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An evaluation system of the setting up of predictive maintenance programmes

MªCarmen Carnero *

Technical School of Industrial Engineering, University of Castilla-La Mancha, Avda. Camilo José Cela s/n, 13071 Ciudad Real, Spain

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Abstract

Predictive Maintenance can provide an increase in safety, quality and availability in industrial plants. However, the setting up of a Predictive Maintenance Programme is a strategic decision that until now has lacked analysis of questions related to its setting up, management and control. In this paper, an evaluation system is proposed that carries out the decision making in relation to the feasibility of the setting up. The evaluation system uses a combination of tools belonging to operational research such as: Analytic Hierarchy Process, decision rules and Bayesian tools. This system is a help tool available to the managers of Predictive Maintenance Programmes which can both increase the number of Predictive Maintenance Programmes set up and avoid the failure of these programmes. The Evaluation System has been tested in a petrochemical plant and in a food industry.

Keywords: Predictive maintenance; Decision making; Analytic hierarchy process; Bayesian tools

1. Introduction

The implications in production and maintenance suggest the need to change the focus of maintenance policies, traditionally centred on short-term issues (use of resources, cost, etc.) towards the consideration of longer-term goals (competitive, sustainability and strategy) [41].

Predictive Maintenance is a maintenance policy in which selected physical parameters associated with an operating machine are sensored, measured and recorded intermittently or continuously for the purpose of reducing, analyzing, comparing and displaying the data and information obtained for support decisions related to the operation and maintenance of the machine [11].

Different questions related to set up a Predictive Maintenance Programme (PMP) are analysed in literature; the problems involved in setting up PMPs are presented in [53] and [54]. [74] looks at the relationship between the complexity of the production environment and the use of predictive and preventive maintenance programmes. [52] gives guidelines for using a Predictive Maintenance Programme. In [16] a control system of the set up of a PMP is developed by means of indicators. In [21] a PMP is developed by considering the lowest cost for replacing the system.

The choice of the best maintenance policy can be made by means of different approaches. One of them is Reliability Centered Maintenance (RCM) (see [64,50]) which is probably the most widely used technique [9]. RCM is a systematic methodology for the allocation of efficient predictive and preventive maintenance aimed at preventing the dominant causes of failure of critical equipment, and, in turn, towards achieving acceptable levels of equipment availability and costs by reducing corrective maintenance [51] and by so doing a structured way of making maintenance decisions is achieved [26]. RCM focuses on the use of Predictive Maintenance [82,57]. Therefore, in [85] RCM is combined with decision theory (utility functions) and [51] presents a methodology for a maintenance evaluation programme based on maintenance indicators and how it is applied to monitoring the effectiveness of the maintenance at a nuclear power station. The maintenance policies included in the methodology are conservative, modification, corrective, preventive, predictive and regulated. [25] proposes that the optimal maintenance policies should be defined in the case of military aero-engines using RCM and Monte Carlo simulation. In [33] uncertainties in the decision making of RCM can lead to non-optimum maintenance strategies, so an alternative approach is discussed to avoid this. In [28] RCM is applied to a medium size steel industry

* Corresponding author. Tel.: +34 926295300; fax: +34 926295361.
E-mail address: carmen.carnero@uclm.es

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demonstrating the features of predictive maintenance. In [27] RCM is described as a compromise between Predictive Maintenance and corrective maintenance to optimise the cost and to ensure the availability of the machines.

The subject of selecting a maintenance policy through the definition of the maintenance concept is looked at in [87] and [88]. [90] describes a model based on operational research methods to assist in generating an optimal maintenance plan for a road, considering minimisation of the Net Present Value (NPV). The discussion regarding the selection of a maintenance strategy can be appreciated in [91] where an optimum maintenance policy is described (including preventive and predictive maintenance) and corresponding maintenance systems, in order to achieve high reliability, availability, safety and productivity, are applied to a robotic car assembly line. In [71] three types of preventive maintenance are considered to select the optimum preventive maintenance time that maximizes availability.

Another option is in [19] that developed a model that provides a choice of no inspection, continuous inspection and periodic inspection for identifying the current state of a deteriorating system using Markov Chain. In [24] the problem of selecting a suitable maintenance policy for repairable systems and a finite time period is analysed using a semi-Markov decision process. In [58] a model for a multi-state semi-Markovian deteriorating system is described; the model allows one of three maintenance decisions (do-nothing, minimal maintenance or replacement) to be taken for each state of the system; the model is able to find the optimal maintenance policies that minimize the expected long-run cost rate of the system.

Another approach to selecting a maintenance policy is by means of multicriteria methods; [9] applies the Analytic Hierarchy Process (AHP) for selecting the best maintenance strategy for an Italian refinery with an Integrated Gasification and Combined Cycle plant, including the alternatives corrective maintenance, preventive maintenance, opportunistic maintenance, condition-based maintenance and predictive maintenance; a criticality index is designed to classify the machines into three groups ranging from the group where a failure can lead to serious safety problems or production losses to the group in which the failures are not relevant. [45] uses the AHP to justify the application of Total Productive maintenance (TPM) in Indian industries; The alternatives considered in this model are the application of a TPM system or a traditional maintenance system. [34] identifies the preferred maintenance policies for one specific weapon of the Norwegian Army by means of AHP; in this case four maintenance echelons are considered and Monte Carlo simulations are used to evaluate the robustness of the decision.

Some examples of effectiveness of PMPs are: in the food industry [1], the paper mill industry [2,70], buildings [3], power plants [43] and nuclear power plants [31,84], petrochemical plant [61], the manufacturing industry [49] and railway systems [62].

The selection of a Predictive Maintenance policy is considered a strategic decision [80] due to its particularities regarding cost, temporal horizon and repercussions in the Production, Quality and Safety departments. However, this strategic decision is lacking in questions related to its setting up, management and control [16].

Up until now it has been customary for large industrial plants, particularly nuclear and petrochemical plants, to apply Predictive Maintenance Programmes and in so doing achieve an increase in competitivity (as a result of improvement in availability and cost reduction), and furthermore an increase in safety in the plant. However, these technological maintenance policies are not applied uniformly in small and medium-sized enterprises, due very often to a lack of information about the benefits of a PMP. This means that plants that could benefit from this kind of maintenance policy do not adopt them and, therefore, do not have the option to improve the competitivity and safety in the plant. The aim of the decision support system proposed in this paper is to provide an evaluation system that will aid in the decision-making process regarding the implementing of PMP's, particularly in small and medium-sized enterprises, and in so doing achieve an improvement in safety levels in plants. The evaluation system of the setting up of a Predictive Maintenance Programme uses a combination of tools belonging to operation research. These tools are the Analytic Hierarchy Process (AHP), Bayesian techniques and decision rules. The AHP provides a hierarchical structure of the problem, the decision rules define the restrictions regarding the problem and the Bayesian tools contribute to reducing uncertainty, if there is not enough information in the industrial plant.

The layout of the paper is as follows. Section 2 is devoted to some notions in relation to Predictive Maintenance. Section 3 looks at the characteristics of Analytic Hierarchy Process. Section 4 presents the Evaluation System of the setting up of a Predictive Maintenance Programme. Section 5 presents the results of applying the System to a petrochemical plant and a food industry. Section 6 draws some conclusions.

2. Predictive maintenance

Predictive Maintenance consists of starting a maintenance operation only when required by the state of the system [21]. As a result continuous or periodic measurement and interpretation of an item is required to determine the need for maintenance [13].

Predictive Maintenance can be disaggregated into two specific sub-categories [32]:

- Statistical-based Predictive Maintenance. The information generated from all stoppages facilitates development of statistical models for predicting failure and thus enables the developing of a preventive maintenance policy [22].
- Condition-based Predictive Maintenance. Condition-based monitoring is related to the examination of wear processes in mechanical components. The wear process is preceded by changes in the machine's behaviour although does not cause sudden mechanical failure.

The advantages of the introduction of a Predictive Maintenance Programme are: (1) exclusive control of the machines that show the beginning of a malfunction; (2) an increase in the availability of the industrial plants [89]; (3) the capacity to carry out quality checks of both internal and subcontracted maintenance interventions; (4) an increase in the safety of the factory [20]; (5) it facilitates certification and ensures the verification of the requisites of the standard ISO 9000; (6) it provides the best scheduling of maintenance actions and enables the effective scheduling of supplies and staff; (7) production quality is optimized as the interruption of operating machinery due to failures is avoided [48]; (8) support in the design phase of equipment, particularly by means of the application of modal analysis [7]; (9) reduction of direct maintenance costs by checking only the equipment that is developing a fault [86]; (10) by keeping to delivery dates, and by satisfying the customers' demand for quality, the image of the company is improved; (11) costs are brought down in relation to spare parts and labour [42]; (12) by maintaining the industrial equipment operational whilst applying the predictive tools, the measuring process does not directly affect the availability of the equipment; (13) a decrease in the costs related to insurance policies as safety within the factory increases; (14) reduction of energy consumption; (15) historical information on each piece of equipment is completed, which helps to determine reliability parameters and to optimize maintenance planning [6]; this information on the machines and equipment is available to the management for decision-making.

