing the intervention.

Considering the above, this study evaluates the repair and inspection techniques generically, assuming the values of the parameters that define its quality and capabilities. These parameters are the mean damage degree of the structure required to be detected or repaired $\eta_{0.5}$, the standard deviation associated to the mean σ, the unit cost of each technique/method α that is assumed as a fraction of the total cost of the infrastructure, and a maximum damage degree η_{max} established as an upper boundary point for the function that describes the capacity of detection/repair of each technique/method.

Although the model can be adapted for any technique and method available for the decision maker, as simplicity, in the application example developed in this work three inspection techniques and two repair methods are considered. Thus, the inspection techniques assumed correspond to techniques of low, medium and high quality, while for repair methods were considered a minor and a major repair in the structure. A minor repair may involve removing the damaged concrete cover, cleaning the corroded rebar and protecting it with some corrosion inhibitor paint. A major repair may involve, in addition to the aforementioned, the replacement of the cover with a sound concrete and resistant to corrosion agents (e.g. carbonation and chlorides), and finally a coating, membrane or sealer may be applied to the concrete surface [27–29].

In practice, it is possible to note that there is more than one "correct" solution for any given repair project and that the economy will often dictate the choice [30]. Nonetheless, the use of repair materials with good quality and with the addition of corrosion inhibitors remains, frequently, the primary and least expensive solution in corrosion protection in RC structures along with good construction practices and proper quality design [31]. In summary, the choice of certain inspection/repair techniques within a maintenance strategy depends on aspects such as the size of the project, the type of inspected phenomenon, accessibility to the area of intervention, socio-economic aspects (e.g. availability of resources) and the use of the structure [32].

2.2. Step 2: Set of criteria and alternatives

The second step of the decision-making model includes the definition of criteria and alternatives by means of probability functions. These functions allow adapting the AHP method to the uncertainties of the degradation of structures and, therefore, to carry out the most properly maintenance planning. In the next points, these mathematical expressions are described as a function of time that enables to address the decision problem from a dynamic approach throughout the service life of the structure.

§2.2.1 *First criterion: probability of damage detection of the inspection method.* The detectability of an inspection technique can be defined according to the probability of damage detection in the structure. For this reason, the damage degree in the reinforcement must first be quantified. This damage degree depends mainly on the rebar diameter and the corrosion rate. Therefore, the higher the corrosion rate, the faster the advance of the damage. So, a common way of expressing the corrosion damage degree in the structure [33] is:

$$\eta(t) = \begin{cases} 0 & ,\text{if } t \leq T_{icorr} \\ \frac{D_0 - D(t)}{D_0} & ,\text{if } t > T_{icorr} \end{cases} \qquad \text{with} \qquad D(t) = D_0 - 2\,V_{corr}\,(t - T_{icorr}), \tag{2}$$

which, for $t \geq T_{icorr}$, the damage degree is invertible as:

$$\eta(t) = \frac{2\,V_{corr}(t - T_{icorr})}{D_0}. \tag{3}$$

Here, D_0 is the initial rebar diameter (cm); $D(t)$ is the rebar diameter over time (cm); V_{corr} is the corrosion rate (cm/year); T_{icorr} is the time of corrosion initiation (years) and t is the time of intervention over the service life of the structure (year). It should be noted that for $t \leq T_{icorr}$ the corrosion does not exist yet and, hence, the corrosion damage is zero. The factor 2 in Eq. (3) considers the uniform corrosion propagation process on the surface of the reinforcement.

Therefore, the quality of an inspection technique θ is usually characterised by a probability of detection function which depends on $\eta^{\theta}_{0.5}$ and σ^{θ} [33]. The detectability function of θ may be modelled in several ways depending on the deterioration mechanism and building structure [34–37]. For corrosion damage, the expression is commonly defined with Eq. (4).

$$P_D^\theta(\eta) = \begin{cases} 0 & ,\text{if } \eta \leq \eta_{min}^\theta, \\ \Phi\left(\frac{\eta-\eta_{0.5}^\theta}{\sigma^\theta}\right) & ,\text{if } \eta_{min}^\theta < \eta \leq \eta_{max}^\theta, \\ 1 & ,\text{if } \eta > \eta_{max}^\theta, \end{cases} \tag{4}$$

where Φ is the standard normal cumulative density function (CDF), $\eta_{0.5}^\theta$ is the damage intensity at which the inspection technique has a 50% probability of detection, and σ^θ is the standard deviation. Nevertheless, Eq. (4) must be adjusted to the requirement of the decision model for which the function must be expressed as a function of time. Thus, considering Eq. (3) as a value of η in Eq. (4), the new expression of detectability may be rewritten as:

$$\mathcal{P}_D^\theta(t) = P_D^\theta\left(\frac{2\,V_{corr}}{D_0}(t - T_{icorr})\right) \quad \text{for} \quad t > T_{icorr}. \tag{5}$$

In Equation (4), there is some *discontinuity* between the upper and lower boundary limits of the detectability function given by the standard normal CDF. This implies an abrupt (vertical) increase of the probability function of detectability at these boundary points, which does not seem to be very representative of reality. To tackle this discontinuity, a new expression is proposed in Equation (6) where p_1 and p_2 are polynomials of degree n. The simplest option for the polynomials is to assume them as linear polynomials and considers even symmetry with respect to $\eta_{0.5}^\theta$, i.e. $n = 1$ and $\eta_{max}^\theta = 1 - \eta_{min}^\theta$.

