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Criticality Analysis for improving maintenance, felling and pruning cycles in power lines.

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Abstract: This paper deals with the process of criticality analysis in overhead power lines, as a tool to improve maintenance, felling & pruning programs. Felling & pruning activities are tasks that utility companies must accomplish to respect the servitudes of the overhead lines, concerned with distances to vegetation, buildings, infrastructures and other networks crossings. Conceptually, these power lines servitudes can be considered as failure modes of the maintainable items under our analysis (power line spans), and the criticality analysis methodology developed, will therefore help to optimize actions to avoid these as other failure modes of the line maintainable items. The approach is interesting, but another relevant contribution of the paper is the process followed for the automation of the analysis. Automation is possible by utilizing existing companies IT systems and databases. The paper explains how to use data located in Enterprise Assets Management Systems, GIS and Dispatching systems for a fast, reliable, objective and dynamic criticality analysis. Promising results are included and also discussions about how this technique may result in important implications for this type of businesses.

Keywords: Criticality Analysis, Asset and Maintenance Management, Decision Support Systems, Risk Management

1. INTRODUCTION

Within the OPEX budget, felling and pruning work is the most important activity for electricity distribution companies. As a general rule, the corridors are treated at fixed intervals along the line as a whole, which leads to low levels of efficiency, given the varied nature of both the vegetation, with its very different growth rates, and the distances from its conductors along the line. In addition, the new Spanish regulatory framework obliges distributors to seek maintenance optimisation tools that focus on "asset management". Therefore, defining a proper methodology to increase the efficiency and effectiveness of felling and pruning maintenance plans, involving a transition from a cyclical maintenance model to a predictive maintenance model, has become a relevant issue for electrical distribution companies in Spain.

In this paper we concentrate on the process followed to provide a very dynamic analysis for the determination of the criticality of the assets. This analysis was used to update the preventive maintenance plans, in general, and to reassign the frequency of vegetation treatment at a power line span level, in particular.

In the sequel, the paper is organized as follows: Section 2 presents the existing requirements for the criticality analysis, conditioning the selection of the technique to be used for that purpose. Section 3 describes very precisely each step of the methodology implementation process using specific examples. Section 4 presents most relevant results obtained, their discussion and implications for the improvement of the management of the felling and pruning works. Finally Section 5 summarizes conclusions of the work and outlines aspects of further interest and research.

2. REQUIREMENTS FOR THE CRITICALITY ANALYSIS

The criticality assessment process to deal with the problem of this paper requires a specific methodology, which must cope with the following requirements:

- The process must be applicable to a large scale of in-service systems within the network (around 200.000), for which PM plans are designed and surrounding vegetation treatment is derived;
- 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 needs in current environments).
- The process must allow easy identification of new maintenance needs for assets facing new operating conditions, for instances new network developments, new demand of services, etc.;
- Connection with the company *Enterprise Asset Management System (EAMS), the Geographical Information System (GIS) and the Dispatching System* should be possible, in order to automatically reproduce the analysis, with a certain cadence, over time.
- Connection with the *Felling and Pruning Management System* of the company, for on-line updates of vegetation status, treatment and budget control;
- The process should be tested in the network showing good practical results.

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After considering all these needs, in this paper we have selected the methodology developed by Crespo Márquez et al. (2016) because it fits properly for this problem resolution. This criticality analysis methodology tries to prioritize the assets within an industrial/infrastructure context, where 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. The criticality analysis is accomplished with the purpose of adjusting assets maintenance strategies to dynamic business needs over time. A justification for this decision, for the purpose of this paper, is based on the fact that most of current quantitative techniques for assets criticality analysis use a weighted scoring method defined as variation of the Risk Probability Number (RPN) method used in design (Duffuaa et al., 2000). This time, however, a very precise procedure must be considered when determining factors, scores and combining processes or algorithms (Moss et al., 1999), and unlike Failure Modes Effects and Criticality Analysis (FMECA) now we do assess assets criticality not failure modes criticality. At the same time, this time the analysis requires a very precise level of indenture in the functional structure of the network, resulting in a massive number of assets. Notice that, besides the needs of ranking the different spans for the felling and pruning work improvement, the organization will use the same information of the rest of the maintainable items, for general maintenance optimization purposes.

