# Paraconsistent Annotated Logic (PAL) Applied in the Decision-Making Process of Maintenance Policy for Kaplan Turbine

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Abstract: Electrical energy is the basis of the Brazilian energy matrix. Therefore, it is clear the need to maintain the availability and operational reliability of hydroelectric plants, so as not to compromise the continuity and conformity (quality) of the electrical energy supply. Ensuring availability along with the reliability of hydroelectric plants can be achieved by employing appropriate maintenance policies that reduce the likelihood of failure or even eliminate its root causes, preventing failure from occurring. The purpose of this paper is to show the use of Paraconsistent Annotated Logic with annotation of two values (PAL2v) combined with Best-worst Method (BWM) in the decision making process of the appropriate maintenance policy for the blades of a Kaplan turbine. The PAL2v method allows better decision making when there are contradictory values/opinions among engineering experts, when assigning the degree of belief or disbelief to any proposition. Based on the engineering experts attribution of belief and disbelief degrees to the criteria involved in the quantification of critical maintenance indicators, it was possible to structure a para-analyser algorithm integrating the values in the Unitary Square on the Cartesian Plane (USCP), and determining a single weight with greater degree of truth (V). By defining the indicator weights, it was possible to determine and prioritize the assertive maintenance actions for the turbine blade system. These maintenance actions (maintenance policy) aim to ensure availability and operational reliability to the energy generation process.

*Keywords*: Paraconsistent Annotated Logic (PAL), Kaplan turbine, Maintenance policy, Availability, Reliability, Critical maintenance indicators.

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## 1. Introduction

Given the growing demand for electricity and the remarkable contribution of hydroelectric energy to the Brazilian energy matrix, it is clear that the operational availability and reliability of the power generation systems must be maintained so as not to compromise the supply of electricity. The constant changes on demand placed by the consumer market, resulting in the need for high supply volumes, make production systems highly dynamic and complex.

Accordingly, the maintenance of industrial assets needs to adapt quickly to high standards of machinery availability and reliability in order to meet production schedules (Chakhunashvili et. al., 2004; Braglia et. al., 2013; Gopalakrishnan, 2018; Melani et.al., 2018 and Luo et.al., 2019).

Hydrogenerators are key pieces of equipment in the Brazilian energy system. Their operational unavailability due to the occurrence of failures can result in unexpected spending by power plant companies. Whenever hydropower plants become unable to supply the required demands, this fact must be reported to the National Electric Energy Agency (ANEEL) and they are forced to buy the missing demand on the free market, usually incurring in very high costs (Melani et.al., 2018).

The availability of a system is linked to the reliability of the industrial assets, therefore, the maintenance policies associated with these assets not only influence their return time (in case of failure), but also may slow down the degradation of reliability (Gopalakrishnan, 2018;Melani et.al., 2018 ; Luo et.al, 2019 and Verheyleweghen, 2019).

Thus, the assurance of availability and reliability of power plants can be achieved by employing appropriate maintenance policies that delay the occurrence of failures or enable the manager to anticipate them as early as possible, before their occurrence. As a result of the improvement of operational availability and reliability hydropower plants increase their revenue, because the greater the availability, the greater the ability to produce a specific product to be sold, in this case electricity.

Facing the need to make assertive decisions in the maintenance management of industrial assets, the maintenance performance indicators have become increasingly applied in industrial processes. The maintenance indicators assistance in the maintenance activities planning, by means of a structured logical approach, guide a planning with optimization of resources employed in maintenance tasks (Bergman et. al.,2009 and Mobley, 2014). Several techniques can be used when making decisions about maintenance planning efficiency, considering that this strategic function has a significant impact on the results of the organization. Some approaches that have been used to achieve an appropriate maintenance policy in power systems are:

(i) Determination of the maintenance significant items (MSI) based on ISO 55000 aspects using the Analytic Hierarchy Process (AHP) combined with Functional trees (FT) and Failure Mode and Effect Analysis (FMEA) of the components. Results of this work contributed to maintenance and asset management hidropower plant (Favarão et.al., 2019);
(ii) Application of fuzzy logic to FMSA (Failure Mode and Symptoms Analysis) focused on the symptoms produced by each considered failure mode and the selection of the most appropriate detection and monitoring techniques and strategies for Kaplan Turbines (Murad et.al.,2020) ;
(iii) Application of the generalized stochastic Petri net (GSPN) modeling tool, aiming to determine the effect that the number of maintenance teams has on the availability and performance of a coal-fired power plant cooling tower. The result was the determination of the optimal size of repair teams in order to maximize the plant's performance with the least possible investment in maintenance personnel (Melani et.al.,2019).

The purpose of this paper is to show the use of Paraconsistent Annotated Logic with annotation of two values (PAL2v) in the decision making process leading to the appropriate maintenance policy for Kaplan turbine blades. PAL allows a better decision making, when there are contradictory values or opinions, by assigning favourable and unfavourable values (degrees of disbelief and belief) in relation to any proposition, thus generating a logic that presents results in four states: true, false, inconsistent and undetermined (Bonilla et.al.,2019; Carvalho and Abe,2018 and Da Costa et.al,1991).

PAL is currently being applied as a decision making method in several areas: financial decision making, artificial intelligence (AI) in robots to deal with contradictions, medical decision making, project management, environmental planning, etc. The significant innovative contribution in the present study is the application of the PAL2v method combined with BWM to the maintenance engineering decision making process, in order to determine adequate maintenance policies for hydrogenerator systems.

Based on the decision makers' attribution of belief and disbelief grades to the criteria involved in the quantification of critical maintenance indicators, it was possible to structure an para-analyzer algorithm integrating the values in the USCP (Unitary Square of the Cartesian Plane), and determining a single weight, which presents a greater degree of certainty (H) (Bonilla et.al., 2019; Carvalho and Abe, 2018 and Da Costa et.al, 1991).

The PAL2v combined with BWM were applied as a weighting tool for Kaplan turbine blades' critical maintenance indicators. This weighting tool is based on extracting beliefs and extracting disbelief grades from experts' opinions. To extract disbelief and belief (to obtain the correct weight of the analyzed variable), the percentage of decision makers' aggregate knowledge about the maintenance, operation, and design of the Kaplan turbine blades was used. To establish the percentage of decision makers' aggregate knowledge the Best – Worst Method (BWM) was applied.

The BWM is a multi-criteria decision-making technique introduced by Rezaei in 2015. In this method, the best and worst choices among the alternatives are defined by means of a paritary comparison between the alternatives analyzed (weight scale 1 to 9 used for comparison). In addition, this method provides consistency checking of the value obtained (weight) for each alternative. It helps decision makers determine the correct value for each alternative weight, avoiding mistakes during the decision making process (Rezaei,2015).

By defining the weights of the critical maintenance indicators, it was possible to determine and prioritize the assertive maintenance actions for the Kaplan turbine blade system. The structure of these indicators was based on the cause and effect analysis (Ishikawa diagram). During Ishikawa diagram analysis were attributed values for the effects of failures modes on turbine blade operation using a scale of 1 to 10 (where 1 means "no failure impact"; and 10 "extremely strong failure impact on turbine blades torque").

Through these critical maintenance indicators, which were evaluated according to the maintenance strategy, operation, and risk of the functionality of the Kaplan turbine blades, it was possible to structure an appropriate maintenance policy, as well as to prioritize the associated maintenance actions, aiming to assure operational availability and reliability to the hydropower generation process under study.

## 2. Maintenance Policy Development using Critical Maintenance Indicators: Case Study on Kaplan Turbines

A country economic performance requires its industries to adjust to innovative options in their production processes, incorporating emerging technologies into the production environment, promoting substantial gains in productivity and flexibility, and thus transforming the nature of industrial labour.

