Energy 147 (2018) 767–781

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Criticality-based maintenance of a coal-fired power plant

Arthur Henrique Andrade Melani [a], Carlos Alberto Murad [a], Adherbal Caminada Netto [a], Gilberto Francisco Martha de Souza [a, *], Silvio Ikuyo Nabeta [b]

[a] Mechatronics and Mechanical System Engineering Department, University of São Paulo, Brazil
[b] Energy and Electrical Automation Department, University of São Paulo, Brazil

ARTICLE INFO

Article history:
Received 2 August 2017
Received in revised form 15 December 2017
Accepted 8 January 2018
Available online 4 February 2018

Keywords:
Criticality-based maintenance
HAZOP
FTA
FMECA
ANP
Coal-fired power plant

ABSTRACT

The need for an evolution from the consolidated RCM (Reliability Centered Maintenance) models is something that quite a few experts have been pointing out for quite some time now. Various authors are frequently considering the addition of different techniques in a RCM analysis to increase its efficiency and quality. The objective of this work is to present a method that identifies the most critical components of a system, in order to contribute to the prioritization of maintenance actions. The method uses reliability and risk analysis techniques, such as Hazard and Operability Study (HAZOP), Fault Tree Analysis (FTA) and Failure Modes and Effects Criticality Analysis (FMECA). It also uses a multi-criteria decision method, the Analytic Network Process (ANP), for ranking the most critical components. The method is applied in the Flue Gas Desulfurization System of a Coal-Fired Power Plant. The results obtained with the implementation of the method indicate the most critical components for which maintenance planners shall focus attention, aiming at increasing the availability and decreasing the risk in relation to the plant operation.

1. Introduction

Although corrective maintenance has always been a common activity in all walks of life, modern industrial society has realized for quite some time now, that in many instances it is seldom the most cost-effective way of keeping machinery and equipment available for production or any other intended purpose. Therefore, since the inception of the industrial revolution some kind of scheduled Preventive Maintenance (PM), based simply on experience, was implemented by the early builders and operators of industrial equipment [1].

As technology evolved, however, and with the development of reliability engineering particularly by the electronics industry, it soon became clear that it would be possible to use more accurate methods in PM instead of relying on experience and judgment alone. It was the airline industry task force, formed in 1960 to investigate the capabilities of preventive maintenance, which led to the development of a series of guidelines to be used by airlines and aircraft manufacturers when establishing maintenance schedules for their aircraft. In 1974, the US Department of Defense commissioned United Airlines to write a report on the processes used in the civil aviation industry for the development of maintenance programs for aircraft [2]. Besides the use of PM, the task force proposed the use of predictive maintenance (PRM) based on the development of machine monitoring and diagnostic techniques where preventive actions are taken when failure symptoms are detected and recognized. This report [3], entitled Reliability-Centered Maintenance (RCM), has become a basic reference for all subsequent RCM approaches to this day.

From its aviation-related onset, RCM experienced a widespread acceptance wherever maintenance is considered a required activity [4–7]. According to NASA [8], RCM and its variations are employed to address reliability issues in order to improve overall equipment effectiveness and lower its life cycle cost.

According to those references, RCM can be defined as a methodology to determine what must be done to ensure that the equipment continues executing its intended functions, with a predefined performance in a specific operational context with a minimized maintenance cost.

As an evolution of the RCM philosophy and considering that maintenance activities may contribute to control business risks, the Risk-Based Maintenance (RBM) philosophy was proposed to

* Corresponding author.
E-mail addresses: melani@usp.br (A.H.A. Melani), carlos.murad@usp.br (C.A. Murad), adherbal@usp.br (A. Caminada Netto), gfmsouza@usp.br (G.F.M. Souza), nabeta@pea.usp.br (S.I. Nabeta).

https://doi.org/10.1016/j.energy.2018.01.048
0360-5442/

determine the priority of maintenance using risk concepts that integrates both equipment failures and asset safety analysis [9,10]. The objective of RBM is to reduce the overall asset operational risk that may result as consequences of unexpected failures of asset pieces of equipment. The high-risk components shall receive priority attention from maintenance planners aiming at reducing their failure probability [11–18].

The decision-making problem regarding the selection of critical components of an asset as for maintenance planning based on RBM concepts can be considered a complex task. The risk profile associated with a component failure mode may be composed of many consequences categories such as threaten to human life, environmental impact, asset damage and loss of production costs. Defining in a monetary base all the consequences may be an extremely difficult and imprecise task. To solve this problem multi criteria decision-making approach may be used once they can handle pair wise comparison of different consequence categories associated with risk description linked to a component failure mode.

The objective of this work is to present a method that identifies the most critical components of a system, in order to contribute to the prioritization of maintenance actions. The method uses reliability and risk analysis techniques, such as Hazard and Operability Study (HAZOP), Fault Tree Analysis (FTA) and Failure Modes and Effects Criticality Analysis (FMECA) to perform asset risk assessment taking as hazards the components failure modes. The consequences for asset performance and safety are evaluated based on criteria that consider threats to human life, environmental impact and operational availability. It also uses a multi-criteria decision method, the Analytic Network Process (ANP), for ranking the most critical components based on their failure consequences evaluation. The method is applied in the Flue Gas Desulfurization System of a Coal-Fired Power Plant.

2. Literature review

The need for an evolution from the consolidated RCM models is something that quite a few experts have been pointing out for quite some time now. As far back as the closing years of the last century Crocker and Kumar [19] already proposed a new approach to RCM using the concepts of soft life and hard life to optimize the total maintenance cost and to find the optimal maintenance policies in the case of military aero-engines using Monte Carlo simulation. In spite of their intention, however, the authors did not provide a conclusive approach about the real advantages of the method application.

Even though risk-based maintenance is in itself an evolution from reliability-centered maintenance proper the application thereof has never ceased to be refined, tuned up as it were. Krishnasamy et al. [20] for instance stated that adapting a risk-based maintenance (RBM) strategy is essential in developing cost-effective maintenance policies, and therefore proposed a RBM methodology comprised of four modules in order to identify critical equipment based on the level of risk and a pre-selected acceptable level of risk. The authors claimed that, in addition to increasing equipment reliability, their approach proved to be capable of reducing the cost of maintenance including the cost of failure when applied to a power-generating unit.

More recently, some authors began to consider that other ingredients should and could be profitably added to the RCM analysis process so as to increase its efficiency and quality. Cheng et al. [21] proposed to borrow case-based reasoning (CBR) from artificial intelligence (AI) and to build a framework for intelligent RCM analysis (IRCMA) considering that the historical records of RCM analysis on similar items can be referenced and used for the current RCM analysis of a new item. In their conclusion the authors stressed that RCM analysis is a much repeated task, and dependent on RCM analysis experience, and indicated that the IRCMA was substituting the traditional computer aided RCM system (CARCMS) within China's military industry, and is becoming the new generation of RCM analysis tool for weapon systems under development.

Being respectively parent and derived concepts, it seems only natural to propose that reliability-centered maintenance and risk-centered maintenance could be the object of a unified approach. Accordingly, Selvik and Aven [22] suggested an extension of the RCM to reliability and risk centered maintenance (RRCM) by also considering risk as the reference for the analysis in addition to reliability. The authors used a case from the offshore oil and gas industry to illustrate and discuss their suggested approach, and concluded that with application of RRCM an improved basis can be established for informing decision makers compared with the RCM method, as the importance of risk and uncertainties is more adequately taken into account.

Both Igba et al. [23] and Sainz and Sebastián [24] are representatives of those authors whose effort is to take the RCM method to wind-powered installations or any similar power generation project independently of its technical complexity or difficulty of access to the industrial plant facilities. In the former paper, the authors stated that they aimed to aim “to take the RCM technique further from just the functional failure analysis and optimization of maintenance strategies by looking more holistically through the application of systems thinking tools & techniques. In their concluding remarks, however, they conceded that limitations with the proposed model focus around the usability. Still within the wind-power domain, Florian and Sørensen [25] later carried out a comparison between two strategies for a lifecycle model built to simulate operation and maintenance activities on the degrading blades of an offshore wind turbine: a conventional condition based strategy and a non-conventional reliability based approach. Maintenance optimization was made for both strategies in terms of lifetime expected cost thereof, and the authors concluded that a reliability-based approach has a higher potential of reducing expenses, mainly because inspections are not carried out unless motivated by a high failure probability in the near future.

In a broader context, i.e., electric power distribution systems, Yssaad et al. [26] on the other hand have approached the subject of the importance and applicability of RCM using a single more conventional methodology based on the FMECA method and its associated Risk Priority Number (RPN). Accordingly, presenting data supplied by an actual electric feeder system (EFS), the authors stressed the importance of assigning maintenance focus levels based on criticality and ranking elements in ascending order above an established inferior “threshold of criticality” value.

Kundu, Chopra and Lad [27] propose an evolutionary risk based maintenance (RBM) methodology to optimize forecast of a gas turbine failures, where risk should be continuously updated with the age of the unit to increase the effectiveness of RBM policy.

The authors claim that, in addition to increasing availability and reducing the overall maintenance cost, their approach leads to the conclusion that Bayesian update can be used to increase the availability and optimize the high value critical assets.

Kiran et al. [28] emphasized the importance of adequate maintenance planning. It is interesting to note that those authors adopt the modern standpoint of placing on the same level equipment efficiency and environmental protection. This latter concern is paramount not only in their cement plant example but also in the majority of present electricity generation plants, particularly in those burning coal.

According to Arunraj and Maiti [29] the Saaty's Analytic Hierarchy Process AHP multi criteria decision making approach was used in the field of maintenance strategy selection considering as decision criteria repair costs, repairability, frequency of equipment failure and failure detection which compose the risk associated with equipment failure.

Kumar and Maiti [30] provide a revision of methods employed to face the multiple criteria decision-making problem of maintenance policy selection. The authors focused on the shortcomings of Saaty's AHP that uses hierarchal approach with crisp values for pair-wise decision, and suggested that once the Analytic Network Process (ANP) handles all kinds of relationships existing between goal, criteria and alternatives, this latter method provides better results and should preferably be used as for maintenance selection problem. As a matter of fact, the preference for ANP over AHP seems to be shared by other authors [31–33].

Because of its hierarchical framework, however, AHP cannot represent problems that involve interdependencies and feedback between criteria and alternatives. This type of relationship, when taken into account in the analysis, can make the obtained results more accurate. When the top-down model fails to present a reliable picture the problem setting, another approach must be taken. The Analytic Network Process (ANP) is a multi-criteria decision technique that, differently from AHP, can take into account theses interdependencies.

