ROBUST METHOD TO EVALUATE COST-BENEFIT FROM PREVENTIVE MAINTENANCE ACTIONS USING HISTORICAL DATA AND AN OPTIMIZATION ALGORITHM

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ABSTRACT

The prediction of the benefits from preventive maintenance actions on electric distribution systems is not straightforward as the prediction the cost of such actions. For this reason most traditional preventive maintenance is based on time (scheduled intervals) and equipment condition (inspection). In this work is proposed a complete methodology to evaluate the cost-benefit relations between preventive maintenance investments and failure rates of feeders, by using historical data and an optimization algorithm. The algorithm identifies the best set of coefficients of a non-linear model, taking account seasonal factors and specialist knowledge. Through the model is possible to explicitly forecast frequency of interruption from feeders, which allows searching optimized combination of investments considering reliability and budget constraints on a maintenance study.

INTRODUCTION

In order to improve system reliability and avoid penalties from regulatory policies, utilities have to invest part of their operational budget in varied types of actions in an optimized manner [1]. To reduce the SAIFI index of a distribution network, one important tool is the use of preventive maintenance, whose benefit, the reduction of failure rates, is not straightforward to predict as the costs of such actions. Most traditional preventive maintenance is based on time (scheduled intervals) and equipment condition (inspection). In [2], the authors present a maintenance scheduling algorithm that determines when and where to perform vegetation maintenance. In [3], the authors present the application of condition based maintenance in power supply equipment. Such methods do not explicitly consider reliability goals.

The mapping of cost-benefit from different types of preventive maintenance through relations between investments and fault occurrences, allows to directly predicting reliability improvements which can be compared with regulatory goals. In [4], the authors present a methodology that takes a cost-effective approach to prioritize maintenance actions, and in [5] is suggested an exponential relation between total maintenance investments and frequency of occurrences in a feeder.

In this paper is proposed a methodology to evaluate the relation between investments and frequency of interruptions using specialist knowledge, historical data and an optimization algorithm. For each type of occurrence cause, such as vegetation, an exponential model is obtained between these occurrences and related investments, such as trimming. The exponential model considers the recent investments in maintenance actions that have high correlation with that cause.

The models obtained through this methodology translate the cost-benefit relations between investments and occurrences, which allows searching optimized combination of investments considering reliability and budget constraints. The investments are directed to the circuits according to the time between failures of each occurrence, indirectly mapped by the method.

The strategy is particularly interesting to utilities with heterogeneous feeders in the same area, that cannot use the same investment plan in every circuit, therefore an individual mapping of cost-benefit based on historical data would permit a better understand of the characteristics of each feeder.

METHODOLOGY

The method developed to model the cost-benefit from preventive maintenance actions consists in identify the types of actions that prevents the main causes of interruptions based on specialist opinion, and search coefficients of an mathematical relation between this mapped investments and frequency of interruptions for each cause, using historical data of investments and interruptions as inputs to an optimization algorithm. The method is based on three hypotheses and explained in detail in this section.

Hypotheses

There is a relation between interruption occurrences and particular mapped investments

The probability of an interruption occurrence is strong related to the amount of maintenance investments in the near past related to the cause of this occurrence. An example is the relation between the probability of interruption caused by vegetation and tree trimming actions in the circuit on the near past. For this reason the method searches a mathematical function between occurrences and mapped investments. The mapping of related investments for each type of cause can be based on specialist knowledge.

Occurrences time series have seasonal components

The frequency of occurrences, especially the ones related to environmental causes, are seasonal dependant with an annual cycle because of the influence of weather and other factors. For this reason, it is adopted that the historical data of occurrences will be seasonally adjusted and the mapping of cost-benefit will be the relation between monthly frequency of interruptions and mapped investments on the near past.