$$P_D^\theta(\eta) = \begin{cases} p_1(\eta) & ,\text{if } \eta \leq \eta_{min}^\theta, \\ \Phi\left(\frac{\eta-\eta_{0.5}^\theta}{\sigma^\theta}\right) & ,\text{if } \eta_{min}^\theta < \eta \leq \eta_{max}^\theta, \\ p_2(\eta) & ,\text{if } \eta > \eta_{max}^\theta. \end{cases} \tag{6}$$

Another choice for p_1, p_2 is to assume they are cubic splines, so the resulting polynomials will agree in monotonicity and concavity at the boundary points of the middle part of P_D^θ, which is generated by the standard normal CDF. Determine the state of conservation of a building is essential to prioritise the intervention in the structure. Furthermore, it is fundamental to evaluate the mechanisms of failure in the building and, consequently, support the decision makers on the prioritisation of the best solutions for repair, maintenance and mitigation of damage [38].

§2.2.2 *Second criterion: efficiency of the repair method.* The efficiency of a repair method can be estimated from the damage degree of the structure after the intervention η_{rep} concerning its damage condition before the repair $\eta(t)$. Similarly to the inspection techniques, the repair method is more effective the greater its repair capacity in the structure. This can be translated directly in terms of durability, where the adaptability of the repair material is a meaningful parameter for the durability of the repair. Consequently, making a proper choice of the repair material is required to have a durable and efficient repair [39].

To measure the effectiveness of a repair method, it is necessary first to define certain parameters. First of all, it is assumed that the repair is made from a specific damage degree in the structure. So, a threshold of damage degree is established from which the repair must be made so that the maintenance is preventive. In [40], it is established that for a cross-sectional loss between 10 % and 25 % of the reinforcement, the structure could present a condition of reduction of its initial capabilities, and the repair works must be carried out. In this way, a threshold damage degree to perform the repair must be set as $0.1 \leq \eta_{th} < 0.25$. Thus, the probability of doing a repair can be formulated as shown in Eq. (7).

$$P_{DR}(\eta) = P[\eta \geq \eta_{th}] = \begin{cases} 0 & \text{, if } \eta < \eta_{th}, \\ 1 & \text{, if } \eta \geq \eta_{th}, \end{cases} \tag{7}$$

where $P_{DR}(\eta)$ is the probability of *doing repair*; η is the damage degree at the intervention time and η_{th} is the threshold established to perform a repair. It should be noted that if $P_{DR}(\eta(t)) = 0$ at the intervention time t, the efficiency is null since no repair work is required.

Another parameter that influences the repair is the capability that has a repair method according to the damage degree. In other words, the damage degree can determine the repair method since for a critical degradation condition, more rigorous repair work may be required. So, this parameter is similar to the effect that the detectability of an inspection technique has on the structure. Hence, through a formulation comparable to Eq. (4) and considering the assumption for Eq. (6), this repair capability can be defined as the probability distribution according to Eq. (8).

$$P_{RR}^{\gamma}(\eta) = \begin{cases} p_1(\eta) & \text{, if } \eta \leq \eta_{min}^{\gamma}, \\ \Phi\left(\frac{\eta - \eta_{0.5}^{\gamma}}{\sigma^{\gamma}}\right) & \text{, if } \eta_{min}^{\gamma} < \eta \leq \eta_{max}^{\gamma}, \\ p_2(\eta) & \text{, if } \eta > \eta_{max}^{\gamma}, \end{cases} \tag{8}$$

where $P_{RR}^{\gamma}(\eta)$ is the probability of improve the damage condition in the structure, $\eta_{0.5}^{\gamma}$ and σ^{γ} are the mean and standard deviation of damage degree associated with each repair method γ to improve the damage degree in the structure; η_{min}^{γ} and η_{max}^{γ} are boundary points for the capabilities of repair methods.

With these parameters previously defined, it is possible to estimate the damage degree in the structure after the repair work η_{rep}. This damage degree after the repair could be equal to zero if the repair method attains to eliminate the damage and return the structure to its original state. However, this whole reparation is not always achieved as many aspects must be taken into account to make a correct repair. A negative value for η_{rep} can also be allowed in some cases, which implies a reinforcement in the structure or a replacement of the damaged element and not only a repair. Nevertheless, the scope of this study is given by the preventive maintenance of the structure through which it is trying to plan repairs before the occurrence of a failure. Thus, the damage degree after repair can be derived from Eq. (9).

$$\eta_{rep} = K_{\eta}\eta(t) = [1 - P_{DR}^{\gamma}(\eta)P_{RR}^{\gamma}(\eta)\zeta^{\gamma}]\eta(t), \tag{9}$$

where $\eta(t)$ is the damage degree at the intervention time; K_η is a coefficient of degradation improvement given by the repair method; and ζ^γ is a coefficient of maximum repair achieved by the repair method γ. Lastly, the efficiency of a repair method may be inferred through a general form that relates the damage degree at the intervention time with the damage degree after repair through the Eq. (10).

