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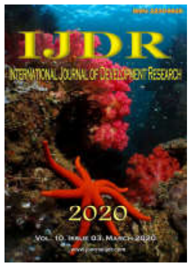

RESEARCH ARTICLE OPEN ACCESS

EXPERT SYSTEM DEVELOPMENT FOR MAINTENANCE MANAGEMENT CONSIDERING RELIABILITY AND FINANCIAL IMPACT MODELS

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ABSTRACT

The electric power sector restructuring associated with the technological developments in the scope of automation, information and data analysis has led the agents involved to search solutions that contribute to the asset operation, maintenance and planning. In this sense, the present work, resulting of ANEEL R&D project PD-07469-0002 / 2018, proposed the development of an Expert System (ES) for the maintenance management of a hydraulic power plant, considering reliability analysis and financial impact models. In this way, the ES was based on the concept of Markovian networks for the calculation of equipment operating probabilities, on the series-parallel method for modeling the equipment and on obtaining reliability curves with Weibull distribution for modeling the risks of each equipment.

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INTRODUCTION

The restructuring of the electric sector associated with technological evolution in the scope of automation, information and data analysis has raised the agents involved (Pereira, 2008), (Assis *et al*, 2019) to seek solutions that contribute to the operation activities, maintenance and planning of your assets, since their management has a direct impact on reliability and financial balance. In this context, the impact on reliability is due to the increased risk of equipment failing when operating under wear conditions resulting in service unavailability (Lafraia, 2001), (Silva Neto and Cugnasca, 2013). In turn, the financial impact is due to the cost of carrying out maintenance on the equipment, its replacement, the effects of stopping production and other damages that may eventually be caused by equipment failure. In order to resolve these impacts, the proposal of policies and models applied to asset management has sought to balance risks and gains in the maintenance of equipment (Kaiser and Gebraeel, 2009), (Fan *et al*, 2011), (Ahmad and Kamaruddin, 2012), (Aven and Jensen, 2013), (Walter and Flapper, 2017). Thus, in order to contribute to the evolution of policies and models applied to asset management, the present work proposed the development of an Expert System for the management of the maintenance of a hydraulic generation plant considering reliability and impact analysis financial models. Therefore, the Expert System was based on the concept of Markovian networks for the calculation of equipment operating probabilities, on the series-parallel method for modeling the equipment and on obtaining reliability curves with *Weibull* distribution for modeling the risks of each equipment.

PROPOSED METHODOLOGY

The methodologies considered in the development of the proposed Expert System are presented below.

Equipment and Risk Modeling: For the modeling of equipment operating probabilities and associated risks, an approach using Markovian networks was used (Brown, 2017). In this sense, the modeling of the equipment that makes up the hydraulic generation plant was carried out using the series-parallel method, while the risk modeling was based on obtaining reliability curves with *Weibull* distribution for each equipment. The input data for the modeling of equipment and risks were obtained from the history of occurrences and maintenance of the hydraulic generation plant, in addition to data found in the literature for similar equipment. This complementation of data is important since to guarantee the correct regression (low *p-value*) for the *Weibull* distribution, about 30 points / observations are required, which is not always feasible. Thus, it is possible to estimate the reliability curve in a conceptual way, either by interpolating the available data, or by knowing the machine's operation. Therefore, information is required on the time elapsed between stops, whether the stop was preventive or corrective, in addition to the characterization of the equipment and its type. Thus, following the basis of the *Markov* model (Brown, 2017), it is important to know the operating time and the stopping time, it is not necessary to know the stopping times, but rather their durations. Table 1 illustrates the proposed input data for the *Markov* method.

Table 1. Input data for equipment and risk modeling

Variable	Description
ID	Event identification
Equipment	Equipment identification
Description	Equipment Description (e.g. motor)
Operating hours (h)	Time between failure (h)
Failure time (h)	Failure time (h)
Cause	Failure (F) or Maintenance (M)
Manual Information	Information included manually

With the information presented in Table 1, it is possible to calculate the reliability curve by equipment or type of equipment, which will be used in system modeling and reliability simulation. Additionally, *beta* and *lambda* values are necessary factors for the description of the *Weibull* curve (Assis *et al*, 2019). As an example, for a motor pump with the characteristics shown in Table 2, it is possible to observe the curve of the failure rate (*hazard function*) in the time illustrated in Figure 1.