Finally, Tang et al. [34] focused on the central question of the identification of maintenance significant items (MSI) in RCM in order to significantly reduce the quantity of items for analysis, and remarked that at present there is little systematic and convenient operation method to identify the MSI. They then go on to propose a combined quantitative and qualitative approach for scoring the MSI that encompasses techniques such as FMEA, risk analysis (RA), analytic hierarchy process (AHP) and fuzzy Borda count (FBC). Presenting a case from the gas and oil industry, they concluded that by applying the systematic analysis method of the MSI, an improved basis can be established for informing decision makers compared with the traditional method in RCM, as the importance of risk of failure mode and influence factor is more adequately taken into account.

The preceding review led the authors of the present paper to identify a research gap that had to be filled in, i.e., in addition to the identification and ranking of equipment from a broader criticality point of view in order to improve the thoroughness of the RCM analysis process and the cost effectiveness of results, the need for an altogether more thorough selection method involving not AHP but the more discriminating ANP (Analytic Network Process) instead.

The proposed method uses functional Tree coupled to System Modeling Language (SysML) Internal Block diagram to acquire, structure and organize knowledge about system operational requirements and their relations with its components performance. The functional analysis serves as a basis for system functional breakdown aiming at identifying the required function of each component in order to support the system to accomplish its mission. The reliability and risk analysis techniques are used to evaluate the system inability to realize desired operational objective in case of occurrence of components failures. Failures impact the performance and effectiveness of not only the associated functional element but also the overall system. That impact may be categorized in loss of performance, repair costs necessary to recover system operational condition, loss of operational safety and environmental effects.

Taking in view that each component failure is associated with a consequence that in certain degree affects system performance, a multi criteria decision-making method, such as ANP, must be used to prioritize the component criticality taking in view the consequence categories. Maintenance planning must consider the higher risk components as priority to avoid asset loss of performance.

3. The proposed method

The objective of the proposed method is to identify the most critical components of a coal-fired power plant in order to prioritize maintenance actions. The method is divided into three steps, as shown in Fig. 1.

The first step is the development of a study of the system through two techniques: Functional Tree and Internal Block Diagram. These techniques are used to acquire knowledge, in a structured way, about how the studied system works. In the second

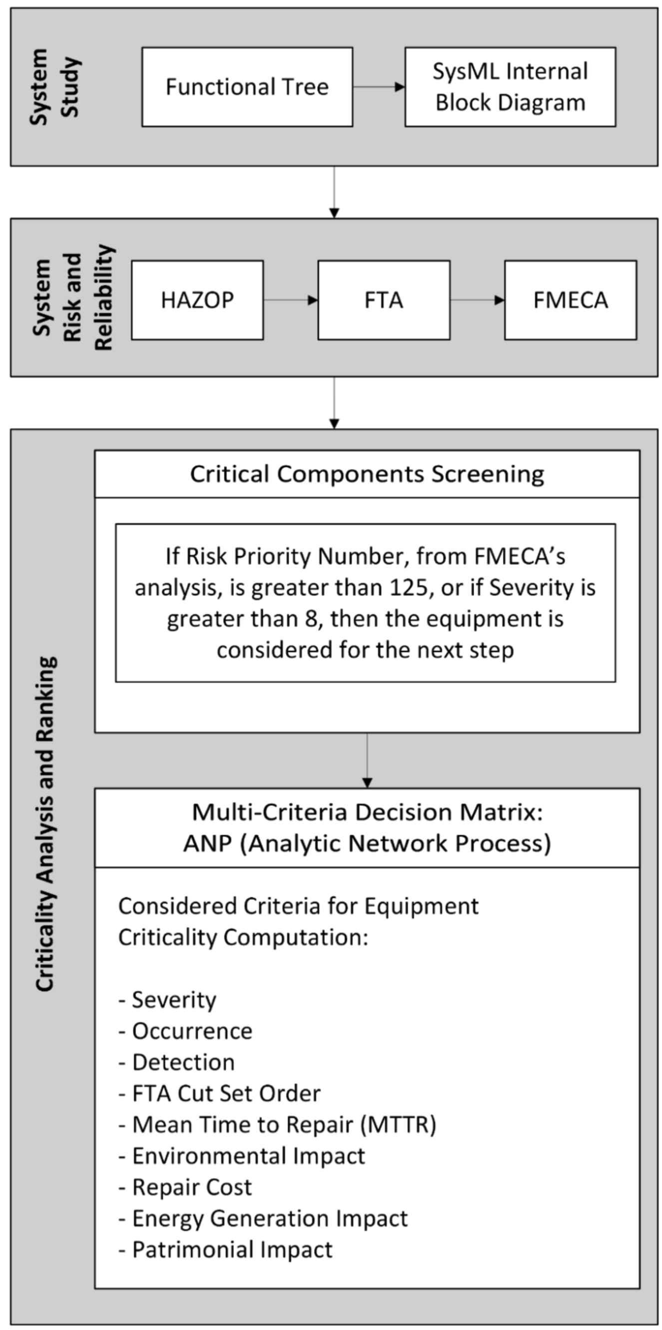

Fig. 1. The proposed method.

step, three reliability analysis techniques are used: HAZOP, FTA and FMECA. The purpose of this phase is to assess how the system components fail, what the consequences of these failures are and how they can be identified. Finally, in the third step, the Analytic Network Process is used to obtain the most critical components.

All the techniques used in this method contribute to the accomplishment of the next, that is, they are developed in an integrated way, aiming at obtaining optimized results. The next items in this section are dedicated to the detailed description of each step performed.

3.1. System study

3.1.1. Functional tree

The purpose of a Functional Tree (FT) is to structure, in a logical and hierarchical way, the interdependence between the different components of a system, in order to expose how each one performs its functions.

The construction of the Functional Tree must be systematized, relying not only on the interrelationships between the components of the given system, but also on the description of the functions of each one. That is why the execution of the FT must be accompanied by the Functional Description (FD) of the system components. In the FD, the main functions of each component and subsystem are listed.

3.1.2. Internal block diagram

The Internal Block Diagram (IBD) is just one out of nine diagrams present in Systems Modeling Language (SysML). SysML is a general-purpose modeling language for application in systems engineering, supporting the specification, analysis, design, verification and validation of a wide spectrum of systems.

The construction of the IBD has the purpose of defining the interfaces and types of information exchange between the components of any system. This diagram highlights the monitored parameters and their relation with the operating condition of the subsystem under analysis [35]. This type of information, not contained in the Functional Tree, is fundamental to the development of HAZOP in the next step of the method.

3.2. Risk and reliability study

The techniques used here are HAZOP, FTA and FMECA. Fig. 2 presents how these techniques are integrated for acquiring knowledge about how the system components fail, what are the consequences of these failures and how they can be identified. First, HAZOP is used to identify deviations of operation parameters in the system and to identify its consequences. Given each identified deviation, the possible causes of it are listed through the application of the FTA technique. Once the Fault Trees for each identified deviation are elaborated, the FMECA is applied, since the basic events listed in the FTA are the failure modes of the system components. Each technique is further described in the next items of this section.

3.2.1. HAZOP

The Hazard and Operability Study (HAZOP) is a structured and systematic technique to identify and document hazards through an existing process. It allows identification and evaluation of abnormal causes of process deviations from normal behavior and its adverse consequences [36–38]. HAZOP is a qualitative technique based on guide-words and its application can be divided into four steps:

1) Define the system in study and its boundaries;
2) Locate system process monitoring points (called nodes) based on SysML internal block diagram analysis;
3) Determine parameters to be monitored in each node;
4) Identify possible parameters deviations, its causes (in the proposed method, this is done by the FTA) and consequences.

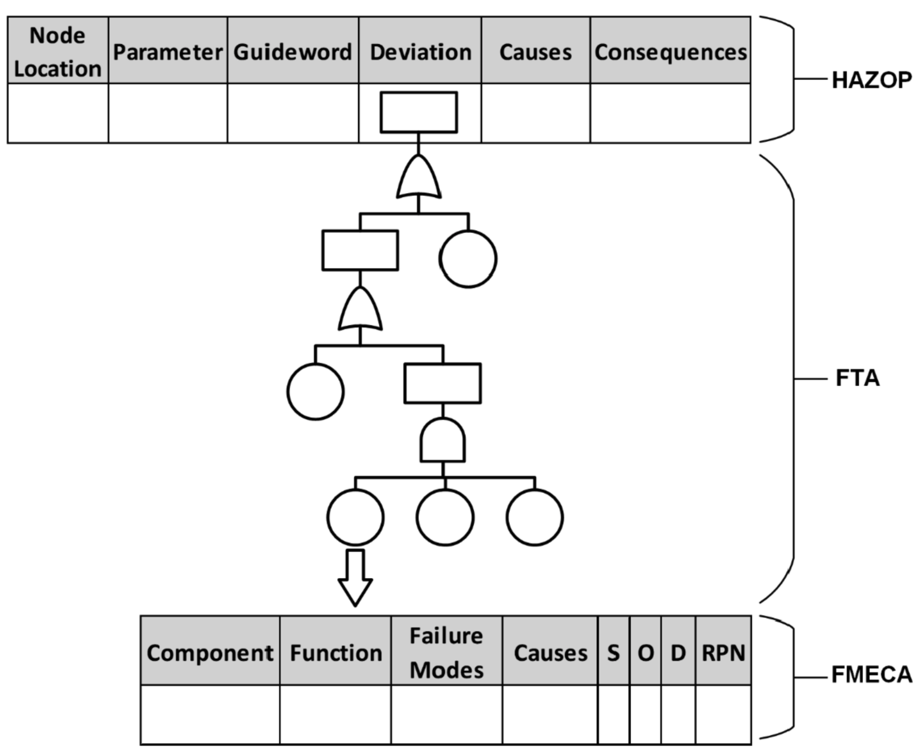

Fig. 2. Risk and Reliability Study by integrating HAZOP, FTA and FMECA.

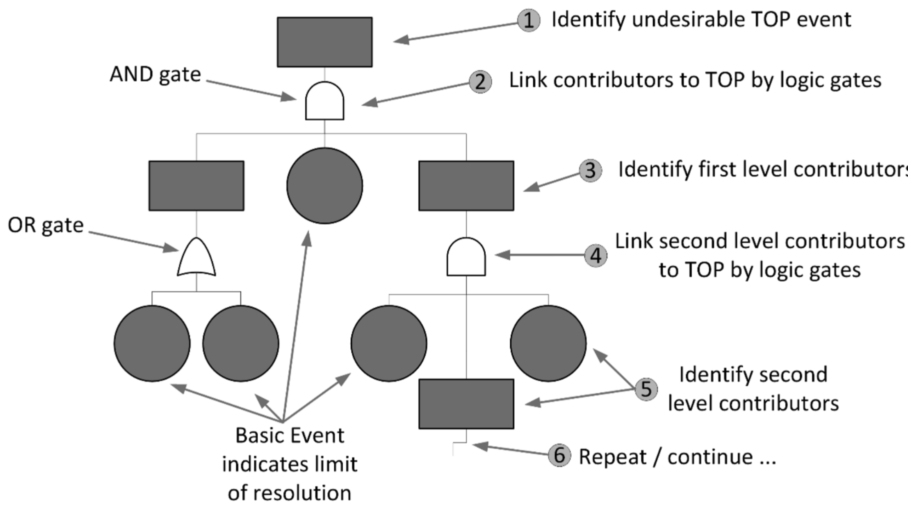

Fig. 3. Basic Logic symbols and steps to build a Fault Tree.