$$eff_R = \frac{\eta(t) - \eta_{rep}}{\eta(t)} = \frac{\eta(t) - K_\eta \eta(t)}{\eta(t)} = 1 - K_\eta, \tag{10}$$

where if is considered the Eq. (9) in the last equation, the efficiency of a repair method may be formulated according to the Eq. (11).

$$eff_R = P^\gamma_{DR}(\eta) P^\gamma_{RR}(\eta) \zeta^\gamma \quad \text{for} \quad P^\gamma_{DR}(\eta) = 1. \tag{11}$$

The efficiency of the repair is essential in maintenance planning. An efficient repair work made in time allows to reduce the intervention costs and ensure the structural reliability. Reliability engineering is dedicated to the maintenance function and is focused on the elimination of repetitive failure. It comprises a strategic activity focused on the future that ensures the best life-cycle cost. So, an efficient repair must allow extending the durability of the structure, preserving its capabilities and its service conditions estimated during the design phase. Regarding the preventive maintenance tasks performed in engineering, studies have found that between 33% and 42% of such tasks have little effectiveness to preserve the reliability of the structures. Therefore, preventive maintenance must be based on reliability in order to decrease these no-value tasks through specific maintenance activities that both prevents failures and extends the service life of the structures [3].

§2.2.3 *Third criterion: cost of the inspection method.* The first two criteria established the capabilities of the inspection and repair methods that can be applied during the maintenance process of a structure. Maintenance planning always aims to apply the intervention with the highest quality and effectiveness to obtain the most optimal results. Nonetheless, the quality of intervention is always related to the operational cost associated with a specific technique or method of intervention. In this way, it is always necessary to make a compensation between the cost and quality of the maintenance planning.

The cost of the inspection technique depends on the capabilities of the equipment to detect the damage (i.e., the minimum damage degree in the structure so that the technique may detect it), the complexity to achieve the structural element to be inspected, the expertise of the operator that carries out the inspection, among others. Thus, the individual cost of each inspection technique θ, see [41], can be expressed through the Eq. (12).

$$C^\theta_{insp} = \alpha^\theta (1 - \eta^\theta_{min})^{20}, \tag{12}$$

where α^θ is the cost associated with an inspection technique assumed as a fraction of the total initial cost of the structure and η^θ_{min} is the minimum damage degree that may be detected for an inspection technique θ. Then, is necessary to consider the value of money over the time. For this, a real cost of the inspection technique is calculated through a net discount rate (r) that gives the Net Present Value (NPV) of the inspection cost throughout the service lifetime of the structure [34]:

$$C^{\theta}_{NPV} = C^{\theta}_{insp} \frac{1}{(1+r)^t}. \tag{13}$$

The interest rate applied in cost analysis is an important parameter of influence and, due to the uncertainty between the estimated costs and the real costs during the building life cycle, it becomes impossible to make accurate projections in long-term [7]. Indeed, considering the discount rate in the formulation gives the chance of performing the same maintenance option at a different time in the future where each one has a different calculated present cost. Thus, the optimisation process provides multiple solutions through the application of the same method but with varying times of intervention [42]. The inspection cost is quite important as it works as a counterbalance to the inspection quality within the decision-making process. It is to be expected that the best option in maintenance planning is to periodically inspect the structure to detect the damage in time. However, this implies an increment in the inspection cost that would directly compromise the total life-cycle cost of the structure.

§2.2.4 *Fourth criterion: cost of the repair method.* Similar to the previous criterion, the repair cost is influenced by the method applied in the intervention and by its capacity to decrease the damage. Moreover, the more effective the repair method is, the greater the cost of the intervention will be. Therefore, this controversy of criteria is quite influential in the decision making regarding the maintenance of structures. The cost of this method depends on the damage condition of the structure and the expected reliability degree of the structure after the intervention. There are repair methods that stop the damage for a while and other methods that decrease the damage degree. Both methods finally achieve the aim of any maintenance intervention, which is to extend the service life of the structure and preserve its durability.

The unit cost of the repair is then related to the efficiency of the method implemented and the cost of a specific repair method can be estimated according to Eq. (14).

$$C^{\gamma}_{rep} = \alpha^{\gamma}[eff^{\gamma}_{R}], \tag{14}$$

where α^{γ} is the cost associated with a repair method that is assumed as a fraction of the total initial cost of the structure, and eff^{γ}_{R} is the efficiency of the repair method γ. Then, as for the inspection cost, the net present value for the repair cost may be formulated with Eq. (15).

$$C^{\gamma}_{NPV} = C^{\gamma}_{rep} \frac{1}{(1+r)^t}. \tag{15}$$

Whether the damage degree is considerable, the repair cost will be high and, even, may be necessary to apply a replacement of the damaged structural element. For this, establishing a damage threshold for a repair work that does not exceed the critical damage of failure is quite meaningful. Studies suggest a damage degree by corrosion higher than 0.25 to reach structural failure [40]. Hence, it is advisable do not exceed such value in order to preserve the preventive maintenance in the structure. Moreover, a failure in a structural element will lead to expensive repair costs.