Table 2. Weibull distribution curve parameter

Parâmetros - *Weibull*	
Beta	0.95
Lambda	0.00033
Average(m)	4,679.24
Variance(σ²)	4,693,761.25
Standard Deviation	2,166.51

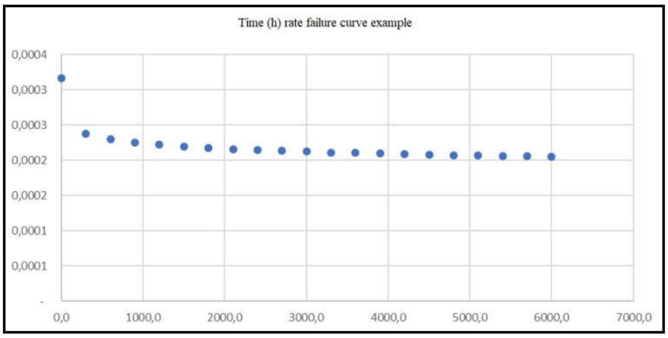

Figure 1. Time (h) failure rate curve (hazard function)

Series-Parallel Equipment Modeling: Although not exclusive to the *Markov* model, the modeling of series-parallel equipment is fundamental for a complete understanding of the reliability model. Sometimes, what matters in the productive environment is the productive flow, which can be dependent or independent of the functioning of a certain equipment. In the electrical sector, it is common to use expressions such as "N-1" to indicate the operating characteristic of a system, pointing out that, if a certain equipment stops working correctly, it can be replaced by another one, so the system can be left with "N-1" equipment and continue to operate. From a practical point of view, other conditions are important, namely: if the equipment is in hot or cold reserve, if it is a "spare part", if it is connected or disconnected, etc. These issues can influence the system repair time, which in the case of hot, connected and running reserve may have resulted in zero system repair time, although the equipment repair time can be long, taking days, such as replacement of a power transformer when there is no spare in place. Despite the complexities that the system can achieve, in practice, mathematical and conceptual modeling is performed systemically with series-parallel equipment, as shown in Figure 2.

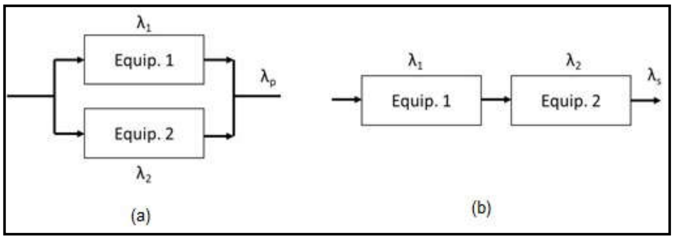

Figure 2. Parallel (a) and series (b) system, considering equipment (λ1 e λ2), parallel λp and series λs failure rates, respectively

From a conceptual point of view, in the system in parallel, considering that both equipment 1 and 2 are sufficient to meet the functioning of the entire system and that the failure rates of equipment 1 and 2 are independent, the system failure will happen if both the equipment is in a state of failure, mutually. In the series system, if one of the equipment goes into a fault state, the whole system will be in failure. Mathematically, the system can be modeled in parallel using the *Markov* model (Brown, 2017).

Time Simulation of Maintenance Policies: In general, time simulation requires knowledge of the equipment's reliability behaviour over time. This modeling is precisely obtained through the reliability curves adjusted by the *Weibull* statistic. At this point, it should be noted that the time step chosen for the present work is one hour. The necessary parameters for this simulation are:

- Reliability curve description;
- Time since the last stop;
- Corrective repair time;
- Preventive repair time;
- Time between preventive maintenance.

At each step in the time scale, the cumulative reliability of each of the elements is calculated, as well as the cumulative reliability of the system, as shown in Figure 3. In addition, Monte Carlo draws are carried out, comparing the random numbers drawn with the equipment reliability value.

