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Multi-criteria prioritization of asset management investments in the power industry

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Abstract: In the power industry, the challenge of asset management is to balance performance, risk and cost. Resource allocation needs to be optimized according to the medium- and long-term and overall objectives of the organization. Electrical systems are complex and have multiple complementary objectives. Thus, advanced methods to support decision-making and investment prioritization are required. The objective of this paper is to review and compare the multi-criteria decision-making methods applicable to investment projects in the electrical industry. To do so, a literature review is conducted. Then, a method for comparing investment projects in the power industry is proposed.

Keywords: Asset management, multi-criteria, decision-making, investment projects, prioritization, AHP, electrical industry.

1. INTRODUCTION

In the power industry, the challenge of asset management (AM) is to balance performance, risk and cost (Biard et al., 2020). Currently, there are issues in each of these areas. First, in terms of performance, the globalization of electricity markets has led to an increase in customer demand for service reliability, as monopoly organizations and regulatory agencies constrain spending and raise revenue expectations. Second, the electrification of transportation, as well as the implementation of Industry 4.0 technologies in several industrial sectors will impact demand and reliability requirements. Indeed, technologies related to Industry 4.0 depend on the continuity of electricity services (Mamun & Islam, 2016).

Electrical assets have a useful life of several decades and many of them are beginning to experience aging-related problems. For some utilities, the level of replacement is currently not sufficient to offset the aging phenomenon (A. Côté et al., 2019). Climate change also accelerates the degradation of network equipment in service. There is also a risk of an increase in the number of climate events affecting network reliability (Khaliq, Mahmood, & Das, 2015).

Thus, the investments required to maintain or improve the reliability and resilience of power system equipment have increased significantly in recent years. However, the financial and human resources available are limited. Optimizing resource allocation to achieve the organization's overall objective in the medium and long term is necessary. The overall goal of an electrical utility can have several distinct elements. Maintaining system reliability is one, but there are several others, including increasing resilience to climate change and reducing greenhouse gases, for example (Hydro-Québec, 2019).

However, investment optimization is a challenge. Power systems are large, complex systems (Xu, Jia, & He, 2010) that hold asset portfolios of multiple categories (Petchrompo & Parlikad, 2019). Thus, there are several categories of heterogeneous equipment, formed by several components, subject to various AM strategies. Organizations that hold asset portfolios of multiple categories have dependency issues in terms of resource allocation between assets and individual equipment performance in relation to overall network performance. In that context, we must elaborate methods to support decision-making and investment prioritization. Thus, the main objective of this article is to consolidate and evaluate the methods of multi-criteria decision-making, as well as the criteria of comparison applicable to the electric domain. To this end, a literature review is conducted and a comparison method for investment projects in the power industry is proposed.

The next section explores the related works. Section 3 details the methodology and results are presented in section 4. A discussion and a conclusion are found in sections 5 and 6 respectively.

2. RELATED WORKS

Gutiérrez, Santis, Martínez, and Villamizar (2019) use literature review to identify performance measures in the gas and oil industries and the Analytical Hierarchy Process (AHP) method to rank them by importance. In the same field, Da Silva Neves and Camanho (2015) use AHP to prioritize IT projects based on their contribution to the overall business strategy.

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For maintenance planning, da Silva, Melani, Michalski, Souza, and Nabeta (2019) use AHP to determine the critical components of a system in the electrical industry. This article is distinguished by the development of comparison criteria based on the ISO 550000 standard. The objective of Chong, Mohammed, Abdullah, and Rahman (2019) is also to prioritize maintenance activities. Their literature review identifies the main factors and methods applied in this area. These authors also conclude that AHP is one of the most widely used methods for multi-criteria analysis and specify the applicable comparison criteria to their context.

However, none of these authors propose methods for comparing investment projects across all phases of the asset life cycle for an asset portfolio of multiple categories. To do so, it is necessary to evaluate the multi-criteria decision-making methods and the comparison criteria applicable to the electrical industry.