§2.2.5 *Set of alternatives to achieve the objective.* In this study, the alternatives attempt to describe the best way to perform an intervention on a structure damaged by corrosion throughout its service life. Therefore, the set of alternatives consists of the combination of the different inspection techniques and repair methods that were considered in Section 2.1. Then, considering a set of inspection technique $\theta = \{I_1, I_2, \cdots, I_n\}$ and a set of repair methods $\gamma = \{R_1, R_2, \cdots, R_m\}$, the set of alternatives can be generated as the vector A

$$A = \begin{pmatrix} I_1R_1 \\ I_1R_2 \\ \cdots \\ I_nR_m \end{pmatrix}. \tag{16}$$

These alternatives seek to determine, for a given intervention time, which one is the best inspection technique to be applied. Subsequently, this inspection technique determines the damage degree, which if it is higher than the threshold damage degree η_{th}, then the repair should be carried out by the method combined with the inspection technique for such alternative.

2.3. Step 3: Pairwise comparison matrix of criteria

For this step, the decision-making model follows the approach of the traditional AHP method elaborating a comparison matrix of criteria to know the priority level among them. In this matrix, the level of importance between criteria is analysed using the weight scale established in Section 1.1. A common problem on this step is to find some inconsistency due to the randomness of the experts' opinion. Thus, if there is some inconsistency in the matrix ($CR \leq 0.1$), the decision maker must review the values of the comparison matrix to improve the consistency ratio and so proceed with the analysis [43].

To deal with this problem, this paper proposes a correction factor λ that must be multiplied by each element of the comparison matrix to achieve a permissible CR for the analysis. This correction factor will avoid modifying as little as possible the experts' judgement since such factor will reduce the inconsistency of the matrix proportionately.

2.4. Step 4: Probabilistic index for each criterion - stochastic approach

The uncertainty in the decision-making for the maintenance planning claims for an analysis from a probabilistic approach. Although the AHP method has been widely validated to solve complex problems in decision-making, the final result is directly influenced by the subjectivity in the weights assignment for each criterion and alternative. In order to bring down the subjectivity, this work proposes the elaboration of the comparison matrices from a stochastic perspective. Herein, an index is proposed for each criterion considered, which is directly related to each alternative. This index is obtained regarding the equations formulated for each criterion in Section 2.2. This proposed approach will allow knowing the priority level of each alternative for each time over the service life of a structure. Table 2 shows a schematic of how the indexes are established for each criterion.

Table 2: Stochastic Index for each criterion.

Criterion	A_1	A_2	A_3	A_n
Inspection cost	I_i	$\cdots$	$\cdots$	I_j

Although they are called "indexes", the values of the previous table will be represented by equations as a function of time that will allow performing the analysis for each time t required. That is, to know the value of such an index accurately, it will be necessary to give the intervention time as an input value in the decision model. In this step, the priority vector of each alternative regarding the criteria considered is calculated as per the same method described in Section 1.1.

2.5. Step 5: Pairwise comparison matrix of alternatives

Once the indexes for each criterion have been established, the matrix of alternatives can be elaborated based on such values. In this step, the new approach for the AHP method is proposed, where instead of the weights assignment for each alternative through expert judgement, these values are calculated. Table 3 shows the structure of the comparison matrix, where it can be noted a similar structure to the traditional AHP method.

Table 3: Comparison matrix of alternatives.

Criterion	A_1	A_2	A_3	A_n
A_1	1	$\cdots$	$\cdots$	a_{ij}
A_2	$\cdots$	1	$\cdots$	$\cdots$
A_3	$\cdots$	$\cdots$	1	$\cdots$
A_n	$1/a_{ij}$	$\cdots$	$\cdots$	1

The a_{ij} values in the matrix are calculated according to the following expressions

$$\xi_{ij} = [(8|I_i - I_j|) + 1]^{S_{ij}} \quad \text{with } S_{ij} = \begin{cases} 1 & , \text{ if } I_i \geq I_j, \\ -1 & , \text{ if } I_i < I_j, \end{cases} \tag{17}$$

where I_i and I_j are two different indexes for a specific criterion established in Step 4, ξ_{ij} is a parameter that consider the level of importance of each alternative regarding a criterion, and S_{ij} is a factor that considers the reciprocity between the elements of the matrix. Then, it is possible to calculate the weight of each alternative through the expression of the Eq. (18).

$$a_{ij} = \xi_{ij}\hat{C} \tag{18}$$

where $\hat{C}$ is a consistency factor that preserves a consistency ration lower that 0.1 in the comparison matrix. Equation (18) considers the same range established in [13] for the importance scale and the principle of reciprocity between the elements.

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2.6. Step 6: Global Priority Vector of Alternatives

Lastly, the pairwise comparison matrix between alternatives and criteria is elaborated based on the matrices generated in Steps 3 and 5. From this stage, the proposed decision-making model does not differ from the traditional AHP method. That is, the final comparison matrix is elaborated based on the local priority vector of alternatives and criteria. Then, the global priority vector is defined for each alternative depending on the time. The intervention time is the main input value of the model since, for each value, the model gives as an output a different global priority vector for the set of alternatives. Therefore, after this stage of the dynamic decision model, it is defined which one is the best alternative to be applied for the maintenance in a given time. In the traditional AHP method, at the end of the process, a comparison matrix is obtained between alternatives and criteria. The dynamic model for decision-making proposed in this paper gives as a final result a graph that represents the curves for each alternative as a function of time. In this way, it is possible to know from the curve for each moment of time in the service life of a structure, which one is the alternative that has the highest priority and how high is this priority concerning the other alternatives.