	EQ1
Lambda	0.00020
Beta	0.95000
Preventive repair time	15
Corrective repair time	25
Time between preventive maintenance	1,000
Time since the last stop(T0)	300

Availability
79%

Hour	Relatived T0	Preventive?	Availability	Failure Chance	Corrective?	Stopped?
		0		72	72	1800
	EQ1	EQ1	EQ1	EQ1	EQ1	EQ1
T0	300					
1	301	0	95.58%	0	0	0
2	302	0	95.56%	0	0	0
3	303	0	95.55%	0	0	0
4	304	0	95.53%	0	0	0
5	305	0	95.52%	0	0	0
6	306	0	95.51%	0	0	0

Figure 3. Maintenance policies time simulation

DATE	HOUR	BASELINE (pu)
1-jan	0	0.05130662
1-jan	1	0.046014906
1-jan	2	0.043484086
1-jan	3	0.046475055
1-jan	4	0.072128365
1-jan	5	0.108595178
1-jan	6	0.756019847
1-jan	7	0.917444309
1-jan	8	0.937908083
1-jan	9	0.967648466
1-jan	10	0.963291083
1-jan	11	0.850828261
1-jan	12	0.508566032
1-jan	13	0.334988515
1-jan	14	0.303928454
1-jan	15	0.260559405
1-jan	16	0.259869181
1-jan	17	0.180033319
1-jan	18	0.162547655
1-jan	19	0.219376064
1-jan	20	0.217995617

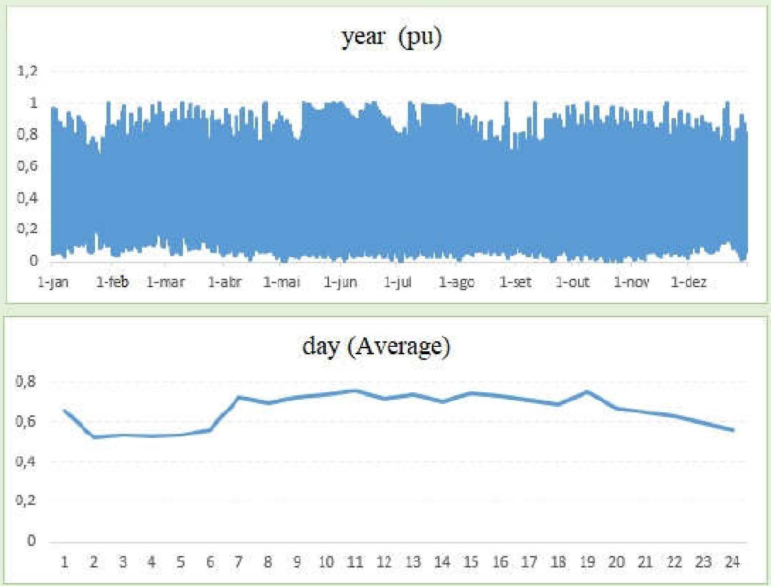

Figure 4. Hourly generation curve example

If the number drawn is greater in one of the cases, a fault situation in the system is characterized, beginning the corrective maintenance period. It should be noted that the simulation considers the periodicity and time interval for preventive maintenance, according to the history of registered data. Thus, at the end of the simulation, the cumulative availability of the system is obtained as one of the results, defined by the relationship between the total hours that the system worked normally and the total hours chosen for simulation. In addition, the hourly condition of each of the simulated blocks serves as an input for calculating maintenance and operating costs.

Cost Calculation Methodology: After the established time simulation of maintenance policies, that is, knowledge of the equipment over time reliability of behaviour, are considered the following operating and maintenance costs:

- Preventive maintenance costs (equipment);
- Corrective maintenance costs (equipment);
- Operation costs;
- Production costs.

Therefore, from the consideration of different scenarios and different maintenance costs (preventive or corrective), the influence of the increase or decrease in maintenance actions on the reliability of the system's operation is verified. It should be noted that for the proposed system, the operation cost was characterized by the cost inherent to the plant's operation, so this value is null during the preventive or corrective maintenance periods. The production cost is fundamental for the simulation of the best moments to stop the system. In the present work, the assured energy of the plant, auction price, as well as the expected generation in each month were considered as input data. Table 3 illustrates an example of input data for costing. Additionally, the system considers the hourly generation curve to perform the cost calculation. Figure 4 illustrates an example of an hourly generation curve.

machine than dispatching (from the difference between spot and contracted prices).