A table composed of six columns is used to implement the HAZOP technique as shown in Fig. 2.

3.2.2. *FTA*

The FTA is a deductive method in which an undesired event, called a top event, is defined and, from there, the causes or combinations of causes that can lead to the occurrence of this event are systematically defined [39–42].

The fault tree itself is made up of events, including the top event, and logical connectors linking them. Basic logical connectors and events are identified in Fig. 3, which also explains briefly how the fault tree is developed. The basic events are usually failure modes at component level.

The AND gate indicates that all sub-events must happen for the main event to occur, whereas the OR gate indicates that the occurrence of only one of the sub-events is required to trigger the main event. This means, therefore, that failures must occur in certain combinations in order for the top event to occur. A combination of basic events which leads to the main event is called a cut set. A minimal cut set is a cut set which cannot lead to the top-level hazard if only one event of the set is prevented, [41].

3.2.3. *FMECA*

The third step of the methodology involves the definition of root causes of failures of components listed in FTA cut sets. The present method uses the Failure Mode, Effects and Criticality Analysis (FMECA) to identify the components (equipment) failure modes and the impacts on their performance [42], once this tool became object of standardization in many industrial areas [43–50]. The analysis tool assumes that a failure mode occurs in an equipment or component through some failure mechanisms that may be eliminated through maintenance actions. As for component failure modes criticality definition the method proposes the use of the Risk Priority Number (RPN), computed as follows:

$$RPN = S \times O \times D$$

In the equation above S stands for Severity (representing the impact of the postulated failure mode on the operation of the equipment under consideration, named as local effect), O means Occurrence (representing the frequency of occurrence of each component failure mode) and D is Detection (indicating the possibility of detection of component failure mode development during plant operation). Their values are set on a scale 1 to 10, as shown in Table 3 presented in section 3.3 The higher the RPN the mode critical is the failure mode.

As shown in Fig. 2, the present paper uses a table composed of eight columns to implement FMECA analysis.

3.3. *Criticality analysis and ranking*

In order to rank the most critical components of the system under study, a screening process is required. Therefore, by analyzing the results obtained through the FMECA, only those components with an NPR greater than 125 or those with severity greater than 8 are considered for the ranking.

The ranking is then performed through the application of the ANP technique. ANP is a multi-criteria decision making technique that structures the decision problem as a network. Although conceptually more complex than its predecessor AHP, the ANP is not limited to a hierarchical structure among objectives, criteria, sub-criteria and alternatives, and can therefore deal with more complex real situations.

The detailed steps for the application of the ANP can be seen in Ref. [51]. The objective of using the ANP technique to rank components in relation to their criticality is to obtain a result that is true

Table 1
Fundamental scale.

Intensity of importance	Definition
1	Equal Importance
2	Weak
3	Moderate Importance
4	Moderate plus
5	Strong Importance
6	Strong Plus
7	Very Strong Importance
8	Very, Very Strong
9	Extreme Importance

Table 2
RI values, depending on the size of the pairwise matrix [52].

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.51	1.54

Table 3
FMECA's severity, occurrence and detection.

Severity	Occurrence	Detection	Score
Dangerously High	$\lambda > 0.01$	Absolute Uncertainty	10
Extremely High	$0.01 > \lambda > 5*10^{-3}$	Very Remote	9
Very High	$5*10^{-3} > \lambda > 2.5*10^{-3}$	Remote	8
High	$2.5*10^{-3} > \lambda > 10^{-3}$	Very Low	7
Moderate	$10^{-3} > \lambda > 5*10^{-4}$	Low	6
Low	$5*10^{-4} > \lambda > 10^{-4}$	Moderate	5
Very Low	$10^{-4} > \lambda > 5*10^{-5}$	Moderately High	4
Minor	$5*10^{-5} > \lambda > 10^{-6}$	High	3
Very Minor	$10^{-6} > \lambda > 10^{-7}$	Very High	2
None	$10^{-7} > \lambda$	Almost Certain	1

to the reality of the decision problem.

For the ANP to rank the components in order of criticality, it is first necessary to define the elements of the network, i.e., to determine which are the criteria and components that will be part of the decision process. It is also necessary to organize such elements into clusters, which contribute not only to better organization of the network but also to represent the influences between groups of elements.

Once the elements of the network are properly defined and clustered, the interdependencies between them need to be represented. In the graphical model, such interdependencies are evidenced through arcs from one element to another, which is influenced by the first. Such influences are also represented by the Influence of Matrix.

Considering a decision problem with clusters, $C_1, C_2, \ldots, C_N$, and elements $e_1^1, e_2^1, \ldots, e_M^N$, where e_M^N is the element M from the cluster N, the Influence Matrix is given by:

$$I = \begin{bmatrix} i_{1,1}^{1,1} & \cdots & i_{1,M}^{1,N} \\ \vdots & \ddots & \vdots \\ i_{M,1}^{N,1} & \cdots & i_{M,M}^{N,N} \end{bmatrix}$$

If $i_{i,j}^{k,h} = 0$, that means the element i, from cluster k, has no influence on element j, from cluster h. But $i_{i,j}^{k,h} = 1$ indicates element i, from cluster k, has some influence on element j, from cluster h.

Once the Influence Matrix is defined, it is also necessary to determine the influences between clusters, as follows:

$$\hat{I} = \begin{bmatrix} \hat{\imath}^{1,1} & \cdots & \hat{\imath}^{1,N} \\ \vdots & \ddots & \vdots \\ \hat{\imath}^{N,1} & \cdots & \hat{\imath}^{N,N} \end{bmatrix}$$

$\hat{\imath}^{k,h} = 0$ means no element from cluster k has any influence on any element from cluster h. But $\hat{\imath}^{k,h} = 1$ indicates some element from cluster k has some influence on at least one element from cluster h.

The next step of the ANP method is to compare the influences of the elements of each cluster on any element through pairwise matrices:

$$P = \begin{bmatrix} p_{1,1} & \cdots & p_{1,n} \\ \vdots & \ddots & \vdots \\ p_{n,1} & \cdots & p_{n,n} \end{bmatrix}$$

A pairwise matrix P compares the elements on a cluster regarding its influence in any other element and is filled with the 1-to-9 Saaty's scale, shown in Table 1. In this matrix, if $p_{i,j} = 9$, for example, the element on roll i is extremely more influent that the element in column j. If $i = j$, $p_{i,j} = 1$.

It is important to note that pairwise matrices are populated by domain experts, and to compare if their judgments are consistent, the Consistency Ratio (CR) is computed as follows:

$$CR = \frac{(\lambda_{max} - n)}{RI \cdot (n-1)}$$

Where λ_{max} is the maximal eigenvalue of P, n is the pairwise matrix size and RI is a Random Index, which value depends on n, as shown in Table 2.

The eigenvectors for each pairwise matrix are derived and aggregated into the Unweighted Supermatrix:

$$U = \begin{bmatrix} u_{1,1}^{1,1} & \cdots & u_{1,M}^{1,N} \\ \vdots & \ddots & \vdots \\ u_{M,1}^{N,1} & \cdots & u_{M,M}^{N,N} \end{bmatrix}$$

In the Unweighted Supermatrix, $u_{i,j}^{k,h}$ represents the influence of element i, from cluster k, on element j, from cluster h, and has a value from 0 to 1, obtained from the eigenvectors of the pairwise matrices. If $u_{i,j}^{k,h} = 0$, element i has no influence on element j, and if $u_{i,j}^{k,h} = 1$, the element i is the only one from cluster h that has influence on element h.

As the pairwise matrices were obtained for each element in ANP analysis, such matrices are also obtained for each cluster, its eigenvectors are also computed and aggregated, forming the Cluster Weights Matrix, $\hat{U}$:

$$\hat{U} = \begin{bmatrix} \hat{u}^{1,1} & \cdots & \hat{u}^{1,N} \\ \vdots & \ddots & \vdots \\ \hat{u}^{N,1} & \cdots & \hat{u}^{N,N} \end{bmatrix}$$

Where $\hat{u}^{k,h}$ represents the influence of cluster k on cluster h and has a value from 0 to 1. Then, the Weighted Supermatrix, W, is computed as follows:

$$W = \begin{bmatrix} w_{1,1}^{1,1} & \cdots & w_{1,M}^{1,N} \\ \vdots & \ddots & \vdots \\ w_{M,1}^{N,1} & \cdots & w_{M,M}^{N,N} \end{bmatrix}, \ where \ w_{i,j}^{k,h} = u_{i,j}^{k,h} \cdot \hat{u}^{k,h}$$

In the Weighted Supermatrix, $w_{i,j}^{k,h}$ represents the weighted influence of e_i^k on e_j^h. Then, W is normalized, obtaining the Normalized and Weighted Supermatrix, Z, as follows:

$$Z = \begin{bmatrix} z_{1,1}^{1,1} & \cdots & z_{1,M}^{1,N} \\ \vdots & \ddots & \vdots \\ z_{M,1}^{N,1} & \cdots & z_{M,M}^{N,N} \end{bmatrix}, \ where \ z_{i,j}^{k,h} = \frac{w_{i,j}^{k,h}}{\sum_i \left(w_{i,j}^{k,h}\right)}$$

In the Normalized and Weighted Supermatrix, $z_{i,j}^{k,h}$ represents the normalized and weighted influence of e_i^k on e_j^h. Finally, Z is raised to large powers until all the values in a row converge to the same number, obtaining the Limit Supermatrix, L, as follows:

$$L = \lim_{x \to \infty} Z^x = \begin{bmatrix} l_1 & \cdots & l_1 \\ \vdots & \ddots & \vdots \\ l_n & \cdots & l_n \end{bmatrix}$$

In the Limit Supermatrix, all columns are equal. In it, l_i represents the final weight of e_i. If e_i represents a criterion, l_i is the importance of that criterion, but if it represents a component, l_i is the ranking criticality of that component.