There are numerous predictive techniques, as can be seen in [32]: lubricant analysis, vibration analysis, thermography, penetrating liquids, radiography, ultrasound, control of corrosion, etc.; each technique is applied to a type of specific industrial equipment. Industrial plants generally have PMPs based on vibration analysis [8] or lubricant analysis whereas medium-sized companies are starting to incorporate them in their Maintenance Departments. Most plants, however, require a combination of techniques [55]. The suitability of vibration analysis for application to rotary and reciprocating machines [80], which can be considered to be the most widely used in general, in addition to its high capacity of diagnosis, make it the most versatile predictive technique.

The head of maintenance is usually directly responsible for the Predictive Maintenance Programme. A PMP usually comprises a director, technicians and operatives. Due to the high level of training required there are few technicians in predictive diagnosis and it is therefore advisable for the specialist to be dedicated exclusively to the drawing up of diagnosis while the lesser qualified technicians are involved in acquiring predictive data. Furthermore, if the specialist technician is occupied in gathering data this is likely to have a negative effect on the performance of a PMP [15]. It is beneficial for the workers involved in corrective activities to have a basic knowledge of the functioning of the PMP in order for them to understand the tasks being carried out in the department [72]. In other cases, depending on the type of maintenance that is being applied, the acquisition of predictive data can be carried out by production operatives [73].

In industrial plants of limited size, mining enterprises, civil engineering machinery, etc., the internal implementation of a PMP is more complex due to the difficulty involved in finding measuring equipment and in training personnel for these areas. Consequently these kinds of enterprises prefer to outsource this activity; in this case the PMP comprises:

(a) *A qualified person belonging to the enterprise.* This person will be responsible for decision making based on the data provided by the outsourced enterprise. They must be experienced in maintenance and be computer literate and must have in depth knowledge of diagnosis.
(b) *Outsourced enterprise.* It carries out tasks related to the gathering, processing and diagnosis of the predictive information and issues periodical reports. The enterprise is responsible for selecting the diagnostic techniques of the PMP, and for indicating the points of measurement, the technical features of the acquisition of the predictive data, the timing of inspections, etc.

In order to carry out the setting up of a PMP, it is vital to understand their technical peculiarities, regarding instrumentation, procedures and uses that make the production of diagnoses possible. The success or failure of the setting up process will depend on the Programme Planner's knowledge of these subjects. The activities carried out in a PMP are [15]:

1. Data acquisition. The acquisition of predictive data is organized by means of routes in order to minimize the time dedicated to this activity. It is preferable if the predictive data is acquired by the same operator in the same place in order to minimize variations in conditions which would affect the measurements and so that these are as repetitive as possible.
2. Information processing. Once the predictive data has been acquired it must be transferred to PC or a workstation to be processed. This transfer is carried out automatically each time a measurement route has been completed. The kind of processing to be carried out will be in accordance with the philosophy of the enterprise. Usually a trend graph is drawn up or a spectral investigation is carried out by means of comparison. Supplementary registers will be acquired or a more advanced analysis will be applied only if deviations in the behaviour are discovered.
3. Drawing up of diagnosis. This is the key activity of a PMP. It is carried out by qualified personnel whose principal objective is to avoid the accumulation of unanalyzed registers and predictive samples. Using the acquired predictive data an analysis of the information is carried out for which the expert uses as an aid graphic representation of the data [73]. Nowadays all vibration analyzers and collectors have associated software programmes that apart from enabling the acquired information to be stored and processed also provide graphics of trend and other types of representation. The technician using

these tools, in addition to his experience, records of past data and graphics, is able to establish the state of the equipment and if this is not satisfactory issue a diagnosis of the failure. The technician has at his disposal an expert system, which using some preliminary data, issues a diagnosis of the state of the equipment and if there is a failure it is able to specify what it consists of and measures to be undertaken for its solution.

4. Transfer of information to personnel responsible for preventive and corrective maintenance tasks: issuing of work orders. The corrective activities are normally carried out by different staff to those responsible for predictive activities. The speed of the operation of transferring information is vital in order for the PMP to be as effective as possible as any delay in this operation will lead to the failure developing further.
5. Diagnosis verification. Once the corrective measures have been carried out it is necessary to acquire predictive data to check if the problem has been resolved. When an incorrect diagnosis has been made the information is stored and the reason for the error is analyzed. By so doing similar errors are avoided.
6. Transfer of information to the computerised maintenance management system (CMMS) and enterprise resource planning (ERP) software. This activity is not as yet very common in industrial plants although the CMMS is beginning to be used for the issuing of predictive work orders, an activity preceding the acquisition of predictive data. The connection between predictive diagnosis software and the CMMS would facilitate the scheduling of maintenance activities and could furthermore contribute to the integration of the PMP with the rest of the enterprise's maintenance policies. The transfer of relevant information to the ERP could aid in the decision taking process as regards costs, human and technical resources production scheduling, etc.
7. Combination of predictive information with the production process [73]. This activity could be of considerable benefit to the enterprise, although only a small number of Production Departments have access to maintenance reports in Spanish enterprises. It is also necessary to draw up the predictive information to be communicated to Management. By so doing the resources available to the PMP can be increased or maintained. This report should include an evaluation of the overall costs of a PMP in relation to its benefits.

One of the future lines of research in Predictive Maintenance is related to the integration of predictive techniques [11]. A PMP integrating vibration and lubricant analysis involves the acquisition of information of both techniques, in order to correlate all the predictive information to obtain an early diagnosis of the root causes of the failures and the prediction of their consequences for the machinery [17].

Besides the benefits previously mentioned obtained through the application of a PMP, the integration of predictive techniques provides the following additional advantages: an increase in the number of pieces of equipment covered by a PMP [79], an increase in the set of anomalies that can be controlled [40], and guarantee of the diagnoses provided as the information from both techniques is contrasted. As all the techniques present deficiencies [12,11,47], it is, therefore, advisable to confirm the diagnosis; each of the predictive techniques detects deterioration in different phases of its evolution [40] and detection of the root causes of the failures [59,79].

On line condition monitoring is increasingly important for plants, especially those in remote or hazardous environments. The concept of condition telemonitoring is used to integrate diagnostic systems into a customer's information technologies infrastructure (intranet or internet) [46]. The new generation information software technologies such as web services, XML signature, XML encryption, UML, etc. can be used for e-diagnostics and provides capabilities of connectivity, manipulation, configuration, performance monitoring, data collection and automatic failure diagnostics, repairing, and maintaining equipment [39]. This new concept is being applied to some nuclear and fossil-fuelled power plants [51]. The combination of a Kalman filter with on-line failure detection is very useful in nuclear power plants [83] but also in railway turnouts for pre-processing predictive data [36].

3. The analytical hierarchy process

The Analytic Hierarchy Process (AHP) has very many real-world applications since it was introduced by Saaty [67]. AHP has been applied in software selection [60], selection of information [78] and manufacturing technology [56], supplier selection [10], as elicitation method of expert opinion to determine the a priori distribution of gas pipeline failures [14] or the pressure increment in the containment building of nuclear power plants [92], in risk-informed safety significance categorization [38], forecasting [35] or project evaluation [44].

Application of this methodology can be found in maintenance for the prioritizing of maintenance activities in buildings [69], determining the rational weights of importance of maintenance priority ranking factors [63,76] and to select a maintenance policy [9,34,45].

AHP is used to identify the preferred alternative and determine a ranking of the alternatives when all the decision criteria are considered simultaneously [77]. The use of AHP instead of another multicriteria technique is due to the following reasons:

- Quantitative and qualitative criteria can be included in the decision making.
- A large quantity of criteria can be considered.
- A flexible hierarchy can be constructed according to the problem.
- A complete classification of alternatives can be obtained.
- It enables the consistency of the judgements provided by the decision maker to be verified [34].

A hierarchy must be constructed to apply AHP. In this hierarchy the relationship between the goal, criteria, subcriteria and alternatives is established.

In a decision-making problem M alternatives A_i ($i=1,2,3,\ldots,M$) and N criteria C_j ($j=1,2,3,\ldots,N$) are considered. In order to determine the relative importance of the alternatives with regard to each of the criteria or between two criteria, linguistic terms are used that include the judgments of the decision maker. The linguistic terms are generally associated to numerical values constituting a scale. The scale proposed by Saaty is shown in Table 1. Miller in 1956 established the psychological limit of 7 ± 2 in a simultaneous comparison and this aspect is taken into account by Saaty to construct the scale [67]. It is possible to see the meaning of each value in the scale and how the values of the scale are arranged at uniform intervals in [1,9], whilst being concentrated on the left-hand side in [1/9,1]. The values used comply to the impossibility of comparing elements with unlike characteristics as this would lead to errors in the resolution endangering the axiom of homogeneity of the AHP. Thus, all the values in the scale must be maintained in the same size order [30]. An alternative scale to that of Saaty was proposed by Ma and Zheng in 1991. This scale uses values uniformly arranged in the interval [1/9,1] and the rest of the values are the inverse of the previous ones. Other scales are described in [77].