Table 3. Input data example for cost calculation

Data for cost calculation				
Date	POWER (MW)	ENERGY (MWH)	ASSURED (MWH)	Price (R$/MW)
1-Jan	61.0	44,032	42,706	195
1-Feb	61.0	36,985	35,871	195
1-Mar	61.0	37,741	36,605	195
1- Apr	61.0	27,393	26,568	195
1-May	61.0	25,161	24,403	195
1-Jun	61.0	21,306	20,664	195
1-Jul	61.0	20,967	21,353	195
1-Aug	61.0	20,967	21,353	195
1-Sep	61.0	23,190	23,616	195
1-Oct	61.0	31,409	30,463	195
1-Nov	61.0	36,534	35,424	195
1-Dec	61.0	40,886	39,655	195
Year	Submarket			
2018	SE			

Table 4. Maintenance Politics Parameters - Base Case

	Intake		Turbine		Generator		Trafo		Voltage R.	
	U1	U2	U1	U2	U1	U2	U1	U2	U1	U2
TM(h)	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
TP(h)	30	30	30	30	30	30	30	30	30	30
TC(h)	10	10	10	10	10	10	10	10	10	10
Cp(R$/h)	100	80	100	80	100	80	100	80	100	80
Cc(R$/h)	300	200	300	200	300	200	300	200	300	200
Co(R$/h)	50	40	50	40	50	40	50	40	50	40
	Bay		Rectifier		Battery		Bay			
	U1	U2	1	2	1	2				
TM(h)	1500	1500	1500	1500	1500	1500	1500			
TP(h)	30	30	30	30	30	30	30			
TC(h)	10	10	10	10	10	10	10			
Cp(R$/h)	100	80	100	80	100	80	100			
Cc(R$/h)	300	200	300	200	300	200	300			
Co(R$/h)	50	40	50	40	50	40	50			

Table 5. Simulation Results - Base Case

mês	Energy (MWh)	Price (R$/MWh)	Preventive Stops (h)	Preventive Costs (R$/h)	Corrective Stops (h)	Preventive Costs (R$/h)	Operation Costs (10^3R$/h)	Results (10^3R$)
1	41,558.08	140.95	148	128.92	6	266.66	518.9	6,929,679
2	35,646.14	165.58	113	196.48	10	300.00	480.94	5,396.11
3	36,788.27	299.27	126	134.29	6	233.33	530.80	10,456.87
4	26,539.69	375.58	150	166.40	12	283.33	502.12	9,437.34
5	23,924.54	407.87	116	140.21	8	275.00	533.00	9,206.59
6	20,187.06	149.83	160	132.16	10	260.00	496.94	2,503.84
7	20,786.21	288.50	114	152.06	6	266.66	537.34	5,440.39
8	19,763.92	506.52	175	139.32	6	266.66	514.23	9,470.46
9	22,647.93	524.73	114	155.61	8	300.00	512.66	11,351.22
10	29,856.66	533.52	160	123.34	2	199.99	527.82	15,381.22
11	34,884.72	413.19	141	156.54	10	260.00	500.51	13,888.94
12	39,949.57	213.74	122	137.70	6	266.66	537.80	7,982.59
Total	352,532.79	318.52	1,639	145.60	90	271.11	6,193.06	105,833.66

Table 6. Simulation results

Case	Energy (MWh)	Preventive Stop (h)	Corrective Stop (h)	Results (10^3R$)	Reliability Plant
TM=1500	352,532.79	1,639	90	105,844.66	93.18
TM=800	345,905.89	3,379	90	104,041.14	86.88
TM=5000	352,733.15	904	308	105,667.05	97.50

As a result, for each simulated scenario, the module provides the values of the costs considered, as well as the amount of money accumulated during the simulation period. From the hourly simulation, it is possible to predict which are the most suitable months for stopping, as well as the hours available for stopping, which is more advantageous not dispatching the

Proposed Architecture: For the development of the proposed Expert System, the ER model (entity-relationship model) was used, which is a conceptual model used in software engineering to represent the structure of the application database.