3. METHODOLOGY

The literature review has two parts. The first deals with multi-criteria analysis methods. The second deals with criteria used for the AHP method. The Systematic Literature Review method was used to select publications. The process is described in Figure 1.

The extraction performed from the predefined keywords returns about 100 unique results. The results are distributed in the three identified databases and may contain duplicates between them. To focus on methods applicable to the technological context and current issues, the publication date is limited to 2010 and beyond.

4. RESULTS

The results of review 1 are presented in Table 1. The table shows only methods used in more than one publication (representing 76% of publications). The other 24% are papers that use a unique methodology developed by the authors or a methodology that is not used by other authors. The methods are also compared to identify whether they meet the following criteria:

1. Fair aggregation of the importance of each criterion
2. Transparency regarding results and process
3. Integration of multiple decision makers' preferences
4. Consideration of criteria with diverse units
5. Easy to understand for decision makers and experts
6. Rapid implementation, even with multiple criteria or alternatives

Criteria 1 to 4 are essential for prioritizing AM investment projects. One of the main challenges for multi-criteria analysis is to establish a fair aggregation of the importance of each criterion (Tlili & Nafi, 2012). Thus, methods that do not fulfill criterion 1 are less well suited to the context. Also, the method must allow transparency. Investment decision-making must also consider multiple stakeholders or decision makers. Therefore, the aggregate opinion of the whole must be considered.

		Review 1: multi-criteria decision making methods	Review 2: Comparison criteria
Databases		Scopus, IEEE explore	
Research elements	Keywords	Multi-criteria, AM, project priorization, Investment priorization	Analytical hierarchy process, AM
	Fields	Title, abstract, keywords	
	Date	> 2010	None
Results (without duplicates)		112 publications	109 publications
Selection criteria	Sector	Theoretical, Utilities, Civil Infrastructure, Physical Asset Management	
	Objective	Prioritize rehabilitation or interventions, assess criticality, health index, vulnerability, sustainability or level of service	
	Element specified	Method identified	Criterias identified
Results		37 publications	29 publications

Figure 1. Process for selecting relevant publications

Table 1. Comparison of multi-criteria analysis methods used in the literature

Method	%	Objective	Criterion 1	2	3	4	5	6
AHP	32	Structure complex decisions and integrate stakeholder perceptions	X	X	X	X	X	
TOPSIS	8	Prioritize alternatives with the minimum distance from the positive ideal solution and the maximum distance from the negative ideal solution	X	X	X		X	X
PROME-THEE	5	Compare the alternatives according to how well they outrank each other in terms of preferences	X		X	X		
Best-worst method	5	Compare the importance of all the criteria and alternatives in relation to the best and worst criteria	X	X	X	X	X	X
Cost benefit	16	Compare each alternative economically		X			X	X
Weight sum	5	Compare alternatives by their impact on the weighted criteria		X	X	X	X	X
Pareto optimality	5	Define a frontier of optimal solutions from an objective function to be optimized	X			X	X	X

In addition, the need to use a uniform unit is an obstacle to conducting this type of analysis. In prioritizing investment projects, the evaluation of several qualitative and quantitative criteria (safety, environment, reliability, risk) must be considered. It is therefore difficult to identify a single unit.

Then, in the second part of the literature review, the comparison criteria applicable to AM are analyzed in 29 publications with the objective of prioritizing AM investments (13 publications), identifying the criticality of assets (8 publications) and other related objectives (8 publications). Related objectives are less frequently identified in the literature, such as achieving an expected level of service or climate change vulnerability assessment.

A criterion often used is asset reliability or criticality. The elements of reliability assessment are often linked to the calculation of asset criticality (Chitpong, Suwanasri, & Suwanasri, 2016; Gharakheili, Fotuhi-Firuzabad, & Dehghanian, 2018; Masukume, Mhlanga, & Mubvirwi, 2020; Suwanasri, Phadungthin, & Suwanasri, 2014). The evaluation of asset criticality is a major (or unique) input to the prioritization of investments. Accordingly, the distribution of occurrence of the criteria used specifically to prioritize AM investments and to identify asset criticality is presented in Figure 2.

