A DECISION SUPPORT TOOL BASED ON ANP AND FMEA TO DETERMINE CAUSE FAILURES

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ABSTRACT
Failure mode and effect analysis (FMEA) is one of the formal techniques for evaluation of failure mode in mechanical and electronic equipments. The FMEA may be a very helpful tool for identifying weak points in the design stage of a product/process. The aim of this paper is to develop a *new maintenance decision strategy* by integrating the criticality of various factors related to failure and repair of a component/subsystem as an alternative to traditional approach of Failure Mode and Effect Analysis (FMEA). The methodology presented is based on *Analytical Network Process* (ANP), a multi-criteria decision making technique.
We propose a *decision support tool analysis* for determining maintenance priority action in which the typical FMEA parameters are modeled. The approach has been validated in a real case study concerning the European Train Control System - E.T.C.S.

Keywords: FMEA, Maintenance, ANP, Risk Analysis

1. INTRODUCTION
The identification and choice of a suitable risk assessment model has been considered as a crucial issue for decades. So far, models used in the practice were developed for different applications and adapted for health and safety at work (Hazards and Operability Study – HAZOP, Failure Methods and Critical Analysis- FMECA, Fault tree analysis, Events tree, etc.).

In our work we focused attention on the FMEA technique. FMEA has been widely standardized, as MIL-STD-1629A, MIL-HDBK-217 in the USA and as BS 5760 in the UK. Industrial users have reported significant benefits from these design tools. Successful users have achieved a 15–45% improvement in quality, and reduction in cost and time to market (Huang *et al.* 2000).

This technique is a well known assessment tool used to identify the components of an equipment most likely to cause failures, and to enhance the reliability of a system through the development of the appropriate corrective actions (Hung *et al.*, 1999).

FMEA is important for directing maintenance tasks and identifying more efficient operational methods and for allocating the recommended actions at those points with higher damage potentials.

The main problem faced in the utilization of this technique is the necessity to help management to consider different parameters simultaneously. Thus, it is useful to adopt multicriteria decision making techniques.

From this point of view in a recent article, Kjellen et al. (2009) pointed out the importance of risk of accidents as a criterion in decision making. Amongst many factors, maintenance practice will also affect the occurrence of accidents.

Multi criteria decision making approach gained momentum in the field of maintenance strategy selection (de Almedia and Bohoris, 1995; Triantaphyllou et al., 1997; Labib et al., 1998) suggested the use of AHP/ANP for maintenance strategy selection considering cost, reparability, reliability, and also used AHP/ANP for selecting the maintenance strategy for an Italian oil refinery based on four important criteria, namely cost, damages, applicability and added value (Pillay *et al*., 2003; Sachdeva, 2008).

Definitely, the aim of our work is to propose an *ANP decision support tool to evaluate systems reliability performance and to select the best maintenance strategy.*

2. ANP APPROACH
ANP (Saaty, 2001) is a comprehensive decision-making technique that captures the outcome of the dependence and feedback within and between the clusters of elements.

The main reason for choosing the ANP as our methodology is due to its suitability in offering solutions in a complex multicriteria decision making process (De Felice *et al*., 2009).

The ANP model consists of the control hierarchies, clusters, elements, interrelationship between elements and interrelationship between clusters. The modeling process can be divided into different phases for the ease of understanding which are described as follows:

PHASE 1: *Pairwise comparison and relative weight estimation.* Pairwise comparisons of the elements in each level are conducted with respect to their relative importance towards their control criterion based on the principle of AHP. Saaty (1980) suggested a scale of 1-9 when comparing two components (see Table 1).