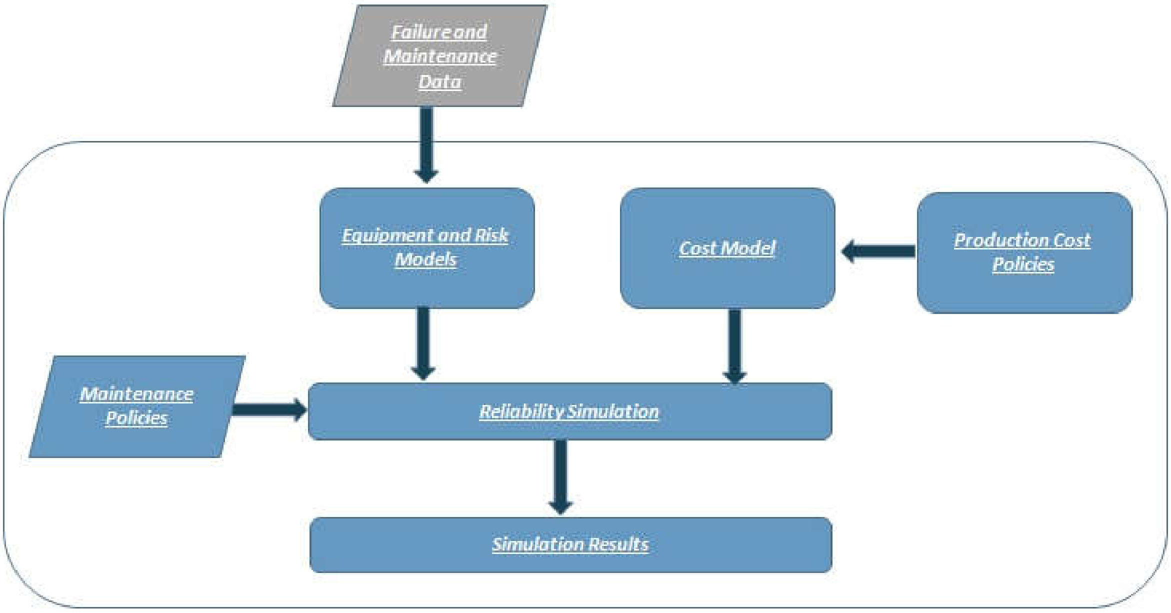

Figure 5. Proposed Architecture

Figure 6. Scenario register (in portuguese)

In general, the ER is composed of several tables (entities) interconnected with each other, each table having a specific set of data. Likewise, the calculations to be performed by the system generate results that can also return values (fill in) for several tables. Based on the methodologies presented above, and using the MER model for its development, the system was characterized by the architecture illustrated in Figure 5.

TESTS E RESULTS

Software Information Register: As described in the previous items, the system developed allows simulating maintenance policies that provide the results of the availability values of each component of the generating units and of the plant as a whole, in addition to the economic value of each policy. Through the simulation of different policies, it is possible to carry out a comparative analysis in order to optimize the practices already adopted or to be adopted by the company. Therefore, initially the user must register scenarios that will be considered in the simulations, taking into account the following criteria:

- Year of generation: represents the base year for the study;
- Submarket: represents the submarket where the generation is located, if the user chooses to use the PLD (spot price);
- Generated energy: If this option is chosen, the program will consider the hourly measurements entered by the user. If not, the program approximates the market data;
- Month price: If this option is chosen, the energy price value informed by the user is used. If not, the PLD is used, considering the year and submarket chosen previously;
- Increases capacity: If this option is chosen, the program considers that, in case of failure of one of the units, the other manages to generate all the expected energy.

Figure 6 illustrates the system screen used to register scenarios. The next step is to register the plant configuration to be used in the simulations. The system allows the registration of multiple configurations.