Cost-benefit relation is non-linear and saturable

The relation between preventive maintenance investments and the frequency of occurrences behaves as an exponential function. In the absence of investments, the number of occurrences should increase rapidly, and in a scenario of exaggerated investments, the marginal reduction of interruptions should saturate. In a past work [6] the authors suggested a cost-benefit linear model that was not suitable to explain the relation between the two variables, therefore the present non-linear formulation is an improved model.

Seasonal adjustment

The seasonal adjustments of the occurrences time series consists in removing the seasonal components through the moving average method [7]. Seasonal coefficients are obtained for each month, in order that seasonal components can be added in a forecast study. To apply the seasonal adjustment method, it is necessary at least 2 years of historical data.

Cost-benefit relations

It is adopted an exponential relation between the monthly frequency of interruptions (INT) and recent mapped investments (MI). The mapped investment of the cause 'k' is a linear combination of the 'N' preventive maintenance investments that assist the reduction of these types of causes, in the current month and the past two months. The coefficients $[B_{n,0}, B_{n,1}, B_{n,2}]$ for each mapped action 'n' and the exponential function coefficients $[\mathrm{a}, \mathrm{b}]$ are obtained by an optimization method and historical data. Each cause is solved independently as an optimization problem.

$$\mathrm{INT}_k(\mathrm{t}) = \mathrm{a}_k * \mathrm{e}^{-\mathrm{b}_k * \mathrm{MI}_k(t)}$$

$$\mathrm{MI}_k(\mathrm{t}) = \sum_{n=1}^{N} \left[B_{n,0} * INV_n(\mathrm{t}) + B_{n,1} * INV_n(\mathrm{t}-1) + B_{n,2} * INV_n(t-2) \right]$$

The coefficients permit to identify the types of investments that best correlate with the reduction of interruptions for that cause and also the temporal lag between the investment and the actual benefit on frequency interruption.

The formulation can be modified in order to take account a larger time period of investments, however this will largely increase the number of variables for the optimization, therefore should be avoided. For the same reason, the number of mapped investments types also should be limited.

Optimization method

The optimization method is used in order to identify the set of parameters that minimizes the error between the estimative of the model and historical data, the objective function is the sum of quadratic errors between the two series, therefore this formulation seeks the model that best forecast the interruption frequency of the feeder with investments as inputs.

$$error = \sum_{t}^{T} \left(\frac{INT_{model,t} - INT_{history,t}}{INT_{history,t}} \right)^2$$

In this work is used the evolutionary strategy algorithm [8], a type of evolutionary algorithm [9]. This type of nature-inspired algorithm uses a set of initial points (population) that is refined through the use of stochastic operators of mutation, recombination and selection until a stop criteria is reached. Figure 1 shows a flowchart of a generic evolutionary optimization algorithm.

Historical data of mapped preventive maintenance (INV_n) and seasonal adjusted interruption occurrences (INT) are used as inputs and the coefficients $[B_{n,0}, B_{n,1}, B_{n,2}]$ for each mapped action 'n' are the variables of the optimization problem. For each individual (set of coefficients) of the evolutionary algorithm population, it is used a robust curve fitting method (with outlier removal) to identify the coefficients of the exponential function $[\mathrm{a}, \mathrm{b}]$ and to evaluate the error function.

SAIFI estimation

The cost-benefit models and seasonal coefficients allow estimating the number of monthly interruptions based on past investments. Through the application of the method to the majority of interruption 'k' causes of the feeders of a region, it is possible to estimate the SAIFI index using the statistical data of the average number of affected customers per interruption ($C_{affected,n}$), of each feeder 'n'. The monthly SAIFI index of the region can be estimated using the following equation.

$$SAIFI = \frac{1}{C_{total}} \sum_{n=1}^{N} \sum_{k=1}^{K} C_{affected,n} * INT_{k,n}$$

Methodology Flow Chart

The methodology of cost-benefit evaluation from preventive maintenance investments can be summarized with the flowchart presented in Figure 2.