Table 1: Semantics scale of Saaty

INTENSITY OF IMPORTANCE a_{ij}	DEFINITION	EXPLANATION
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it

The result of the comparison is the so-called dominance coefficient aij that represents the relative importance of the component on row (i) over the component on column (j), i.e., aij=wi / wj. The pairwise comparisons can be represented in the form of a matrix (Saaty, 2007). The score of 1 represents equal importance of two components and 9 represents extreme importance of the component i over the component j.

$$A = \begin{vmatrix} w_1/w_1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \dots & w_2/w_n \\ \dots & & & \dots \\ w_n/w_1 & w_n/w_2 & \dots & w_n/w_n \end{vmatrix} = \begin{vmatrix} a_{11} \dots\dots a_{1n} \\ a_{21} \dots\dots a_{2n} \\ \dots\dots\dots \\ a_{n1} \dots\dots a_{nn} \end{vmatrix}$$

PHASE 2: *Priority vector.* After all pairwise comparison is completed the priority weight vector (w) is computed as the unique solution of $Aw = \lambda_{max}w$, where λ_{max} is the largest eigenvalue of matrix A.

PHASE 3: *Consistency index estimation.* The consistency index (CI) of the derived weights could then be calculated by: $CI = (\lambda max - n)\ n - 1$. In general, if CI is less than 0.10, satisfaction of judgments may be derived (Saaty, 2005).

3. THE RESEARCH METHODOLOGY

The FMEA design and implementation requires a careful knowledge of the system (Anthony *et al.*,1998). A combination of techniques is therefore needed to perform system level availability modeling of complex heterogeneous control systems, considering both structural and behavioral studies (Puente et al., 2002; Bowles, 2003). For this reason we proposed a new decision multicriteria methodology. Below methodological steps are illustrated (Figure 1).

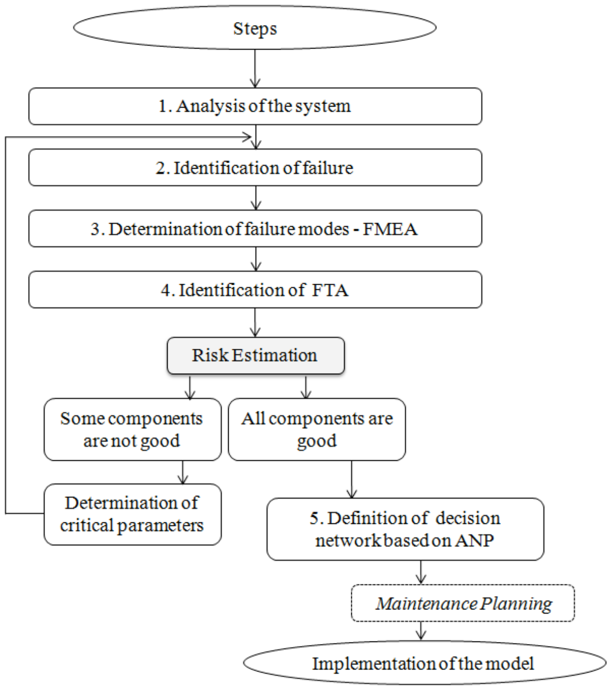

Figure 1: Methodological steps

The aim of our formal model is:

- to check the completeness of the specification of the ETCS;
- to use it for a systematic derivation of test cases;
- to evaluate at an early stage the specification of the European stardized interfaces of ETCS according to the national railway environment.

Here below are the methodological steps proposed:

STEP 1 - Analysis of the system. This preliminary activity represents a focal analysis as it supplies information about the organization of processes and procedures of each level.

STEP 2 - Identification of failure. This activity mainly consists of the identify failure that could characterize the system.

STEP 3 - Identification of failure modes – FMEA. This activity mainly consists of the identify failure modes: the aim is to integrate information coming from operational fields with global level effects.

STEP 4 - Identification of FTA. A fault tree structure is proposed to analyze undesired events with different levels of operation quality.

STEP 5 - Definition of decision network based on ANP. In this phase the main objective was to assess design and/or operational procedure alternatives which could improve reliability and maintainability of the whole system. The multi-criteria analysis allowed to obtain a numerical assessment on the representative of the various components, usually characterized by a qualitative measurement.

4. CASE STUDY: THE E.T.C.S.

As case study we analyzed the European Train Control System. The ETCS is a signalling, control and train protection system designed to replace the many incompatible safety systems currently used by European railways, especially on high-speed lines (see Figure 2).