The quantified judgment on pairs of criteria C_i and C_j are represented by an n-by-n matrix A:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{1}$$

where the a_{ij} is the relative importance of C_i to C_j. The entries a_{ij} are defined by the following rules [63]:

1. If $a_{ij}=\alpha$, then $a_{ji}=1/\alpha$, $\alpha\neq0$.
2. If C_i is judged to be of equal relative importance as C_j, then $a_{ij}=a_{ji}=1$; $a_{ii}=1$ for all i.

To obtain the weight of each alternative, Saaty applied the matricial expression (2).

$$Aw = nw, \tag{2}$$

where w is an eigenvector of A with eigenvalue n.

It is necessary to calculate the maximum eigenvalue $\lambda_{\max}$ from the expression (3) where ($\bar{w}$ is the normalized eigenvector of A and $\lambda_{\max}\geq n$.

$$A\bar{w} = \lambda_{\max}\bar{w}, \tag{3}$$

The closer $\lambda_{\max}$ is to n, the more consistent coherent will be the judgments provided. The Consistency Index (CI) is used as a measurement of the consistency of the judgments expressed [67].

$$\mathrm{CI} = \frac{\lambda_{\max}-n}{n-1} \tag{4}$$

The Consistency Ratio (CR) is obtained by dividing the CI value by the corresponding Random Consistency Index (RCI) evaluated by Saaty through the generation of a random matrix with different dimensions (n) [67]. A $\mathrm{CR}\leq0.10$ is considered acceptable [35].

According to AHP the final preference of each alternative is given by a synthesis process. Synthesis from the goal node multiplies the weight of each parent node times the local priorities of its children nodes and of those children times the local priorities of their children. This process continues down to and including the alternatives.

4. Evaluation of the setting up of a predictive maintenance programme

The selection of variables used in the Evaluation System of the setting up of a Predictive Maintenance Programme is based on literature, on past experience in the setting up of some PMPs in process plants and besides information supported by experience from other PMP' managers has been incorporated.

4.1. Scenario variables

The evaluation of the setting up of a PMP has the following scenario variables that characterize the evaluation depending on different typologies of enterprises:

Table 1
Scale of relative importances [67]

Intensity of importance	Verbal scale	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Demonstrated importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above numbers	If activity *i* has one of the above (non-zero) numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	–

4.1.1. Enterprise size (ES)

[74] states that the number of employees in a plant is a variable dependent on the investment in technology and an internal maintenance group to care for equipment is likely to be required. This variable facilitates a differentiation of levels of scale in other variables. For example, maintenance costs can be great for small companies, but insignificant for a large corporation, therefore, the scale of the variable associated in inferior levels may not be representative for a certain group of companies. This variable permits the discrimination of specific characteristics of each company. The distinctions are:

(a) The amount of economic resources designated to the setting up of a PMP.
(b) The quantity and quality of human resources that the Maintenance Department has.
(c) Organizational differences between the sizes of the companies examined.
(d) Different levels of planning of the maintenance activities.

The levels of scale of this variable have been defined according to the quantity of employees that make up the enterprise: a large company (the number of employees is superior to 250), a medium-size company (between 250 and 50 employees) and a small company (less than 50 employees). This definition belongs to the definition from the European Union of small and medium-size companies. Their sales are inferior to 50 million euros, and no more than a fourth of their capital belongs to a higher company. The incorporation of a superior number of levels for this variable does not improve the capacity of distinction between the specific conditions of each enterprise. This is because it is necessary to determine a comparative pattern for those which are near excellence and for those which are at the opposite extreme.

4.1.2. Productive process (PP)

A correlation has been proved to exist between each activity sector with a type of productive process. The productive processes considered are continuous, intermittent and by projects. The values of these variables are obtained from a questionnaire and from the activity sector that the enterprise belongs to and it is associated with a determining position in the product-process matrix. In [66] the dependency between the type of process and the characteristics in relation to the Maintenance function has been checked.

The incorporation of this variable makes it easy to characterize each company:

(a) Characteristics of Maintenance Department, such as level of training supplied by the company or numbers of employees.
(b) The quantity of activities of each maintenance policy developed.
(c) Differentiation in the type of industrial machines used.
(d) Priority of objectives sought through with the application of a PMP between: availability, product quality, spare store management and safety (personal and environmental).
(e) Presence of a Maintenance Department or outsourcing of maintenance activities.
(f) Restrictions are introduced for variable groups, when the questionnaires are not completed, averaging the general behaviour of the enterprises in each activity sector.

The following scale values in this variable are considered:

- *Continuous process*. A limited quantity of final products, that is to say, low flexibility, and vital implications in relation to safety or quality. Sectors of chemical, petrochemical, nuclear and electrical industries are considered in this level.
- *Intermittent process*. It is characterized by a superior flexibility. It includes the manufacturing and food sectors.
- *By project process*. The flexibility is highest. The public construction and transport sector are in this level.

4.2. Decision variables

The size of the company (large, medium or small) influences in the capacity of the enterprise to develop an internal PMP. This is due to the fact that the large and medium-size enterprises generally have a larger amount of human, technical and economic resources at their disposal and this favours the internal application of a PMP. However, a small company may have the optimum conditions previous to set up, whilst a large enterprise, with greater economic resources, may be far from satisfying these conditions. Therefore, in order to evaluate this subject a set of requirements has been established to which both large, medium-size and small enterprises must comply for the internal application of a PMP. If these requirements do not verify the result provided by the evaluation system, the enterprise would be orientated towards the alternative of outsourcing a PMP (if necessary). If the enterprise complies with some but not all of the requirements for the implementing of a PMP, the enterprise could design organizational, technical and/or economic improvements. If the evaluation system considers that these improvements are possible in this enterprise then the decision will be oriented towards the carrying out of a series of improvements that would guarantee the success of the PMP when implemented.

One way of guaranteeing the successful implementation of a PMP is to evaluate if a quantity of essential requirements are available, and then if these are being applied properly. The variable Capacity to set up a Predictive Maintenance Programme (CST-PMP) permits the evaluation of the company's aptitude for applying a PMP, or the need to improve previously the structure of the Maintenance Department to acquire the essential previous conditions. CST-PMP is composed of the variables: Strategic decision (SD) and Maintenance Department state (MDS) as can be appreciated in Fig. 1. These variables joined with the second and third level variables are as follows:

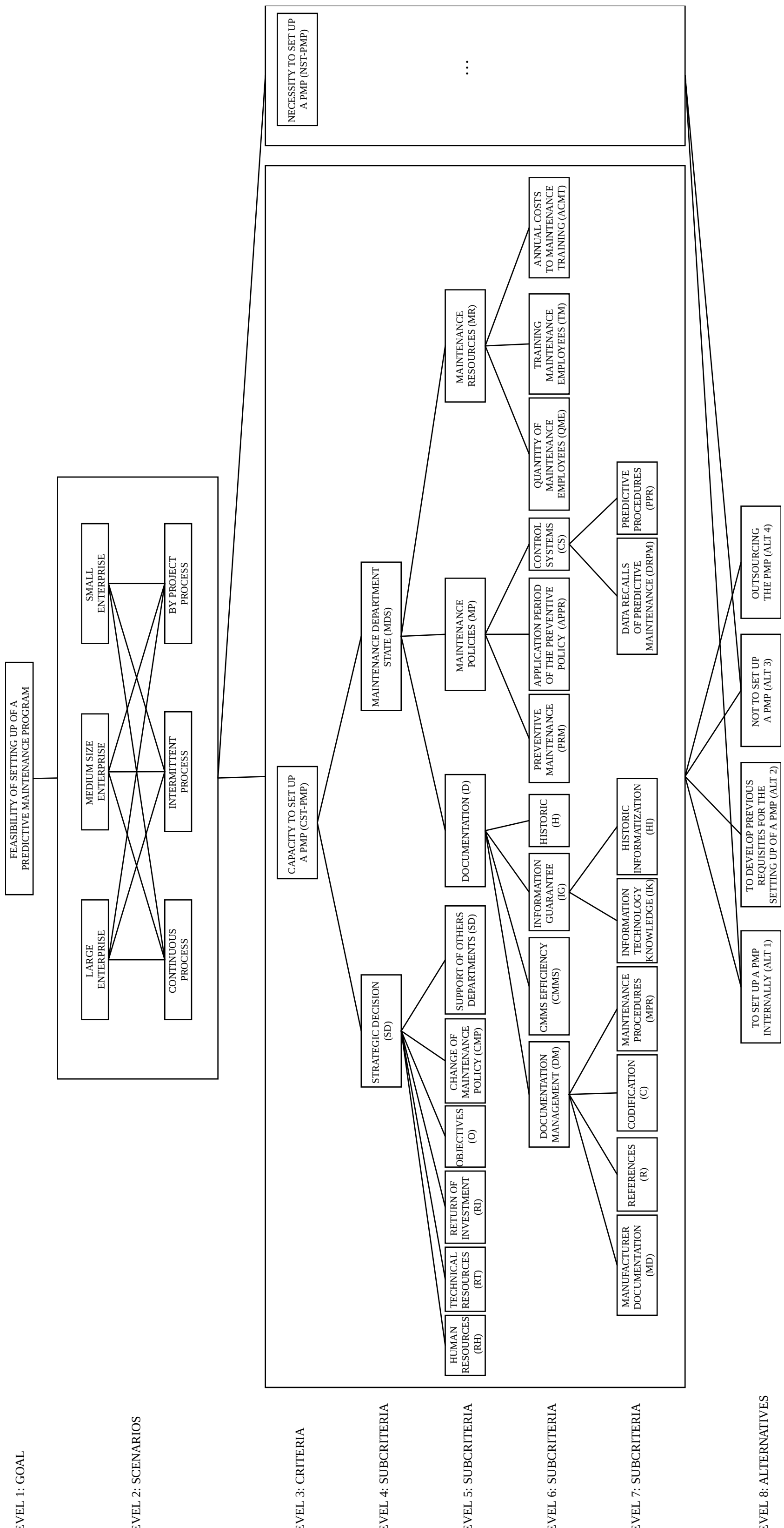

Fig. 1. Hierarchy of the capacity to set up a PMP.

4.2.1. Strategic decisions (SD)

Decision making can be influenced by personal evaluation, technical training and the quantity and quality of information held by the company management. The relevancy of the judgement provided by the management means that this variable considers the support that exists regarding the implementation of a PMP, and the previous knowledge held by the management regarding these programs. The quantification of this variable is fundamental to guarantee the continuity of the PMP, because in order to develop a project the support of the enterprise management is essential, but the level of agreement provided can be different in each situation This variable is composed of:

(a) *Human resources of the PMP (HR).* The level of human resources provided in the PMP is considered or the existence of enough available personnel.
(b) *Technical resources of the PMP (TR).* It evaluates the economic quantity with which the management can supply the PMP. The purpose of this capital is for the acquisition of the most appropriate instruments for the kind of processes and machines of the industrial plant, as well as, to cover training and management costs arising from the PMP.
(c) *Return of investment period (RI).* The period of time in which the management expects to obtain economic results. The objective of this variable is to estimate the support time for the Programme, considering the long return of investment period that characterizes PMPs.
(d) *Objectives (O).* Maintenance strategy must be derived from business strategy in the same way as operational strategy has always been (see [81]). The objectives aimed by means of the PMP must also be in accordance with those established in the maintenance strategy. Thus, if the strategy of the Maintenance Department is to achieve the greatest availability of the plant whilst providing the greatest safety, the objectives established could be to achieve a 20% increase in plant availability and a 30% decrease in the number of catastrophic failures. These objectives are in accordance with those that can be achieved with a PMP and the implementation of the PMP should therefore be viable.
(e) *Change of maintenance policy (CMP).* When the objectives sought coincide with those supplied by a PMP, a similar situation could be achieved by increasing the effectivity of the present maintenance policy used by the enterprise. This variable evaluates: the practicality or suitability of optimizing the present maintenance policy; if it recommends the change of maintenance policy or the incorporation of a new policy.
(f) *Support of other departments (SD).* The advantages of Predictive Maintenance can influence not only in the Maintenance Department but also the Operations, Safety, Quality, Inventory and Financial Departments. The support of each Department given to the new policy increases the efficiency and confidence in the PMP, especially during the design and adjustment phases. The Maintenance Department can depend on different areas inside the hierarchical structure of the company, can be an independent Department or with direct dependency on the Production Department or Process Engineer [65]. The decisions regarding the implementation of a PMP depend on this dependence.

4.2.2. Maintenance department state (MDS)

This variable evaluates if the company has a suitable structure to introduce a PMP. It is composed of the following variables:

4.2.2.1. Documentation (D). It gives information about the documental state of the Maintenance Department. It evaluates the existence and the level of excellence of a series of characteristics that are essential for introducing a PMP. It is composed of the following variables:

1 CMMS efficiency (CMMS). The presence of a Computerized Maintenance Management System (CMMS) in an industrial plant has been considered a previous requirement for the implementation of a PMP. Its application is not strictly necessary to develop the technical specifications of a PMP, but its existence provides organizational qualities, training and programming. These aspects whilst not guaranteeing the success of a predictive implementation contribute to increasing the probability that this can be obtained. The application of CMMS must have been evaluated positively within the enterprise to obtain the profits mentioned.
2 Information guarantee (IG). The PMPs require software and systems for signal acquisition to obtain information [55]. The presence of a suitable state of this variable favours the implementation of the PMP. It is composed of the variables:
  – *Information technology knowledge (IK).* The systems of acquisition, processing and analysis of predictive information are similar to computer systems (especially as far as the technique of vibration analysis is concerned), and in most cases it is necessary to transfer the information to personal computers or workstations. Therefore, in order to implement a PMP it is considered necessary for the personnel of the maintenance department to be computer literate and therefore to be able to use and maintain the predictive equipment and the information it provides.
  – *Historic informatization (HI).* If there is CMMS in the Maintenance Department, we could assume the existence of historic data from machines, although, in certain circumstances the rate of references compiled or the reliability of the information is very low (generally, the database of the CMMS only gathers data from specific pieces of equipment or from a certain date, or alternatively the records of machinery failures are not up to date). Deficiencies of this variable may indicate that the predictive data will also not be up to date if a PMP is implemented, meaning that it would therefore be

of no use. These aspects demonstrate the necessity of this variable to be independent. Its transcendence is due to its being a requirement for the correct and quick application of the Programme.

3 Documentation management (DM). It evaluates the management process and the relevancy of the information that is available to the enterprise regarding the utility aspects of the PMP. It is composed of:
   - *Manufacturer documentation (MD).* This question is essential to select the points of measurement or sample acquisition, as well as to provide diagnoses. It indicates a preoccupation regarding the control of the information inside the Maintenance Department.
   - *References (R).* This variable checks the presence of references in maintenance documents and other documents of the company. Its purpose together with the variable Codification is to detect the level of control of the information and the capacity of the enterprise to manage the documental changes related directly to the technical modifications in the industrial machinery.
   - *Codification (C).* The existence of codification in the activities, equipment and maintenance documentation are analysed in this variable. The identification of executed activities improves the control and the management of the maintenance activities, and therefore, the productivity of the Maintenance Department [37]. The machinery codification of the plant and its own maintenance documentation has been added to this codification. The first is vital for establishing the predictive routes, and the second is an essential condition in the diagnostic process.
   - *Maintenance procedures (MPR).* The application of a PMP requires comparison of technical information. This aspect can be achieved if it is defined by procedures of predictive acquisition, processing and diagnosis.

4 Historic (H). This variable facilitates the selection of the critical machines and the evaluation of the different characteristic of the implementation Programme, such as the frequency of acquisition of data, the presence of reiterative failures, modifications in the design of machinery, etc.

4.2.2.2. Maintenance policies (MP). The rate of application of the different maintenance policies is an exponent of the state of maintenance in the industrial plant. The adaptation of the percentage of activities of each maintenance policy with the percentage that has been considered optimum previous to the implementation is the matter indicated in this variable. It is vital to develop a PMP with the application of typical activities of a preventive maintenance policy. This decision criterion is composed of:

1. Preventive maintenance (PRM). It is the rate of preventive maintenance activities applied in the industrial plant, measured in man-hours.
2. Application period of the preventive policy (APPR). According to the application time of the preventive policy a stable state will be achieved, which is defined as a state with stabilized profits of the preventive programme.
3. Control systems (CS). Particular industrial plants develop certain activities of a PMP, although they do not explicitly have a Programme. It has been established that when one or some of the following characteristics are not present, there is no PMP:
   - Specific personnel to apply diagnostic activities.
   - Technical resources for processing the predictive measures and its transformation in other formats.
   - Capacity to emit diagnoses and provide estimates regarding the remaining life time of machinery.
   - Suitable scheduling of maintenance activities from the predictive data according to the necessities of the Production Department.

The continuous control of vibratory or lubricant variables is not considered as a PMP, if there is no capacity for diagnosis during the intensification of the anomaly. However, if the enterprise has instrumentation and capacity to maintain the devices, this must be considered in the Evaluation System. It includes a variable that shows the existence of these characteristics and that facilitates the predictive implementation when the proper devices necessary for the programme have been chosen. The third level variables are:

- *Data recalls of predictive maintenance (DRPM).* This variable shows if the predictive data recall agree with the type of predictive techniques that must be applied in the industrial plant, according to the type of machinery has been used.
- *Predictive procedures (PPR).* The presence of procedures for the application of predictive techniques provides the know-how that will be essential for the implementation of a PMP.