The referred methodology can be applied to the problem of this paper if we properly develop the following steps:

1. Determine frequency levels and the frequency factors;
2. Determine criteria and criteria effect levels to assess functional loss severity;
3. Determine non-admissible functional loss effects;
4. Determine criteria weights in the functional loss severity;
5. Determine severity scales per criteria effect;
6. Determine criticality limits.

The methodology has been developed with the premise that the *results derived from the criticality analysis must be aligned with the priorities of the company*. It implies that the methodology must serve to the company target, and not in the opposite way. As a result, we will remark some aspects of the methodology that have been slightly adapted, with the aim of the results show, as faithfully as we can, the reality of the business.

3. THE CRITICALITY ANALYSIS PROCESS

3.1. Determine frequency levels and frequency factors

The criticality concept is defined as the product of the failure frequency of and item times the possible consequence of its functional loss (as in Equation 1):

$$CR = FFxC \qquad (1)$$

Therefore, the first step is to determine the frequency levels and the frequency factors. Frequency levels allow us to differentiate the assets by its failure recurrence. The frequency factor is the weight that we assign to each frequency level in order to use it within the criticality algorithm. Concerning the frequency levels, the most extended models define four levels: low, medium, high and very high failure frequency. In order to define the threshold among these frequency levels, a form of Pareto analysis is used, in which the elements are grouped into 4 frequency categories according to their estimated functional loss recurrence. The use of Pareto approach guarantees that all items are properly distributed in the matrix spectrum, in order to maximize the sensitivity of the methodology. Thresholds values assigned must show the real management strategy of the company. Assuming that during the last years the company priority was more availability than efficiency. It is assumed that this fact led the assets to be a little over maintained, maintenance as well as felling and pruning work has been intense and equally carried out for all different lines, without prioritization, and as a consequence very low failure events are registered. With this in mind, we can clearly explain that the majority of assets will be located within the lowest failure frequency band. The frequency levels can be classified as follows (Table 1):

Table 1. Frequency Levels and frequency factors

Annual Frequency Failure	Classification	Frequency factor
2≤f	Very High	2
1≤ f <2	High	1,5
0,5≤ f <1	Medium	1,2
< 0,5	Low	1

The definition of the frequency failures can be done using, for instance, a form of Pareto analysis, 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 frequencies. 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 (e.g., in Table 1 according to existing operating conditions of assets, the review team has decided to define a category named 'low', including a group of assets having less than one failures per year [f/y], easing our corrective maintenance operations, and serving as a reference for the rest of the selected asset categories).

Once we have defined each level and the frequency failure thresholds, we must assign a failure frequency factor. This value will be given to each frequency in order to compute a criticality value.

3.2. Determine criteria and criteria effects levels to establish functional loss severity

To define a certain objective criteria to assess an asset functional loss, most theoretical models propose the consideration of two main arguments: *integrity and sustainability.* Integrity goes first, and issues like personal and industrial safety as well as environmental care, are considered under this argument**.** Sustainability is related to management efficiency and continuous improvement and it is based on assets integrity; aspects like *availability, quality of service and maintenance* costs, are included within this topic. It is important to remark that sustainability do not directly imply a certain monetary expense, even an estimated "profit loss" or "production loss", but can also be related to reputational or image lost, repercussion on the stakeholders or even hypothetical penalties for the loss of a certain service level.

3.3 Determine non-admissible effects

At this point, the process requires the definition of those functional loss effects that will have the consideration of "non- admissible", for the business. This first requires deciding in what criteria is this concept applicable. This consideration represents the allocation of the maximum punctuation, in total, in functional failure consequence to the asset (100 in our case), regardless its results in the rest of the criteria assessment. Looking back to the business asset management policy, it was decided to apply this "non-admissible" condition just for criteria related to *Industrial safety, Environment and Quality of service* (see Table 2, first three columns). We therefore have defined as non-admissible consequences, the maximum level of severity in industrial safety, environmental criteria.

3.4 Determine criteria weights in the functional loss severity;

Every single criteria criterion must have a specific weight in order to change subjective opinions of the criticality steering team members into a numeric value, ranking the asset according to how important is its function to meet business goals. Analytic Hierarchy Process (AHP) techniques helped to solve this problem and the reader is referred to Crespo Márquez (2007) (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 this specific process. For instance, we just limited 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 $\{w_i\}=\{30, 12, 35, 14, 9\}$. This means, for instance, that the review team considers the impact on industrial safety to be almost two times more important than the impact of a failure on network availability.