3. Application example

This section presents a numerical example for the illustration of the proposed decision-making model. The hypothetical case study comprises building structures and other common structures with an indicative design working life of 50 years as indicated in [44]. The criteria and alternatives considered to attain the goal of the decision problem have already described in the previous section. Considering that the decision model is formulated under a stochastic approach, the values of the parameters involved were assumed with a lognormal distribution and are summarized in Table 4.

Table 4: Values of random variables for parameters [36, 40].

Variable(s)	Units	Distribution and Value(s)
D_0	cm	$LogN, \mu = 1.6, \sigma = 0.020$
η_{th}	(percentage)	0.12
V_{corr}	cm/year	$LogN, \mu = 0.015, \sigma = 0.0015$
T_{icorr}	year	$LogN, \mu = 5.91, \sigma = 1.27$

These parameters are used to determine the damage degree in the structure during its useful life. Subsequently, the inspection techniques and repair methods must be defined. The inspection techniques to be applied for maintenance can differ according to the mechanism of damage. This work considers generically three different techniques according to certain parameters that define their capacities. These parameters are shown in Table 5. In the same way as the previous one, the parameters associated with the repair methods regarding the capacity to restore the damage are defined. The description of each of these parameters has already been developed in the previous section and the values are presented in Table 6. For the repair were considered only two methods

405 so as not to overextend the number of alternatives analysed. Thus, these methods correspond to a major repair and a minor repair in the structure.

Table 5: Parameters estimated for the Inspection Techniques.

Inspection Method	$\eta_{0.5}$	σ	η_{max}	α
A	0.15	0.015	0.78	0.003
B	0.18	0.030	1.00	0.005
C	0.22	0.015	1.00	0.004

When establishing the different inspections and repairs, the set of alternatives is obtained from the combination of each technique between each other. In this way, a total of six intervention alternatives are established for the numerical example that will be evaluated in the final comparison matrix.

Table 6: Parameters estimated for the Repair Techniques.

Repair Method	$\eta_{0.5}$	σ	η_{max}	ζ	α
A	0.15	0.015	0.78	0.90	0.023
B	0.26	0.030	0.72	0.90	0.015

410 Once the initial parameters have been defined and the decision problem has been appropriately structured, the comparison matrix for the second level is elaborated. This is a matrix between criteria whose main objective is to determine the level of importance of each attribute concerning another. After consulting with some experts regarding the weights assignment for the matrix, an inconsistency in the results was found through a Consistency Ratio (CR) equal to 0.359. To satisfy the admissible CR value (< 0.1) and proceed with the analysis, each
415 element of the matrix was multiplied by a correction factor λ to reduce the inconsistency. Thus, for a correction factor $\lambda = 0.333$, the new value of the consistency rate was $CR = 0.074$. Table 7 shows the pairwise comparison matrix for criteria with the final weights after applying the correction factor. In this table, C_1, C_2, C_3, and C_4 correspond to the first, second, third and fourth criterion respectively, which have been described in Section 2.2.

Table 7: Pairwise comparison matrix of criteria.CR=0.074.

	C_1	C_2	C_3	C_4	Priority Vector
C_1	1	1.400	0.500	0.250	0.475
C_2	0.714	1	1.500	0.385	0.202
C_3	2.000	0.667	1	0.500	0.177
C_4	4.000	2.600	2.000	1	0.146

After calculating the weights so that they fulfil the consistency, the priority vector is calculated. For this case,
420 from Table 7 it can be seen that for the assigned weights, the criterion of highest priority is the detectability of each inspection technique while the cost of repair is the one with the least priority. Subsequently, the process

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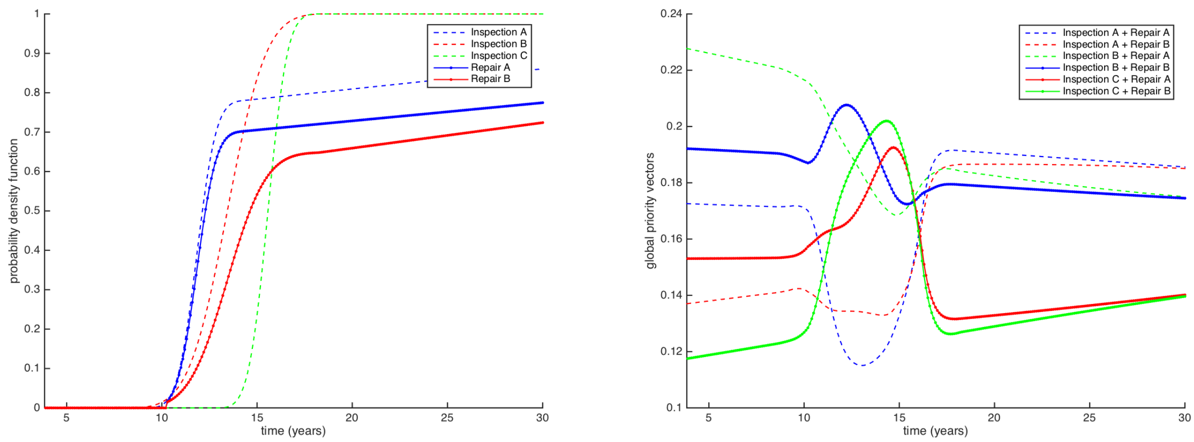
continues with an analysis of the successive level. At the next level, a comparison matrix between alternatives for each criterion is performed. In this way, four six-by-six matrices are necessary for this numerical example. Bearing in mind that the proposed decision model needs a given time t as an input value to provide the results, this study does not show the values of these four matrices of comparison of alternatives. Actually, the main result of this proposed model is not to determine a final comparison matrix, but a set of curves generated according to the priority of each alternative as a function of time. Hence, once the probabilistic indexes have been established, the weights of this comparison matrix are calculated for each time t of the service life of the structure.

