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RESEARCH ARTICLE OPEN ACCESS

A TOOL FOR PRIORITIZING DISTRIBUTION SYSTEM EQUIPMENT RENEWAL PLANS BASED ON MULTI-CRITERIA ANALYSIS AND ESTIMATION OF REMAINING USEFUL LIFE

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ABSTRACT

This work presents a tool developed to assist decision making for maintenance and replacement of assets based on the determination of priority equipment in a renovation plan. Different data sources and multi-criteria evaluation were used in an integrated way, focusing on individual distribution substation equipment. The necessary parameters were obtained from accounting, georeferencing and maintenance data for substation equipment, using well-established reports such as the Asset Control Report (ACR), Geographical Database of the Distribution Company (GDDC) and history of the maintenance system . With this information, it is possible to determine several essential parameters for controlling the life of equipment, such as depreciation of assets, replacement values, in addition to allowing the estimation of the remaining technical useful life with the application of machine learning techniques. When evaluating assets by different indicators, multi-criteria analysis is then used to determine a ranking of equipment priorities. In this case, the Analytic Hierarchy Process (AHP) method was used, where a pair-by-pair comparison of the parameters under analysis is performed, based on weights established by the planner. Thus, the criteria adopted for judging the equipment were: 1) accumulated depreciation; 2) economic benefit; 3) exchange cost; 4) shutdown impact; 5) DEC and FEC of the set and; 6) obsolescence level. Therefore, the tool presented in the work provides a detailed view of the individual situation of the distributor's main assets, making it possible to rank the assets based on the analysis of their criteria. The priority list can also be sorted by feeders, entire substations and regional maintenance, allowing you to identify where depreciation is highest and the correlation with the operating costs assigned to that region. Finally, the tool also makes it possible to establish a periodic renewal plan, as it allows for the monitoring of the main characteristics of the assets.

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INTRODUCTION

One of the challenges for companies in the electricity sector is to determine the optimal time to replace their equipment. As field-installed equipment degrades, whether due to its age or situations external to the system, they tend to have a greater number of failures, putting the operation at risk. Thus, an efficient asset renewal plan aims to assist in the exchange of this equipment, not allowing the network to reach critical situations, but enabling an early view of asset behavior using maintenance assessment strategies, statistical analysis and lifetime monitoring.

One of the techniques used for these assessments is the estimation of the remaining useful life. This parameter can be understood as the amount of time the asset can operate before requiring replacement. By obtaining this value, it is possible to plan and optimize the operation of equipment, based on the estimation of its last year in the base and what costs and financial returns the equipment will generate in this period. Therefore, the purpose of the tool presented in this article is to assist in the asset renewal plan, from the multi-criteria analysis of distribution substation equipment, presenting as the main development assumptions: estimation of remaining useful life and frequency of equipment maintenance using machine learning techniques; estimation of maintenance costs; calculation of equipment revenues (based on current regulations); criticality assessment of regions (via indicators of continuity of electrical sets), and individual criticalities (based on obsolescence notes). Additionally, using different data sources and creating notes using the analysis criteria, a substation prioritization ranking is created for an equipment replacement plan, presenting the results in interactive maps applying business intelligence. This paper is organized as follows: Section 2 presents the theoretical guidelines used in this work and describes the most relevant models used for the proposed technical solution. Section 3 presents the innovative analytical tool to optimize energy asset renewal decisions. Finally, Section 4 presents this work's conclusions.

MATERIALS AND METHODS

In this section, the theoretical guidelines used in the model proposed by this work will be described, in addition to the general specification of the created solution.

Methodological guidelines: One definition for asset management is to operate a group of assets during the entire technical life cycle, ensuring an adequate return on investments and ensuring service and safety in accordance with the standards established by norms (Schneider, 2006). Within the context of energy distribution, this task can become complex as companies must achieve different goals, having to seek a balance between adequate returns on their investments and maintenance of quality levels of energy supply to the population. The returns on these investments made in the network, and the standards that describe the quality indicators that must be achieved by Brazilian distributors, are regulated by ANEEL (National Electric Energy Agency), being described by the PRODIST (Electric Energy Distribution Procedures in the National Electric System) and PRORET (Tariff Regulation Procedures) instruments. It is then up to companies to manage their investments and services in order to comply with the rules established by the regulatory agency. According to (Zampolli, 2012), some of the points that an efficient asset management plan must present: 1) Plan scope and guidelines; 2) Data and descriptions of the assets considered; 3) Activities, tasks, people responsible and prioritizations; 4) Lifecycle Strategies; 5) Financial forecasts; 6) Assessment practices; 7) Continuous improvement actions. In other words, good asset management must monitor assets throughout their life cycle, collecting information on the status of equipment, evaluating this data and predicting important information in order to understand their operation and make predictions of failures and economic returns. From a history of asset monitoring information, it is possible to apply a model that characterizes assets based on monetary returns, in addition to reliability and risk analyses, as illustrated in Figure 1.