The criteria used in the proposed method to take part in the decision problem are:

- Severity: represents how severe the effects of a fault are from the point of view of the equipment. An index varying from 1 to 10, shown in Table 3, is used to express severity and considers the possibility of deaths or injuries and degree of component operational degradation. The worst the local effect the higher is the component severity.
- Occurrence: represents how often the equipment fails. The occurrence evaluation shall ideally be based on power plant failure historical data, but, in case of lack of internal information, it can be estimated based on published failure database or even on expert opinion elicitation. The occurrence ranking is associated with the likelihood that the failure mode will occur during operational campaign of the component under analysis. The higher the likelihood of occurrence the higher the occurrence ranking, as shown in Table 3.
- Detection: represents the detectability of a fault, i. e., if the failure can be detected before it happens. The easier the failure mode development (meaning the detection of component degradation) is detected the lower is the detection index, defined according to Table 3. The detection evaluation can be based on measurements of parameters (such as vibration, temperature or flow) indicated on plant distributed control system (DCS) or even offline collected on inspection routes. Detection requires data gathering, comparison to standards, trending over time and comparison to limits set in plant for specific equipment. Condition monitoring can prevent costly electrical power generation interruption due to equipment failures once it recognizes faulty condition in the early equipment operational degradation stages.
- FTA Cut Set Order: represents the possibility of a component failure to interrupt a process in the plant. The analysis is based on minimal cut sets configuration. Minimal cut sets are categorized as singlets, doublets and so on, according to the number of failure events in the cut set. Cut set information is used in assessing qualitatively the importance of a particular component. If component failure appears in one or more of the low-order cut sets, its failure probability (or reliability) is likely to have a strong effect on system failure occurrence.
- Mean Time to Repair (MTTR): represents the time consumed for the repair of a certain equipment. Corrective maintenance consists of the actions taken to restore a failed system to operational status. There is a time associated with each corrective action, named time to repair (TTR). A great many factors affect the uncertainty in repair time. Those factors range from ability to diagnose the cause of failure to the availability of equipment and skilled personnel to carry out the repair procedures. So, for a given piece of equipment, repair require different lengths of time and may be represented by their mean value, named MTTR. The greater the MTTR the lower the equipment availability.
- Repair Cost: maintenance costs are dependent on equipment maintenance policy, which can be simply divided in preventive and corrective maintenance. Preventive maintenance is carried out at predetermined intervals and is intended to reduce the degradation of components due to cumulative damage failure mechanisms. Otherwise, corrective maintenance is carried out after a failure. To calculate the cost of corrective maintenance, important data are considered, to be: logistic time (associated with acquisition and delivery of spare parts), active repairs and diagnosis tasks time (associated with labor costs) and spare parts costs. The cost of preventive maintenance in a given time interval is dependent on costs of materials (spare parts and tools), maintainers labor costs and monetary cost of energy production loss due to preventive maintenance shutdown. In case of component failure, not only corrective maintenance cost is considered but also the resources spent in preventive tasks are also considered because they were spent in a non-effective way since those tasks do not avoid the occurrence of failure. Maintenance costs must be accessed through historical accountability database.
- Environmental Impact: represents the pollution generated by the equipment failure or the fact that it is inoperative. All energy conversion methods used to produce power electricity have some environmental impact. The impacts may have an active effect like the emission of airborne pollutants or may have a passive effect like habitat modification. For the present analysis the environmental impact of equipment/component failure is associated with an increase of air emissions, particularly SO_x, NO_x, CO, CO_2 and hydrocarbon that are considered air pollutants, in comparison with the evaluated admissible emission values evaluated during plant commissioning. The impact also includes increase of water use to keep Rankine cycle performance and increase in volume of solid waste, mainly ash.
- Energy Generation Impact: represents the power plant performance loss in terms of net electrical power output due to component/equipment failure. This performance loss is strictly related to the plant design. Generally, performance of thermal power plants is evaluated through energetic performance criteria based on First Law of Thermodynamics. Based on plant energy balance it is possible to gain insight about what are the effects of pieces of equipment failures on plant performance. That analysis is difficult to be executed due to lack of numerical information regarding failure influence on thermodynamics variables. Nevertheless, this analysis can be based on historical data where plant electrical power output decrease is correlated with a specific equipment/component failure mode. The higher that decrease the more important is the equipment as for plant performance.
- Patrimonial Impact: represents the total financial impact generated to the plant due to a certain failure. For each equipment/component failure event, there is a potential harm or adverse consequences to power plant besides loss of electrical power production. Consequences may be quantified in terms of damage radii (that represents the area in which the damage really occur) and damage to equipment located inside the damage radii. Besides equipment damage, there must happen effects to human being, including plant workers and communities surrounding the plant, such as exposition to heat, fire, explosions and chemical hazards (including toxic effects). Specifically to plant workers, depending on the process and materials used, there are potential workplace hazards at different locations of the coal fired power plant.

These criteria are organized into clusters. The first comprises the criteria from FMECA (Severity, Occurrence, Detection). The second one represents the criteria related to maintenance (MTTR, FTA Cut Set Order, Repair Cost). And, in the third, the criteria related to the consequences to the power plant due to the failure of one component are included (Environmental Impact, Generation Impact, Patrimonial Impact). There is still a fourth cluster reserved for components to be ranked. Fig. 4 shows the network model developed, presenting the criteria and the components considered.

The production of electrical power by the combustion of coal is a mature and well-established technology in the industrialized countries of the world. Some 40% of the world's electricity production is based on coal combustion. The world's coal-fired capacity is 1440 GW out of a global capacity of 4509 GW [53].

A conventional coal-fired power plant, as Fig. 5 shows, produces electricity by burning coal in a boiler (steam generator), where water is heated to produce high pressure and high temperature steam. The high-pressure steam flows initially through the throttle

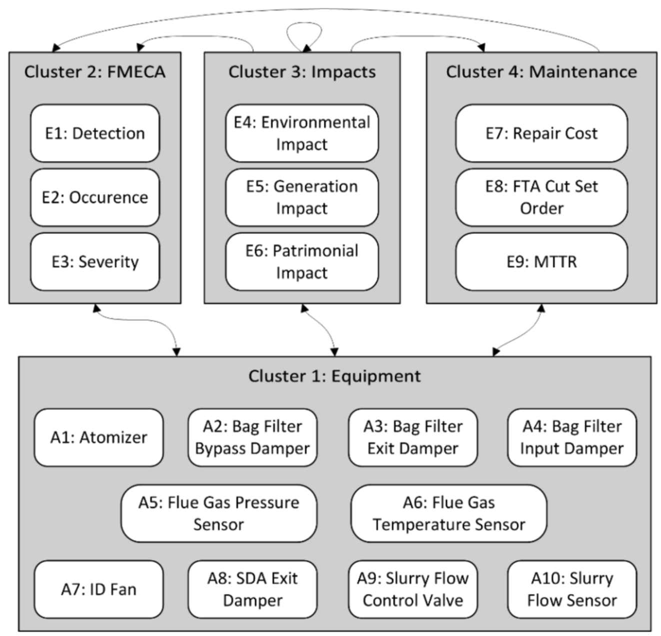

Fig. 4. ANP diagram.

valves and then flows to the governor valves. The governor valves control the flow of the steam into a series of steam turbines (high, intermediate and low pressure) to drive the turbine blades, causing the turbine shaft to rotate at very high speed. The generator mounted at one end of the turbine shaft spins to produce electricity. The exhaust steam from the turbines is cooled, condensed back into water, and then goes through a series of pre-heaters and pumps, raising back its temperature and pressure, to be able to return to the steam generator, starting the whole process again. Coal-fired power plants are highly complex and custom designed on a large scale for continuous operation, 24 h a day, 365 days per year [54].

The Brazilian plant where the study was conducted produces something around 700 MW of electrical power and supplies electricity to more than 75% of the state where it is located. Although the proposed method was implemented in the whole plant, only its results for the Flue Gas Desulfurization System (FGD) are presented in this paper.

3.4. Study of the flue gas desulfurization system

The purpose of the FGD system is to clean the boiler flue gas of sulfur dioxide (SO_2) and sulfur trioxide (SO_3), as well as the particulate material (basically, fly ash). The ducts that leave the boiler are connected to a complete FGD system (see Fig. 6), which consists of: a Spray Dryer Absorber (SDA), Recycle Storage Silo, SDA Feed Tank and SDA Feed Slurry Delivery System, one Bag Filter, one Ash Handling and Storage System (which consists of: Ash Pneumatic Transport Line and Dust Silo).

In the SDA, the flue gas gets in contact with finely atomized droplets of slurry. The SDA feed slurry, injected through rotary atomizers, is a mixture of the lime milk produced at the slaking plant, dilution water and recycled dust (basically, fly ash, calcium hydroxide and calcium sulfite). The SDA feed slurry, in the form of the droplets, provides the reagent (i.e., calcium hydroxide) necessary to absorb the sulfur oxides in the flue gas in an acid-base reaction which produces calcium based salts (e.g., calcium sulfite and sulfate), according to the following reactions:

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O$$

$$Ca(OH)_2 + SO_3 \rightarrow CaSO_4 + H_2O$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

The amount of fresh lime of lime slurry flow from the lime plant is controlled by the SO_2 at SDA inlet flue gas and SO_2 content at the outlet of fabric filter.

The gas temperature is controlled by the amount of slurry injected through the rotary atomizer and sprayed into the SDA, in order to get the highest efficiency of above reactions; therefore, indirectly, the temperature control algorithm influences the amount of water needed for the proper SDA operation. For this purpose, it is important to keep the temperature at SDA outlet as low as possible, although over the adiabatic saturation value (15–18 °C above-consolidated during design stage) in order to guarantee adequate drying of solids and to avoid moisture condensation in the Bag Filter.

After the SDA, the flue gas with particulate material enters the Fabric Filter for final particulate control. Upon entering the Bag

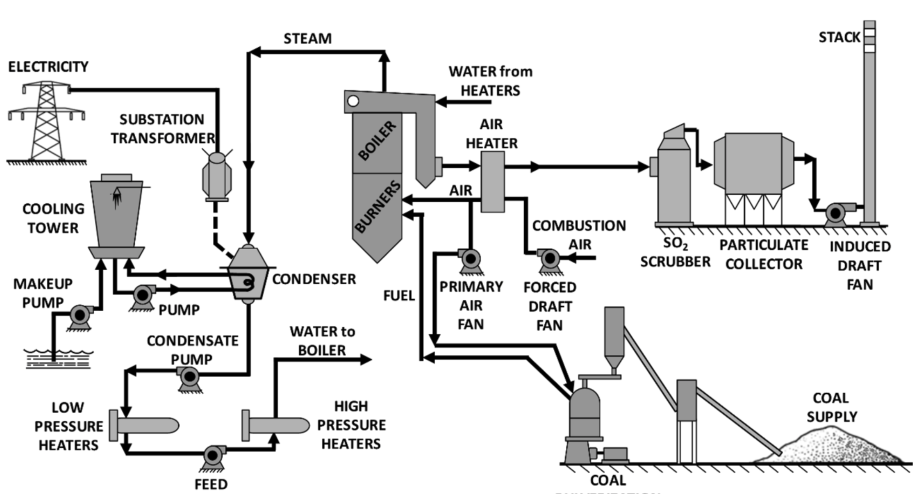

Fig. 5. Schematic of a typical pulverized coal-fired power plant (Woodruff, 2005).

