Criticality analysis for maintenance purposes. A study for complex in-service engineering assets

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ABSTRACT

The purpose of this paper is to establish a basis for a criticality analysis, considered here as a prerequisite, a first required step to review the current maintenance programs, of complex in-service engineering assets. *Review* is understood as a reality check, a testing of whether the current maintenance activities are well aligned to actual business objectives and needs.

This paper describes an efficient and rational working process and a model resulting in a hierarchy of assets, based on risk analysis and cost-benefit principles, which will be ranked according to their importance for the business to meet specific goals. Starting from a multi-criteria analysis, the proposed model converts relevant criteria impacting equipment criticality into a single score presenting the criticality level.

Although detailed implementation of techniques like Root Cause Failure Analysis (RCFA) and Reliability Centred Maintenance (RCM) will be recommended for further optimisation of the maintenance activities, the reasons why criticality analysis deserves the attention of the engineers, maintenance and reliability managers are here precisely explained. A case study is presented to help the reader to understand the process and to operationalize the model.

Keywords: Criticality, Maintenance management,

1. INTRODUCTION

In this paper we deal with the strategic part of the maintenance management definition and process (as in EN 13306:2010 [1]), which is related to the determination of maintenance objectives or priorities and the determination of strategies. A more operational second part of the definition refers to the strategies implementation (maintenance planning, maintenance control, supervision, and continuous improvement).

Part of this strategy setting process, that we refer to, is devoted to the determination of the maintenance strategies that will be followed for the different types of engineering assets (i.e. specific physical assets such as: production processes, manufacturing facilities, plants, infrastructure, support systems, etc.). In fact, maintenance management can also be considered as "…the management of all assets owned by a company, based on maximizing the return on investment in the asset" [2], also their safety and their respect for the environment. Within this context, criticality analysis is a process providing a systematic basis for deciding what assets should have priority within a maintenance management program [3], and has become a clear business need in order to maximize availability during assets' operational phase.

This type of assets criticality analysis, performed during their operational phase and for maintenance purposes, is therefore different to criticality analysis which is carried out during assets design. At that point, the objective (more linked to asset's reliability assessment) is to identify critical areas so that different design alternatives to achieve a specified availability target can be optimized and compared [15]. Description of specific techniques for criticality analysis during design can be found in MILSTD 1629A [16], also in [17] and [18]. These techniques use, for instance, the Risk Priority Number (RPN) method, fuzzy logic or approximate reasoning to prioritize failures modes (not assets).

When prioritizing assets for maintenance purposes, and during their operational phase, a large number of quantitative and qualitative techniques can be found in the literature [3]. On some occasions, there is no hard data about historical failure rates, but the maintenance organization may require a certain *gross assessment* of assets priority to be carried out. In these cases, qualitative methods may be used and an initial assets assessment, as a way to start building maintenance operations effectiveness, may be obtained [10].

This paper, however, is about the process to follow on other occasions, lately becoming more frequent, when the maintenance organization has important amounts of data for complex in-service assets for which a certain maintenance strategy has been previously developed and implemented. Therefore we have evidences of assets behavior for current operational conditions of the asset, and we launch the criticality analysis with the purpose of adjusting assets maintenance strategies to business needs over time.

Most of current quantitative techniques for assets criticality analysis use a weighted scoring method defined as variation of the RPN method used in design [4]. These weighted scoring methods might appear simple, but in order to reach acceptable results, a precise procedure should be considered when determining factors, scores and combining processes or algorithms [15]. The analysis involves another important issue which is the level of detail required, compromising objective effectiveness (missing focus of subsequent maintenance efforts) and also data collection efforts.

The criticality number to obtain (C), as a measure of risk associated to an asset, is derived by attaching a numerical value to the probability of failure (function loss) of the asset (the higher probability, the higher the value), and attaching another value to the severity of the different categories of asset functional loss consequences (the more serious consequences for each category, the higher the value). The criteria and the relative weighting to assess severity and probability may vary widely for different companies according to their maintenance objectives and KPIs. The two numbers are multiplied to give a third which is the criticality number (C). Of course, assets with the higher (C) will be recognized to be the more critical assets and will deserve special attention from the maintenance (sometimes now called: assets) management organization.

The reader may notice now how the "detectability" factor, used as part of the equation of RPN in design, is not considered now in operations in C. This is because detectability is not an attribute of the assets we are ranking, but of the failure modes for which design alternatives were explored (see [12]).

The inspection and maintenance activities will be prioritized on the basis of quantified risk caused due to failure of the assets [6]. The high-risk assets are inspected and maintained usually with greater frequency and thoroughness and are maintained in a greater manner, to achieve tolerable risk criteria [7].

Although this technique is becoming popular, some authors mention [6] that most of the risk analysis approaches are *deficient in uncertainty and sensitivity analysis.* This may constrain yielding proper results and decisions based on misleading results may generate non-essential maintenance efforts spent in less important areas. To avoid this, risk analysis for asset criticality should be evaluated in well planned manner ensuring that significant sources of risk are reduced or eliminated [5].

In this paper we propose a criticality analysis taking into account the following process design requirements:

1. The process must be applicable to a large scale of in-service systems within a plant or plants. A reason for this is the fact that PM programs to be evaluated using this criticality analysis are set by plant equipment (placed in a technical location in the plant), and therefore we are forced to deal with this large number of items in the analysis;
2. The scope of the analysis should be, as mentioned in previous point, the same for which the current PM program is developed and implemented;
3. The analysis should support regular changes in the scale adopted for the severity effects of the functional losses of the assets (this is a must to align maintenance strategy in dynamic business environments).
4. The process must allow easy identification of new maintenance needs for assets facing new operating conditions;
5. General guidelines to design possible maintenance strategy to apply to different type of assets according to the results of the analysis (criticality and sources of it) should be provided;
6. Connection with the enterprise asset management system of the company should be possible to automatically reproduce the analysis, with a certain cadence, over time;
7. The process should be tested in industry showing good practical results.