The hydroelectric generation industry is one of the industrial processes that requires extreme availability and reliability. This is due to its importance in the development of today's society and the risks involved in the production process (which may affect integrity and personal assets).

The present work aims to determine the proper maintenance policy for Kaplan turbines used in hydrogeneration by means of critical maintenance indicators. These indicators aim to reflect the operation mode, maintenance mode, and risk associated to Kaplan turbine operation, as well as how much the energy system can be affected (reliability and operational availability) by the failure modes that may occur. The case study development steps are:

I. Drawing up of the Kaplan turbine Functional Tree (breakdown structure);
II. Determination of critical maintenance indicators for Turbine blades using cause and effect analysis (Ishikawa diagram);
III. Application of Best-Worst Method (BWS): Assignment of indicators weights (failures modes and turbine blades components) based on expert's knowledge;
IV. Application of Best-Worst Method (BWS) to assess and balance the degree of knowledge (%) of each engineering expert (decision maker);
V. Drawing up of PAL table for engineering experts to assign the degree of belief: For each failure mode as well as turbine blades components, probability values (0 to 1) should be assigned to the degree of belief.
VI. Determination of concentrated knowledge (weight %) to assessing each failure Mode: belief and disbelief extractors;
VII. Determination of belief and disbelief extractor;
VIII. Result for each failure mode and component: favorable degree of evidence and unfavorable degree of evidence (obtained by weighted average);
IX. Determination of degree of certainty (H) and degree of uncertainty (G) and establishment of level of requirement (0.5). The level of requirement "determines the responsibility of the analysis, or the degree of caution to use the analysis, which depends on the further use of the results (such as an indicator for decision making) and its implications. For a level of requirement of 50%, assessments

will be carried on with at least 50% of certainty" (Gianetti, et. al.,2009).

X. To Construction of the para-analyzer algorithm: USCP (Unitary Square on the Cartesian Plane);
XI. Determination of critical maintenance indicators (weight for each failure mode and components analyzed);
XII. Development of proper maintenance policy for the Kaplan turbine blades system and prioritization of maintenance tasks (execution planning).

Propeller type turbines, such as Kaplan turbines are designed to operate where a small head of water is involved. For Kaplan turbines the angle (or pitch) of the blades can be altered to suit the water flow. The adjustable pitch feature of Kaplan turbines allows these types of turbines to operate efficiently at a wider range of water head, allowing for variations in the water level in the dam. Kaplan turbines can be used in sites having a typical head range of 2–40 meters.

Kaplan turbines can be divided into 3 systems: Speed Regulator, Turbine, and Axis, Turbine blades are a sub-system of the Turbine System. Figure 01 illustrates the turbine functional tree.

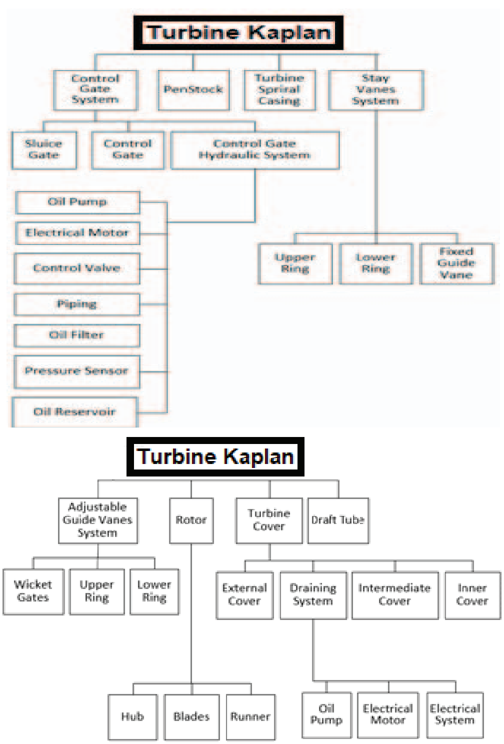


Fig.1.Turbine functional tree.
Source: Authors.