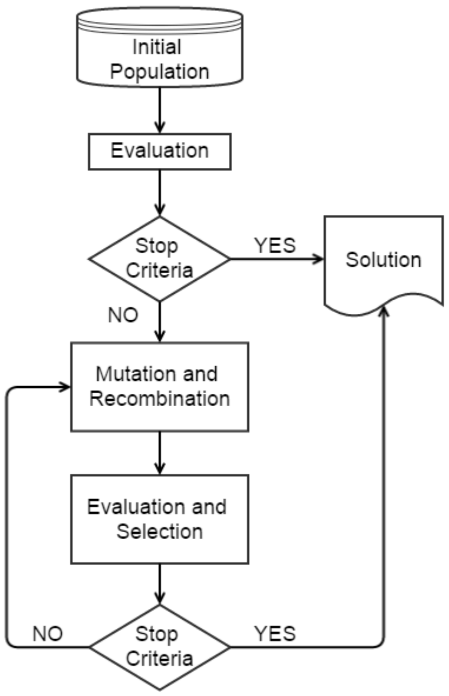

Figure 1: Flowchart for the evolutionary optimization algorithm

RESULTS

The method was tested together with Celesc, one of Brazil's largest utilities with 2.6 million consumers, whose biggest regional centre includes several heterogeneous feeders in the same area. It was used five years of monthly data of preventive maintenance investments and interruptions data from 36 feeders. Also a maintenance specialist with over 20 years of experience being maintenance manager supported the mapping between investments and causes of interruptions.

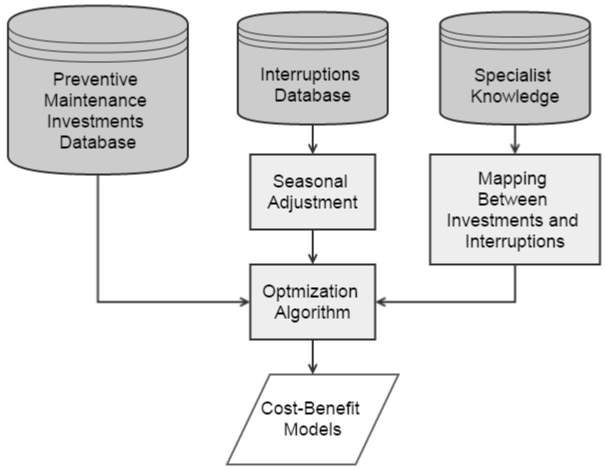

Figure 2: Flowchart of the proposed preventive maintenance cost-benefit evaluation method

The utility classifies the interruptions on 99 different possible causes, 14 of this causes represents over 80% of the identified interruptions during the study period and were the causes used to test the method. The major interruption cause is related to vegetation on the grid, which is a reflection associated with the fact that the absolute majority of feeders on Brazil are overhead lines. In this work the results will focus on the application of the methodology for two different causes: vegetation and lightning on one particular feeder with 166 Km of length in an urban area. Table 1 shows the mapping of the associated investments for each cause.

Table 1: Mapped maintenance investments for interruption causes of vegetation and lightning

	Vegetation	**Lightning**
Tree Trimming		
Construction Standard		
Civil Structure		
Lightning Arrester		
Earthing		

Preventive maintenance investments associated with the vegetation cause are tree trimming actions, changes on construction standard, especially from simple overhead lines to compact spacer cable standard, and maintenance on the civil structure. In the case of interruption by lightning surges, preventive maintenance on earthing systems and lighting arresters are the mapped investments. These both interruption causes are strongly dependent with weather conditions, in such cases the maintenance actions reduce the probability of interruptions.

The seasonal adjustment of the interruptions data is shown in Figure 3 for the cause of vegetation. The original data has strong seasonal components on the periods of summer. The seasonal adjustment has a smooth effect on the time series and permits to use the data from several years to identify the mathematical model.