Filter, the flue gas is cleaned by barrier filtration (bags suspended on seven chambers) and released to the Induced Draft Fans, which will remove the de-dusted gas from the fabric filter and forward it to the flue gas stack.

The functional tree of the FGD is shown in Fig. 7. It is possible to notice that the developed tree has seven branches, which represent the subsystems of the FGD. Fig. 7 shows only the details of two of the seven branches, due its size and complexity.

To make such analysis more complete, a functional description of the system was developed, which lists the main function of each component and subsystem presented in the functional tree. A piece of the FD performed is presented in Table 4.

Based on the obtained functional tree, internal block diagrams were developed to represent the interfaces between the previously defined components. As an example, Fig. 8 presents the IBD for the FGD as a whole, considering its seven subsystems and presenting what kind of information they exchange with each other. Other internal block diagrams have been developed for each subsystem.

It is easy to note that IBD and FT present complementary information about a given system. The two techniques allow the acquisition of knowledge about the functioning of the system in a well-structured manner.

3.5. FGD risk and reliability study

HAZOP identifies monitoring points in the system, in addition to the parameters to be monitored, for the detection of component failures, allowing for predictive maintenance actions to be taken. It also highlights the consequences of these failures. Although HAZOP usually presents a list the causes of an observed deviation, these causes are presented, in the proposed method, through FTA.

The development of Fault Trees enables the identification of basic events, which lead to the occurrence of the top event or deviation.

Fig. 9 shows an example of the application of the HAZOP and FTA techniques together. Note that the node location corresponds to an internal block diagram connector (Fig. 8). In general, the connectors present in the IBD (lines that connect blocks and represent information exchange between them) are the places where a node of the HAZOP must be defined, since a deviation in a parameter observed in these nodes indicates a fault that interferes directly in the system operation.

Alongside HAZOP and FTA, the FMECA technique is applied to determine the RPN of each failure mode of components, which are present in the base of the fault tree. Table 5 shows an example of the FMECA application for the engine present in the FTA of Fig. 9.

3.6. FGD most critical components

For the ranking of the most critical components, that is, those whose failures cause greater losses to the plant, the ANP was used. It is important to note that the ANP was only developed considering those components with RPN greater than 125 or for those with severity greater than 8. This happens because the application of the ANP to all the components of the system is impracticable, since this technique is based on pairwise comparisons between them. Fig. 4 shows the ANP network model developed, presenting the criteria and the components considered.

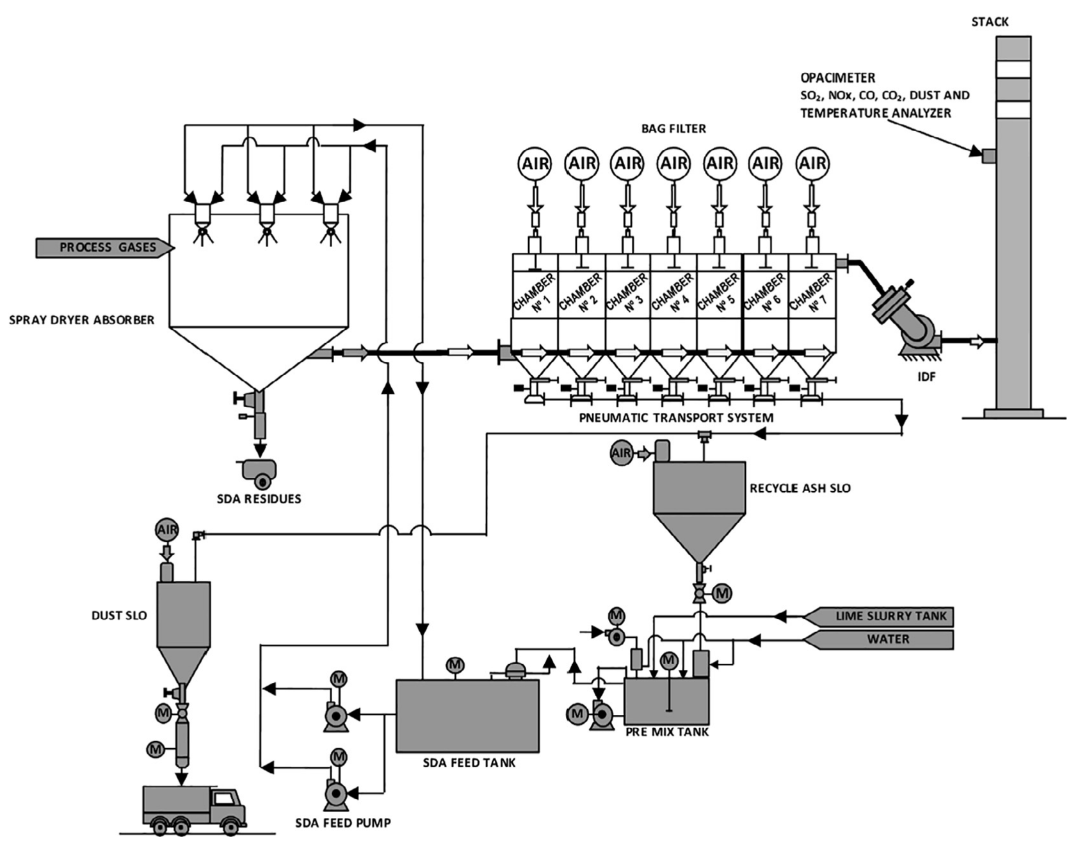

Fig. 6. Flue gas desulfurization system.

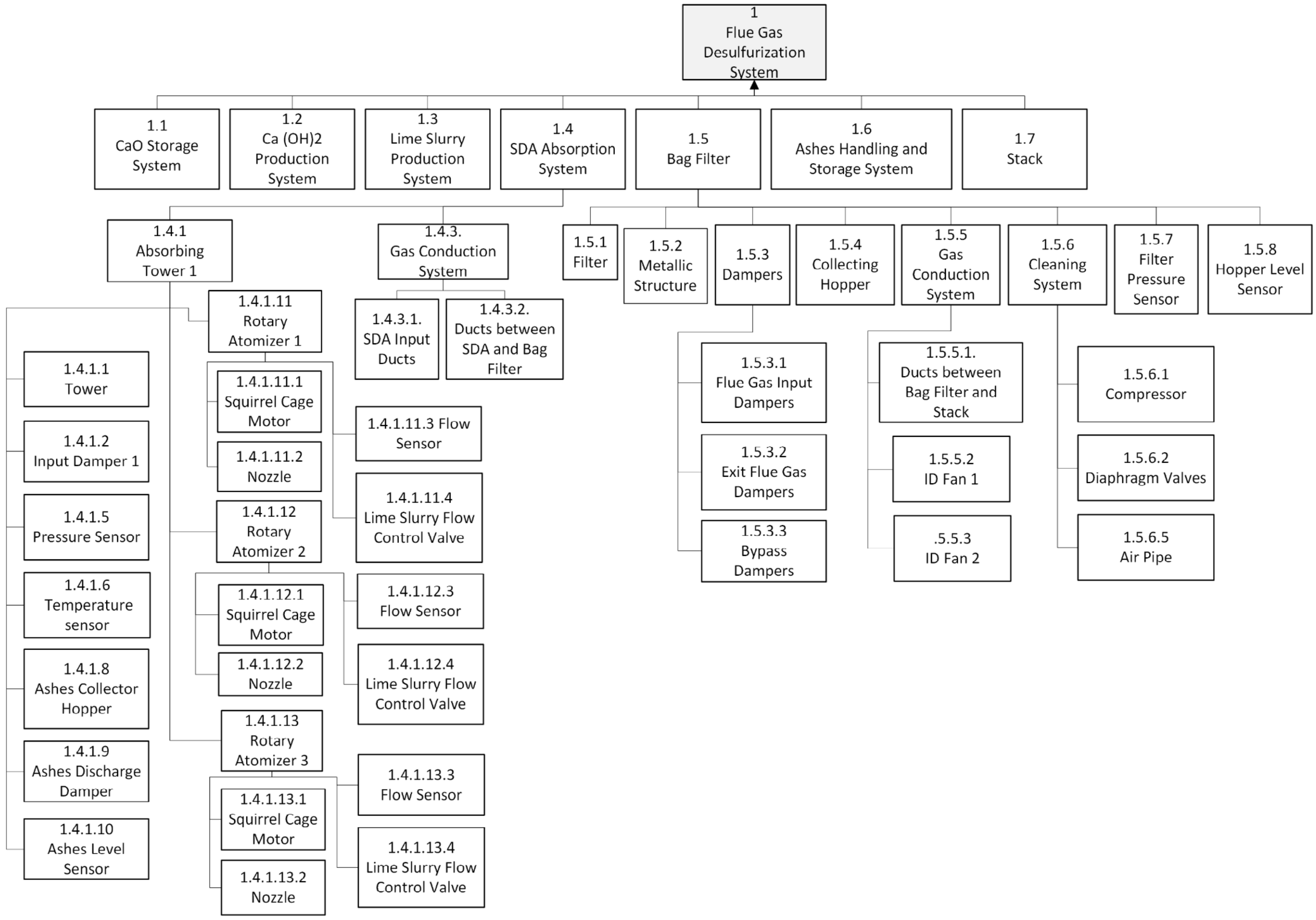

Fig. 7. Partial functional tree of FGD

Table 6 shows the influence matrix obtained through the developed model. In it, the number 1 represents the existence of an influence of the line element under the column element, while the number 0 shows that there is no dependency between the elements of the line and the column.

Once the Influence Matrix has been defined, the Pairwise Matrices need to be developed so that the rankings are done by the ANP, as shown in section 3.3. The Pairwise Matrices were elaborated through queries to system experts, who had to answer a questionnaire with questions like the one presented in Table 7. In it, it is possible to see that the system expert must compare, for example, the criteria present in the cluster “Impacts” in relation to a failure of the “ID Fan” component using the fundamental scale presented in Table 1. Thus, if the “Generation Impact” is strongly influenced by this component rather than the “Environmental Impact”, the system expert must choose the number 5 closest to the “Generation Impact”. Table 7 shows the answers of the system experts for the given example.