4.2.2.3. Maintenance resources (MR). It supplies information about aspects such as the presence of available time, the existence of training programmes, a qualified person responsible for implementing the PMP, etc. It is composed of the following variables:

1. Quantity of maintenance employees (QME). It has been demonstrated that according to the activity of the sector, a typical quantity of maintenance employees exists. The variation of that value is noticeable in the existence of idle time, and consequently with personnel that can be incorporated directly into the PMP.
2. Training of the maintenance employees (TM). A superior qualified worker is needed to make technical and organizational decisions regarding the implementation, maintenance and extension of a PMP [75]; this characteristic is a restriction in the Evaluation System and quantifies the level of qualifications of the Maintenance Department.

3. Annual costs designated to maintenance training (ACMT). A nil or minimum value of this variable contributes negatively to the implementation of a PMP, because its success, from a technical perspective depends on the economic quantity designated to this concept [53].

Until now only the capacity of the enterprise to apply a PMP has been considered, but it is also necessary to evaluate if the Programme is essential for the industrial plant. So the variable Necessity to set up a Predictive Maintenance Programme (NST-PMP) is introduced. It is composed of the second level variables:

4.2.3. Safety (S)

It quantifies the level of safety in the industrial plant. It has been structured in two concepts according to the object of the consequences of the accidents; so, the subcriteria considered are:

4.2.3.1. Personal safety (PS). It is composed by the subcriteria:

1 Probability of occurrence of annual personal accidents (PPA).
2 Personal consequences for the more probable type of accident that may occur (PC).

The last two variables assess the danger of the accidents and it has been denominated risk (R_s). The Risk is evaluated from the expression (5).

$$R_s = \text{Consequences} \times \text{Probability} \tag{5}$$

where the probable consequences of the accident are specified from PC and the probability is quantified from the frequency (see [23]) (number of accidents occurring causing injury in a fixed interval of time) or number of accidents PPA, over a total of n, applying the expression (6).

$$R_s = \sum_{i=1}^{n} \text{PC}_i \times \text{PPA}_i \tag{6}$$

4.2.3.2. Environmental safety (ES). It comprises the subcriteria:

1 Probability of occurrence of annual environmental accidents (PEA).
2 Environmental consequences for the more probable type of accident that may occur (EC).

The variables PEA and EC are incorporated in the expression (7) to evaluate the risk that exists for the environment.

$$R_s = \sum_{i=1}^{n} \text{EC}_i \times \text{PEA}_i \tag{7}$$

This quantification of safety is intrinsic to the company and is not linked to specific industrial machinery; this last particularity has been incorporated later through the variable Number of critical machines in the industrial plant (NCM). This distinction between plant safety and machinery safety is due to the necessity to characterize a global level of safety in the industrial plant, in accordance with the consequences of failures, related to the specific activity of each enterprise. This variable distinguishes a nuclear and chemical plant, with similar conditions with respect to the total quantity of employees.

4.2.4. Quality (Q)

Quality referring to aspects that directly influence the satisfaction of the client has been taken into account and, therefore, the concept of product quality is complemented by a suitable supply time. It has been structured in: product and process quality.

4.2.4.1. Process quality (PQ). The influence of the PMP in the productive process in relation to the satisfaction of the client has been taken into consideration in:

- The minimization of the transmission of imperfections from some productive lines to others, or from some machines to others.
- Suitable supply time complying with the requirements of the client.

4.2.4.2. Product quality (PDQ). Product quality optimisation can be a benefit of a PMP. The evaluation of the necessity to improve the quality of products manufactured is the reason for introducing this variable. The decrease of the vibrations and the optimising of the operating conditions of the machinery, through correct lubrication, contribute to improving the final quality of the products.

4.2.5. Maintenance costs (MC)

A decrease in maintenance costs is one of the objectives of a PMP, although its attainment depends on a correct implementation, in relation to technical and organizational aspects. The aspects evaluated in this criterion are:

4.2.5.1. Spares costs (SC). The quantity of spares in stock is directly linked with the percentage of preventive activities supplied. A decrease in corrective activities is linked with the use of minor quantities of spares, because some catastrophic breakdowns are eliminated, and this reduces the influence on other components of the machinery. The necessity to diminish the spares stock is evaluated.

4.2.5.2. Repair costs from the preventive and corrective maintenance activities (RC). A maintenance department with excessive repair costs arising from traditional maintenance policies can significantly reduce these costs through a PMP. This is due to the fact that a PMP is able to detect anomalies in machinery at the beginning of their development and when they are therefore less serious; furthermore, they can avoid an anomaly in one component influencing another component in the system. A further advantage is that if a PMP is correctly integrated with the rest of the maintenance policies, preventive maintenance activities can be considerably reduced (where some items may be over maintained, that is replaced prematurely [80]), and consequently their associated costs will similarly be reduced. Excessive costs show the necessity to modify the maintenance policy applied. Some of these activities can be considered unnecessary because they induce costs but do not contribute to improving the operativity of the machinery.

4.2.6. Number of critical machines in the industrial plant (NCM)

The existence of critical machinery due to safety, quality, production or maintenance is essential to establish the necessity of a PMP. The number of pieces of critical machinery is a relevant factor in the Evaluation System because it can direct the decision towards outsourcing, when the cited quantity is not near a certain value. To quantify this variable each piece of machinery must be individually analysed and the most suitable type of maintenance to apply must be defined.

4.2.7. Availability of plant (A)

The evaluation of the viability of a PMP establishes the necessity of availability of the industrial plant according to the type of production process. This factor can be completed with the loss of production occasioned by a breakdown in the critical machinery.

4.2.8. Optimisation (OP)

To evaluate the necessity to improve the scheduling of the activities of the Maintenance Department with a suitable management of the policies applied and the spares stock.

A descriptor was associated to each criterion. Each descriptor is composed of a set of levels in a scale ordered in terms of its attractiveness [5]. Quantitative and qualitative descriptors have been defined. Some examples of descriptors and scales are shown in Table 2. As the criteria have different units, each one has been converted to a normalized scale.

4.3. Hierarchy

It is composed of two scenario variables, 47 decision variables and four alternatives:

- Alternative 1 (ALT 1). To set up a Predictive Maintenance Programme internally.
- Alternative 2 (ALT 2). To develop previous requisites for the setting up of a Predictive Maintenance Programme.
- Alternative 3 (ALT 3). Not to set up a Predictive Maintenance Programme.
- Alternative 4 (ALT 4). Outsourcing the Predictive Maintenance Programme.

An incomplete hierarchy has been used to apply a superior specificity in the emission of judgement because it has been considered that the preferences must be modified in the different scenarios suggested. The hierarchy of the Evaluation System is shown in Figs. 1 and 2.

4.4. Priorities

To construct the judgement matrices the following procedure has been applied [4]. It began with the comparison of the most and the least important criteria, followed by the second most important with the least important, and so on, thereby completing (from top to bottom) the last column of the matrix. The most important criterion is then compared to each of the other criteria, in order of increasing attractiveness, thereby completing (from right to left) the first row of the matrix. Next, the most important criterion is compared with the second most important criterion, the second most important criterion with the third, and so on, thereby completing the diagonal border of the upper triangular portion of the matrix. Finally, the remaining judgements were assessed. There are $n(n-1)/2$ judgements required to develop each judgement matrix, n being the number of criteria in the matrix; reciprocals are assigned in each pairwise comparison. Table 3 shows the pairwise comparison matrix for level 4 of the hierarchy corresponding to the Necessity of a Predictive Maintenance Programme in a medium-size enterprise with intermittent process. Row element is x times more important than the column element.

The same process has been applied to the different scale levels of each descriptor. Thus, in the case of the criterion Application period of the preventive policy (PPV) the descriptor number of years that the policy of preventive maintenance has been applied in the enterprise has been associated to it. The judgement matrix obtained from the pairwise comparison of the scale levels associated to the previously mentioned descriptor is shown in Table 4.

Some local preferences for criteria corresponding to the evaluation system in a large company are shown in Table 5.

Table 2
Descriptors and scale levels.