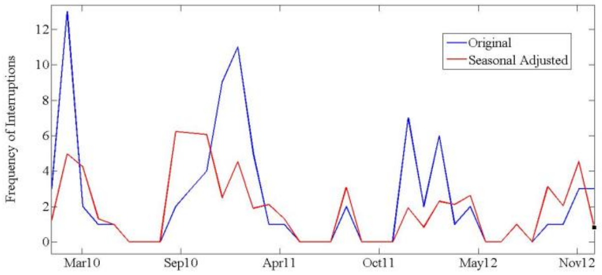

Figure 3: Interruptions caused by vegetation, original and seasonal adjusted data

The application of the method to the vegetation cause results on the exponential model of the Figure 4, the exponential model relates mapped investments (in Brazilian currency) with frequency of interruptions without seasonal components. The points colored in red were removed by the outliers filter and were not taken account for the curve fitting. The interruption series forecasted using the model can be compared to the original data on Figure 5. The total number of interruptions forecasted in the period deviates less than 10% from the historical data. The forecasted series has a tendency to be conservative because the modeling process uses historical data from a long period and have outlier removal. For this reason, the method cannot successfully predict the frequency of interruptions of February 2010, when the frequency of interruptions was greater than the usual for that month.

The coefficients of the mapping relations show that maintenance investments on the construction standard of the grid have the stronger impact on reduction of interruptions caused by vegetation for this feeder, since the coefficients of this type of investment are greater. Also tree trimming investments have a short period impact since only the coefficient for the current month has a strong value. The coefficients of the model for the vegetation cause are presented in Table 2. The average absolute error between original and forecasted data is of 1.82 interruptions.

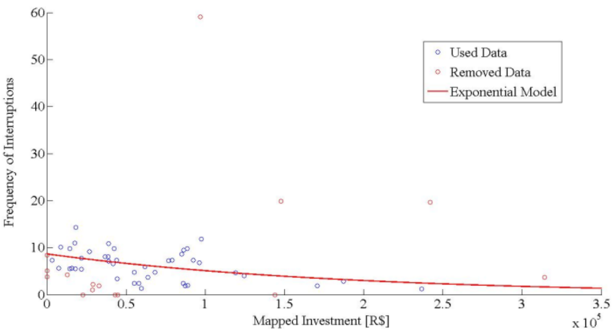

Figure 4: Exponential model for vegetation cause

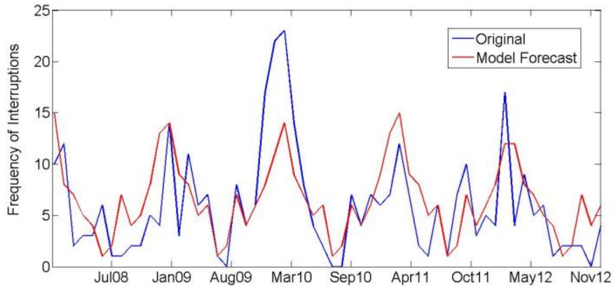

Figure 5: Interruptions forecast for the vegetation cause

Table 2: Coefficients of the cost-benefit model for vegetation cause

<table>
<tr><th colspan="4">Coefficients</th></tr>
<tr><td></td><td>B_0</td><td>B_1</td><td>B_2</td></tr>
<tr><td>Tree Trimming</td><td>9.81</td><td>0</td><td>0.56</td></tr>
<tr><td>Construction Standard</td><td>10.13</td><td>23.35</td><td>72.86</td></tr>
<tr><td>Civil Structure</td><td>44.38</td><td>3.56</td><td>10.34</td></tr>
<tr><th colspan="2">Exponential Function</th><th colspan="2">Average Absolute Error</th></tr>
<tr><td>a</td><td>b</td><td colspan="2">Avg_Abs_Error</td></tr>
<tr><td>7.68</td><td>2.42e-06</td><td colspan="2">1.82</td></tr>
</table>

The error function of the optimization converges in few iterations to its local minimum, as can be seen in Figure 6.