The traditional AHP model proposes in its last step a final comparison matrix between criteria and alternatives to calculate the global priority vector (GPV) of each alternative. The proposed dynamic model has been constructed and solved using the MATLAB software, version R2015a. Then, by introducing the time as an input value, the dynamic model allows evaluating the AHP method proposed for each time systematically. The final result of this simulation is depicted in Figure 2(b) where it can be seen the curves of the distribution function of alternatives concerning time. Figure 2(a) shows the probability density function that defines the capabilities for each inspection technique and repair method over the time. This distribution depends on the parameters defined in Table 5 and 6 as well as the damage degree in the structure. Also, the distribution of inspection and repair capabilities influence the final priority of each alternative as shown in Figure 2(b).



(a) Capabilities of Inspection and Repair

(b) Priorities of Alternatives

Figure 2: (a) Probability Density Function for different intervention methods and (b) Global Priority Vector of Alternatives throughout time

As can be seen in Figure 2(b), each alternative has a higher priority than another depending on the lifespan of the structure. This is an expected result since the damage degree and the state of conservation of the structure change over time. Therefore, to better visualise the result of the figure, Table 8 shows a summary that is the final outcome of the dynamic model proposed in this paper for decision-making.

This table allows visualising the best alternative (inspection + repair) to be applied in the maintenance planning during a specified period of time ($\Delta Time$). Also, it allows seeing clearly the level of priority that each alternative has for that period. It should be noted that the example described in this section is merely established as a hypothetical case study that allows verification of the application of the dynamic decision model proposed.

Table 8: Best alternatives for the maintenance planning.

$\Delta Time$ (year)	Best Alternative	GPV_{min}	GPV_{max}	GPV_{med}
0.0 11.4	Inspection (B) + Repair (A)	0.202	0.233	0.224
11.5 13.4	Inspection (B) + Repair (B)	0.197	0.208	0.204
13.5 15.5	Inspection (C) + Repair (B)	0.183	0.202	0.197
15.6 15.7	Inspection (C) + Repair (A)	0.177	0.180	0.179
15.8 16.5	Inspection (B) + Repair (A)	0.175	0.182	0.179
16.6 30.0	Inspection (A) + Repair (A)	0.182	0.193	0.188

4. Discussion of results

The multi-criteria decision-making models are a useful tool for the maintenance planning of constructed structures and infrastructures. In general, the criteria considered within the maintenance of structures conflict with each other regarding the obtaining of an optimal result. So, the cost/quality relationship of the intervention works must be analysed in detail since the parameters that define these criteria tend to change over time. These changes occur in a random manner generating uncertainties that make the analysis complex. Therefore, it is necessary to generate tools that are simple to apply and, at the same time, effective for the maintenance process. This paper develops a dynamic model for decision-making that can be used for the maintenance planning of concrete structures. This model is based on the AHP, which has already been widely developed in several fields of research.This method has great advantages and limitations. Among its advantages, the AHP has a clear structure that facilitates its application in any decision problem. Also, it allows controlling the weights assignment of criteria through the consistency ratio, which gives some robustness to the analysis an acceptable approximation to other results obtained from different analytical methods. However, its main shortcoming lies in the high subjectivity with which the analysis is established. For instance, when the comparison matrices are performed, an essential requirement is different experts' judgement about the degree of importance between criteria. This leads to an inconsistent comparison matrix for which the decision maker must necessarily readjust its values, according to his own opinion once again, until finding the consistency between weights. In this way, the subjectivity in the allocation of weights for each criterion/alternative could be decisive when evaluating the best intervention alternative in a structure maintenance planning.

To counteract this subjectivity and take advantage of the traditional AHP method, this study proposes the formulation of indexes that describe each criterion from a stochastic perspective. These indexes are then used to determine the weights of each alternative instead of being established nominally by experts or by the decision maker. Thus, by developing the method from a probabilistic approach, some variables must be randomly

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considered according to a particular probability distribution. The parameters adopted in Table 4 were assumed based on other studies found in the literature. The authors recognize that the best way to establish the value of these parameters is through a particular case study where these variables can be periodically measured to obtain a database that defines such distribution. Nevertheless, this would entail the development of a comprehensive work to obtain an extensive database for each parameter, which goes beyond the aims of this investigation. Hence, in many other studies in the engineering area, it is common to assume a lognormal or normal distribution for those parameters that are unknown *a priori*.