Criterion	Descriptor	Scale levels
Environmental consequences for the more probable type of accident that may occur (EC)	Environmental consequences	None, waste, acoustical contamination, small leak, relevant leak irreparable environmental damage
Data recalls of predictive maintenance (DRPM)	The predictive data agree with the type of predictive techniques that must be applied in the industrial plant	Yes, without influence, no
Preventive maintenance (MRP)	Percentage of preventive activities applied	100%, 75%, 50%, 25%, 0%

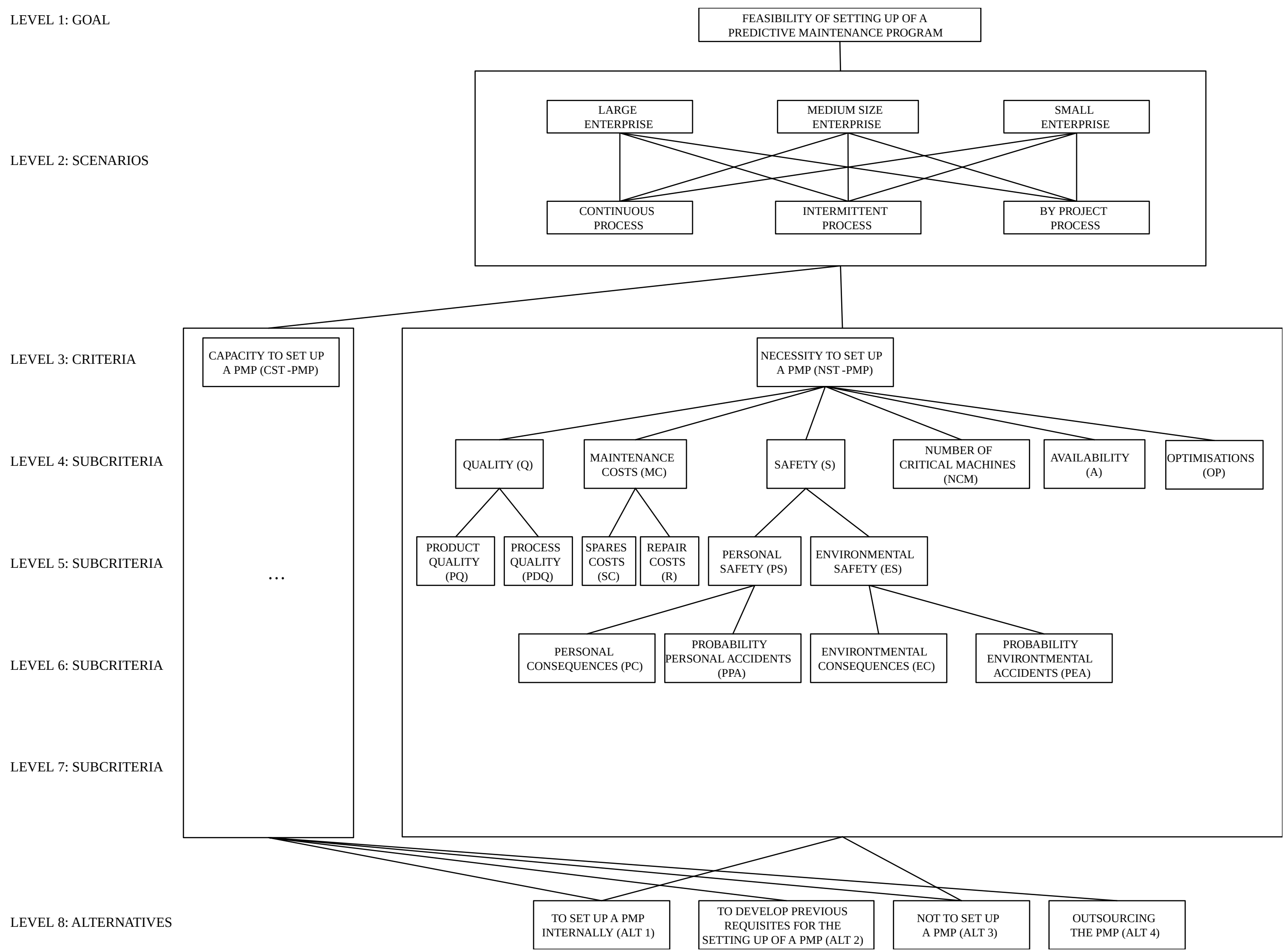

Fig. 2. Hierarchy of the necessity to set up a PMP.

Table 3
Pairwise comparison matrix for level 4 of the hierarchy in a medium-size enterprise with intermittent process

	Availability	Safety	Quality	Maintenance cost	Number of critical machines	Optimisations	Local priorities
Availability	1	1	3	3	4	4	0.310
Safety		1	2	2	4	4	0.264
Quality			1	4	2	3	0.184
Maintenance cost				1	2	3	0.110
Number of critical machines					1	3	0.082
Optimisations						1	0.050

The Consistency Index (CI) and Consistency Ratio (CR) are included. The consistency ratio has values inferior to 0.1 in all the cases, and therefore, is considered acceptable.

In most cases it has been necessary to make a judgement matrix for each scenario. LE, ME and SE have been used to identify a large, medium-size and small enterprise. The subscripts 1, 2 and 3 indicate a continuous, intermittent and by project process. However, there are some specific cases in which the judgements matrix could be independent from the scenario; in this case the subscript i is included. Thus, Table 6 shows the local priorities in the case of large enterprises with continuous process, medium-size enterprises with an intermittent process and small enterprises with project-associated processes. Table 7 shows local priorities that arise when the criteria that are compared are independent from the scenario variables.

4.5. Decision rules

In the evaluation process there is a series of requirements that must be imposed for the correct development of a PMP, and with which the industrial plant must comply. These decision rules have been elaborated through the semantics defined in the expert systems based on rules [18]. The structure of the decision is 'if (condition 1) and (condition 2) and… (condition N) then ALT X'.

If CST-PMP = ALT 1 and NST-PMP = ALT 1 then ALT 1.
If CST-PMP = ALT 1 and NST-PMP = ALT 3 then ALT 3.
If CST-PMP = ALT 2 and NST-PMP = ALT 1 then ALT 2.
If CST-PMP = ALT 2 and NST-PMP = ALT 3 then ALT 3.
If CST-PMP = ALT 3 and NST-PMP = ALT 1 then ALT 4 and ALT 2.
If CST-PMP = ALT 3 and NST-PMP = ALT 3 then ALT 3.
If CST-PMP = ALT 4 and NST-PMP = ALT 1 then ALT 4.
If CST-PMP = ALT 4 and NST-PMP = ALT 3 then ALT 3.

4.6. Conditioned probabilities to control uncertainty in decision making

The industrial plant may not have at its disposal the necessary information for evaluating the most suitable alternative from the evaluation system, or it may wish to have access to the results provided by the evaluation system in other similar enterprises. Therefore, it is proposed that they use the information available in the database in relation to enterprises that have similar scenario variables to those specified by the enterprise seeking this information.

A series of alternatives A_i is available for the evaluation of the setting up of a PMP. It can be assumed that the quantity of alternatives presented rises to M, that is to say $i = 1,2,\ldots,M$. N scenario variables V_j, $j = 1,2,\ldots,N$ are available. Each of the scenario variables can present a different value S_k, $k = 1,2,\ldots,K$. The probability of selecting an alternative A_i, is evaluated from expression (8).

$$P\left(\frac{A_i}{([V_1(s_k)] \cap [V_2(s_k)] \cap \ldots \cap [V_N(s_k)])}\right) = \frac{P(A_i)P\left(\frac{[V_1(s_k)] \cap [V_2(s_k)] \cap \ldots \cap [V_N(s_k)]}{A_i}\right)}{P([V_1(s_k)] \cap [V_2(s_k)] \cap \ldots \cap [V_N(s_k)])} = \frac{P(A_i)P\left(\frac{[V_1(s_k)] \cap [V_2(s_k)] \cap \ldots \cap [V_N(s_k)]}{A_i}\right)}{P(V_1(s_k))P(V_2(s_k))\ldots P(V_N(s_k))} \tag{8}$$

Scenario variables are considered to be independent (a previous analysis has been developed), a characteristic which was previously required for the application of the AHP.