The design of the runner blades is crucial for an efficient turbine. The blades extract the energy of the flowing water and convert it into rotational energy and then to electrical energy. Therefore, the blade design must be optimized to extract as much energy as possible to achieve the highest possible efficiency, and at the same time to avoid cavitation.

To structure the critical maintenance indicators for Kaplan turbine blades, a cause and effect analysis (Ishikawa Diagram) of operation factors and respective failure modes affecting the blade profile and the fastening elements was developed. Figure 02 shows the diagram.

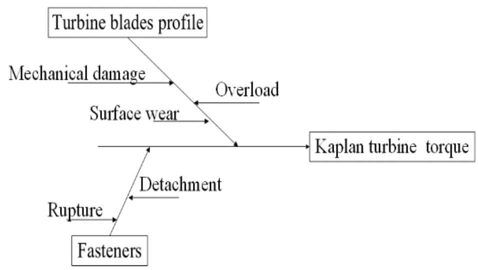


Fig.2. Ishikawa Diagram.
Source: Authors.

The Ishikawa diagram was developed employing: the professional experience of engineering experts; work meetings to apply the Brainstorming management tool; maintenance failure and technical data provided by the studied hydroelectric plant; and field research with direct observation of Kaplan Turbine operation.

The identified failure modes may affect the integrity of blade function, of blade profile, and of blade fasteners. Consequently, the occurrence of these failures will cause deviations on the value of the turbine torque and compromise energy generation.

A scale with values from 1 to 10 was assigned to the following failure modes: overload, mechanical damage, surface wear, fasteners detachment and rupture associated with the operation factors fasteners and turbine blade profile in order to rank the impact intensity of each factor and respective failure modes on the Kaplan turbine torque, where 1 corresponds to no failure impact and 10 to extremely strong failure impact.

In order to reduce / eliminate inconsistencies in the decision making process (values attributed to the maintenance indicator variables), PAL2v combined with the Best-worst method (BWM) was applied, aiming to obtain assertive values for critical maintenance indicators for the Turbine blades system. Initially, were listed seven knowledge fields (skills) needed to assess the impacts of failure modes on turbine torque. By means of BWM application, the weights of the knowledge fields distribution were obtained for each decision maker (maintenance engineering expert).

The decision makers' skills aggregated weights are used in the extraction of belief (favourable evidence) and disbelief (unfavourable evidence) during the application of PAL2v. Belief and disbelief extractors are intended to extract uncertainties from the values to be assigned to failure modes (their impacts on turbine torque), during the decision making process to determine the most consistent weight.

Table 01 presents the results of applying BWM to determine the weight distribution for technical knowledge fields necessary to analyze Kaplan turbine operation factors and respective failure modes in relation to the expertise of each maintenance engineer.

Table 01 - BMW application (weights).

| Technical knowledge (K) to analyse the Turbine Kaplan failures modes | Eng.1 | Eng.2 | Eng.3 | Eng.4 |
|---|---|---|---|---|
| (K1) Reliability and Risk Analysis | 0.123 | 0.349 | 0.091 | 0.059 |
| (K2) Maintenance management | 0.123 | 0.222 | 0.299 | 0.137 |
| (K3) Product Quality Management (Materials and Manufacturing Process) | 0.379 | 0.148 | 0.299 | 0.027 |
| (K4) Failure mechanisms (cavitation, corrosion, fracture) | 0.123 | 0.089 | 0.121 | 0.206 |
| (K5) Professional experience in hydroelectric power plant | 0.030 | 0.028 | 0.026 | 0.330 |
| (K6) Electrical and Automation (Instrumentation) | 0.099 | 0,074 | 0.091 | 0.103 |
| (K7) Lubrication, Hydraulics and Pneumatics | 0.123 | 0.089 | 0.073 | 0.137 |

*Source: Authors.*

After the BWM application to determine the weight distribution for technical knowledges (building base of the extractors of belief and disbelief), the PAL2v method is applied to the case study

The four decision makers (maintenance engineering experts) assigned a belief grade according to a scale from 0 to 1, where zero stands for total disbelief and one for total belief, to each impact value (1 to 10) identified in relation to operation factors and respective failure modes. This process provides the belief probability for each number of the impact scale (assesses the impacts of failure modes on the turbine torque).