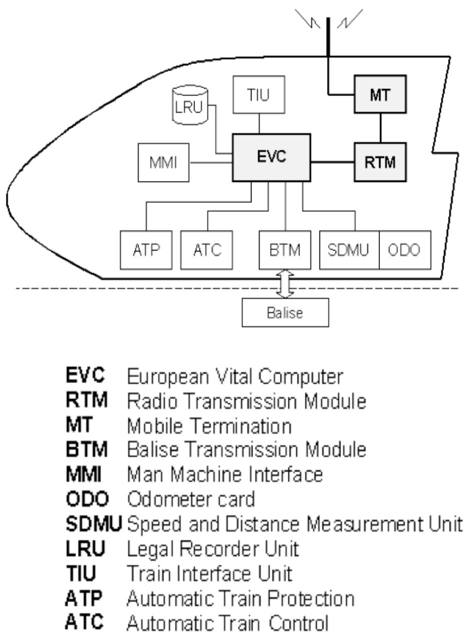

Figure 2: European Train Control System - E.T.C.S. framework

E.C.T.S. requests the observance of high safety and reliability standards (BS 5760, MIL-HDBK-217, MIL-STD1629A) thus is a proper case study for our work. Here below we analyzed methodological steps.

STEP 1 - Analysis of the system. The European Train Control System is a European project aiming at the cross-border operation of trains without obstacles, i.e. the free movement of train operators along various infrastructures while maintaining the necessary level of safety, thus creating real interoperability in the area of control command and signalling. In this context we note that computer systems used in critical control applications are rapidly growing in complexity, featuring a very high number of requirements together with large, distributed and heterogeneous architectures, both at the hardware and software levels. Traditional functional testing techniques based, for example, only on Fault Tree Analysis reveal inadequate for the verification of modern control systems, for their increased complexity and criticality properties (Frosig, P., 1995).
Here below (Table 2) we show a description of major components of the system.

Table 2: Components of system and Failure Rate

DESCRIPTION	FAILURE RATE
RADIO BLOCK CENTRE	
Safety Centre	*3,07E-06*
Functional Keyboard	*1,23E-05*
Interface Operator – Alarm – Remote control	*4,25E-06*
Interface TLC-LD & GSM-R	*4,00E-06*
Power RBC	*5,22E-06*
Encoder LEU	
Interconnection with relay electric system	*1,43E-07*
Distribution-Power	*3,99E-07*
LEU (Encoder)	*1,36E-06*
Front End Diagnostic	*2,37E-06*
Interconnections Balise & LEU	*2,07E-07*
Filter Module	*1,27E-07*
Splitter Module - FED	*9,20E-09*
Splitter Module - BUS I/O	*9,20E-09*
GPS Module	*3,63E-06*
Boa Balise	*4,50E-07*

STEP 2 - Identification of failure. In modelling the European Train Control System, different modeling aspects have been integrated:

- Components;
- Scenarios;
- Functions

are shown on different model levels.
When modelling the component view, the focus is on communication and interaction of different subsystems. A general representation of these nets shows the subsystems and their interfaces, every subsystem being detailed on additional levels. The scenario-based view is the modelling of operational procedures. Its main

elements are the interaction between on-board and trackside equipment and the sequence of events required to maintain operation. The functions are represented at lower model levels. The functions are specifically associated with the objects of the process aspect and represent the activities or the response to interaction requirements following from the scenarios.
In Table 2 is a definition of failure rate for major components.

STEP 3 - Identification of failure modes- FMEA. For FMEA analysis we adopted MIL-STD-1629 standard. We evaluated failures considering:

- The consequences of failure are the worst conceivable (conservative assumption);
- Failure is never contemporary to another (analyzing a fault at a time);
- The devices are in normal operation.

In appendix (Table 3) we show an example of "*Identification of failure modes*".

STEP 4 - Identification of FTA. For modeling fault we used the technique FTA (Fault Tree Analysis), deemed appropriate to highlight the dependencies between logical and functional components of the subsystem that can lead to abnormality determination of exercise (Top Event) and to quantify the probability of occurrence. FTA analysis assumes that the subsystem at the beginning of the mission is fully efficient, that every component is in good working condition and that all redundancies planned are active. The mission time was assumed to be 24 hours, or equal to the time of daily use of the subsystem. Here below (Figure 3) is an example of FTA.