5. DISCUSSION

Considering the results, an initial proposition for a decision-making methodology for prioritizing investments in AM in the electrical industry can be developed.

5.1 Proposed methodology

AHP and BWM methods are the most suitable for the context of this research. The BWM method is similar to the AHP method, but it is based on comparing the importance of all the criteria in relation to the "best" and "worst" criteria. It is therefore a less time-consuming method than AHP, but also less sophisticated in comparing the opinions of several decision makers.

The AHP method has been widely used since its development by Thomas L. Saaty. (Garni, Kassem, Awasthi, Komljenovic, & Al-Haddad, 2016). The advantage of this method is its simplified implementation. This simplicity allows decision makers and experts to understand quickly and makes it transparent. It is also suitable for consistency assessment. On the other hand, it can be time-consuming when many alternatives or criteria must be compared (Wu & Abdul-Nour, 2020) Also, the choice of scale in the pairwise comparison process has an effect on the final ranking. The choice of scale must be considered in relation to the application case, the decision maker's preferences, and the variation in the weights of the attributes obtained (Elliott, 2010; Franek & Kresta, 2014).

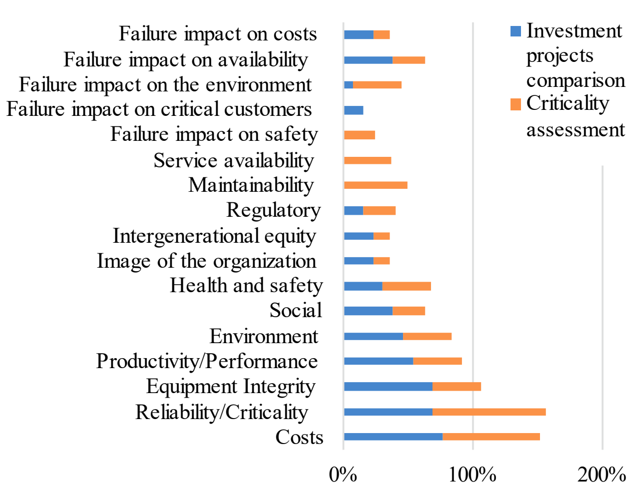

Figure 2 Criteria used to prioritize AM investments and to identify asset criticality

The AHP method is applicable to organizations with asset portfolios, such as the electrical industry (Petchrompo & Parlikad, 2019). In this context, investment project alternatives to compare can be as broad as the number of assets or asset classes. To overcome this limitation, the proposed methodology uses AHP only to weight the criteria from the opinion of several decision makers. Then, the AHP method is combined with the WSM method. The WSM method makes it possible to assess projects according to their impact on the weighted criteria.

Therefore, the first steps consist in breaking down the organization's overall goal into multiple criteria (see proposed framework in Figure 3). Then, a pairwise comparison is conducted to identify how one criterion contributes to another in achieving the overall goal. The scale defined by the author is used for the pairwise comparison (Saaty, 1987). Despite the problems associated with the choice of scale, it remains a preferred option (Franek & Kresta, 2014). Next, the consistency ratio is computed, and constancy is ensured. The priority vector (normalized eigenvector) is then generated to represent the weight of each element of a level of the structure with respect to the superior hierarchical element.

The final score of each project is calculated with (1), where m_i is the evaluated level (1 to 5) of the project with respect to criterion i and w_i is the weight of criterion i, resulting from the AHP process. Then, the scores obtained make it possible to rank all the alternatives in order of importance in relation to the preferences of the decision makers.

$$Project\ score = \sum_{i=1}^{c} w_i m_i \qquad (1)$$

The 5-level ordinal scale is proposed by Chitpong et al. (2016); Masukume et al. (2020). The number of levels must be equal for each criterion. The next sections detail the criteria applicable to investment project comparison in the electrical industry. The methods used to calculate the selected criteria are also defined.