The same process is performed to define the weights for operation factors turbine blades profile and fasteners, in relation to their impact on the Kaplan turbine operation under study.

With the input value of belief ($a_{ij}$), were calculated: (i) the value of disbelief ($b_{ij}$), (ii) belief extractor ($be_{ij}$), and (iii) disbelief extractor ($de_{ij}$) using equations (1) to (3).

$$b(ij) = 1 - aij \quad (1)$$

$$be(ij) = a(ij) * P1 \quad (2)$$

$$de(ij) = b(ij) * \mathrm{P2} \quad (3)$$

Where: b(ij) = disbelief value obtained by PAL2v; a(ij) = belief value assigned by the decision maker (maintenance engineering expert); be(ij) = final value of the belief obtained by the belief extractor; de(ij) = final value of the belief obtained by the disbelief extractor; $P_1$ = weight of knowledge concentrated on assessment skills; $P_2$ = weight of knowledge concentrated on other skills.

For each failure mode the para-analyzer algorithm represented in the CUSP (Cartesian Unitary Square Plane) was structured. Figure 03 presents the results of the weight assignment analysis for the indicator related to the impacts of the rupture failure on the fastening torque of the fasteners.

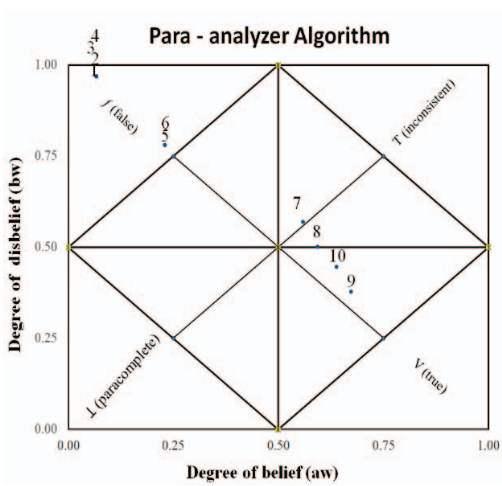


Fig.3. Cartesian Unitary Square Plane for rupture failure mode maintenance critical indicators. The indicator weight was determined by the weighted average value that presents the highest degree of certainty (H).

Source: Authors.

The final result values for favourable evidence or belief (aw) and unfavourable evidence or disbelief (bw), both values obtained (scale from 1 to 10) by extraction process, are calculated applying extractors weighted average. The final weight attributed to each failure mode and operation factor (blades profile and fasteners) is decided by the highest degree of certainty (H) and lowest degree of uncertainty (G), according to equations (4) and (5).

$$H = aw - bw \qquad (4)$$
$$G = (aw + 1) - bw \qquad (5)$$

As a result of the rupture failure mode (Kaplan turbine blade fasteners), a weight of 9 was obtained, that is, the occurrence of the failure by rupture of the fasteners presented very high impact on the turbine torque, damage that can consequently interrupt the power generation process.

Thus, to determine the impact weight of the failure modes and operation factors (blades profile and fastening elements) that affect the turbine torque (analyzed in the Ishikawa diagram in Figure 1), the method that combines PLA2v with BWM was applied. It was done in order to obtain values that are more consistent by extracting disbelief from the judgment of the decision makers. Figures 4 and 5 present the result of all weights determined by the highest H (degree of certainty).