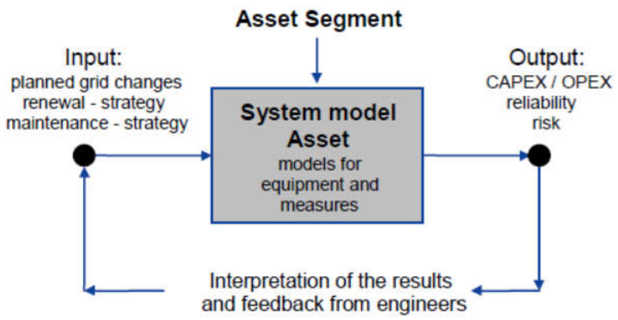

Figure 1. The link between strategy and costs (Schneider, 2006)

Network assets degrade over time, directly impacting companies' quality goals. Therefore, investments must be made in order to replace equipment, maintain the levels required by regulatory bodies and renew the remuneration base of distributors. For that, an efficient management must involve: maintenance strategies, determination of the conditions in which the assets are found, simulations, statistical analysis of failures and monitoring of the technical useful life. The economic analysis must be carried out throughout the asset's life cycle, which is understood by the period that the equipment is operating in the company. Life cycle analysis, in addition to providing deeper knowledge about the behavior of the asset, helps companies to define the right time for disposal and how this disposal should be done in order to minimize the associated environmental impacts (Zampolli, 2015). The model used for the distributors is defined based on three parameters: CAPEX- CAPitalEXpenditure - (blue), Technical Revenue (yellow) and OPEX - OPerationalEXpenditure - (red), as shown in Figure 2. The component modules cover all the distributors' revenues.

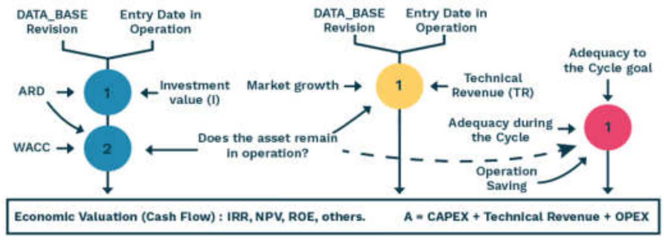

Figure 2. Evaluation model form energy distribution (Authors)

Maintenance cost forecasting can be performed through historical maintenance data modeling. It is possible to project, in a future time interval, the expected cost of maintenance to be performed on an equipment, or set of equipment. In general, prediction can be done in a variety of ways, from simpler to more complex techniques. Again, the choice of modeling technique rests with the sample of available data. If the data sample is limited in terms of size and number of attributes, the use of simpler methods, such as linear regression, is indicated. On the other hand, if the available data show patterns such as trends or seasonality, it is recommended to use more complex techniques, such as non-linear time series models (Hirschey, 2009). The Remaining Useful Life (RUL) is the remaining lifetime of an asset at a given time of operation, its estimation is essential to predict the time after which an asset will no longer be able to meet its operational requirements. RUL is typically random and, as such, must be estimated from available information sources, such as information obtained from monitoring of health and condition (Si et al., 2011). In this way, asset maintenance and/or renewal plans can be drawn from the RUL, in order to optimize operational efficiency.

Database and Integrations: The information for using the models proposed in this work is presented below:

- Asset Control Report (ACR), providing the accounting information of the equipment, serving as input for the analysis of regulatory remuneration and CAPEX of the company;
- Geographical Database of the Distribution Company (GDDC);
- System with maintenance information for the main substation and network equipment;
- System with information on interruptions in the medium voltage network.