3.5 Determine severity scales per criteria effect

The next step is to define the severity levels for each criteria effect. These levels will measure the severity of the consequences of a failure. In the same way that we have defined the failure frequency levels, the first step is to assess how many different levels must be defined for each criterion. In this project, the steering team decided that four levels was an optimum number to develop a precise and massive analysis. For each criterion, the consequences that a functional loss implies, in every level, must be determined. *Each definition must be as simple and explicit as possible.* If we are able to define it very simply, we will limit the possible debates later, in the working groups. See Table 5 for a criterion scale example (Environment).

3.6 Determine criticality limits.

The determination of the criticality limits is a relevant business issue since it will later impact the number of assets for which a certain strategy will be addressed. In this paper example the limits considered were as in Table 2.

Table 2. Criticality limits

Criticality	Criticality Value
Not Critical	90-200
Semi-critical	50-89
Critical	1-49

Data layers in the GIS	Acronym	Content
Fire risk zone	ZRF	Yes/No
Place of public interest	LIC	Yes/No
Special protection zone (animals)	ZEPA	Yes/No
Natural park	EEDN	Yes/No
Vegetation fraction covered(%)	FCC	%
Railway crossing	FFCC	Yes/No
Main road crossing	CP	Yes/No
Populated zone	ZP	Yes/No
High frequency of persons area	AFP	Yes/No
Other network crossing AT, MT, BT,..	CoR	Yes/No

Set the quantitative criteria for the assignment of the category low, mid, or high criticality to an asset, like that in Table 2 is very important decision that may condition organizational efforts to be dedicated later to the management of the different categories 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.

Table 4. Data captured in the different GIS layers in the case study

4. RETRIEVING DATA TO EASY PROCESS AUTOMATION

At this point, the process would be ready to start, assessing asset by asset, for a massive number of assets (over 200.000 for high & mid voltage lines in our example). All the assets are registered in the company assets register of the Enterprise Assets Management System (EAMS) that is connected to the GIS and therefore to the geo-referenced database of assets. An example of data concerning the geographical location of the asset is presented in Table 4, where data available in the different layers of the GIS is presented.

At the same time, fault location functionality of the dispatching systems can be used by a dispatch centre to provide information about the potential number of customers to be affected when a failure takes place in a given location of the network. An electricity distribution grid contains a large number of power lines and equipment distributed over a wide area. A great number of these equipment are power protection equipment capable of detecting power faults as they occur, protecting consumers and the grid itself from the consequences of these faults. When a fault is detected in a remote location, it is necessary to dispatch repair teams to the field to locate the place where the fault occurred. At the same time, in a smart grid the electricity distribution is managed through a communications network enabling remote monitoring and control of power equipment. If the number and location of sectionalizers and switches in a power line is known, and the number of customers served through that line is also known, the number of customers impacted by a fault of an asset of that line can be estimated (See U.S. Department of Energy, December 2014).

According to previous information, we have found an important room for improvement when developing the criticality analysis process. If previous assets data is available, the criticality

4.1 Redefinition of criteria effects levels

A first step in the automation process is to convert rules determining criteria effects levels using now assets data that is available in the systems (GIS Geo Data Base or in the network dispatching systems). Computers can then easily interpret these converted rules and automatically assign severity to the assets, for each specific criterion, saving an enormous time of analysis and producing a very robust and objective judgment. For instance, let's do that exercise to propose an equivalence of original criteria rules to new automated rules that are now based on assets GIS data, for the Environment criteria. We present that equivalence of rules in Table 5;

Table 5. Sample environment criteria effects level conversion (using GIS Data)

ORIGINAL		AUTOMATION	
Quality service: 35 % CATASTROPHIC: CA HIGH: A MEDIUM: M LOW : B		Quality service: 35 % CATASTROPHIC: CA HIGH: A MEDIUM: M LOW : B	
Loss of continuity of electric service superior to 20,000 customers, critical essential facilities, tip lines or customers < = 30Kv	CA 100	The failure of the equipment produces: • Loss of non redundant line • Loss of critical essential customers • Loss of more than 20.000 customers • Loss of customers in lines more than 30Kv	CA 100
Same for • 2.000 - 20.000 customers • Line loss> = 30KV in N-1 configuration	A 35	The failure of the equipment produces: • Loss between 2.000 and 20.000 customers • >=30Kv, N-1 lines	A 35
Same for: • 200 - 2.000 customers • Essential customers in medium voltage (<30Kv) • >=55Kv, N-1 lines	M 12	• Loss of between 200 and 2.000 customers • Loss of customers in medium voltage (<30Kv) • >=55Kv, N-1 lines	M 12
Any case not included in the above	B 1	Any case not included in the above	B 1

4.2 Automatic assessment of functional failure consequences

At this time, failure consequences for all selected criteria, and for each single asset (maintainable item) can be assessed. To illustrate this point, the corresponding pseudo-codes can be written

These codes describe, in IT language, the rules to be followed for each particular criterion during the automatic criteria consequences assessment.