The ANP was implemented through the software Super-Decisions [55]. The pairwise comparisons between elements and clusters, acquired from the questionnaire, were implemented in it. Table 8 shows the Unweighted Supermatrix, while Table 9 shows the Weighted Supermatrix. The Limit Matrix is shown in Table 10.

Looking at Table 10, you can see that the most critical equipment is A7 (ID Fan), followed by A1 (Atomizer), A3 (Bag Filter Exit Damper), A8 (SDA Exit Damper), A4 (Bag Filter Input Damper), A9 (Slurry Flow Control Valve), A10 (Slurry Flow Sensor), A5 (Flue Gas Pressure Sensor) and A6 (Flue Gas Temperature Sensor). Table 10 also shows the importance of each criteria on the decision-making process. The most important criterion is E6 (Patrimonial

Table 4
Partial functional description of FGD.

Nº	Description	Function
1	FGD System	Remove SO_2, SO_3 and ashes from flue gas
1.1	CaO Storage System	Receive, store and send CaO to the $Ca(OH)_2$ production system
1.2	Ca(OH)2 Production System	Produce $Ca(OH)_2$ and send it to the lime slurry production system
1.3	Lime Slurry Production System	Produce lime slurry ($Ca(OH)_2$ + water + ashes)
1.4	SDA Absorption System	Remove SO_2, SO_3 and reduce flue gas temperature
1.5	Bag Filters	Remove ashes from flue gas
1.6	Ashes Handling and Storage System	Conduct ashes and store it in the respective silos
1.7	Stack	Conduct flue gas to the atmosphere

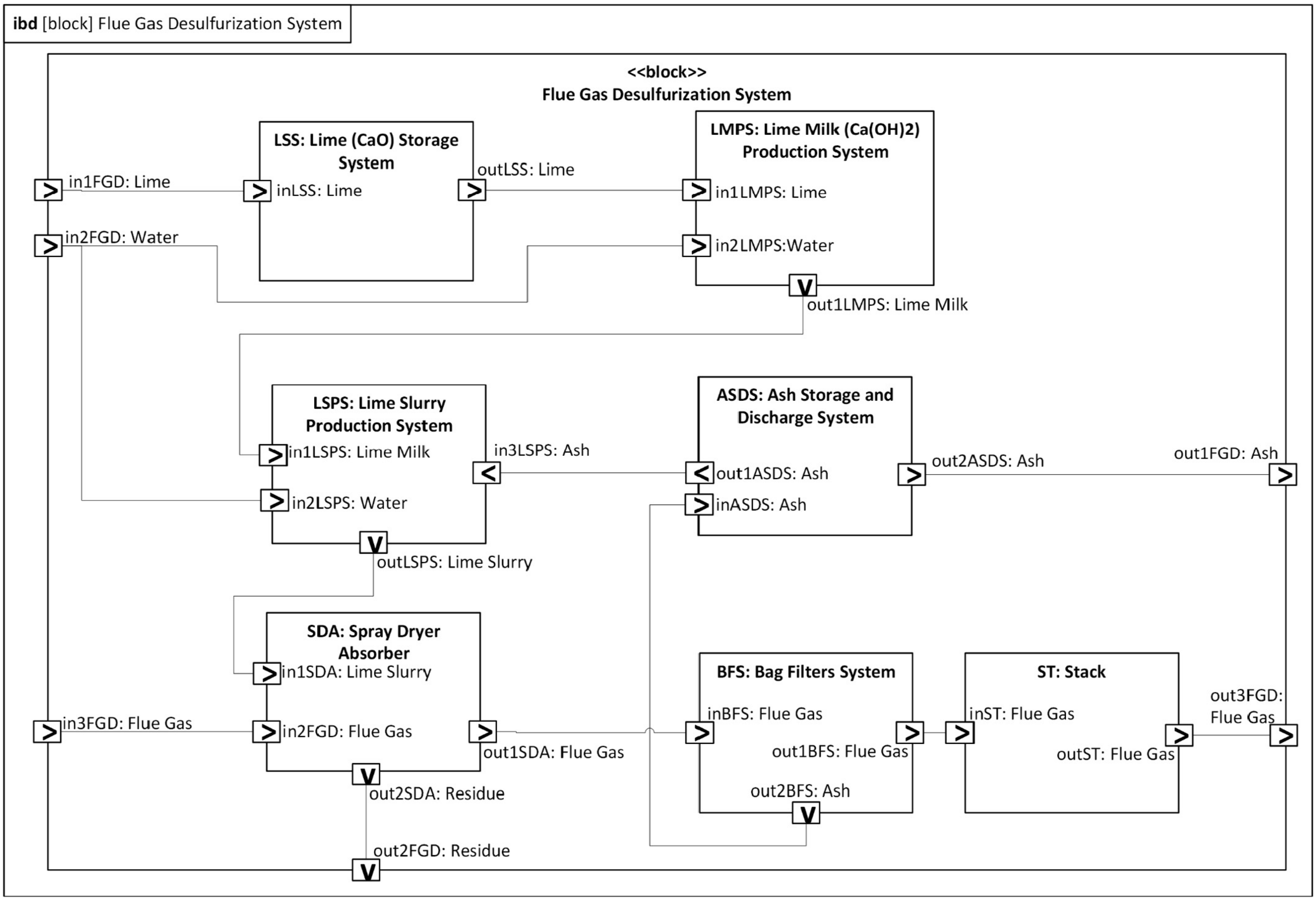

Fig. 8. Internal block diagram of FGD

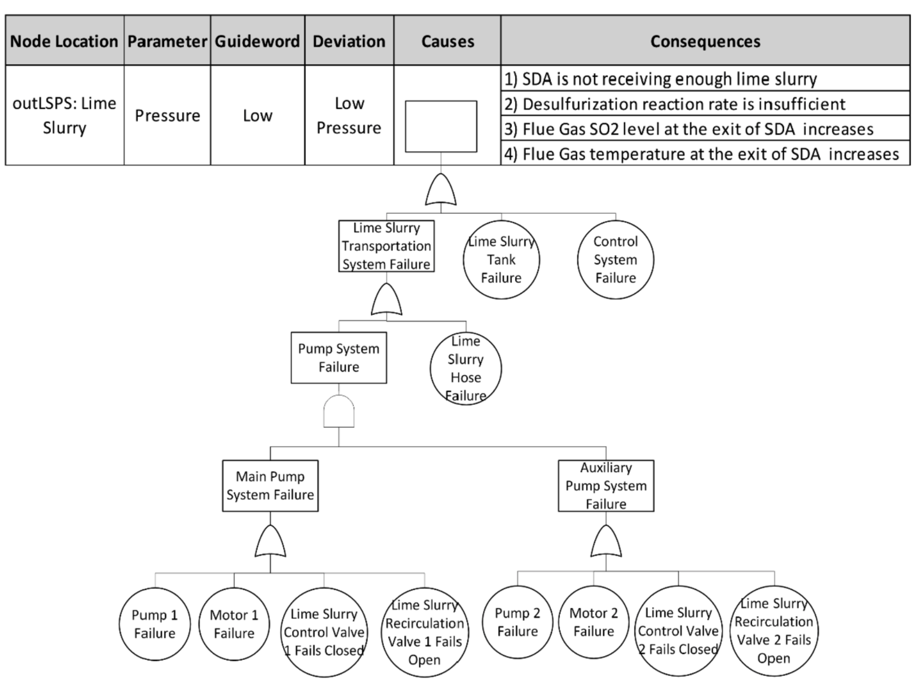

Fig. 9. HAZOP-FTA example.

Table 5
FMECA example.

Component	Function	Failure Modes	Causes	S	O	D	RPN
Motor 1	Transformation of electrical energy into mechanical energy to drive the pump	Does not operate	1) Failure at circuit breaker	5	3	4	60
			2) Loss of insulation of coils	7	1	4	28
			3) Motor overheating	6	4	2	48
			4) Locking of the motor shaft	7	2	5	70
			5) Inadequate ventilation	6	4	2	48
			6) Low or incorrect supply voltage	5	7	2	70
		Excessive vibration	1) Bearing failure	5	6	3	90
			2) Shaft misalignment	7	2	3	42

Table 6
Influence matrix.

		C1										C2			C3			C4		
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	E1	E2	E3	E4	E5	E6	E7	E8	E9
C1	A1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
	A2	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
	A3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
	A4	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
	A5	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
	A6	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
	A7	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
	A8	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
	A9	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
	A10	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
C2	E1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
	E2	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	1	0	1
	E3	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	0	1
C3	E4	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	0	0	0
	E5	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	0	0	0
	E6	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
C4	E7	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	0	0	0
	E8	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0
	E9	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0

Impact), followed by E3 (Severity), E4 (Environmental Impact), E5 (Generation Impact), E8 (FTA Cut Set Order), E7 (Repair Cost), E2 (Occurrence), E9 (MTTR) and E1 (Detection).

The results were shared with the engineering team of the plant and it was possible to realize that these are in agreement with the perception of the team and with historical data of the plant. In fact, the components responsible for the most critical failures of the FGD system were ID Fan and Atomizer. When the ID Fan fails, the flue gas cannot be expelled by the stack, accumulates inside the pipe and, consequently, forces the power generation to stop. In addition, this hot gas can spread through the plant, causing damage to personnel and equipment. When the Atomizer fails, the desulfurization reaction does not occur, causing the emission of toxic gases to the atmosphere. Also, the temperature of the gas is not properly diminished and it gets very hot to the mango filters, which are not designed to withstand such temperature and can catch fire.

3.6.1. *Sensitivity analysis*

SuperDecisions allows the user to perform a sensitivity analysis on the obtained results, aiming to verify whether the results change with a change in the influence that an element has over another. Consider, for example, the Patrimonial Impact, which is the criterion with highest weight. In the weighted supermatrix (Table 9), the column E6 (corresponding to Patrimonial Impact) shows which elements influence this criterion (A1 to A10, E3, E4, E5 and E7).

It is possible, then, to analyze how the alternatives priorities change when the influence of one of them over a criterion changes. Fig. 10, for example, shows what happens with alternatives ranking when the influence of the Atomizer (A1) over the Patrimonial Impact changes. In it, the Y-axis shows the alternatives priorities and the X-axis shows the influence of A1 over E6. Considering the results in Table 9, this influence value (abscissa) is 0.053. At this value, it is possible to observe that the ranking of the alternatives follows the results presented in the limit supermatrix. The ranking

Table 7
Comparisons with respect to “ID Fan” in “Impacts” cluster.