In the sequel the paper is organized as follows: Section 2 shows first, briefly, the proposed criticality analysis process description. Then, more precisely and in the different Subsections, the notation of the mathematical model supporting the process is introduced, as well as every step of the process to follow, including model equations. Along this second Section of the paper, a practical example helps to exemplify the process and model implementation. Section 3 tries to turn, the previous process and model, into a powerful management tool. In order to do so, this Section explains how to handle data requirements properly and how to benefit from model outputs and results using suitable graphical representations. Section 4 is devoted to the interpretation of possible results, offering clear guidelines to ensure maximum benefits from the analysis. Conclusions of the paper are finally presented in Section 5.

2. PROCESS DESCRIPTION AND RATIONAL

In this Section we describe a comprehensive process to be followed by a *criticality review team* (defined as in [11]) in order to generate a consistent criticality analysis based on the use of the PRN method together with multi criteria techniques to select the weights of factors deriving in the severity of an asset.

The process consists in a series of steps determining the following:

1) Frequency levels and the frequency factors;
2) Criteria and criteria effect levels to assess functional loss severity;
3) Non admissible functional loss effects;
4) Weights (contribution) of each criteria to the functional loss severity;
5) Severity categories, or levels, per criteria effect;
6) Retrieving data for actual functional loss frequency for an element (r);
7) Retrieving data for maximum possible effects per criteria;
8) Determination of Potential asset criticality at current frequency;
9) Retrieving data for real effects per criteria;
10) Determining observed asset criticality at current frequency;
11) Results and guidelines for maintenance strategy.

The first five steps of the process determine the elements configuring the algorithm in the mathematical model that will be later used to rank assets, once their in-service operational data is retrieved from the enterprise assets management system. Steps 6, 7 and 9 are data gathering related steps. In these Sections the reader will see that assets' data required will be:

- Engineering data concerning maximum possible asset functional loss effects (step 7); and
- Operational data showing information about current frequency of their functional loss (step 6) and functional loss effects (step 9);

Steps 8) and 10) are presenting results for potential and current observed criticality of the assets. Discussion of these two facts will drive to a set of conclusions and action items that will be presented in Step 11).

The process followed to assess the criticality of the different assets considered is supported by a mathematical model, whose notation is now presented:

i: 1…*n* criteria to measure severity of an element functional loss,

j: 1…*m* levels of possible effects of a functional loss for any criteria,

z: 1…*l* levels of functional loss frequency,

e_{ij}: Effect *j* of the severity criteria *i*,

w_i: Weight given to the severity criteria *i* by experts, with $\sum_{i=1}^{i=n} w_i = 1$,

M_i: Maximum level of admissible effect for criteria i, with $M_i \leq m, \forall i$,

MS: Maximum severity value,

v_{ij}: Fractional value of effect j for the severity criteria *i*,

S_{ij}: Severity of the effect *j* for the severity criteria *i*,

pe_{rij}: Potential effect *j* of criteria *i* for the functional loss of element *r*,

f_r: Value for the frequency of the functional loss of element *r*,

ff_z: Frequency factor for frequency level *z*,

fe_{rz}: Boolean variable with value 1 when *z* is the level of the observed frequency of element *r* functional loss, 0 otherwise,

af_z: Average frequency of functional loss for frequency level *z*,

S_r: Severity of the functional loss of element *r*,

C_r: Criticality of element *r*,

re_{rij}: Current probability of the effect *j* of criteria *i* for the failure of *r*,

S'_r: Current observed severity of the functional loss of element r,

C'_r: Current criticality of element *r*,

Subsequent Sections of the paper present precisely the different steps of the process, and introduce the mathematical model supporting them. The model is applied to an example which illustrates a practical industrial scenario.

2.1. DETERMINING FREQUENCY LEVELS AND FREQUENCY FACTORS

To manage the frequency levels a form of Pareto analysis is used, in which the elements are grouped into z frequency categories according to their estimated functional loss frequency importance. For example, for z=4, the categories could be named: very high, high, medium and low functional loss frequency. The percentage of elements to fall under each category can be estimated according to business practice and experience for assets of the same sector and operational conditions (for instance, according to existing operating conditions of our assets, in Table 1 the review team has decided to define a category named “Low”, including a group of 5 assets having less than 2 failures per year [f/y] and with an average functional loss of 1.2 f/y, easing our corrective maintenance operations, and serving as a reference for the rest of the assets selected categories. Assets with more than 7 f/y are considered to complicate enormously corrective operations, and as soon as severity in consequences of the functional loss increases, current management will consider those assets as very critical). Then, average values for frequencies falling inside each group can be estimated and frequency factors per category calculated (see example in Table 1).

In the model mathematical formulation, if af_z is the average frequency of functional loss for frequency level *z*, then the frequency factor vector is defined as follows:

$ff_z = \frac{af_z}{af_1}$, for $z=1 \ldots l$ levels of functional loss frequency

Asset	f/y
a	1
b	2
c	5
d	7
e	3
f	1
g	1
h	6
i	8
j	1

Asset	f/y	Category (z)	% (z)	af_z	ff_z
i	8	Very high	10%	8	6.7
d	7	High	20%	6.5	5.4
h	6				
c	5	Medium	20%	4	3.3
e	3				
b	2	Low	50%	1.2	1.0
j	1				
g	1				
a	1				
f	1				

Table 1. Calculation of frequency factors per selected functional levels

2.2. CRITERIA, AND CRITERIA EFFECT LEVELS, TO ASSESS FUNCTIONAL LOSS SEVERITY:

This part of the analysis should reflect the business drivers recognized by management and shareholders [15]. For the severity classification, this study focuses the attention on both, safety and cost criteria (similarly to [6]). For the safety severity categories, similar hazard severity categories to the ones used in MIL-STD-882C are adopted. This standard proposes four effect categories that can now be reframed as follows:

- catastrophic, could result in multiple fatalities
- critical, resulting in personal injuries or even one single fatality
- marginal, and
- negligible

As cost factors we may selected different criteria for which the functional loss effect can be classified in different levels that can, at the same time, be converted into cost using a certain contract or standard that the company must honor.
In the example for this paper, the following criteria are selected (assuming that we are dealing with the criticality of a collective passenger's transportation fleet):

- Operational reliability: measuring the potential impact of a functional loss to the system where the asset is installed. The effects could be classified in different levels like: No Affection (NA), stopping the system less than x min (S <x), stopping the system more than x min (S> x) or leaving the system out of order (OO). Each one of these affection levels can be later translated to cost of the functional loss, and the corresponding factors could be obtained.
- Comfort: evaluating whether the functional loss of the element may: have no affection on comfort (NA), affect a passenger (P), a car (C) or the whole train (T). Again, each one of these affection levels can be later translated into cost of the functional loss, and the corresponding factors could be obtained.
- The "corrective maintenance cost" could be selected as another cost related criteria. Effects could be classified in very high, high, medium and low corrective maintenance cost, and we could proceed similarly to what has been presented in Table1, classifying the elements' costs and finding averages costs and the corresponding factors for each effect classification level.

2.3. DETERMINING NON ADMISSIBLE FUNCTIONAL LOSS EFFECTS

At this point, the process requires the definition of those functional loss effects that would be considered as "*non-admissible*" for each specific criterion. For instance, in Table 2, those categories of effects being considered non admissible are presented with dark grey inverse video. For this case study the review team has considered that catastrophic & critical effects on "Safety", besides the "Out of order" condition of the system, are non-admissible effects of a functional loss of an element.

The model will allocate a maximum value for overall severity (MS) to those assets (elements of the transportation fleet) whose functional loss may produce non-admissible effects for any of the selected criteria. Therefore, those elements will become of maximum severity regardless their functional loss effect on any other criteria under consideration.

Criteria to measure Severity			
Safety criteria	Cost related criteria		
	Operational reliability	Comfort	CM Cost
Category of effects per criteria			
Cat & Cri (C)	**OO**	Train (T)	VH (10%)
Marginal (M)	S>x	Car (C)	H (20%)
Negligible (N)	S<x	Passenger (P)	M (20%)
NA	NA	NA	L (50%)

Table 2. Table presenting non admissible effect categories

In the mathematical model we will use the following notation for this purpose:

M_i: Maximum level of admissible effect for criteria *i*, with $M_i \le m, \forall i$

MS: Maximum value for overall severity

And in our example,

[*i*]=*safety, operational reliability, comfort, CM cost*

and $[M_i]=3,3,4,4$ as maximum levels of admissible effects for each criteria, finally it will be considered MS=100.

2.4. CRITERIA WEIGHTS IN THE FUNCTIONAL LOSS SEVERITY

To determine these weights various considerations can be taken into account, for instance:

- Criteria correlation to business KPI’s.
- Budget allocated to each cost related criteria within the maintenance budget.
- Impact of each criterion on the brand and/or corporate image. For instance, in the previous example the management (or the criticality review team) could consider that "operational reliability" and/or "comfort" criteria could have also impact on the brand image, increasing its weight versus corrective maintenance cost.
- Considerations measuring the importance of the safety factor considering standards, contracts or market rules.
- Etc.

Regardless all these considerations, assigning criteria weights may contain a certain subjective judgments from the experts involved. In order to make this judgment as much consistent as possible, AHP techniques can be used, and a model presenting the multi-criteria classification problem in a logic decision diagram, can help to solve the multi-criteria decision sub-problem at the highest decision nodes of the diagram (the reader is referred to Bevilacqua et al. [8] for additional information concerning AHP utilization with this purpose). A major advantage of the AHP approach is that both qualitative and quantitative criteria can be included in the classification scheme. In addition, the assignment of weights to the different parameters is considered as a positive characteristic of the method [9]. The reader is referred to [3] (Section 9.4.1, steps of the process 6 & 7, pages 121 & 122, concerning the *Quantification of judgments on pair alternative criteria* and the *Determination of the criteria weighting and its consistency*) for a detailed description of the utilization of the AHP in our methodology.
On the other hand, the amount of subjectivity involved in the process of pair-wise comparisons is often viewed as the main limitation of this method, another problem arises when the number of alternatives to rank increases forcing to an exponential increase in the number of pairwise comparisons . That´s why we just limit the method utilization to the severity criteria level, not to the asset criticality classification level.

In the example of this paper, w_i , weight given to the severity criteria *i* by experts, resulting from the AHP analysis are assume to be equal to $[w_i]=10,30,20,40$. This means, for instance, that the review team considers corrective maintenance cost consequences are two times more important than those related to comfort, or that operational reliability consequences are three times more important than admissible safety consequences. Notice that, this is considered, after using AHP, to be a subjective but consistent judgment of the review team.

2.5. DETERMINING SEVERITY PER CRITERIA EFFECT

In the mathematical model proposed, an effects severity matrix is defined, for any element included in the analysis (r), as follows:

$$S_{ij}=\begin{cases} MS, & for \quad M_i<j\leq m, \quad \forall i \\ w_i v_{ij}, & for \quad 1\leq j\leq M_i, \quad \forall i \end{cases} \qquad (1)$$

Where

$v_{ij}=\frac{e_{ij}}{e_{ik}}$, with *k*= M_i and $j\leq M_i$, and with $v_{ij}=1$ for $j=M_i$ and $\forall i$

And e_{ij} is the effect *j* of the severity criteria *i, and* v_{ij} is the fractional value of effect *j* for the severity criteria *i*.