The previous expression will be applied to the two phases that constitute the Evaluation System, that is, the evaluation of the capacity to carry out the set up of the PMP and the

Table 4
Pairwise comparison matrix for the scale levels of descriptor number of years that the preventive maintenance policy has been applied in the enterprise

	>20 years	10–20 years	5–10 years	2–5 years	1–2 years	<1 year	Local priorities
>20 years	1	3	5	7	8	9	0.462
10–20 years		1	3	5	7	8	0.259
5–10 years			1	3	5	7	0.140
2–5 years				1	3	5	0.074
1–2 years					1	3	0.040
<1 year						1	0.024

Table 5
Local preferences in large company

CRITERIA	LOCAL PRIORITIES	CRITERIA	LOCAL PRIORITIES	CRITERIA	LOCAL PRIORITIES
Safety	0.441	Maintenance Procedures	0.250	CMMS efficiency	0.400
Availability	0.321	Codification	0.250	Documentation management	0.200
Number of critical machines	0.134	Manufacturer documentation	0.250	Information guarantee	0.200
Quality	0.049	References	0.250	Historic	0.200
Maintenance cost	0.033				
Optimisations	0.023				
CI	0.11	CI	0.00	CI	0.00
CR	0.09	CR	0.00	CR	0.00
Preventive Maintenance	0.500	Annuals cost to maintenance training	0.333	Data recalls of Predictive Maintenance	0.500
Application period of the preventive policy	0.250	Maintenance training	0.333		
Control systems	0.250	Quantity of maintenance employees	0.333	Predictive procedures	0.500
CI	0.00	CI	0.00	CI	0.00
CR	0.00	CR	0.00	CR	0.00

evaluation of the necessity of that PMP. By particularizing the previous expression to the variable Capacity to set up a Predictive Maintenance Programme (CST-PMP) we obtain:

$$P\left(\frac{A_i}{([V_1(s_k)] \cap [V_2(s_k)])}\right) = \frac{P(A_i)P\left(\frac{[V_1(s_k)]\cap[V_2(s_k)]}{A_i}\right)}{P([V_1(s_k)] \cap [V_2(s_k)])}$$
$$= \frac{P(A_i)P\left(\frac{[V_1(s_k)]\cap[V_2(s_k)]}{A_i}\right)}{P(V_1(s_k))P(V_2(s_k))}$$
$$= \frac{\frac{1}{4}}{\frac{1}{3}\,\frac{1}{3}}P\left(\frac{[V_1(s_k)] \cap [V_2(s_k)]}{A_i}\right) \tag{9}$$

By applying the general expression to the variable Necessity to set up a Predictive Maintenance Programme (NST-PMP) we obtain:

$$P\left(\frac{A_i}{([V_1(s_k)] \cap [V_2(s_k)])}\right) = \frac{P(A_i)P\left(\frac{[V_1(s_k)]\cap[V_2(s_k)]}{A_i}\right)}{P([V_1(s_k)] \cap [V_2(s_k)])}$$
$$= \frac{P(A_i)P\left(\frac{[V_1(s_k)]\cap[V_2(s_k)]}{A_i}\right)}{P(V_1(s_k))P(V_2(s_k))}$$
$$= \frac{\frac{1}{2}}{\frac{1}{3}\,\frac{1}{3}}P\left(\frac{[V_1(s_k)] \cap [V_2(s_k)]}{A_i}\right) \tag{10}$$

Therefore in order to evaluate the probability of an enterprise applying an alternative A_i, when it has at its disposal certain specific values associated to the scenario variables, it is necessary to know:

$$P\left(\frac{[V_1(s_k)] \cap [V_2(s_k)]}{A_i}\right),$$

The values obtained from the analysis carried out of the population of enterprises analysed up to that moment.

In order to integrate the results from the variables CST-PMP and NST-PMP, the alternative selected after applying the decision rules of the model is called $\tilde{A}_l$. We are going to add $\tilde{V}_i$ and $\tilde{V}_j$ to the variables CST-PMP and NST-PMP that can take the values A_i, $i=1,\ldots 4$ and A_j, $j=1,2$, respectively. The probability of getting an alternative $\tilde{A}_l$ is:

$$P\left(\frac{\tilde{A}_l}{([\tilde{V}_i(A_i)] \cap [\tilde{V}_j(A_j)])}\right) = \frac{P(\tilde{A}_l)P\left(\frac{[\tilde{V}_i(A_i)]\cap[\tilde{V}_j(A_j)]}{\tilde{A}_l}\right)}{P([\tilde{V}_i(A_i)] \cap [\tilde{V}_j(A_j)])}$$
$$= \frac{\frac{1}{4}P\left(\frac{[\tilde{V}_i(A_i)]\cap[\tilde{V}_j(A_j)]}{\tilde{A}_l}\right)}{P[\tilde{V}_i(A_i)]P[\tilde{V}_j(A_j)]} \tag{11}$$

The previous expression can be quantified from the results obtained with other companies that have already applied the Evaluation System.

5. Results

The Evaluation System has been tested in a petrochemical plant and in a food industry. The information needed to apply the model has been obtained by using a questionnaire. The following is an analysis of these two companies.

The food enterprise was set up in 1974 and is dedicated to working with livestock and the packaging and distribution of dairy products. Its installations include computer-controlled automatic systems for optimizing the feeding of the livestock

Table 6
Variations of the eigenvectors with the size of enterprise and the type of process

Criteria	$(LE)_1$ LOCAL PRIORITIES	$(ME)_2$ LOCAL PRIORITIES	$(SE)_3$ LOCAL PRIORITIES
Quality	0.049	0.178	0.220
Maintenance cost	0.033	0.080	0.210
Safety	0.441	0.262	0.220
Number of critical machines	0.134	0.071	0.070
Availability	0.321	0.353	0.220
Optimisations	0.023	0.056	0.061
CI	0.11	0.05	0.00
CR	0.09	0.04	0.00

Table 7
Variations of the eigenvectors in criteria independent of size of enterprise and type of process

Criteria	$(LE/ME/SE)_i$ LOCAL PRIORITIES	CRITERIA	$(LE/ME/SE)_i$ LOCAL PRIORITIES	CRITERIA	$(LE/ME/SE)_i$ LOCAL PRIORITIES
CMMS efficiency	0.400	Maintenance procedures	0.250	Information technology	
Documentation management	0.200	Codification	0.250	Knowledge	0.500
Information guarantee	0.200	Manufacturer documentation	0.250	Historic	
Historic	0.200	References	0.250	Informatization	0.500
CI	0.00	CI	0.00	CI	0.00
CR	0.00	CR	0.00	CR	0.00

and it represents one of the most advanced systems of the region. It has an annual production of 7,000,000,000 litres. The enterprise has 23 pumps, 3 compressors, 33 engines, 3 pneumatic systems and 18 machine-tools, of which 2 are considered critical in relation to availability, although the main objective of the enterprise is to achieve product quality. The annual costs generated by repairs are 30,000 euros. The enterprise has 29 workers of which one is dedicated to maintenance activities. The workers do continuous 10 h shifts. The company does not have a CMMS or historical information about the machinery and failures and the maintenance operators are not university graduates nor do they have computer skills. The enterprise has an annual budget of 600 euros for the training and recycling of maintenance staff. 25% of the maintenance activities undertaken in the enterprise are preventive, 25% are predictive and the remaining 50% are corrective. The preventive maintenance policy has been applied for the last 10 years.

The results provided by the Evaluation System in the food industry are:

- In the analysis of the Capacity to develop the setting up of a Predictive Maintenance Programme (CST-PMP) the Evaluation System suggests developing previous requisites for the setting up of a Predictive Maintenance Programme (ALT 2); the global priority is 0.284.
- In the variable Necessity of implementation of a Predictive Maintenance Programme (NST-PMP), the Evaluation System suggests the alternative of not to set up a PMP (ALT 3) with a global priority of 0.640.
- Clustering the results by means of the decision rules, the Evaluation System suggests not setting up a Predictive Maintenance Programme.

Nevertheless, the food industry decided to outsource a PMP. In the questionnaire the non-compliance with objectives established in the setting up of the PMP could be seen. The company lacked technical and organizational aspects that direct the decisions towards outsourcing. The aspects that have influenced in the result are: lack of historical information regarding machinery, lack of CMMS, lack of computer skills in relation to maintenance personnel and no qualified manager for the PMP. Besides, some mistakes have been developed in the setting up of the PMP: not only critical machinery has been incorporated in the PMP, different diagnostic techniques were applied in vibration and lubricant analysis in their lower technological level, when more sophisticated diagnostic techniques would have been more suitable.

Predictive efficiency is an indicator that informs us about the costs caused by low quality in the PMP. The objective is to evaluate the technical quality of the PMP. For each time period it is defined as [16]:

$$\sum_i \frac{\text{Number of positive failures detected (predictive maintenance)}}{\text{Number of total failures}} 100 \tag{12}$$

The predictive efficiency is 0.33% in the food industry. This low predictive efficiency is due to the low assignation of resources to training, consulting and acquisition of instrumentation.

The PMP has no influence over corrective and preventive maintenance activities, so these maintenance policies are maintained and there is a similar state (or an increase in activities) to that previous to the set up of the PMP (see Fig. 3). This behaviour increases the maintenance cost, limits the success of the PMP and interferes with its operation. Only 10% of the machinery of the PMP is critical; consequently, the profits that the PMP can provide in critical machinery do not compensate the cost that the PMP generates in noncritical machinery. The set up PMP has not been controlled and no extensions of the PMP have been made. The company did not consider that the objectives established with the PMP had been reached, however, the company had appreciated some positive results such as the detection of failures and collaboration of productive personnel.

Sensitivity analysis allows us to examine how the ranking of options might change under different weighting [29]. Saaty establishes: 'one would take the existing priorities and perturb them by small values up and down in combinations and note the resulting stability of the priorities of the alternative' [68].

The maintenance manager was consulted to verify the local priorities of criteria. He suggests varying the criterion Quality (Q) because maybe its local priority was too little in contrast with the importance given to it in the company. The sensitivity analysis (see Table 8) checks that there was no change in the ranking of alternatives. The global priority, with the change in local priority in the criterion Quality, is 0.610 in the alternative not to set up a Predictive Maintenance Programme (ALT 3).