It should be noted that these random variables have a high sensitivity in the final result of the work. Moreover, according to Eq. (3), it can be inferred that the corrosion rate is very influential in the damage degree obtained over time. In turn, the advance of the damage over time affects the choice of one or another inspection technique, as well as the decision to perform or not the repair action in the structure. Therefore, it is necessary that these parameters are carefully assumed by the decision maker so that the maintenance planning is adapted to each particular case, i.e. the degradation mechanism, environmental exposition, type of structure, and so on.

Another aspect to be mentioned regarding the numerical example are the parameters assumed for the inspection and repair techniques. Since the example of the previous section corresponds only to a hypothetical case study, the assumed parameters correspond to techniques and methods chosen generically. However, regarding inspection techniques, these techniques can be any available in the market to detect corrosion. Also, these parameters should be adjusted after each intervention to update the capabilities of each technique. The costs were established according to referential costs concerning the initial cost of the structure. Several investigations [36, 37, 45–47] adopt the same criteria (referential cost), and the functionality of the analysis allows then to adapt the study to any market or any case.

For the comparison matrix of criteria, however, it is necessary to perform the weights assignment of each criterion according to the original method proposed by the AHP. In this first stage of the analysis, it is defined which criterion is more important for the maintenance of the structure (the goal of the decision problem), for which it is necessary to develop a detailed study. Regardless of the amount or the knowledge of the experts involved in the judging of the weights between criteria, some inconsistency can always be expected as has been investigated in other studies [24]. Therefore, to interfere as little as possible in this judgment, this paper suggests the application of a correction factor λ that allows reducing the inconsistency. The value for this factor can be found automatically once the model is formulated within the MATLAB platform. Otherwise, the decision maker should manually search for the value that allows a proper consistency in the matrix. In the example, it could be seen that for a correction factor of $\lambda = 1/3$, the consistency ratio of $CR = 0.359$ could be reduced to $CR = 0.074$.

From the comparison matrix of criteria, it can be seen that the detectability of the inspection techniques is the most important to consider for the decision problem. This can be an expected result because if the inspection technique fails to detect the damage correctly, the repair work could not be carried out in time, leading to the failure of the structure. However, a certain degree of subjectivity always exists in the matrix that is set based on judgements. That is, depending on the type of structure or the maintenance budget established, the criterion

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with the highest priority may be another different than the one shown in the example. Nonetheless, for the hypothetical example of the previous section, the order of importance of criteria is shown in Table 7.

For the previous matrix, the intervention time does not directly influence in the weights assignments whereby the scale of importance formulated for the AHP method is used. However, for the comparison matrix of alternatives, the weights are not estimated but are calculated based on proposed indexes. These indexes consider the criteria from the stochastic perspective allowing the method to adapt to the uncertainties of structures degradation. The method for the elaboration of these matrices has been explicitly developed in Section 2 of this paper. Considering that there is then a set of four matrices for each given time, in the numerical example, these matrices have not been exposed in this paper. The proposed model allows calculating (through MATLAB) a set of matrices for each time. Then, the dynamic model gives at the end of the process, not one, but a series of matrices with which the global priority vector is calculated for each moment of time. Thus, with these matrices, the curves are elaborated for each alternative that is the final result of the decision-making model that has been formulated in this investigation.

In Figure 2(a), it can be seen the capabilities of detection/repair of each inspection technique and repair method throughout the life of the structure. With the passage of time, the level of corrosion damage in the reinforcement is increasing. This corrosion damage, if it is not treated in time, causes the formation of cracks due to the expansion of the oxidation products (rust), concluding in the spalling of the cover. The higher the damage degree, the higher the probability that it will be detected by a specific inspection technique. The parameter $\eta_{0.5}$ allows knowing the mean damage degree that define the detectability of each technique concerning the damage degree. The lower this value, the higher the ability to detect the damage in the early stages of degradation. However, as can be seen in the figure, the inspection technique A has *a priori* the highest initial detectability. On the other hand, as early as the maximum damage degree value η_{max} has been reached, this technique becomes less efficient than the other two since greater damage does not significantly alter its detectability. This controversy in the inspection process is quite typical in real cases, so it is not obvious to know in advance which technique is the best for the maintenance planning.

With the method of repair, the same situation presented with the inspections may occur. There is a certain damage degree from which a minor repair is not convenient from the viewpoint of the repair capacity of such method. For this, it is essential that the inspection technique attain to adequately detect the damage degree of the structure to be able to decide to correctly perform the repair. The threshold damage degree established in this work to perform the repair allows maintenance to be preventive. By performing the intervention before the occurrence of the failure, it avoids falling into high costs that affect the maintenance of the structure.

The most worthwhile and meaningful outcome of this paper can be seen in Figure 2(b). The curves in this figure allow defining decision-making practically and dynamically. Once defined the initial parameters that will be used in the decision-making model, it is possible to obtain a similar curve for each case of study. Regardless of the time established to perform the intervention, this curve will allow the decision maker to know in advance what are the material resources he needs to implement the maintenance intervention, namely the technique of inspection and repair method. However, the repair method will only be applied if the damage degree detected by the inspection is higher than the threshold damage degree, which is also defined by the decision maker. Depending on whether it wants to give a more or less conservative approach to maintenance, this value for the threshold damage degree should be established between 0.1 and 0.25 according to other studies. This will allow intervening the structure always in a period previous to the structural failure, ensuring the durability by means of the preventive maintenance.