In the example we are following, the effects matrix is included (last 4 rows) in Table 3, where relative values for the different effects for each criteria are presented. Units for these relative values are based on cost (for *i=2,3,4*) or in a dimensionless rule of proportionality of the effect (*i=1*). The interpretation of Table 3, is as follows: a comfort functional loss, for instance, that in Table 2 is presented as having an effect to the entire train, may have a potential cost of 4,500 $; or, another example, an admissible effect on operational reliability stopping the system more than x minutes (s>x), may cause a potential cost of 10,000 $.

Criteria to measure Severity			
Safety criteria (dmnl) (weight:10%)	Cost related criteria (e.g. based on penalization cost and CM budget, $)		
	Operational reliability (weight:30%)	Comfort (weight:20%)	CM Cost (weight:40%)
Category of effects per criteria and functional loss			
Non admissible	**Non admissible**	4,500	300
1,5	10,000	3,000	150
1	5,000	600	50
0	0	0	10

Table 3. Effects matrix per functional loss

At this point is important to understand that, for a given functional loss, these are maximum possible effects per criteria, but not actual observed effects (later, real observed effects of functional losses, will be considered in the analysis, which are in fact conditional probabilities to reach a certain effect once a functional loss takes place). In the example that is presented, the corresponding effects severity matrix (according to Equation 1, and for MS=100) is included in last for rows of Table 4.

Criteria to measure Severity (S_{ij})			
Safety criteria (dmnl) (weight:10%)	Cost related criteria (e.g. based on penalization cost and CM budget, $)		
	Operational reliability (weight:30%)	Comfort (weight:20%)	CM Cost (weight:40%)
Category of effects per criteria and functional loss			
100	**100**	20	40
10	30	13.3	20
6,6	15	4	6.3
0	0	0	1,2

Table 4. Effects severity matrix per functional loss

The interpretation of Table 4, is as follows: a comfort functional loss impacting the train (maximum effect), will count for 20 points of severity (up to 100), while a comfort functional loss impacting only one car will count for 13.3 points of severity (this is calculated proportionally to the functional loss potential cost values). Notice how a non-admissible effect of a functional loss will count for a 100 (maximum value) regardless the effect in any other criteria.

2.6. RETRIEVING DATA FOR ACTUAL FUNCTIONAL LOSS FREQUENCY

Actual data for frequency of functional losses can be retrieved and captured in the variables $fe_{rz,}$ these variables conform, for each asset *r,* a vector of *l* elements, once there are $z=1\ldots l$ levels of functional loss frequency. Thus, fe_{rz} are Boolean variables with values:

$$fe_{rz} = \begin{cases} 1, & \text{When z is the observed frequency category of element r functional loss} \\ 0, & \text{Otherwise.} \end{cases}$$

Example: For functional loss frequencies expressed in Table 1, the criticality analysis review team could retrieve the asset *b* functional loss frequency and this would expressed as:

$$[fe_{bz}]= 0, 0, 1, 0$$

The frequency factor to apply to this element would be the result of the following scalar product:

$$f_r=\sum_{z=1}^{z=l} ff_z fe_{rz} \qquad (2)$$

In our example:

$$f_b=1x0+3.3x0+5.4x1+6.7x0=5.4$$

And therefore 5,4 would be the frequency to consider for the element when finally calculating its criticality.

2.7. RETRIEVING DATA FOR MAXIMUM POSSIBLE EFFECTS PER CRITERIA

Data concerning maximum potential effects, when a functional loss of an element happens, can be retrieved and captured in the variables pe_{rij} , these variables conform, for each asset *r,* a matrix of *n x m* elements, once there are *i*: 1...*n* criteria to measure severity of an element functional loss, and *j*: 1...*m* levels of possible effects of a functional loss for any criteria. . Thus, pe_{rij} are Boolean variables with values:

$$pe_{rij,} = \begin{cases} 1, & \text{When } j \text{ is the level of maximum potential effect of the functional loss} \\ & \text{of an element } r \text{ and for the severity criteria } i \end{cases}$$

0, Otherwise.

Assume, as an example, that for the effects severity matrix expressed in Table 4, the criticality analysis review team retrieves potential effects of a functional loss of an element *r*, this could be represented with the following *potential effects matrix*:

$$[pe_{bij}] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Then, we can model the Severity of the functional loss of element r as follows:

$$S_r = Min\left(MS, \sum_{i=1}^{i=n} \sum_{j=1}^{j=m} pe_{rij} S_{ij}\right) \qquad (3)$$

In the previous example, the severity of the asset *b* would result in:

$$S_b = Min(100, 100+30+13.3+6.3) = 100$$

This, in fact, represents a weighted average type of algorithm, where the weights are introduced through the value of the different criteria effects, as calculated in Equation 1. In this way, consistency in the Severity calculation of one element with respect to another is ensured. It has been experience how by giving maximum severity to inadmissible effects, like for instance in our previous example, the different roles of actors represented in the review team are safeguarded (for instance, *safety department* people in the review team of our example), discussions in the meetings are reduced and consensus is more easily reached.

Notice how, in case of good data integrity for frequency and functional loss effects of the elements under analysis, the review team can and must concentrate its efforts in the selection of the severity criteria and in establishing proper weights according to business needs.

2.8. DETERMINING POTENTIAL CRITICALITY AT CURRENT FREQUENCY

The criticality of the element is finally calculated as

$$C_r = f_r \times S_r \qquad (4)$$

Thus, for asset *b* of the example previously introduced:

$$C_b = 1 \times 100 = 100$$

2.9. RETRIEVING DATA FOR REAL EFFECTS PER CRITERIA

Actual data for real element functional loss effects can be retrieved and captured in the variables $re_{rij,}$ these variables conform, for each asset *r,* a matrix of *n x m* elements, once there are *i*: 1…*n* criteria to measure severity of an element functional loss, and *j*: 1…*m* levels of possible effects of a functional loss for any criteria.