The petrochemical plant comprises four subsidiaries and also participates directly or indirectly in over 50 enterprises.

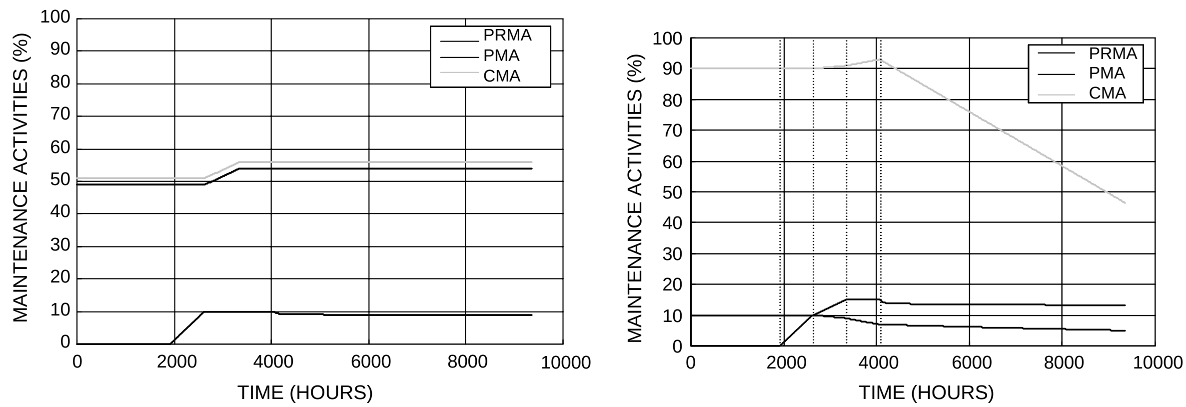

Fig. 3. Evolution of the corrective (CMA), preventive (PMA) and predictive (PRMA) maintenance activities in a food industry (left) and in a petrochemical plant (right).

The analysis undertaken in this paper refers exclusively to the subsidiary dedicated to the production of liquid petroleum gases obtained in the process of refining from crude oil. This subsidiary was created in 1957. Its maximum production is 6000 bottles per day. It has a total of 120 machines of which 18 are pumps, 8 are compressors, 43 are engines, 20 are pneumatic systems, and 4 machine-tools, the rest being machinery of lesser importance. Two machines are considered critical in relation to safety and availability in the plant. The costs related to repairs are 30,000 euros per year, but all the machinery is considered to be important and as a result all the equipment has been incorporated in the PMP starting with the most critical. The enterprise has 33 workers of which 8 belong to the Maintenance Department. There are two 8 h workshifts. The enterprise has a CMMS which stores historical information about failures and machinery. The maintenance personnel have computer skills; one of the workers of the Maintenance Department is a university graduate, whilst the rest have received professional training oriented towards maintenance specialities. 30,000 euros a year are invested in the training and recycling of maintenance personnel. 25% of the maintenance activities undertaken in the enterprise are corrective, 25% are predictive and the remaining 50% are preventive. The preventive maintenance policy has been applied over the last 10 years.

The petrochemical plant had the following results from the Evaluation System:

- In the analysis of the Capacity to develop the setting up of a Predictive Maintenance Programme (CST-PMP) the Evaluation System suggests the alternative to set up a PMP internally (ALT 1); the global priority is 0.409.
- In the variable Necessity of implementation of a Predictive Maintenance Programme (NST-PMP), the Evaluation System gives to set up a PMP (ALT 1) as the alternative with a global priority of 0.674.
- Clustering the results by means of the decision rules, the Evaluation System suggests setting up a Predictive Maintenance Programme.

The results obtained to set up a PMP in this industry are the opposite case to the food industry. The predictive efficiency was 83.3% in the petrochemical plant. The PMP has permitted the elimination of the preventive maintenance as can be

Table 8
Sensitivity analysis in a food industry

Decision variables	Local priorities
Safety (S)	8.5
Personal safety (PS)	7.4
Quality (Q)	22.8
Maintenance costs (MC)	13.7
Environmental safety (ES)	1.1
Availability of plant (A)	38.6
Probability of occurrence of annual personal accidents (PPA)	6.2
Product quality (PDQ)	15.2
Number of critical machines in the industrial plant (NCM)	10.2
Repair costs from the preventive and corrective maintenance activities (RC)	9.1
Process quality (PQ)	7.6
Optimisation (OP)	6.2
Personal consequences for the more probable type of accident that may occur (PC)	1.2
Spares costs (SC)	4.6
Probability of occurrence of annual environmental accidents (PEA).	0.9
Environmental consequences for the more probable type of accident that may occur (EC)	0.2

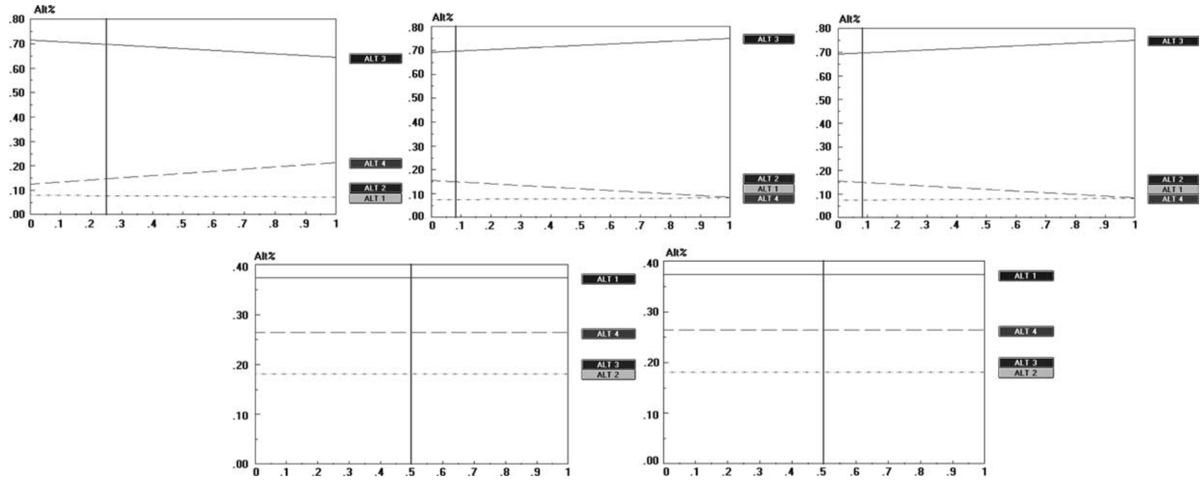

Fig. 4. Sensitivity analysis (variables human resources (HR), technical resources (TR), return of investment period (RI), process quality (PDQ) and product quality (PQ) (from left to right and from top to bottom).

appreciated in Fig. 3. The industry has obtained the following benefits: a reduction in insurance costs and maintenance costs (80%) in the first months of the setting up; a similar reduction was obtained in corrective maintenance. The decrease in corrective maintenance and preventive maintenance costs are 90 and 94%, respectively, a year after the set up. The cleanliness of the plant has improved and the number of accidents due to machinery included in the PMP is nil. The tendency towards the optimum is due to suitable assignation of resources, control and verification of the results of the PMP and adequate treatment of the traditional maintenance activities when the PMP is set up. The PMP set up was controlled. The PMP has been operating for some years and the initial investment has been recovered.

To develop the sensitivity analysis the maintenance manager considered the increase in the local priorities assigned to the criteria Product quality (PDQ) and Process quality (PQ). An analysis of criteria Human resources (HR), Technical resources (TR) and Return of investment period (RI) are considered too. There is no change in the ranking of alternatives proposed by the Evaluation System. Fig. 4 shows the sensitivity analysis corresponding to the petrochemical plant.

6. Conclusions

In the Evaluation System designed technological, organizational and control issues, have been incorporated that up until now had not been sufficiently researched in the topic of a Predictive Maintenance Programme. The design of an Evaluation System for the set up of a Predictive Maintenance Programme has been achieved. The scenario variables and decision variables detail theoretical criteria that must be considered when the setting up of a Predictive Maintenance Programme is going to be developed establishing why these criteria must be considered and their implications in the decision making. The evaluation system combines the hierarchy and mathematics of an Analytical Hierarchy Process with Bayesian characteristics and deterministic decision rules that transfer the theoretical aspects of decision making to a practical structure of utility to the enterprise. The results obtained are consistent as can be verified in its application to petrochemical and food industry. The aspects analysed contribute to develop the theoretical and practical decision making about the life cycle of Predictive Maintenance Programmes.

The direction for future research is related to the necessity to extend the analysis developed to additional companies. This will allow more accurate levels of variables to be obtained and to verify if new decision variables are needed in the decision to set up a PMP in the future. This analysis would enable a relationship between the results obtained by the Model and each activity sector to be established.

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