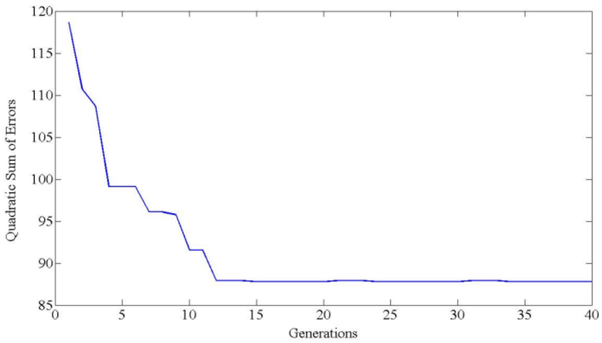

Figure 6: Error function for the application of vegetation cause

The application of the method to the lightning cause presents similar results, with an average absolute error between original and forecasted data of 3.4 interruptions. Figure 7 shows the exponential model for the lightning cause and Figure 8 shows the forecast and original data.

The coefficients for the lightning cause indicates that both mapped investments, on lightning arrester and earthing, have similar impacts on the reduction of interruptions, with the strongest coefficients being the one of the immediately past month. This cause also presents an atypical month on February 2011, which the model also forecast a more conservative response.

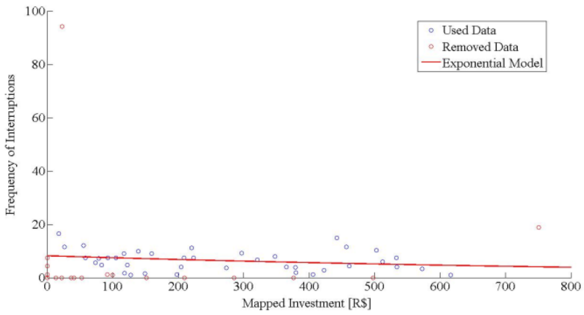

Figure 7: Exponential model for lightning cause

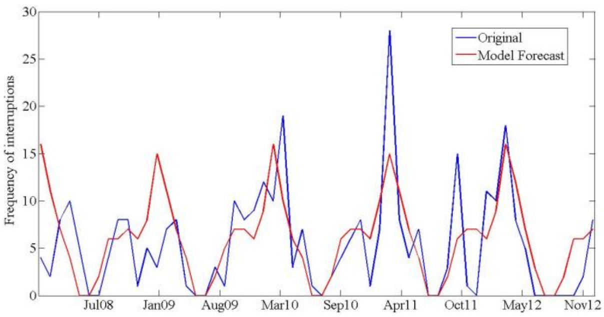

Figure 8: Interruptions forecast for the lightning cause

Table 3: Coefficients of the cost-benefit model for lightning cause

Coefficients			
	B_0	B_1	B_2
Lightning Arrester	0.08	12.38	0.74
Earthing	0	14.81	2.02
Exponential Model		**Average Absolute Error**	
a	b	Avg_Abs_Error	
6.48	2.34e-05	3.41	

CONCLUSION

This paper proposed a method to model the cost-benefit from preventive maintenance investments on electric distribution systems. The methodology uses historical data of investments and of frequency of interruptions, and the relational mapping between investments and each cause as inputs to an optimization method that seeks to identify parameters of a mathematical model by minimizing the error between reference data and forecasted data. The main advantages of the proposed method are as follows: 1) Permits to forecast frequency of interruptions of each modeled cause, permitting to estimate the SAIFI index, therefore can be used in studies that explicitly consider reliability goals; 2) The models are obtained directly from historical data of each feeder, therefore the method can be applied to networks with heterogeneous feeders in the same area; 3) The coefficients of the models permits to identify the types of investments that can better contribute on the reduction of interruptions of each cause.

The application of the methodology using real data from a Brazilian utility shows that the method can successfully forecast frequency of interruptions using maintenance investments as inputs. This can be a powerful tool to be integrated with traditional maintenance strategies in utilities, using data from their own feeders.

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