> re_{rij} = current probability of the effect *j* of criteria *i* for the functional loss of element *r,* with $\sum_{j=1}^{j=m} \Re_{rij} = 1$.

Assume, as an example, that for the effects severity matrix expressed in Table 4, the criticality analysis review team could retrieve data concerning real element functional loss effects for asset *r*, this could be represented with the following *real effects matrix*:

$$[re_{rij}] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0.1 & 0 \\ 0.2 & 0.3 & 0.8 & 0.9 \\ 0.8 & 0.2 & 0.1 & 0.1 \end{bmatrix}$$

Then, we can model the Severity of the functional loss of element r as follows:

$$S'_r = Min\left(MS, \sum_{i=1}^{i=n} \sum_{j=1}^{j=m} re_{rij} S_{ij}\right) \qquad (5)$$

In the previous example, the severity of asset *r* would result in:

$$S'_b = Min[100, 6.6 \times 0.2 + (30 \times 0.5 + 15 \times 0.3) + (13.3 \times 0.1 + 4 \times 0.8) + 6.3 \times 0.9] = 31.1$$

2.10. DETERMINING OBSERVED CRITICALITY AT CURRENT FREQUENCY

The criticality of the element is finally calculated as

$$C'_r = f_r \times S'_r \qquad (6)$$

In the previous example presented

$$C'_b = 1 \times 31.1 = 31.1$$

So real criticality is much lower than potential (100)

3. CRITICALITY ANALYSIS AS A PRACTICAL MANAGEMENT TOOL

For complex in-service engineering assets, the implementation of the model must be fast and automatic over time. Also, the results of the analysis, and corresponding maintenance strategic actions carried out as a consequence of it, must be accountable in the future.

In order to easy the data entry process (considering now the need to rank an important amount of elements), and to make the interpretation of the analysis results user friendly, the following process, as a result of previous implementation in complex and large engineering assets, is recommended:

1. Retrieve asset's data for frequency and potential severity effects (Table 5). Data must show assigned frequency and severity criteria categories, per asset. It is frequently convenient, to save time and easy analysis replications, that the list of assets can be directly retrieved (to the scope of the analysis) from the Enterprise Assets Management System database.

Assets	Frequency	Severity criteria			
	FE	**PE$_1$** (Safety)	**PE$_2$** (Op. Reliability)	**PE$_3$** (Comfort)	**PE$_4$** (CM Cost)
a	L	L	M	VH	H
b	L	VH	H	H	M
c	M	L	M	L	H
d	H	H	H	H	M
e	M	L	M	M	L
f	L	L	L	H	M
g	L	M	VH	M	L
h	H	H	L	L	L
i	VH	L	VH	M	L
j	L	L	L	L	L

Table 5. Frequency & Potential effects qualitative matrix:

2. Convert this qualitative data into quantitative data (Table 6) considering the weights of each criteria and the model explained in previous paragraph. It is very important to separate qualitative and quantitative datasets. A reason for this is related to the possibility to test sensitivity of changes in the criteria weights for criticality assessment, modifying the final ranking of the assets, but not changing data retrieved in step 1.

Assets	Frequency	Severity criteria				Severity	Criticality
	FE	**PE$_1$**	**PE$_2$**	**PE$_3$**	**PE$_4$**		
a	1	0	6,6	20	20	46,6	46,6
b	1	100	10	13,3	6,3	100,0	100,0
c	3,3	0	6,6	0	20	26,6	87,8
d	5,4	30	10	13,3	6,3	59,6	321,8
e	3,3	0	6,6	4	1,2	11,8	38,9
f	1	0	0	13,3	6,3	19,6	19,6
g	3,3	15	100	4	1,2	100,0	330,0
h	5,4	30	0	0	1,2	31,2	168,5
i	6,7	0	100	4	1,2	100,0	670,0
j	1	0	0	0	1,2	1,2	1,2

Table 6. Current frequency and Potential effects quantitative matrix.

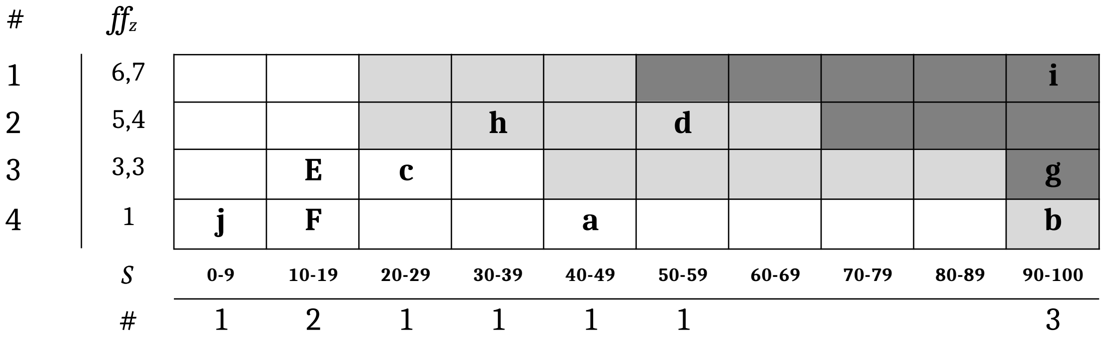
3. Se the quantitative criteria for the assignment of the category low, mid or high criticality to an asset, like, for instance, in Table 7.

Criticality level	% of assets	Criticality value interval	Assets	Area color in matrix (Fig. 1&2)
Critical	20%	326-670	g, i	Dark grey
Semi-critical	30%	90-325	b, d, h	Grey
Not critical	50%	0-89	a, c, g, e, f, j	White

Table 7. Criticality criteria assignment.

This decision may condition organizational efforts to be dedicated later to the management of the different category of assets. This is a business issue and consensus should be reached within the review team and the management team before any further process development.

4. Populate, with assets, the *potential criticality matrix* representation (in Figure 1). Notice that this matrix considers current (observed) frequencies and potential severities, for each equipment functional loss.