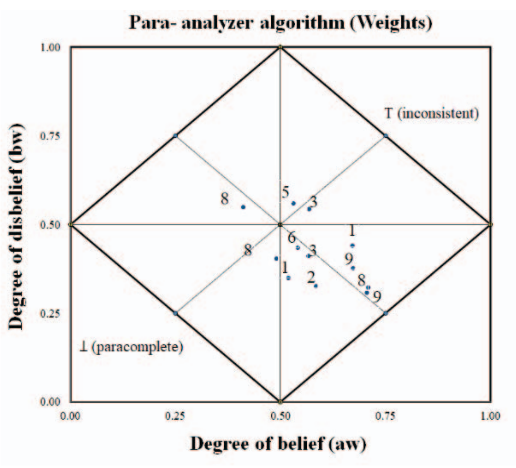


Fig.4. CUSP - Cartesian Unitary Square Plane for maintenance critical indicators for operation factors and failure modes (Weights).
Source: Authors.

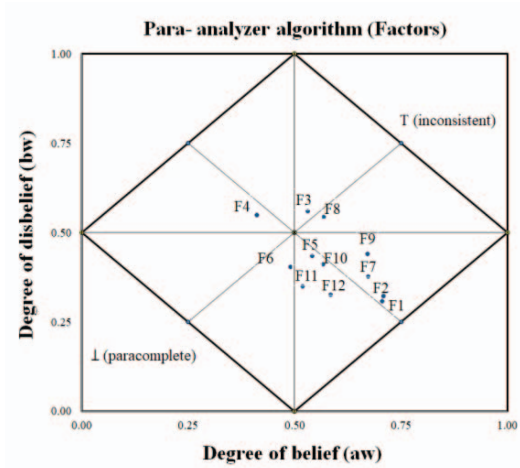


Fig.5. CUSP - Cartesian Unitary Square Plane for maintenance critical indicators for operation factors and failure modes (Factors). Indicators weights obtained by respective weighted average with the highest degree of certainty (H) .Weights for maintenance indicators are identified as: F1 (Turbine blades profile), F2 (Fasteners), F3 (Overload impact), F4 (mechanical damage impact), F5 (surface wear impact), F6 (fasteners detachment impact), F7 (rupture impact), F8 (Overload occurrence probability), F9 (mechanical damage occurrence probability ), F10 (surface wear damage occurrence probability), F11(fasteners detachment occurrence probability) and, F12 (rupture occurrence probability).
Source: Authors.

When the weighting based on experts' opinions is confronted with PAL2v combined with Best-Worst method aplication, it can be noted that points representing the failure modes and turbine operation factors maintenance indicators are closer to the truth line (T), that is, the most consistent weight (greater degree of certainty - H) is taken as a critical maintenance indicator for the analysed variable.

The weights positions for Kaplan turbine operation factors and failure modes show that, most of the weights are close to the true (v) region. This result indicates that experts have agreed on the choice of variables/indicators. This is because both informations about maintenance failures history and their knowledge about kaplan turbine design are acceptable for reliable decision making.

On the other hand, there are weight results (minority) close to the paracomplete and inconsistent regions, which suggests that data supplied were not sufficient and/or an increased divergence between experts' opinions. However, the final weight was accepted as it contained the highest degree of certainty (H) pointed out during the failure mode effects analysis of Kaplan turbine blades operation. To calculate the critical maintenance indicator the function for each failure mode analysed was applied as in equation (6).

$$\mathrm{CMI} = \mathrm{FMW} * \mathrm{PMF} * \mathrm{CM} \qquad (6)$$

Where: $C_{MI}$ = Critical maintenance indicator; $F_{MW}$ = Failure mode weight (obtained applying the PAL2v combined with Best-worst method); $P_{FM}$ = Weight for failure mode probability occurrence (obtained applying the PAL2v combined with Best-worst method) and; $C_W$ = Component weight (obtained applying the PAL2v combined with Best-worst method).