5.2 Proposed criteria

The proposed decision structure and suggested criteria are summarized in Figure 3. The calculation elements are developed in such a way that they are not considered in several comparison criteria. This uniqueness is necessary to avoid overvaluation. However, certain elements could be transferred from one criterion to another.

5.2.1 Health, safety and environment

The effect can be assessed on a qualitative ordinal scale to determine the "Low", "Moderate" or "High" positive impact (Lucio & Teive, 2007). Decreased risk related to maintenance practices (da Silva et al., 2019), operation activities and reduced probability of occurrence (Syed & Lawryshyn, 2020) are elements that can be considered.

The reduction of future environmental impacts, use of non-renewable resources, quantity of components, energy consumption, emissions or waste, noise and visual pollution are other factors that influence the environmental criteria assessment. Visual pollution can be estimated with the length of a circuit and its visual impact factor (Espie, Ault, & Burt, 2003). Also, the use of recycled materials, the reuse of infrastructure and the improvement of the quality of the environment can be considered.

5.2.2 Productivity and Performance

The impact on productivity is based on a change in equipment capacity or its importance in the network to satisfy demand. To do this, the average load can be compared to the rated load of the equipment.

5.2.3 Costs

The cost analysis should include all life cycle costs (replacement, operation, maintenance, etc.) and consider inflation and the time horizon, i.e., present value. The calculation of expenditures should also include the costs of avoided penalties, if applicable, and depreciation, including residual book value. The current costs can be obtained from the median cost per intervention (L. Scholten, Scheidegger, Reichert, Mauer, & Lienert, 2014). A distinction between capital expenditures and operational expenditures can be made. For investments involving additional revenues, the difference between revenues and expenditures in present value is considered.

5.2.4 Resilience

According to Ciapessoni et al. (2019), “Power system resilience is the ability to limit the extent, severity, and duration of system degradation following an extreme event.” Resilience is still infrequently discussed in the literature related to electrical utilities, but there is a growing interest. The Department of Energy-supported Grid Modernization Laboratory Consortium proposed a few metrics to evaluate resilience level, such as cumulative duration of customer outages, the average number of customers with outages over a given period, and unmet demand, with a distinction for critical customers.

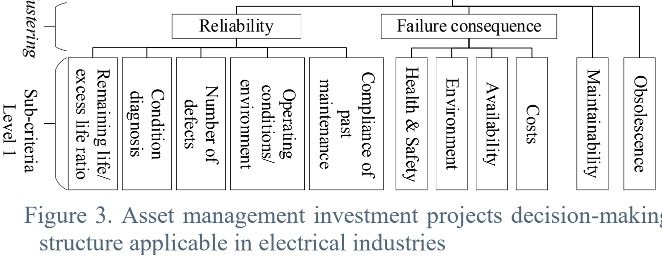

Figure 3. Asset management investment projects decision-making structure applicable in electrical industries

Power outages for critical services are also relevant indicators, as well as recovery time, lost revenue and costs (National Academies of Sciences & Medicine, 2017).

However, unlike reliability measures, there is no consensus in the literature on resilience measures and methods used to compare projects affecting system resilience are not sufficiently developed. Nevertheless, to be able to compare alternatives based on their added value, it is essential to evaluate the cost of the lack of electrical system resilience (National Academies of Sciences & Medicine, 2017).

5.2.5 Criticality related to reliability

Asset criticality can be calculated by aggregation or individually depending on the available data or the expected level of detail. If aggregation is used, the number of assets must be considered (Morad, Abdellah, & Ahmed, 2013; Lisa Scholten, Scheidegger, Reichert, Mauer, & Lienert, 2013).