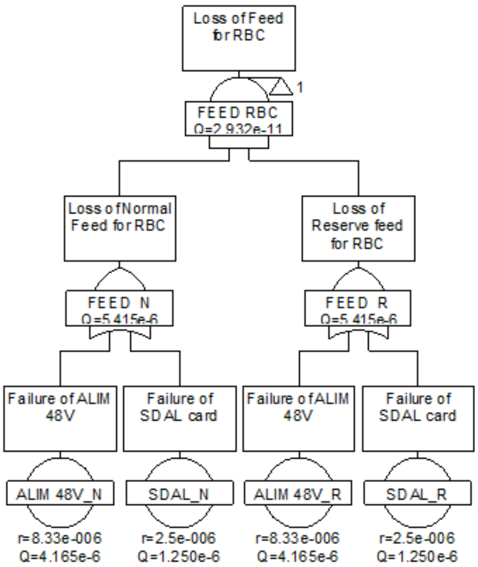

Figure 3: FTA example for "loss of feed for RBC"

STEP 5 - Definition of decision network based on ANP. In this phase we proposed an ANP model to develop a maintenance plan to reduce the unacceptable risk to an acceptable level. We distinguished between "*preventive maintainability*" and "*corrective maintainability*".

The definition of the network scheme proposed involved expert people in maintenance problems. We established a "FMEA team" including Mechanical Engineerings, Quality Experts, the Maintenance Experts Once the network structure of the maintenance decision making problem is defined (see Figure 4 in Appendix), the priorities of the scheme are calculated using pairwise comparisons.

Definitely, the network was characterized by the following clusters: Radio Block Center, Encoder, Boa Balise, Failure Causes, Failure Effects, Failure Modes, Alternatives that include Preventive Maintainability and Corrective Maintainability.

Here below (Figure 5 and Figure 6) we illustrate some results:

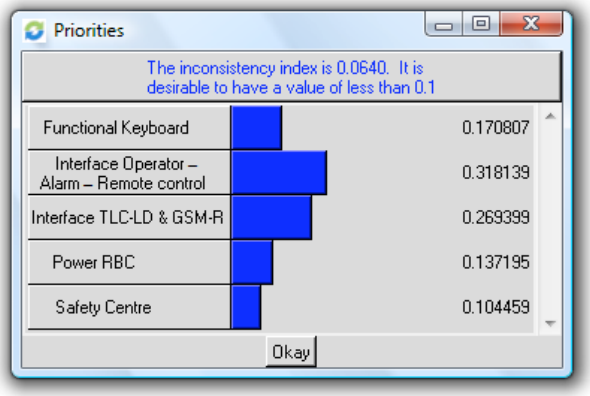

Figure 5: Priority vector for "Corrective Maintainability" node in "RADIO BLOCK CENTER" cluster

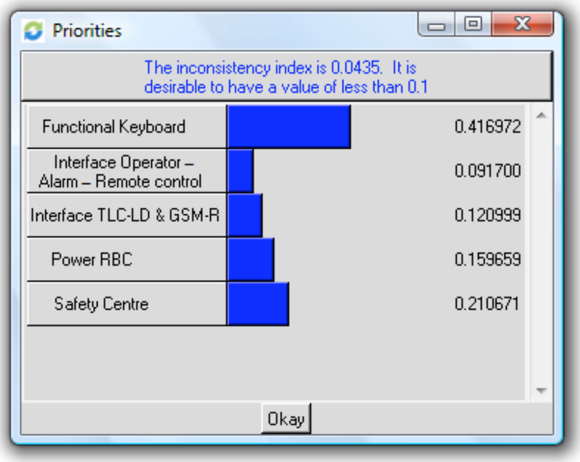

Figure 6: Priority vector for "Preventive Maintainability" node in "RADIO BLOCK CENTER" cluster

Once defined all comparison judgments we obtain a ranking of global priority for "Preventive Maintainability" and for "Corrective Maintainability" (Table 4).