The integration of data is shown in Figure 3 below, where the general bases are linked by the information on the equipment number and the operational number.

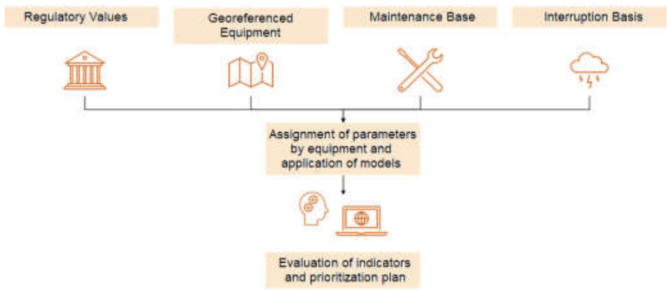

Figure 3. Data Integration (Authors)

Machine Learning Models

RUL Estimation Model: The RUL can be realized from the calculation of the difference between the age of the equipment and the Technical Useful Life (TUL), estimated through the implementation of machine learning models that estimate this variable. To estimate the TUL, nine variables were used (see Figure 4) as input attributes for a machine learning model. These models, in turn, perform a regression task and result in the TUL value of each equipment. In all, four Machine Learning algorithms (Machine Learning - ML) were used: Multiple Linear Regression, Random Forest, Decision Tree and Gradient Boosting.

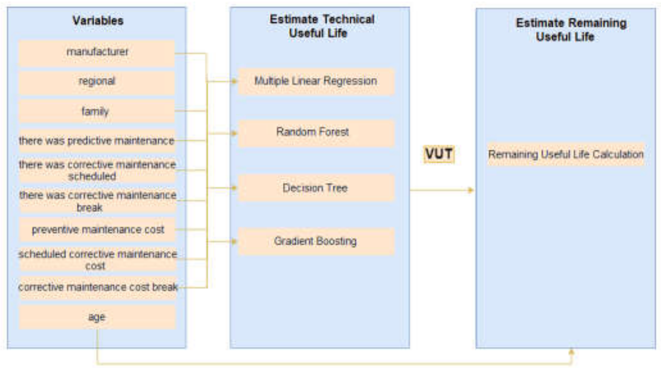

Figure 4. Main methodological flow (Authors)

After some experiments, Multiple Linear Regression was used to train a simplified model, since the others are machine learning algorithms with greater computational complexity and, consequently, are more likely to overfit the model for simpler tasks. From this, for each TRU (Type of Registration Unit), the training and validation of the model was carried out through three main steps: pre-processing, TUL estimation via ML and analysis of variables and errors. The training flow is illustrated in Figure 5.

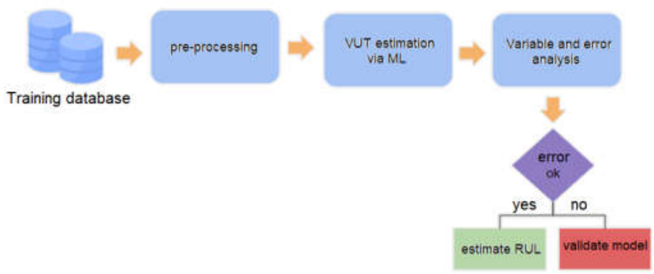

Figure 5. Training flow (Authors)

Maintenance projection model: Machine learning models for projecting the frequency of maintenance of assets have, as predictor variables, five general information about the equipment (manufacturer, regional, family, TRU, and age), in addition to data that contain information about maintenance performed previously (cost and the frequency of this maintenance). Considering these variables, two machine learning models were generated: one for the frequency of corrective maintenance and another for preventive maintenance. In addition, we chose to use corrective and preventive maintenance frequency variables as input data for the corrective maintenance model, since the occurrence of preventive maintenance can impact the occurrence of correctives. Similarly, for the preventive maintenance frequency projection model, the variables of the two types of maintenance were used.

Multi-criteria analysis models: In the literature, there are several methods for analyzing decision making based on multiple criteria. One of the most used is the Analytic Hierarchy Process (AHP). Originating from the work of Professor Thomas L. Saaty (Saaty, 1991), this method is based on concepts of linear algebra, operations research and psychology. It is a simple method, in which you can choose the best options from a group of different alternatives using qualitative and quantitative parameters. In this method, a pair-by-pair comparison of the parameters under analysis is performed, based on weights established by the planner. As values are normalized, criteria can be compared on different scales. The objective is, from the determination of critical criteria, and from the attribution of weights and the pair-by-pair comparison of these multiple criteria, to find the priority alternative in a portfolio of options, ensuring uniformity in the evaluation method. Figure 6 illustrates the general idea of the method of comparison between evaluation criteria.