#	ff_z										
1	6,7										i
2	5,4				h		d				
3	3,3		E	c							g
4	1	j	F			a					b
	S	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-100
	#	1	2	1	1	1	1				3

Figure 1. Potential criticality matrix representation

Notice that shaded areas in the matrices in Figures 1 and 2, mean minimum criticality level of all elements in that area.

5. Retrieve quantitative data, using a unique matrix, and now for current observed frequency and severity effects per element (See Table 8).

r	**fe**	RE1				RE2				RE3				RE4				Severity					
		L	M	H	VH	L	M	H	VH	L	M	H	VH	L	M	H	VH	**re_1**	**re_2**	**re_3**	**re_4**	**S´r**	**Criticality**
a	1	1,0				0,1	0,9			0,7	0,2	0,1		0,5	0,5			0	13,5	2,13	3,75	**19,4**	19,4
b	1	0,8	0,2			0,2	0,3	0,5		0,1	0,8	0,1		0,1	0,9			1,32	19,5	4,53	5,79	**31,1**	31,1
c	3,3	1,0				0,5	0,5			1,0				0,8	0,2			0	7,5	0	2,22	**9,7**	32,1
d	5,4	0,8	0,1	0,1		0,3	0,2	0,5		0,1	0,9			0,0	1,0			1,66	18	3,6	6,3	**29,6**	159,6
e	3,3	1,0				1,0				0,1	0,2	0,7		1,0				0	0	10,1	1,2	**11,3**	37,3
f	1	1,0				1,0				0,7	0,2	0,1		1,0				0	0	2,13	1,2	**3,3**	3,3
g	3,3	0,8	0,2			0,2	0,3	0,5		0,5	0,5			1,0				1,32	19,5	2	1,2	**24,0**	79,3
h	5,4	0,8	0,1	0,1		1,0				1,0				1,0				1,66	0	0	1,2	**2,9**	15,4
i	6,7	1,0				0,0	0,0	1,0		0,2	0,8			1,0				0	30	3,2	1,2	**34,4**	230,5
j	1	1,0				1,0				1,0				1,0				0	0	0	1,2	**1,2**	1,2

Table 8. Frequency and current observed effects quantitative matrix.

6. Populate, with assets, the *current criticality matrix* representation (Figure 2). Notice that this matrix considers current (observed) frequencies and severities, for each equipment functional loss.

#	ff_z										
1	6,7				**i'**						
2	5,4	**h'**		**d'**							
3	3,3	**c'**	**e'**	**g'**							
4	1	**f', j'**	**a'**		**b'**						
	S	**0-9**	**10-19**	**20-29**	**30-39**	**40-49**	**50-59**	**60-69**	**70-79**	**80-89**	**90-100**
	#	4	2	2	2						

Figure 2. Current criticality matrix representation

7. To easy further analysis, populate with both assets with potential and observed functional loss severity, a criticality matrix representation (Figure 3). In the matrix in Figure 3 we can compare results obtained in two previous criticality matrices: potential and current.

ff_z										
6,7				**i'**						**i**
5,4	**h'**		**d'**	**H**		**d**				
3,3	**c'**	**e, e'**	**c, g'**							**g**
1	**j,f',j'**	**f, a'**		**b'**	**a**					**b**
S	**0-9**	**10-19**	**20-29**	**30-39**	**40-49**	**50-59**	**60-69**	**70-79**	**80-89**	**90-100**

Figure 3. *Potential and Current criticality matrices* representation

8. Automatic generation of the criticality report, listing the assets ranking per criticality levels, and within each level, classify the assets by common frequencies and severities. Rational for this is related to the type of strategy that will be required to manage them. Realize that, for managers, the most important outputs from this analysis are these lists of assets falling under different criticality categories and subcategories.

4. INTERPRETATION OF CURRENT AND FUTURE RESULTS

Once all these data is available to the analyst some guidelines for the interpretation of results are the following:

- Assets whose representation in matrix of Figure 3 is similar to the one in Figure 4. For all these elements observed criticality (S'_x, ff'_x) is lower than potential (S_x, ff'_x). Regarding these elements, some of the following statements could be applicable:

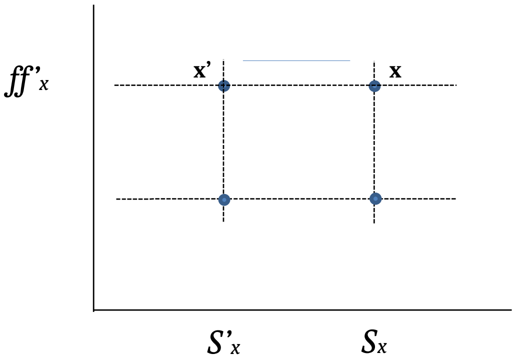


Figure 4. Potential and Current criticality representation (within the matrix)

1. Dynamic capabilities to avoid serious failures consequences or fault propagation are somehow in place, and although some of the assets may still have a high frequency of failures (see for instance asset *i* in Figure 3), consequences are low due to this fact.
2. Passive mitigation mechanism to avoid consequences of functional losses have been successfully introduced (redundancy, passive safety and environmental protections, etc.).
3. Predictive maintenance programs are mature, and levels of potential and functional failures are properly selected once the consistency of the failure mode PF interval is well studied and known (See Moubray's Maxim 2 formulated in [13]).