Table 4: Global Priority

Component	Global Priority for Preventive Maintainability	Global Priority for Corrective Maintainability
Safety Centre	0,23	0.15
Functional Keyboard	0,25	0.23
Interface Operator – Alarm – Remote control	0.30	0.27
Interface TLC-LD & GSM-R	0.35	0.29
Power RBC	0.15	0.24
Interconnection with relay electric system	0.16	0.19
Distribution-Power	0.18	0.28
LEU (Encoder)	0.21	0.13
Front End Diagnostic	0.19	0.14
Interconnections Balise & LEU	0.27	0.22
Filter Module	0.24	0.21
Splitter Module - FED	0.13	0.17
Splitter Module - BUS I/O	0.26	0.24
GPS Module	0.14	0.20
Boa	0.38	0,29

Established priorities of actions is necessary to implement the maintenance programs. In appendix (Table 5 and Table 6) we propose as an example a preventive and corrective program (we show only a partial implementation).

5. CONCLUSION

The unexpected failures, the down time associated with such failures, the loss of production and, the higher maintenance costs are major problems in any process.

It is necessary to develop a specific methodology to assess the reliability of systems/components. In fact, the failure of a system is rarely the result of a single cause, but rather the result of a combination of a series of interacting events.

As a result, risk-based maintenance must not be perceived as a static exercise to be performed only once. It is a dynamic process, which must be continuously updated as additional information becomes available.

For this reason in our work, we have proposed a methodology to develop an optimum risk-based maintenance strategy. The paper presents a new methodology for designing maintenance programs based on Analytic Network Process.

This approach:

1. allows to integrate classical methodology based on the FMEA technique with a multicriteria decision making approach;
2. ensures to take in consideration different parameters simultaneous. This will contribute to guarantee the reliability and availability of the whole system.

Further developments could be oriented in applying the approach in several fields (automotive, aeronautic, etc.).