The registration of the plant configuration is done through the following steps:

- Registration of each equipment (element) that will be considered in the simulation;

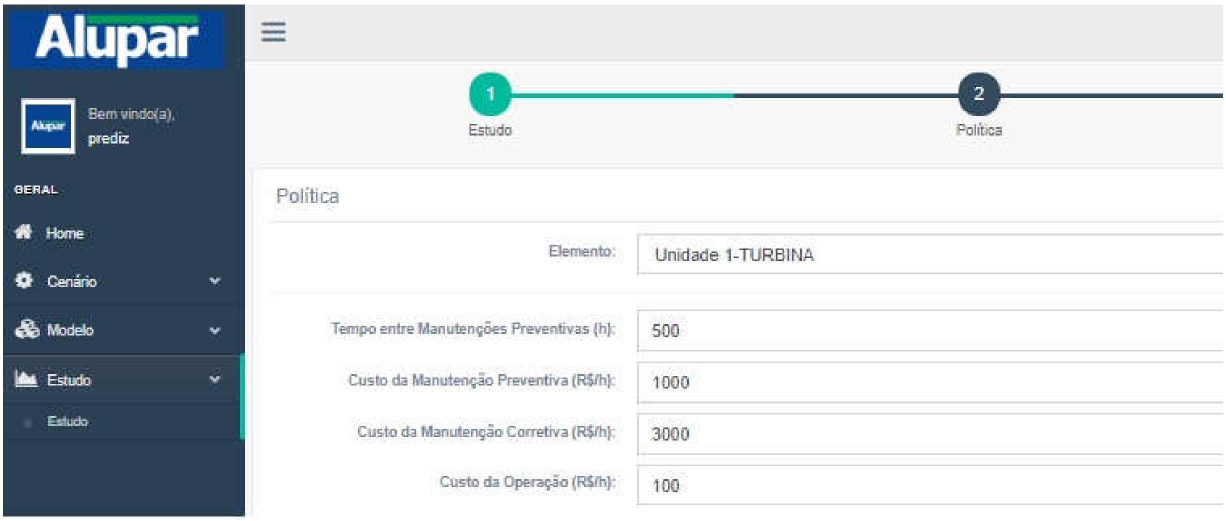

Figure 7. Scenario and configuration selected for the study (in Portuguese)

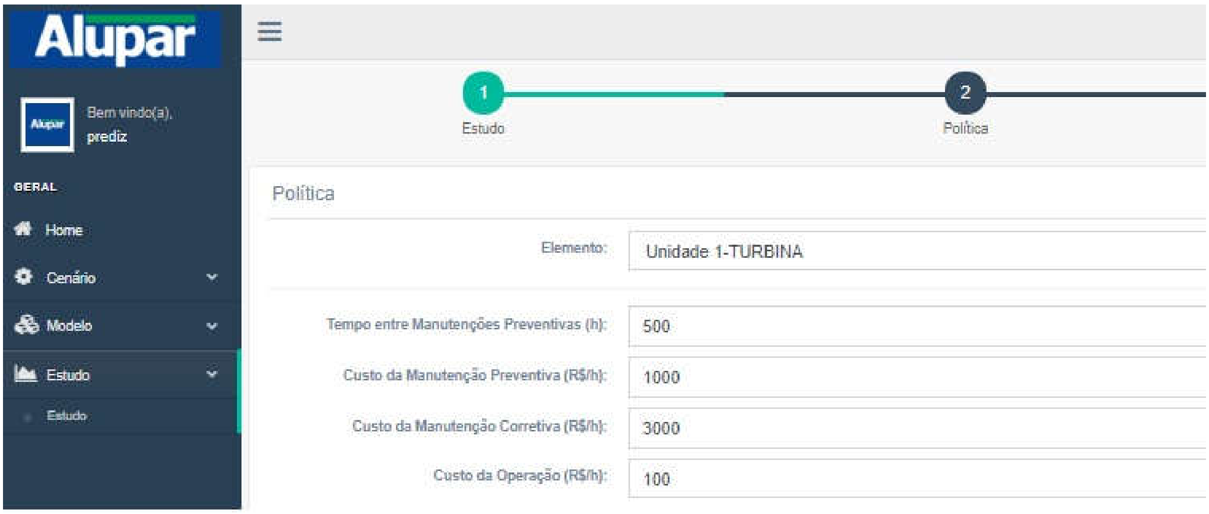

Figure 8. Registration of information specific to the maintenance policy (in Portuguese)

- Association of each element with its respective generating unit;
- Connection between the elements to generate the plant's series-parallel model.