For instance, for the previous two cases, the pseudo-code that was used in the case study for the automatic assessment of the environmental criteria is presented in Figure 1.

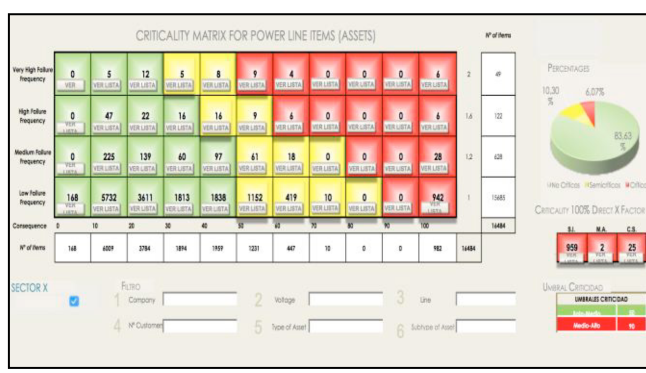
Once the assessment for each criterion is completed, the criticality of the assets, as a result of multiplying the frequency factor times the consequence of the functional loss can be computed. A real production criticality matrix is shown in figure 2.

Figure 1. pseudo-code for environmental criteria

```
Function: Value EN

Define EN, Fire_risk_zone, SCI_zone, SPAB_zone, natural_spaces_zone like character;
Define Coverage fraction like whole number;
Read Fire_risk_zone, SCI_zone, SPAB_zone, natural_spaces_zone, Coverage fraction
    Algorithm:
        If (Fire_risk_zone ="YES" | SCI_zone ="YES" | SPAB_zone ="YES" |
        natural_spaces_zone ="YES") & coverage fraction >60% Then
                Write "CA"
        Else
                If (Fire_risk_zone ="YES" | SCI_zone ="YES" | SPAB_zone ="YES" |
                natural_spaces_zone ="YES")
                Then
                        Write "A"
                Else
                        If (Fire_risk_zone ="NO" | SCI_zone ="NO" | SPAB_zone ="NO" |
                        natural_spaces_zone ="NO") & coverage fraction >0% Then
                                Write "M"
                        Else
                                Write "B"
                        ENDIF
                ENDIF
        ENDIF
Endfunction
```

Figure 2. Real production criticality matrix



5. FINAL RESULTS OF THE METHODOLOGY APPLICATION

In this Section we review main results obtained through the use of the methodology described above, some of these results are quantitative results, but some other are related to organizational aspects of the process and implications to the business.

With respect to quantitative results, considering this process for the 200.000 maintainable items of the selected power lines, all them could be ranked within a period of one month.

And 50% of this time, approximately, was dedicated to pre-processing and arranging data available in the referred business systems. This represent an enormous reduction of time to accomplish this type of analysis, we estimate a 80% reduction of time for the same number of assets following a non-automated process. In the case that the assets would increase in number, referred reduction of time would be of course even greater.

Percentage (out of the total number of assets) of critical items in the different categories are listed in Table 10, showing a very important amount of assets resulting non-critical (close to 70%), these items could immediately be subjected to a risk-cost-benefit analysis to discard preventive maintenance tasks. At this point it was important to focus attention on:

Table 10. Percentage of items per each criticality category

TYPE OF ASSET	CRITICAL	SEMI-CRITICAL	NOT CRITICAL
SUPPORTS	6,4%	12,8%	41,6%
AERIAL SPANS	1,9%	4,9%	14,2%
UNDERGROUND BRANCHES	0,4%	0,3%	7,0%
MANEOUVERT ELEMENTS (S&S)	1,0%	2,7%	6,9%
TOTAL	**9,7%**	**20,7%**	**69,7%**

- Task accomplished with a higher frequency than stated in the legal directives;
- Task that were designed beside legal tasks, with the initial intention to have a better control of systems dependability;
- Task that when discarded really represented cost savings for the business (many tasks do not really represent cost savings when discarded because of similar parallel tasks that mast be accomplished).
- Task that when discarded do not represent early deterioration of the items.