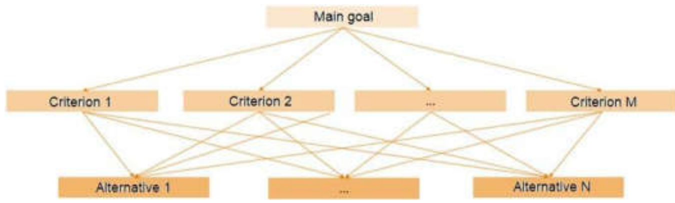

Figure 6. Multicriteria analysis scheme for selection of alternatives (Authors)

Figure 7 shows the criteria that were used for the development of the tool, in two hierarchical levels.

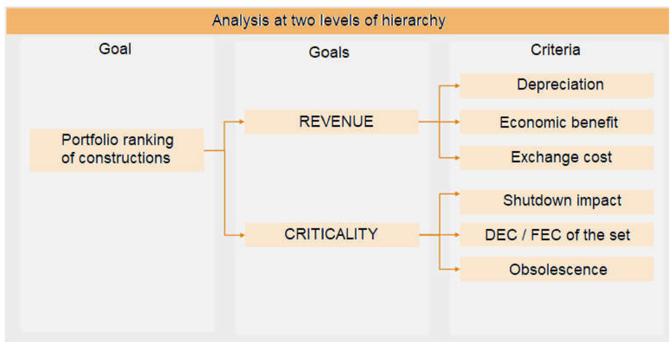

Figure 7. Hierarchical decision tree for this work (Authors)

RESULTS

Asset Renewal Expert Tool: The Asset Renewal Specialist Tool's main objectives are to present diagnostic results and studies of projections and prioritization of equipment replacement, focusing on individual equipment in distribution substations. In the created dashboard, reports can be classifiers of the following groups:

- Diagnosis: presentation of historical data from the asset control manual, maintenance and occurrences, in order to enable an analysis of the current situation of equipment and the evolution of maintenance.
- Projections: results of studies to estimate the remaining useful life of individual assets, based on their maintenance histories, and projection of the frequency of maintenance until their failure.
- Renovation prioritization: equipment prioritization model for renovation, based on the creation of rankings resulting from multi-criteria analysis.

One of the panels presents the result of the evaluation of the individual equipment or by substation, according to the result of the integration between ACR and GDDC. In this way, each equipment can be georeferenced, based on its GDDC registration information, and associated New Replacement Value (NRV), Market Value in Use (MVU), and Accumulated Depreciation Value (ADV) values to each position. Figure 8 presents this tool report. The available graphics are: Bubble map with the location of the equipment, in which the bubble size is proportional to the NRV, while the color follows a scale proportional to the ADV; Accumulated Depreciation: Graph with the percentage of MVU and ADV of the equipment; Base Value: Comparison between MVU and NRV of the selection; Remuneration per year: Regulatory Reinstatement Quota (RRQ) and Net Capital Remuneration (NCR) calculation of the selection.

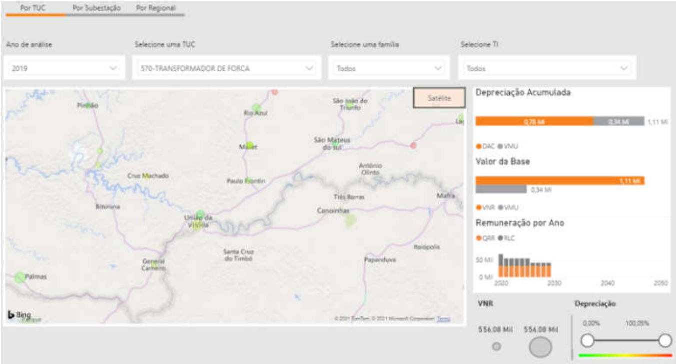

Figure 8. Diagnostics - Revenue (Authors)

Projections using AI

The RUL Projections dashboard presents comparisons of current equipment age and expected life projection, that is, in how many years the equipment is expected to leave the base due to breakdown.