Which of the following criteria from the Impact cluster is more important or most affected by a ID Fan fault?																		
Environmental Impact	9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9	Generation Impact
Environmental Impact	9	8	7	6	5	4	3	2	1	2	3	4	~~5~~	6	7	8	9	Patrimonial Impact
Generation Impact	9	8	7	6	5	4	3	2	~~1~~	2	3	4	5	6	7	8	9	Patrimonial Impact

Table 8
Unweighted supermatrix.

		C1										C2			C3			C4		
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	E1	E2	E3	E4	E5	E6	E7	E8	E9
C1	A1	0	0	0	0	0	0	0	0	0	0	0.056	0.143	0.118	0.202	0.067	0.137	0.243	0.071	0.185
	A2	0	0	0	0	0	0	0	0	0	0	0.105	0.071	0.118	0.064	0.133	0.068	0.091	0.071	0.092
	A3	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.111	0.064	0.133	0.137	0.048	0.142	0.088
	A4	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.118	0.064	0.133	0.137	0.091	0.071	0.092
	A5	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.059	0.064	0.067	0.035	0.047	0.071	0.051
	A6	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.059	0.064	0.067	0.035	0.048	0.071	0.048
	A7	0	0	0	0	0	0	0	0	0	0	0.061	0.286	0.118	0.222	0.133	0.245	0.248	0.284	0.206
	A8	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.118	0.064	0.133	0.137	0.091	0.084	0.093
	A9	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.118	0.128	0.067	0.035	0.047	0.067	0.091
	A10	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.064	0.064	0.067	0.035	0.046	0.067	0.054
C2	E1	0.169	0.311	0.493	0.493	0.54	0.54	0.25	0.2	0.143	0.5	0	0	0	0	0	0	0	0	0
	E2	0.443	0.196	0.311	0.311	0.163	0.163	0.25	0.4	0.286	0.25	0	0	0	0	0.667	0	0.75	0	0.25
	E3	0.387	0.493	0.196	0.196	0.297	0.297	0.5	0.4	0.571	0.25	0	0	0	1	0.333	1	0.25	0	0.75
C3	E4	0.701	0.196	0.413	0.413	0.413	0.413	0.109	0.276	0.558	0.311	0	0	0	0	0	0.167	0	0	0
	E5	0.106	0.311	0.26	0.26	0.26	0.26	0.345	0.128	0.122	0.196	0	0	0	0	0	0.833	0	0	0
	E6	0.193	0.493	0.327	0.327	0.327	0.327	0.547	0.595	0.32	0.493	0	0	0	0	0	0	0	0	0
C4	E7	0.444	0.25	0.25	0.25	0.333	0.333	0.085	0.25	0.25	0.333	0	0	0	0	0	1	0	0	0
	E8	0.111	0.5	0.5	0.5	0.333	0.333	0.644	0.5	0.5	0.333	0	0	0	0	0.667	0	0	0	0
	E9	0.444	0.25	0.25	0.25	0.333	0.333	0.271	0.25	0.25	0.333	0	0	0	0	0.333	0	0	0	0

would change only if the influence value increases to 0.75 (when the lines on Fig. 10 intersect). The same sensitivity analysis was carried around to other alternative-criterion pairs and no changes in the ranking were observed for small variations (±20%) in the influences values presented in Table 9.

As stated in the introduction to this paper, nowadays preventive maintenance (PM) relies heavily on reliability/risk-based maintenance (RCM) and one can find, as exemplified in the references, a vast quantity of papers on the subject. However, the authors set out to try and find new ways of treating it from a wider “criticality” perspective. This objective seems to have been fully attained. Firstly, by carefully drawing up functional trees and SysML Internal Block Diagrams (IBD) for the selected systems and levels within the scope of the research study. As a matter of fact, the use of Internal Block Diagrams, a distinctive characteristic of the present study, proved to be a most useful contribution to the method. Secondly, by applying well known and widely accepted techniques: HAZOP, FTA and FMECA. Finally, by introducing a new approach that consisted of two phases: Critical Components Screening and Analytic Network Process (ANP).

Although the more commonly used Analytic Hierarchy Process (AHP) provides adequate compensation for an unavoidable disadvantage of any method based on expert judgement, to wit, possible uncertainty and inconsistency, by using ANP the authors had clearly in mind the need to avoid the shortcomings exhibited by AHP. Subsequently, when comparisons were made between ranking figures provided by the proposed method and data gathered over a couple of years by those running and maintaining the actual plant, results proved to be entirely satisfactory and the authors became convinced of the soundness of their approach.

In the authors' opinion, the main advantage provided by the present method, in addition to its thoroughness and soundness, is that it can be applied not only to coal-powered electricity generation plants as previously shown, but to other plants in the energy, chemical and petrochemical industries.

The results obtained with the implementation of the method allow maintenance plans to be developed, increasing the availability and decreasing the risk in relation to the operation of the plant. Additional work can be developed to integrate the proposed

Table 9
Weighted supermatrix.

		C1										C2			C3			C4		
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	E1	E2	E3	E4	E5	E6	E7	E8	E9
C1	A1	0	0	0	0	0	0	0	0	0	0	0.056	0.143	0.118	0.135	0.033	0.053	0.162	0.071	0.123
	A2	0	0	0	0	0	0	0	0	0	0	0.105	0.071	0.118	0.043	0.067	0.026	0.06	0.071	0.062
	A3	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.111	0.043	0.067	0.053	0.032	0.142	0.059
	A4	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.118	0.043	0.067	0.053	0.06	0.071	0.062
	A5	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.059	0.043	0.033	0.014	0.031	0.071	0.034
	A6	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.059	0.043	0.033	0.014	0.032	0.071	0.032
	A7	0	0	0	0	0	0	0	0	0	0	0.061	0.286	0.118	0.148	0.067	0.094	0.166	0.284	0.137
	A8	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.118	0.043	0.067	0.053	0.06	0.084	0.062
	A9	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.118	0.085	0.033	0.014	0.031	0.067	0.061
	A10	0	0	0	0	0	0	0	0	0	0	0.111	0.071	0.064	0.043	0.033	0.014	0.031	0.067	0.036
C2	E1	0.024	0.044	0.07	0.07	0.077	0.077	0.036	0.029	0.02	0.071	0	0	0	0	0	0	0	0	0
	E2	0.063	0.028	0.044	0.044	0.023	0.023	0.036	0.057	0.041	0.036	0	0	0	0	0.167	0	0.25	0	0.083
	E3	0.055	0.07	0.028	0.028	0.042	0.042	0.071	0.057	0.082	0.036	0	0	0	0.333	0.083	0.192	0.083	0	0.25
C3	E4	0.401	0.112	0.236	0.236	0.236	0.236	0.062	0.158	0.319	0.178	0	0	0	0	0	0.038	0	0	0
	E5	0.061	0.178	0.149	0.149	0.149	0.149	0.197	0.073	0.07	0.112	0	0	0	0	0	0.192	0	0	0
	E6	0.11	0.282	0.187	0.187	0.187	0.187	0.313	0.34	0.183	0.282	0	0	0	0	0	0	0	0	0
C4	E7	0.127	0.071	0.071	0.071	0.095	0.095	0.024	0.071	0.071	0.095	0	0	0	0	0	0.192	0	0	0
	E8	0.032	0.143	0.143	0.143	0.095	0.095	0.184	0.143	0.143	0.095	0	0	0	0	0.167	0	0	0	0
	E9	0.127	0.071	0.071	0.071	0.095	0.095	0.077	0.071	0.071	0.095	0	0	0	0	0.083	0	0	0	0

Table 10
Limit supermatrix.

		C1										C2			C3			C4		
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	E1	E2	E3	E4	E5	E6	E7	E8	E9
C1	A1	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.056
	A2	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038
	A3	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043
	A4	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041
	A5	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026
	A6	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026
	A7	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086
	A8	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042
	A9	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036
	A10	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027
C2	E1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	E2	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046
	E3	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093	0.093
C3	E4	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091	0.091
	E5	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
	E6	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097	0.097
C4	E7	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	E8	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066	0.066
	E9	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042

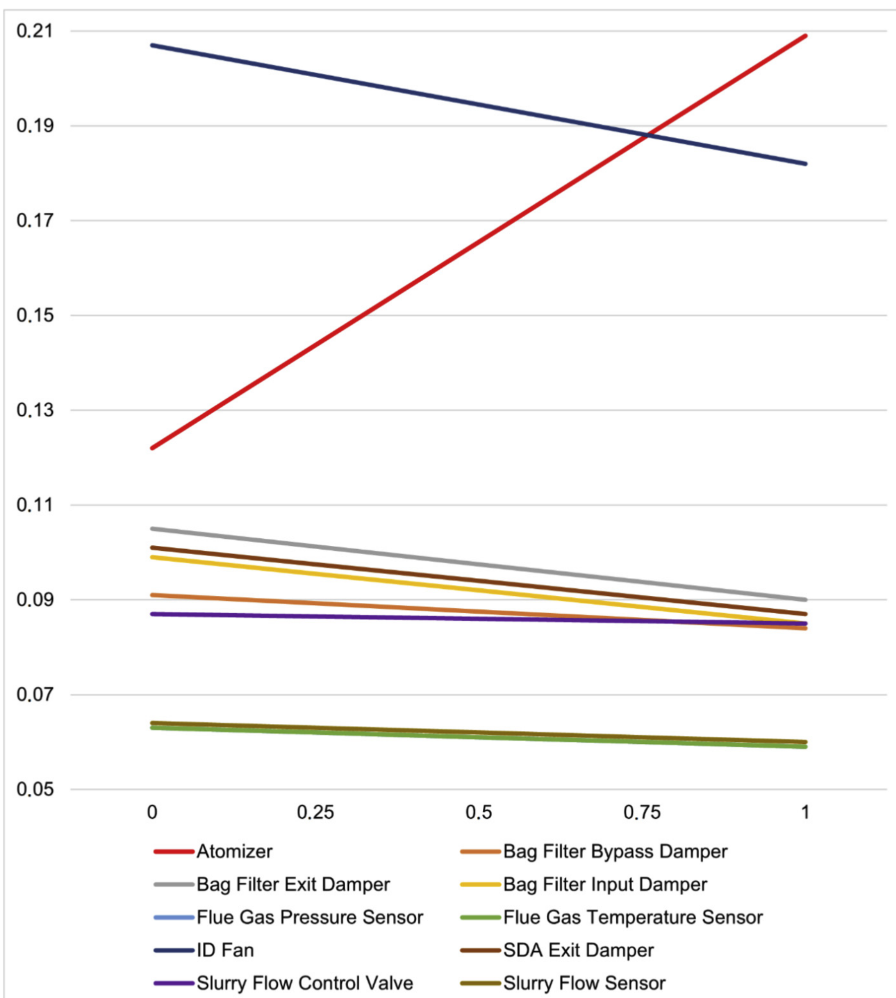

Fig. 10. Sensitivity analysis example.

method with business management software, facilitating the use of the obtained results by the entire engineering team.