5.2.5.1 Reliability

Reliability can be evaluated at asset and system level. As power systems are considered large complex systems, modelling and simulation tools can be useful. Also, the projected reliability calculation should be prioritized over the historical failure rate calculation. Historical data may not reflect recent improvements and the projected equipment condition.

Thus, the probability of failure (PoF) must be estimated. To do so, condition and inspection data (Lucio & Teive, 2007), parameters of reliability laws or residual life (Tlili & Nafi, 2012) must be considered. If the age of the asset is used in the calculation, an aggregation can be done. The age of the main equipment is then considered (Tanaka, Tsukao, Yamashita, Niimura, & Yokoyama, 2010). A service life exceedance ratio can also be used to aid in the comparison of multiple assets (Han, Hwang, Kim, Baek, & Park, 2015). The following elements can also affect PoF:

- Equipment design or operating conditions, affected by the number of similar assets that have failed due to those causes (Catrinu & Nordgård, 2011)
- Maintenance compliance (da Silva et al., 2019)
- The number of elements with defects (Tanaka et al., 2010)
- The detectability of the failure (Suwanasri et al., 2014)

5.2.5.2 Failure consequence

To estimate failure consequence, elements presented in the following sections are considered. To calculate asset criticality, these elements are used to evaluate the impact of the failure on these criteria. When evaluating alternatives, the impact of the project on the improvement of these elements is considered.

Potential impact on health, safety and environment can be determined by a qualitative ordinal scale. The occurrence of events associated with the element over a predetermined time horizon (e.g., 5 years) can assist this analysis (da Silva et al., 2019).

For availability, the impact can be evaluated with or without distinction for critical customers. Availability can be aggregated at the level of systems or subsystems. This assessment should consider:

- The availability of the element itself, other equipment and components (Suwanasri et al., 2014)
- Configuration or contingency (Chitpong et al., 2016)
- Alternative resources (Kalutara, Zhang, Setunge, Wakefield, & Mohseni, 2014)
- Interrupted voltage level (Gharakheili et al., 2018)
- Customer Minutes Lost (Estebaranz Peláez, Nieto-Martin, & Butans, 2015)

In the absence of accurate data on the connections between equipment and critical customers, the scale proposed by Morad et al. (2013) can be used:

1. Urban area, high density (critical infrastructure)
2. Urban area, medium density (industrial and urban)
3. Rural area, medium density
4. Rural area, low density

The impact is estimated with the costs relative to energy not supplied, i.e., the number of customers affected and average consumption multiplied by revenue per kW consumed. The repair costs and Value of Lost Load must also be considered. A median or average value based on historical data can be used (Morad et al., 2013; L. Scholten et al., 2014).

Next, the maintainability impact evaluation considers the availability of spare parts, their procurement time, the level of expert knowledge (Suwanasri et al., 2014) and the mean time to repair (da Silva et al., 2019). Obsolescence considers the sum of the quantity of equipment without spare parts, discontinued, or without a specialist holding sufficient knowledge to maintain the asset (Tanaka et al., 2010).

Finally, the calculation methods defined for each criterion make it possible to construct a 5-level scale to evaluate the impact of investment projects on each of them.

6. CONCLUSIONS

As previously defined before, investment optimization for power systems is a challenge, as they hold asset portfolios of multiple categories. In that context, methods for supporting decision-making and investment prioritization must be elaborated. Based on a literature review, this paper proposes a method and criteria for comparing asset management investment projects in the power industry. This contribution distinguishes itself by conducting a recent literature review, in a framework that goes beyond the exclusive prioritization of maintenance activities. The scope of the review extends to investments related to the entire physical asset life cycle. Currently, no publication targets this scope.

The next step is to develop a case study to demonstrate the applicability of the proposed method. The case study could be aimed at prioritizing investments for a generation, transmission and distribution network that includes assets in all phases of the life cycle. Artificial intelligence and Industry 4.0 tools could benefit this analysis. In addition, the calculation of environmental and safety-related elements could also be developed with the aim of presenting an evaluation scale.

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