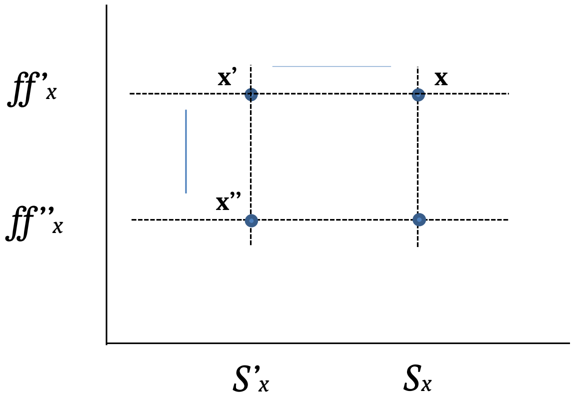


Figure 5. Representation of criticality changes, in a matrix, over time

- Assets whose representation in current criticality matrix (Figure 2) over time ($x' \rightarrow x''$ *for* $t''=t'+\Delta t$) is improving in criticality due to a reduction in functional loss frequency over time ($ff'_x \rightarrow ff''_x$), as in Figure 5. For all these elements observed criticality is becoming lower and some of the following statements could be applicable:

  iv. At time *t'*, the opportunity for an operational reliability improvement was detected. For instance, through a benchmarking of industry standards for current assets operational conditions existing PM programs were optimized; or for example, operational reliability enhancements were discussed with equipment vendors offering their experience and best estimates to consider environmental factors and current operating conditions inside existing PM programs.

  v. An elimination of failure latent root causes in assets was accomplished. Some programmatic and organizational measures were introduced to discard these latent failure causes (Root Cause Failure Analysis Effect).

  vi. There have been proper adjustments of the PM program to existing asset operational conditions by accomplishing a RCM program (Reliability Centred Maintenance effect). RCM programs reached lower failure rates in critical assets, but also possibly lower failure consequences as explained in ii. RCM programs should be carried out once no abnormal functional loss frequency, in high severity equipment, is found (i.e. it is convenient once point v is accomplished).

- In many occasions, cost-risk-benefit analysis may lead to the discard of PM activities for non-critical assets (for instance, for those in the white area in Figure 1). Assets with criticality (S'_y, ff_y), as shown in Figure 6, could become the target of the analysis if they deserve important preventive attention at the moment of the analysis (favorite candidate assets would be: j, f & e in Figure 1, notice how asset c is in the white area, but could potentially become semi-critical in case of increasing its functional loss frequency, therefore it would not be a favorite candidate asset for this analysis).

  The PM tasks to discard should not be those ones avoiding early equipment deterioration; otherwise a significant increase in the LCC of the asset could happen. Nevertheless, even taking into account this consideration, we may expect an increase in functional loss frequency (see Figure 6, $ff_y \rightarrow ff'_y$) and criticality (S'_y, ff'_y) as a result of less monitoring, inspection, or calibration activities on the asset (activities typically discarded or reduced after the analysis). Severity of the assets failures should also be under control before any discard of PM activities. Functional loss severity could make the asset to exceed the low criticality area, white area in the matrix, increasing business risk. Resulting criticality after discarding PM activities (S''_{Y}, ff'_{Y}) should remain within the white area in the matrix (see Figure 6).

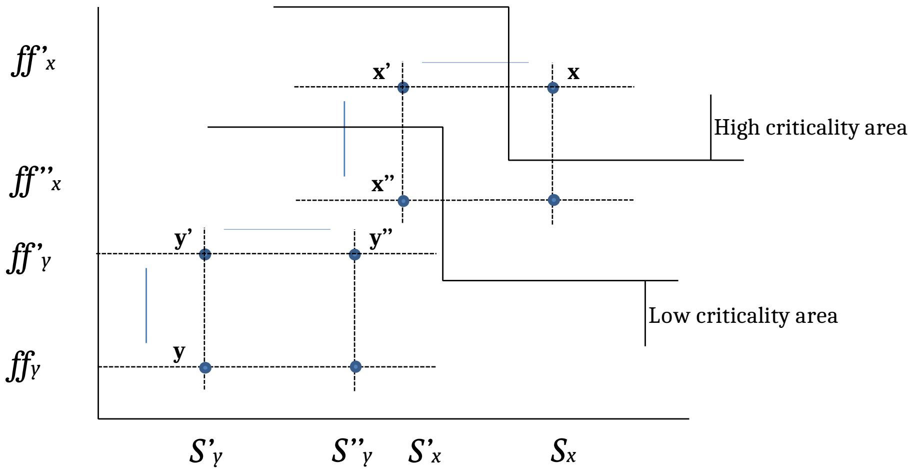


Figure 6. Risk-cost-Optimization programs for non critical (y) assets

It is important to notice that failures with minor consequences tend to be allowed to occur, precisely because they may not matter very much. As a result, large quantities of historical data are normally available concerning these failures, which mean that there will be sufficient material for accurate actuarial analyses if required.

- In other occasions, assets may remain with a high severity and very low functional loss frequency (See asset b in Figure 1). To these elements the Resnikoff Conundrum is applicable (this conundrum states that in order to collect failure data, there must be equipment failures, but failures of critical items are considered unacceptable, causing damage, injury and death. This means that the maintenance program for a critical item must be designed without the benefit of failure data which the program is meant to avoid). For a failure with serious consequences, the body of data will never exist, since preventive measures must of necessity be taken after the first failure or even before it. Thus actuarial analysis cannot be used to protect operating safety. This contradiction applies in reverse at the other end of the scale of consequences, as we have discussed in the previous bullet. Therefore, for these elements, maintenance professionals should turn their attention away from counting failures (in the hope that an elegantly constructed scorecard will tell us how to play the game in the future), towards anticipating or preventing failures which matter [11].

5. VALIDATION OF THE MODEL AND THE MODEL STRENGHTS

Since 2007, authors have implemented this model in a series of critical infrastructures in Spain and South America, through different collaboration and R&D projects with a clear purpose of infrastructure maintenance reengineering and alignment to business needs. The type of infrastructure analyzed were: Electrical power generation plants (all types, including renewable energy plants), network utilities (electricity, gas & water), transportation systems (like the one we use as an example in this paper) and networks, army warships, etc. Over 250.000 assets have been ranked in different type of plants or infrastructure in general. Over these years the methodology depicted in this paper has been upgraded and different utility models (including software tools) have been developed.