Acknowledgement

The authors thank FDTE (Fundação para o Desenvolvimento Tecnológico da Engenharia) and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for the financial support.

References

[1] Smith AM, Hinchcliffe G. RCM - gateway to world class maintenance. first ed. California, USA: Butterworth-Heinemann; 2003.
[2] Moubray J. Reliability-centered maintenance. second ed. New York: Industrial Press, Inc.; 1997.
[3] Nowlan FS, Heap HF. Reliability-Centered-Maintenance. USA. 1978.
[4] Afefy IH. Reliability-centered maintenance methodology and application: a case study. Engineering 2010;2:863–73. https://doi.org/10.4236/eng.2010.211109.
[5] SAE. JA 1011 evaluation criteria for reliability-centered maintenance (Rcm) processes. 2009.
[6] IAEA. Application of reliability centred maintenance to optimize operation and maintenance in nuclear power plants. Vienna, Austria: International Atomic Energy Agency; 2007.
[7] GAO. FAA's proposed plan for implementing a reliability centered maintenance process for air traffic control equipment. Washington, DC, USA. 2006.
[8] NASA. Reliability-centered maintenance guide for facilities and collateral equipment. USA. 2008.
[9] Pintelon L, Gelders L, Puyvelde F Van. Maintenance management. Leuven, Belgium: Acco Publishers; 2000.
[10] Liu DJ. Application of risk based inspection (RBI), reliability centered maintenance (RCM) and risk based maintenance (RBM). Norway: University of Stavanger; 2013.
[11] Vesely WE, Rezos JT. Risk-based maintenance modeling: prioritization of maintenance importances and quantification of maintenance effectiveness (NUREG/CR-6002). Washington, DC, USA. 1995.
[12] Arunraj NS, Maiti J. Risk-based maintenance-Techniques and applications. J Hazard Mater 2007;142:653–61. https://doi.org/10.1016/j.jhazmat.2006.06.069.
[13] Carazas FJG. Risk-based decision making - method applied on electrical power generation industry for critical equipment and maintenance policy selection. Brazil: University of Sao Paulo; 2011.
[14] Murad CA. New product development considering reliability, risk analysis and quality tools. Brazil: University of Sao Paulo; 2011.
[15] COGCC. Risk-based inspections: strategies to address environmental risk associated with oil and gas operations. Denver, CO. 2014.
[16] Khalifa M, Khan F, Thorp J. Risk-based maintenance and remaining life assessment for gas turbines. J Qual Maint Eng 2015;21:100. https://doi.org/10.1108/13552510810877674.
[17] Ravish PYM. Risk based maintenance in electricity network organizations. Holland: Delft University of Technology; 2016.
[18] Ambühl S, Dalsgaard Sørensen J. Sensitivity of risk-based maintenance planning of offshore wind turbine farms. Energies 2017;10:505. https://doi.org/10.3390/en10040505.
[19] Crocker J, Kumar UD. Age-related maintenance versus reliability centred maintenance: a case study on aero-engines. Reliab Eng Syst Saf 2000;67:113–8. https://doi.org/10.1016/S0951-8320(99)00052-6.
[20] Krishnasamy L, Khan F, Haddara M. Development of a risk-based maintenance (RBM) strategy for a power-generating plant. J Loss Prev Process Ind 2005;18:69–81. https://doi.org/10.1016/j.jlp.2005.01.002.
[21] Cheng Z, Jia X, Gao P, Wu S, Wang J. A framework for intelligent reliability centered maintenance analysis. Reliab Eng Syst Saf 2008;93:806–14. https://doi.org/10.1016/j.ress.2007.03.037.
[22] Selvik JT, Aven T. A framework for reliability and risk centered maintenance. Reliab Eng Syst Saf 2011;96:324–31. https://doi.org/10.1016/j.ress.2010.08.001.
[23] Igba J, Alemzadeh K, Anyanwu-Ebo I, Gibbons P, Friis J. A systems a Reliability-Centred Maintenance (RCM) of wind turbines. Procedia Comput Sci 2013;16:814–23. https://doi.org/10.1016/j.procs.2013.01.085.
[24] Sainz JA, Sebastián MA. Methodology for the maintenance centered on the reliability on facilities of low accessibility. Procedia Eng 2013;63:852–60. https://doi.org/10.1016/j.proeng.2013.08.279.
[25] Florian M, Sørensen JD. Planning of operation & maintenance using risk and reliability based methods. Energy Procedia 2015;80:357–64. https://doi.org/10.1016/j.egypro.2015.11.440.
[26] Yssaad B, Khiat M, Chaker A. Reliability centered maintenance optimization for power distribution systems. Int J Electr Power Energy Syst 2014;55:108–15. https://doi.org/10.1016/j.ijepes.2013.08.025.
[27] Kundu P, Chopra S, LAD KB. Development of a risk based maintenance strategy to optimize forecast of a gas turbine failures. Int J Perform Eng 2015;11:407.
[28] Kiran S, Prajeeth Kumar KP, Sreejith B, Muralidharan M. Reliability evaluation and risk based maintenance in a process plant. Procedia Technol 2016;24:576–83. https://doi.org/10.1016/j.protcy.2016.05.117.
[29] Arunraj NS, Maiti J. Risk-based maintenance policy selection using AHP and goal programming. Saf Sci 2010;48:238–47. https://doi.org/10.1016/j.ssci.2009.09.005.
[30] Kumar G, Maiti J. Modeling risk based maintenance using fuzzy analytic network process. Expert Syst Appl 2012;39:9946–54. https://doi.org/10.1016/j.eswa.2012.01.004.
[31] Van Horenbeek A, Pintelon L. Development of a maintenance performance measurement framework-using the analytic network process (ANP) for maintenance performance indicator selection. Omega (United Kingdom) 2014;42:33–46. https://doi.org/10.1016/j.omega.2013.02.006.
[32] Aragonés-Beltrán P, Chaparro-González F, Pastor-Ferrando JP, Pla-Rubio A, An AHP. (Analytic Hierarchy Process)/ANP (Analytic Network Process)-based multi-criteria decision approach for the selection of solar-thermal power plant investment projects. Energy 2014;66:222–38. https://doi.org/10.1016/j.energy.2013.12.016.
[33] Chemweno P, Pintelon L, Van Horenbeek A, Muchiri P. Development of a risk assessment selection methodology for asset maintenance decision making: an analytic network process (ANP) approach. Int J Prod Econ 2015;170:663–76. https://doi.org/10.1016/j.ijpe.2015.03.017.
[34] Tang Y, Liu Q, Jing J, Yang Y, Zou Z. A framework for identification of maintenance significant items in reliability centered maintenance. Energy 2016;118:1–9. https://doi.org/10.1016/j.energy.2016.11.011.
[35] Delligatti L. SysML distilled: a brief guide to the systems modeling language. first ed. USA: Pearson Education; 2013.
[36] Guo L, Kang J. An extended HAZOP analysis approach with dynamic fault tree. J Loss Prev Process Ind 2015;38:224–32. https://doi.org/10.1016/j.jlp.2015.10.003.
[37] Mechhoud EA, Rouainia M, Rodriguez M. A new tool for risk analysis and assessment in petrochemical plants. Alex Eng J 2016;55:2919–31. https://doi.org/10.1016/j.aej.2016.05.013.
[38] Fuentes-Bargues JL, Gonzalez-Gaya C, Gonzalez-Cruz MC, Cabrelles-Ramirez V. Risk assessment of a compound feed process based on HAZOP analysis and linguistic terms. J Loss Prev Process Ind 2016;44:44–52. https://doi.org/10.1016/j.jlp.2016.08.019.
[39] Senol YE, Aydogdu YV, Sahin B, Kilic I. Fault Tree Analysis of chemical cargo contamination by using fuzzy approach. Expert Syst Appl 2015;42:5232–44. https://doi.org/10.1016/j.eswa.2015.02.027.
[40] Vesely WE, Goldberg FF, Roberts NH, Haasl DF. Fault tree handbook (NUREG-0492). Washington, DC, USA. 1981.
[41] Ortmeier F, Schellhorn G. Formal fault tree analysis - practical experiences. Electron Notes Theor Comput Sci 2007;185:139–51. https://doi.org/10.1016/j.entcs.2007.05.034.
[42] Kabir S. An overview of fault tree analysis and its application in model based dependability analysis. Expert Syst Appl 2017;77:114–35. https://doi.org/10.1016/j.eswa.2017.01.058.
[43] MIL-STD-1629A. Procedures for performing a failure modes and effects criticality analysis. Washington, DC, USA: USA Department of Defense; 1980.
[44] X60-510. Techniques d'analyse de la fiabilite des systemes - procedures d'analyse des modes de defaillance et de leurs effets (AMDE). France, Paris: Association Française de Normalisation (AFNOR); 1986.
[45] BS5760–B5765:1991. Reliability of systems, equipment and components. Guide to failure modes, effects and criticality analysis (FMEA and FMECA). London, UK: British Standards Institution; 1991.
[46] DIN EN 16602-30-02. 2014 Space product assurance - failure modes, effects (and criticality) analysis (FMEA/FMECA). Berlin, Germany: Deutsches Institut fur Normung; 2014.
[47] IEC. ISO/IEC31010:2009 Risk management — risk assessment techniques. Geneva, Switzerland: International Electrotecnical Commission; 2009.
[48] ISO/TR12489:2013. Petroleum, petrochemical and natural gas industries - reliability modelling and calculation of safety systems. Geneva, Switzerland: International Organization for Standardization; 2013.
[49] SAE. J1739_200901 potential failure mode and effects analysis in design (design FMEA), potential failure mode and effects analysis in manufacturing and assembly processes (process FMEA). New York, USA: Society of Automotive Engineers; 2009.
[50] IEC60812. Analysis techniques for system reliability — procedure for failure mode and effects analysis (FMEA). Geneva, Switzerland: International Electrotechnical Commission; 2006.
[51] Saaty TL, Vargas LG. Decision making with the analytic network process. second ed. Boston, MA: Springer US; 2013. https://doi.org/10.1007/978-1-4614-7279-7.
[52] Saaty TL. Fundamentals of decision making and priority theory with the analytic hierarchy process. first ed. RWS Publications; 1994.
[53] OECD. OECD factbook 2015-2016: economic, environmental and social statistics. Paris: OECD Publishing; 2016.
[54] Speight JG. Coal-fired power generation handbook. first ed. New Jersey, USA: John Wiley & Sons; 2013.
[55] Saaty T, Saaty RW. SuperDecisions Software n.d. https://www.superdecisions.com/(accessed July 1, 2017).