The final result of the turbine blades system critical maintenance indicator is show in Table 02.

Table 02- Critical maintenance indicator for Turbine blades system.

| Factor | CW | Failures Modes | $F_{MW}$ | $P_{FM}$ | $C_{MI}$ |
|---|---|---|---|---|---|
| Turbine blades profile | 9 | Overload | 3 | 5 | 135 |
| | | Mechanical damage | 1 | 8 | 72 |
| | | Surface wear | 3 | 6 | 162 |
| Fasteners | 8 | Detachment | 1 | 8 | 64 |
| | | Rupture | 2 | 9 | 144 |

*Source: Authors.*

The failure caused by the wear of the turbine blade profile implies the most critical weight, that is, it is the failure mode that most impacts the Kaplan turbine torque. The failure mode corresponding to the detachment of fasteners has the lowest critical indicator of maintenance, demanding a lower priority of participation in the process of development of a maintenance policy. Table 3 presents the structured maintenance policies with the associated tasks.

Table 03 - Kaplan turbine blades maintenance policy: tasks prioritization.

| Factor turbine | Failure Mode | Maintenance tasks | *C |
|---|---|---|---|
| Turbine blades profile | Overload | Check structural integrity (cracks)<br>Check blades shape design | 3 |
| | Mechanical damage | Check blade surface quality<br>Check structural integrity (cracks) | 4 |
| | Surface wear | Check blade surface quality | 1 |
| Fasteners | Detachment | Check tightness / damage | 5 |
| | Rupture | Change fastener periodically | 2 |

***C = Classification (priorization)**

*Source: Authors.*

By means of the values determined in the critical maintenance indicator (turbine blade system) it was possible to establish the proper maintenance policy. It is aimed to avoid the occurrence of these failure modes (identified in the Ishikawa diagram and measured), ensuring reliability and operational availability of Kaplan turbine blades.

Critical maintenance indicators help both the maintenance policy development and the prioritization of the planning for the execution of associated tasks. This prioritization is determined by the values of the critical maintenance indicator of each failure mode that affects the Kaplan turbine torque.

Therefore, the most critical failure modes should have priority in decision-making, directing tasks and modes of execution, planning, and resource optimization within the maintenance policy framework for the turbine blade system.

## 3. Conclusion

Electricity is the basis of the Brazilian energy matrix. Therefore, it is clear the need to maintain the availability and operational reliability of hydroelectric plants, so as not to compromise the continuity and compliance (quality) of electricity supply to the end consumer. For that purpose, it is necessary to employ adequate maintenance policies that reduce the probability of failure or even eliminate its root causes, preventing failures from occurring and interrupting the power generation process.

The present study applied the Paraconsistent Annotated Logic with annotation of two values (PAL2v) in conjunction with the Best-Worst method (BWM). This method is used to evaluate decision makers' ability to assign criticality weights to the factors and respective failure modes that impact on the hydro generator blade system. They were used as a tool to obtain critical indicators of maintenance. With this tool, it was possible to arrive at greater consistency and reduction of uncertainties (extracted by the extractors of belief and disbelief of values) for the weights attributed by the decision makers. It was also possible to determine the criticality (degree measured from 1 to 10) of the impacts caused on the turbine torque by the occurrence of each failure mode identified in the cause and effect analysis (Figure 01).

The PAL2v combined with the BWM proved to be effective in determining the failure mode weights, ensuring reliability in the decision-making of the construction of the maintenance criticality indicator, since most of the weights obtained were concentrated in the true (V) region of the para-analyzer algorithm (CUSP - Cartesian Unitary Square Plane - PAL analysis), indicating assertiveness in the choice of values.

The values contained in the critical maintenance indicator, structured for the turbine blade system, show the degree of impact of each failure mode that affects the performance of the operation of the blade system of the hydrogenerator turbine. This indicator directly assisted in the development of the appropriate maintenance policy, which includes tasks aimed at reducing and/or eliminating the probability of failure modes occurring.