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APPENDIX

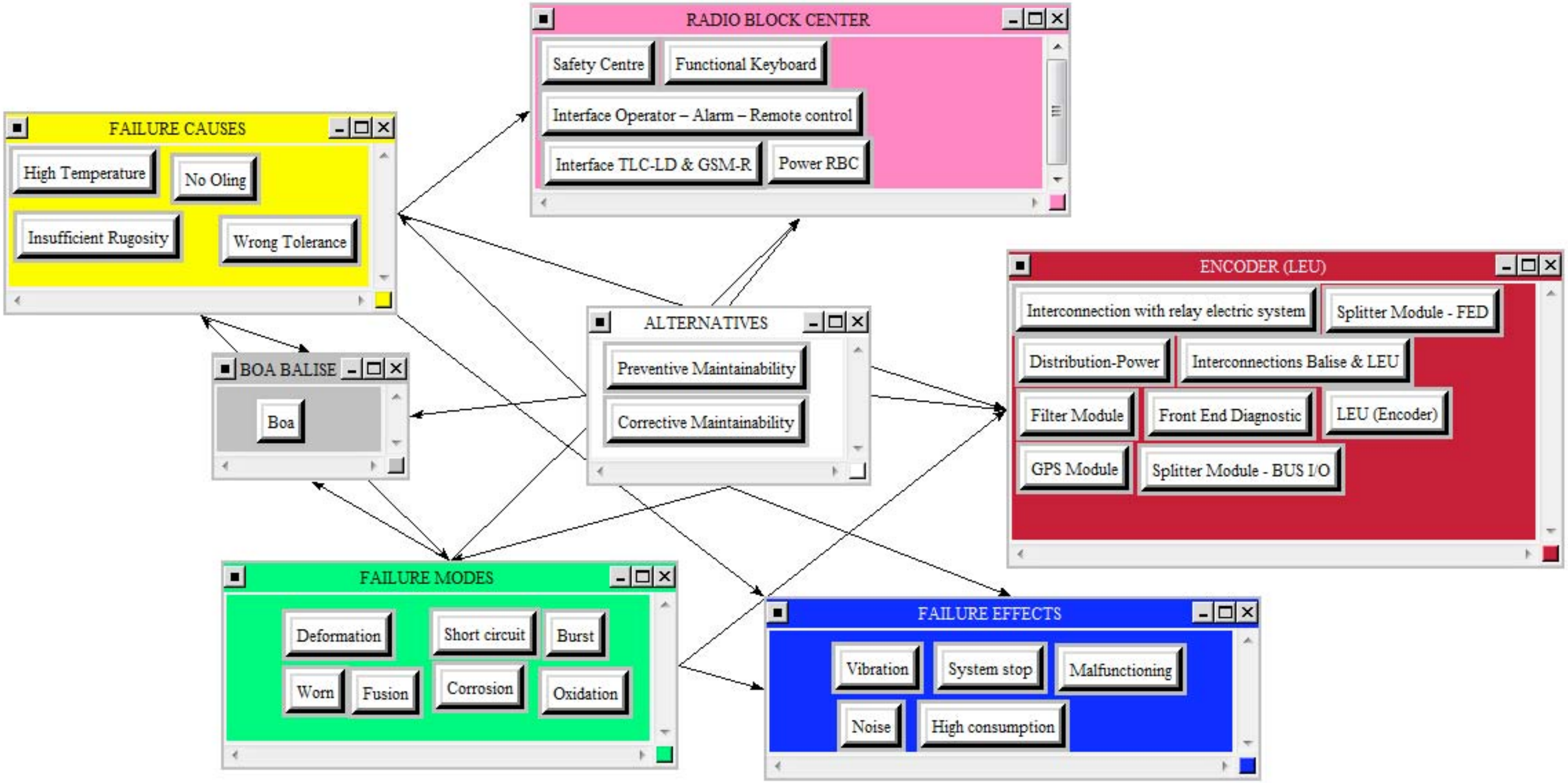

Figure 4: ANP Model

Component: *Safety Centre*				**FMEA**							
Subsystem: **RBC**											
N.	Part N.	Symbol	Function	Mode and cause of failure	Functioning	Failure Effects			Method of Detection	Compensation measures	Criticality Level.
						Local	Main Component	Final			
1	/	XyZ	Making the internal connections between sections of processing and interface guidelines and distribute the supply voltages.	Mechanical failure	Continuous	Lack connections and / or power between sections of processing and interface guidelines	ECTS Central Out of order	Prevent the train running under the jurisdiction of RBC	Diagnostic Test	Immediate replacement equipment of failure	A failure or disorder that prevents or influences multi-gear trains.

Table 3: FMEA Example

Preventive Maintainability

Component: **BOA Balise**
Subsystem: **BOA**

Step	Action	Frequency [months]	Tools	Materials		Number of operators		Duration of action [min]	Total hour/operator
				Identification	Quantity [No.]	No.	Skill		
1	Visual inspection of BOA Monitor the presence of debris within the limits allowed. Control correct positioning of Boa. Control of the efficiency of the electric connections	12	Toolbox			1	Necessary a specific knowledge of the system. Operators must be able to make medium repairs.	7	0,12
2	Proper tightening of control cable to LEU cabinet	12	Toolbox			1	Not necessary a specific knowledge of the system. Operators must be able to make easy repairs.	7	0,12
3	Verify the functionality is not interested in normal operation (eg switching to telegram by default).	12	Toolbox			1	Not necessary a specific knowledge of the system. Operators must be able to make easy repairs.	6	0,10

Table 5: Preventive Maintainability Example

Corrective maintainability

Component: **BOA**
Subsystem: **BOA**

Symbol	Failure Mode	Mapping of failure	Standard procedure	Tool	Number of operators		Duration of action	Observations
					Specialization	Quantity No.	[h]	
BOA	Out of order	Self-revealing	1) Location component failure 2) Isolation component 3) Removal 4) Replace failed component 5) Realignment 6) Functional Tests	Toolbox	Medium	1	0,333	

Table 6: Corrective Maintainability Example