As an example, average number of assets ranked per power plant was over 9.900, while for regasification plants over 14.000 assets, or 700 (non- repetitive assets) for a train model. There is no reference in literature to a methodology dealing with such a massive asset criticality assessment.

Again, as an example trying to validate the methodology, Figure 7 presents a case study where 9921 systems are analyzed in a four years old power plant. Purpose of the study was to audit current maintenance management. For this particular case, after a first round of analysis (prior to the method application) the review team decided to rank only 4816 of those assets, considered now as technical locations (TLs) in the ERP of the company. The only reason for this was the consideration of the rest of the assets (5015, up to the total amount 9,921) as auxiliary equipment of the plant that were not relevant for the suggested maintenance study.

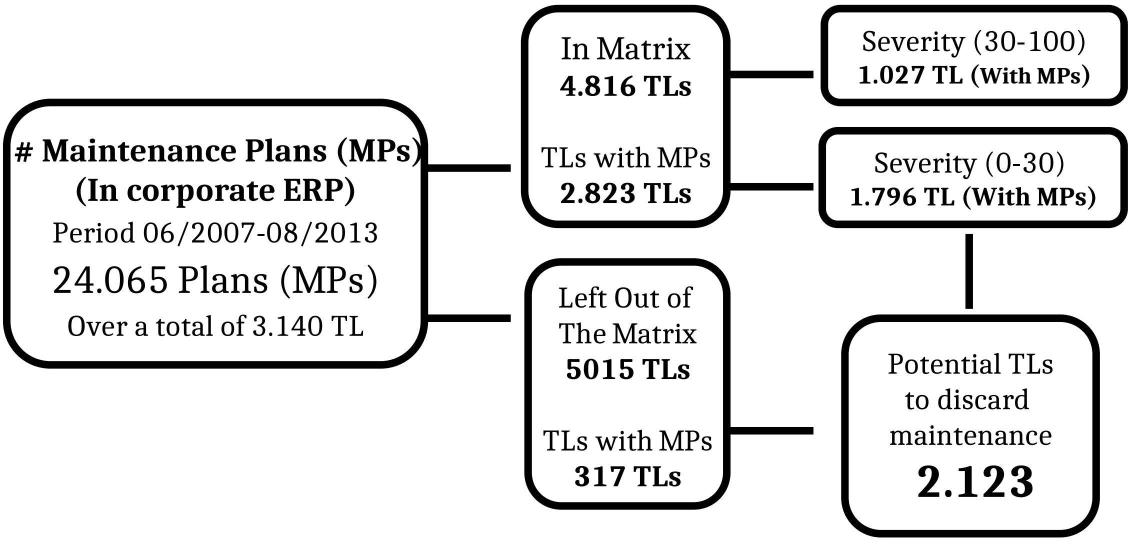


Figure 7. Case Study: Priority for 9921 systems – Power plant – Results 1

After two months the criticality analysis process was finished, the team realized that 2,123 technical locations of the plant (Figure 7) had assets with preventive maintenance plans (MPs) assigned having null or very low severity in consequences and deserving probably less maintenance efforts. It was curios to appreciate (See Figure 8) how preventive maintenance efforts in low criticality assets, after four years of operation of the plant and considering a planning horizon of 5 more years, would be almost 40% higher than in medium and high criticality items. For this case study around 70% of the 41,387.7 h were discarded, directly changing hours assigned to them in the MPs introduced in ERP, and 10% of those hours were dedicated to high criticality equipment preventive MPs. After 5 years of operation, in 2013, same performance of the plant was reached with a 30% savings in overall maintenance cost (direct & indirect cost) only by redirecting and aligning maintenance efforts to business needs using this criticality analysis. Similar results have been obtained when dealing with this issue in other scenarios, even for companies showing high maturity levels in many in maintenance related topics.

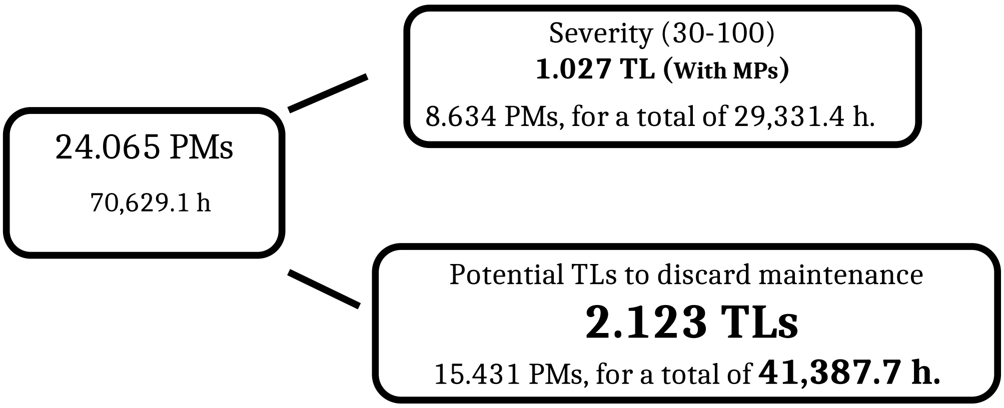


Figure 2. Case Study: Priority for 9921 systems – Power plant – Results 2

6. CONCLUSIONS

This paper contains the design of a process and model for criticality analysis with maintenance purposes and specific design constraints. The methodology ensures analysis consistency to business needs and for existing data of in-service complex engineering assets. At the same time, there is an effort to describe how to turn this process into a practical management tool. Issues arising related to extensive data handling and easy results representation are addressed. Finally, guidelines for results interpretation are offered. The authors believe that this type of analysis will become a must for complex in-service assets maintenance strategy review and redesign. Further research can use this methodology for the improvement of specific operational scenarios, or to refine the different steps of the process presented in this work.

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