Concerning the impact of these results on the felling and pruning work, the percentage of spans per category are listed in Table 11, showing also results of a 68% of spans resulting non-critical spans, and a 23% of semi critical, while only 9% spans resulted to be critical.

Table 11. Percentage of items per each criticality

TYPE OF ASSET	CRITICAL	SEMI-CRITICAL	NOT CRITICAL
AERIAL SPANS	9%	23%	68%

This information could be crossed or combined with the vegetation growth models that were developed for each cell of 5x5 m of the entire network, and which provide an annual growth rate [meters/year] of that cell. The vegetation growth models are not part of this paper but very interesting tools because they also allow a 3D simulation of the network.

The combination of models: Span criticality vs. Vegetation growth per span corridor, allows again a risk-cost-benefit analysis to discard felling and pruning tasks per line span (so now with much more detailed level of indenture than before) and improves dramatically the effectiveness and efficiency of felling and pruning treatments. Then the suggested period of treatment is calculated as in Equation 2.

$$Suggested\ Period\ of\ Treatment\ (per\ span) = \ Mini\ (Ti) \quad (2)$$

$$with\ i = \ 1 \ldots n\ number\ of\ cells\ per\ span.$$

Where T_i is the time for the vegetation of cell i to reach the above mentioned limiting factors of the cell, considering the analysis of vertical and horizontal growth rates, and taking percentiles of, for instance, 95%, 75% and 50%. Of course the more critical the span the more conservative we are in our estimations (the higher admissible vegetation growth rate).

6. SUMMARY OF ADVANCES

Improved knowledge of the network and the vegetation underneath it. Transportation and distribution companies spend millions of Euros every year on vegetation management, but do not have sufficient information about it to maximise the efficiency of this treatment. With the right information, it is possible to find out where the vegetation is within the network, the area it occupies and its growth rate, and based on these details it is possible to calculate the optimum frequency for the treatments. Furthermore, an enhanced knowledge of the network and the vegetation for the providers of the felling and pruning services will lead to a reduction in the cost of their operations. The areas involved in improving knowledge of the network aimed at improving the competitiveness of the felling and pruning services, to reduce the financial risk of their operations.

Prioritisation of work based on the asset's criticality. The criticality analysis is considered a prerequisite or a necessary stage to review the existing maintenance programs, as well as the felling and pruning programmes associated with the assets (overhead power lines spans in this case). The level of indenture selected is the maintainable item, for which the maintenance plans are developed, resulting in a massive number of assets. Later, inspection and maintenance activities on these assets, plus suitable frequency of vegetation treatment, will be prioritized on the basis of quantified risk caused due to failure of the assets. The high-risk assets will be inspected and maintained with greater frequency and thoroughness, and vegetation will have a deepen treatment and analysis, to achieve tolerable network risk criteria.

Focusing on business needs. The results obtained through this methodology will provide extremely valuable information that will ultimately maximise management efficiency in the network, channelling the felling and pruning services provider in a way that must be consistent with business needs. The information will be managed on a centralised basis by means of a so called "*Felling and Pruning Management System*" based on GIS technology, which will use a multi-variable analysis to produce optimised maintenance plans for the short and medium term, minimising expenses, monitoring risks, making the work done by the contractor carrying out the work sustainable, and complying with the applicable Spanish and autonomous regional legislation. The implementation of the strategy presented in this paper was expected to provide the business with an annual saving of 33% in felling and pruning budget resulting in a dramatic efficiency improvement.

7. CONCLUSIONS

In this paper we show a practical way to implement criticality analysis in a power distribution network, we exemplify the concepts and procedure using several maintainable items of the lines.

We demonstrate the importance of the selection of a suitable methodology, allowing the study of assets criticality to the required indenture level.

We explain how, in this digital era, this process can be automated thanks to assets existing data in business systems like EAMS, GIS and dispatching systems. Automation requires simple rules translation and algorithm development.

Results in the application of the method to extensive number of assets in power lines were considered relevant by different businesses, because of the extent of the savings, but also because of the "easy-to-implement" technique. In most of cases a relevant decrease of the budget assigned, specially to felling and pruning task, but also to preventive maintenance, was reaching significant values (many times around the 30%).

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