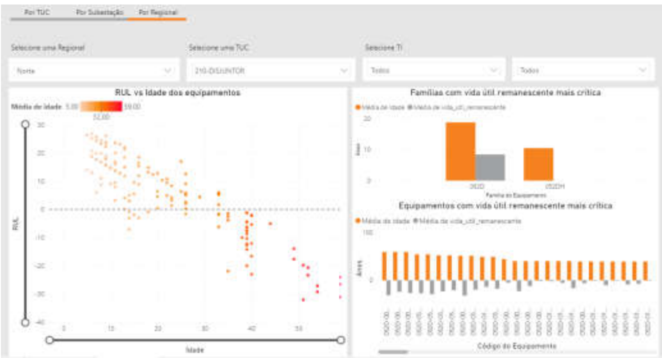

Figure 9. Projections - RUL (Authors)

Prioritization Plan: The print screen in Figure 10 presents the results of the calculations of attributes and weights of each attribute, together with the Overall Weight and Ranking obtained. In addition, it is possible to apply an obsolete equipment filter, to present the ranking that has been flagged as obsolete.

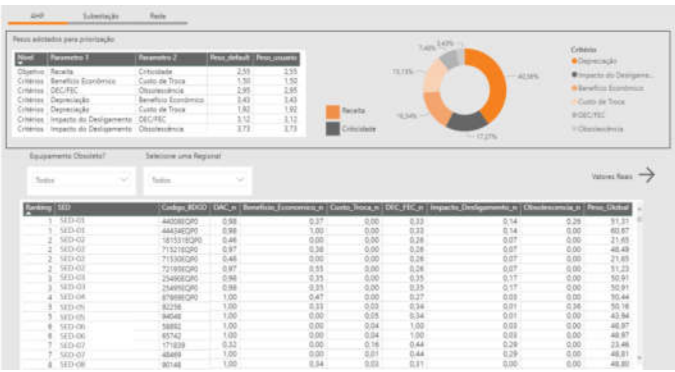

Figure 10. Prioritization Analysis - AHP (Authors)

The second print screen (see Figure 11) presents the reports referring to the prioritization of substation equipment, based on the application of the multi-criteria evaluation for each equipment. Thus, the following are presented: Graph with the estimated replacement cost for the selected equipment; Geo-referenced view of priority substations for a renovation plan; Table consolidating the results, showing: TRU, Equipment code, Ranking in prioritization, ADV, Revenue calculated until the end of life, Maintenance calculated until the end of life, Net Present Value (NPV) and Estimated replacement cost. To view the reports, there are two slide filters, one to select the ranking interval you want to view and the other to delimit the depreciation of the equipment that will appear in the list.

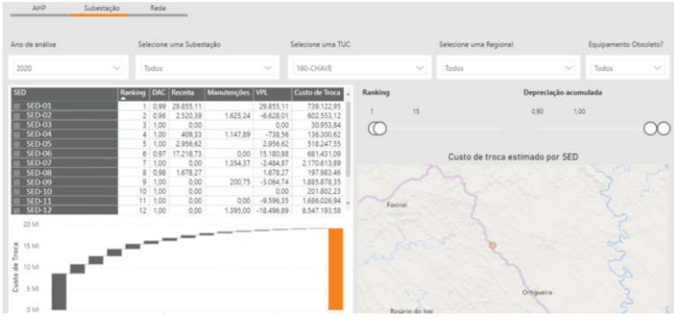

Figure 11. Prioritization Analysis - Substation Equipment (Authors)

CONCLUSION

A model was presented in this work to assist in asset renewal assessment plans, in order to assess the life cycle of equipment, make forecasts and calculate economic indicators. This model uses databases consolidated by distributors, which makes it replicable. The tool developed integrates information from the different databases, performs economic forecasts and calculations, applies the weights of the multi-criteria evaluation methodology and presents the results in an interactive way with the user. Finally, the Remaining Useful Life (RUL), maintenance cost and asset replacement studies, plus the AHP methodology, created a tool with high added value for planners. Since it is possible to identify critical and/or highly failure-prone assets; optimize replacement plans, whether due to loss of remuneration or increased operating costs, and present consistent data that supports the company's decision-making.

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