Finally, a simulation study must be registered which, in addition to applying a previously registered scenario and configuration (Figure 7), also uses specific parameters related to the maintenance policy and information for modeling the reliability curves of the elements (*Weibull*). Regarding maintenance policies, the software allows to register, for each element, the times between preventive maintenance, in addition to the costs related to preventive, corrective maintenance and operating costs, as shown in Figure 8. Regarding the modeling of the reliability curves of each equipment, the following information is needed (Figure 9):

- Preventive maintenance time (h);
- Corrective maintenance time (h);
- Time since the last maintenance (h);
- *Lambda* e *Beta* (curve model parameters).

SIMULATION RESULTS

Initially, it sought to establish a base case for simulation. Then, variations of parameters were proposed to obtain other maintenance policies in order to compare them.

Base Case: In relation to the base case, for the calculation of the energy price, the PLD with base year 2018 and the Southeastern submarket was used. The energy generated was approximated with market data and the option to increase capacity was not used. As shown in Figure 10, for the initial simulations, a configuration with two units and 9 elements in series-parallel was considered for the plant. Regarding the specific parameters of the maintenance policy for each element, for the base case, the values shown in Table 4 were adopted.

where:

- TM: Preventive Maintenance Interval;
- TP: Preventive Maintenance Time Duration (h);
- TC: Preventive Maintenance Time (h);
- Cp: Preventive Maintenance Cost (R$/h);
- Cc: Corrective Maintenance Cost (R$/h);
- Co: Operation Cost (R$/h).

Table 5 presents the results of the simulation for the base case. According to Table 5, for each month, the results of energy generated and price, number and cost of preventive and corrective stoppages, operation cost, in addition to the result consisting of the value obtained from power generation, are subtracted the preventive, corrective maintenance and operating cost.

Figure 9. Registration of information for modeling the reliability curves of each element (in Portuguese)

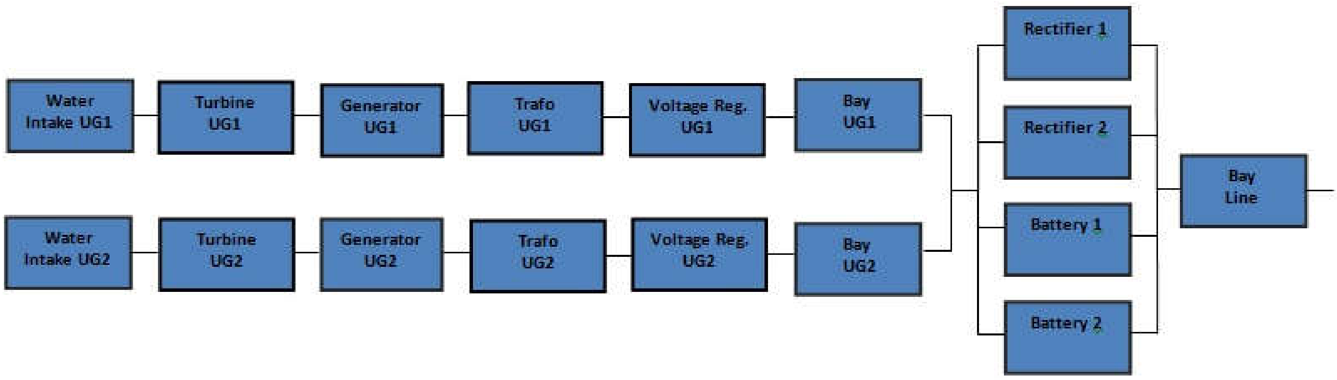

Figure 10. Series-parallel model considered

The annual calculation is recorded in the last line of the table. For the base case, preventive maintenance totalled 1,639 hours. Failures that resulted in corrective stops of the units totalled 90 hours in the year. Due to the random nature of the application of faults in the plant's equipment, the results obtained for the same maintenance policy may vary in each simulation. In this way, the developed system allows the user to choose the number of simulations to be performed and provides an aggregated result of the cases.