It can also be seen in Figure 2(b) that the curves of the alternatives have a diffuse behaviour between 10 and 16 years of service life of the structure.This is because the degree of global priority between the different alternatives undergoes abrupt changes for this period. Also, this behaviour can be influenced by the probability distribution of the techniques and methods shown in Figure 2(a). Respectively, for this same period of time, there is a high controversy regarding which technique/method has an improved capacity to deal with damage in the structure. This controversy is then addressed by the AHP method that finally considers simultaneously all the criteria established to determine which one is the best alternative through the global priority vector.

Another secondary outcome of this dynamic decision model is the Table 8, which is nothing more than a detailed description of Figure 2(b). However, the benefit of this table is to know precisely the period in which apply a particular alternative of intervention. It should be noted that the value of the global priority vector is a very important indicator of decision-making. Furthermore, it should also be noted that of the six alternatives initially proposed for the numerical example, the alternative composed by the inspection technique A and the repair method B is the only one that does not deserve to be considered during the whole service life of the structure. Nevertheless, these results should be interpreted as a preliminary analysis of the best alternatives for the maintenance of structures based on a vector of priorities. In turn, this vector of priorities indicates the level of importance of each alternative against the criteria considered. Then, this result allows knowing the consistency of the alternatives for the established criteria through a certain ranking of importance. Therefore, the decision maker could choose a second-best alternative in the case that the analysis results in two different alternatives that do not differ considerably concerning their global priority.

Moreover, the model has proven its dynamic feature according to the example of Section 3, whose main advantage is to be a support for decision-making regarding the maintenance of structures. For this, the proposed model comprises the elaboration of a set of global comparison matrices between alternatives and criteria that determine a curve for each alternative over the time. For this particular case, the dynamic decision model analysed more than three hundred global comparison matrices for each moment of time to obtain the final result shown in Figure 2(b).

Lastly, it should be emphasized about the importance of considering maintenance planning from the design phase of the project. Most of the construction regulations are focused just on the execution of the works to guarantee their quality. However, several studies have shown that the degradation of the infrastructures over time is inevitable, so that only efficient and optimised maintenance planning can guarantee its durability. In this way, the models for maintenance planning developed in the literature could be implemented within these regulations as tools that guarantee adequate performance during the infrastructure life cycle.

5. Conclusion

This paper consists on a study that may contributes to help decision makers to choose the most suitable intervention for the maintenance planning of RC structures. The developed AHP-based dynamic decision-making model can be applied as a preliminary analysis to decide how to inspection and to repair structures over its whole service life. The AHP method has been widely developed and applied in the literature. In this paper, it has been employed for the maintenance planning of RC structures with corrosion risk. It has been sequentially presented how to apply the proposed model from a probabilistic perspective. This approach deals more adequately with the uncertainty inherent in the degradation of structures and reduces the subjectivity of the traditional method. The following conclusions can be drawn from the present research:

- After its application in a numerical example, the dynamic decision-making model proposed has proven to be a useful support tool for the maintenance planning of structures. This model allows determining the best alternative of intervention (i.e. inspection + repair) to be applied throughout the service life of the structure.
- The formulation of each criterion indexes allows introducing a stochastic analysis into the traditional AHP method, which is formulated originally according to subjective analysis. Thus, the study of probabilities enables to adapt the AHP method to the uncertainties given in the context of maintenance and the structural degradation.
- In the proposed model, the allocation of weights for each criterion is not developed based on expert judgement (subjective approach) but based on a probability analysis that determines the occurrence of each criterion (objective approach) in order to determine its importance in the decision making process for maintenance management. Then, this stochastic approach allows an analysis whose values obtained are adjusted to a probability density function, which provides better reliability of the results. However, although there are still factors (e.g. type of material, environment, construction process, etc.) that can influence the results of the model, this study presents a worthwhile advance in the study of the maintenance management of structures.
- It is recognised the need to develop a statistical analysis to be able to define the parameters that were assumed here as random variables. This is an analysis that will be time-consuming since must be collected an extended and reliable database to define the type of distribution for each parameter properly. However, these parameters, assumed as random variables for this study, may be updated and adjusted after each intervention to obtain a more suitable maintenance planning for each case.
- As future work, the application of the model in real cases for the maintenance of existing structures is recommended for more comprehensive validation of the model. This will allow refining the model and analysing the real capabilities of the intervention techniques that are very important to guarantee the durability of the structures.

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- It is important to note that, although the model has been applied to a case of corrosion-induced degradation in RC structures, it can be adapted to other types of structures and other degradation mechanisms through an adjustment of the stochastic indexes reformulating the equations in Section 2.2. Furthermore, it can also be adapted for a greater number of alternatives as well as additional criteria and sub-criteria.

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Highlights of the Manuscript

1. Stochastic indexes are proposed to address uncertainties of the degradation process.
2. The model proposed has proven to be a useful support tool for the maintenance planning.
3. The model generates a ranking of intervention alternatives for structures with corrosion degradation.

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