The calculated maintenance critical indicator also prioritizes the tasks associated with the most critical (most financially adverse) failure modes, allowing the optimization of resources (material, human and financial) during the maintenance planning stage. It ensures reliability and operational availability of the electricity generation system, together with improvement in the maintenance management processes.

## References


Braglia, M., Castellano, F., Frosolini, M. (2013). An Integer Linear Programming Approach to Maintenance Strategies Selection. International *Journal of Quality & Reliability Management* 30, 991 – 1016.

Bergman B. et. al. (2009). *Robust Design Methodology for Reliability*.Wiley.

Bonilla, S.H., Papalardo, F., Tassinar, C., Sacomano, J.B., Carvalho, F.R. (2019). Contribution of the Paraconsistent Tri-Annotated Logic to emergy accounting and decision making. *Ecological Modelling* 393, 98–106.

Carvalho, F. R., Abe, J. M. (2018). *A Paraconsistent Decision-Making Method*. Springer International Publishing.

Chakhunashvili A, Johansson P.M., Bergman B.L.S. Variation mode and effect analysis. Proceedings of the Annual Reliability and Maintainability Symposium RAMS 2004,364-369.

Da Costa, N.C.A., Vago, C., Subrahmanian, V.S. (1991). The Paraconsistent Logics Ps. *Zeitschrift fur Mathematische Logik und Grundlagen der Mathematik* 37, 139-148.

Favarão, R., Melani, A.H., Murad, Michalski, M.A., Souza, G.F.M., Netto, A.C., Nabeta, S.I. (2019). Defining Maintenance Significant Items Based on ISO 55000 and AHP: A Hydropower Plant Case Study. 29th European Safety and Reliability Conference -ESREL 2019. 22-26 September, Hannover-Germany.

Gianetti, B. F., Bonilla, S.H., Silva, C.C., Almeida, C.M, V.B. (2009). The Reliability of Experts' Opinions in Constructing a Composite Environmental Index: The Case of ESI 2005. *Journal of Environmental Management* 90, 2448 - 2459.

Gopalakrishnan, M., Skoogh, A. (2018). Machine Criticality Based Maintenance Prioritization: Identifying Productivity Improvement Potential. *International Journal of Productivity and Performance Management* 67, 654 - 672.

Luo, X., Zhang, S., Ge, Z., Li, L. (2019). A maintenance time estimation method based on maintainability design attributes. 29th European Safety and Reliability Conference - ESREL 2019. 22-26 September, Hannover-Germany.

Melani, A. H., Murad, C. A., Netto, A.C. and Souza, G.F.M. (2018). Criticality-based Maintenance of a Coal-fired Power Plant. *Energy* 147, 767 - 781.

Melani, A.H., Murad, C., Netto, A.C. Souza, G.F.M., Nabeta, S.I (2019). Maintenance Strategy Optimization of a Coal-Fired Power Plant Cooling Tower through Generalized Stochastic Petri Nets. *Energies* 12, 19-51.

Mobley, R. K. (2014). *Maintenance Engineering Handbook*. McGraw-Hill.

Murad, C., Melani, A.H., Murad, Michalski, M.A., Netto, A.C. Souza, G.F.M., Nabeta, S.I (2020). Fuzzy-FMSA: Evaluating Fault Monitoring and Detection Strategies Based on Failure Mode and Symptom Analysis Fuzzy Logic. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering* 20, 1-25.

Rezaei,J.(2015).Best-worst multi-criteria decision-making method. *Omega* 53, 49-57.

Verheyleweghen, A., Srivastav, H., Barros, A., Jaschke, J. (2019). Combined Maintenance Scheduling and Production Optimization. 29th European Safety and Reliability Conference - ESREL 2019. 22-26 September, Hannover-Germany.