Sensitivity Analysis: For comparison of different maintenance policies, in addition to the base case with time between maintenance of 1500 hours, cases with time between maintenance of 800 and 5000 hours were considered. Each policy was simulated 10 times and the aggregated results are shown in Table 6. Regarding the base case, it was observed that the case with a time between maintenance of 800 hours generated worse financial results for the company due to the significant increase in the number of preventive stops, decreasing the plant's availability.

The case with a maintenance time of 5000 hours, when compared to the base case, reduced the time for preventive stops, but increased the number of stops due to plant failure. The Financial result, in relation to the base case, was very close, with a small advantage for the case with longer time between maintenance.

Conclusions

In order to contribute to the evolution of policies and models applied to asset management, the present work presented the stages of development of an Expert System for the maintenance management of a hydraulic generation plant, considering reliability analysis and impact financial models. For this purpose, the concept of Markovian networks was considered for the calculation of equipment operating probabilities, the series-parallel method for modeling the equipment and obtaining reliability curves with *Weibull* distribution for modeling the risks of each equipment. In order to validate the proposed system, initial simulations were considered from a hydraulic plant with two units and 9 elements in series-parallel. Initially, an attempt was made to establish a base case for simulation and then variations of parameters were proposed to obtain other maintenance policies in order to compare them. The results obtained showed that in relation to the base case (1500 hours between maintenance), a shorter time between maintenance (800 hours) allowed a generated worse financial results, due to the expressive increase in the number of preventive stops, decreasing the plant's availability. On the other hand, a longer time between maintenance (5000 hours), allowed a reduction in the time for preventive stops. In this case, the financial result, in relation to the base case, was very close, with little advantage for the case with longer time between maintenance.

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REFERENCES

Ahmad, R.; Kamaruddin, S. (2012). An overview of time-based and condition-based maintenance in industrial application. *Computers & Industrial Engineering*, v. 63, n. 1, p. 135-149.

Assis, E. M.; Lima, G. A. C.; Prestes, A.; Marinho, F; Costa, L. A. N. (2019). *q*-Weibull Applied to Brazilian Hydropower Equipment. *IEEE Transactions on Reliability*, v. 68, n. 1, p. 122-132.

Aven, T.; Jensen, U. (2013). Stochastic Models in Reliability. *New York: Springer-Verlag*. 2. ed..

Brown, Kevin (2017). Markov Models and Reliability.

Fan, H.; HU, C.; Chen, M.; Zhou, D. (2011). Cooperative Predictive Maintenance of Repairable Systems with Dependent Failure Modes and Resource Constraint. *IEEE Transactions on Reliability*, v. 60, n. 1, p. 144-157.

Kaiser, K. A.; Gebraeel, N. Z. (2009). Predictive Maintenance Management Using Sensor Based Degradation Models. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, v. 39, n. 4, p. 840-849.

Lafraia, J. (2001). *Manual de confiabilidade, mantenabilidade e disponibilidade*. Qualitymark, Rio de Janeiro (in portuguese).

Pereira, F. E. L. (2008). Determinação do Intervalo de Manutenção Programada da Proteção de Linhas de Transmissão Considerando-se Penalidades Associadas à Indisponibilidade. *Tese de Doutorado*. PUC-Rio (in portuguese).

Silva Neto, A. V.; Cugnasca, P. S. (2013). Utilização de Dados de Histórico na Manutenção Preditiva de Equipamentos Elétricos, Eletrônicos e Programáveis em Aplicações Metroferroviárias. *In: 19ª Semana de Tecnologia Metroferroviária*. São Paulo (in portuguese).

Walter, G.; Flapper, S. D. (2017). Condition-based maintenance for complex systems based on current component status and Bayesian updating of component reliability, *Reliability Engineering & System Safety*, v. 168, p. 227-239.

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