Game Theory Supporting a Decision-Making Process to Reduce Losses in Hydro Generating Plants Overhaul Delays

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Abstract

Overhaul maintenance stoppages for hydro-generating units must have their activities carefully planned to avoid delays in the execution schedule that affect power generation. However, usually postponements will happen. Such delays not only considerably jeopardize the maintenance overhaul schedule, but also lead to increased expenses due to Hydropower generation interruption, representing substantial monetary losses and even legal penalties for the generating power company. To reduce said losses caused by delays in overhauls, different scenarios of workforce teams are proposed for carrying out activities defined in the schedule. Each scenario presented associates a specific delay time with a respective cost. As a decision-making methodology regarding which scenario managers should choose to minimize losses the Max-min technique, belonging to Game Theory methodology, is proposed in this paper. A case study of an overhaul in a hydro-generating plant is presented as a way of validating the method, exemplifying how the financial losses due to delay were reduced as a result of the choice of the best scenario by the plant's operation and maintenance managers.

Keywords
Game Theory, Max-min technique, Maintenance overhaul schedule, Decision-Making Process. Hydropower generation.

1. Introduction

Hydro generating plants perform preventive maintenance campaigns to overhaul their equipment, which requires attention from the operation and maintenance teams due to the high costs associated with the need to interrupt the generating units. Preventive maintenance activities are extremely important because, when properly implemented, they are able to restore the reliability of the equipment and reduce the chances of unplanned downtime of the assets, in addition to ensuring the consistency of the power transmission throughout the dispatch period (Moghbeli et. al. 2020).

Preventive maintenance programs carried out in generating units can take place at different intervals, their duration varying due to the scope of long, medium or short-term repair activities, in addition to the scheduled replacement of components. The execution of maintenance activities is influenced by the fact that assets that make up a hydro generating unit are characterized by different sizes and complexity. Accordingly, the preventive shutdown of the hydro generating equipment requires adequate planning by organizational areas such as logistics and human resources, in addition to the preparation and acquisition of spare parts, tools and instruments (Canto 2008; Aktel and Unluakin 2018).

The geographic location of plants may also require extra care from logistics managers when planning overhauls, since power generating plants are generally located in regions that are far from large centers, sometimes even in somewhat inhospitable places. Besides, when it is necessary to interrupt the operation of a power generating plant, the National Energy Operator requires previous mandatory communication in order to analyze the request and grant authorization. All this complexity obliges managers to invest good periods of time for planning stoppages.

The quality of the energy production and the benefits for the generating companies are the main effects that stimulate the improvement of renovation programs for the equipment of their plants (Moghbeli et. al 2020). In addition, the execution of plant restructuring programs through scheduled maintenance is capable of reducing the rates of unexpected failures (Canto 2008). Some authors approach the problem as generation maintenance schedule (GMS).

The focus of this research lays in offering solutions to plant managers for situations in which delays in overhaul schedules will be inevitable. In this case, game theory can be a useful tool for evaluating different proposals regarding financial losses that will impact the business group involved. Hence, this paper implements the Maxi-min method in a real environment where delays are expected to occur and shows how the different strategies are evaluated and chosen in order to minimize the financial impact on the hydro generating business.

2. Literature Review

Bhuyan (2016) points out that game theory is not just theory; on the contrary, it has expanded. Despite mostly used in economics, it is now applied in many areas such as business, engineering, biology, computer science, political science, psychology and philosophy. After maintaining that game theory is the formal study of conflict and cooperation between intelligent rational decision-makers, the paper closes with a quotation from the British writer Charles Lamb's work: 'Man is a gamming animal. He must always be trying to get the better in something or other'.

Hernandez et. al. (2002) while stating that maintenance management is the effective and economical use of resources to keep equipment in, or restore it to, a serviceable condition, use a game theoretic approach where a product designer and a maintenance manager are modeled as two players in a Leader-Follower game, and strategies for designing product components are derived accordingly. This approach is shown to yield satisfactory solutions without requiring complete integration of complex and difficult individual decisions. Besides, the knowledge and expertise of each decision-maker are utilized while keeping computational problems at a tractable level.
Kilpi et. al (2008) present a model for analyzing the potential of several strategies to capture pooling benefits in the availability service of repairable aircraft components against a variety of external conditions, where the cooperative strategies were tested in a game theoretic setting both from the viewpoint of total efficiency and from the perspective of each participant. Results suggest that pooling may be beneficial, but also that conflicting interests may complicate the emergence of efficient pools.
Pourahmadi et. al. (2016) propose a method to quantify the generating units' criticality on the bulk power system reliability performance. The proposed approach utilizes a solution concept of game theory and evaluates the contribution of each generating unit on the overall system reliability when a higher-order contingency occurs. According to the presented results, the proposed approach succeeds in fully recognizing the critical generating units from the viewpoint of system reliability, and can be further utilized in the implementation of modern maintenance approaches such as RCM and the re-enforcement of decisions in bulk electric power systems.
In Jong (2010) and subsequently in Jong and Smit (2019) game theory is applied and contract types are described as mechanism designs in the search of optimal solutions for the allocation of decision rights and risks in aviation maintenance contract relationships involving uncertainty and significant exogenous risk exposure. Findings show that, under certain conditions, collaborative contracts result in a higher utility than performance contracts for all contract parties.
Jin et al. (2015) under game-theoretical framework propose a multi-party, multi-criteria, and multi-item service delivery mechanism to maximize the utilities of all the stakeholders. The goals are achieved by jointly optimizing the maintenance, the spares inventory, and the repair capacity under the game-theoretical framework. Results show that in the wind power industry a single or a consolidated multi-item contract could be advantageous over multiple single-item contracts as it ensures a higher profit margin at a lower customer's cost.
Husniah et al. (2015) use a Nash game theory formulation in order to obtain a win-win solution for a two-dimensional service maintenance contract for a dump truck operated in a mining industry. Subsequently, Husniah et al. (2018) model a usage-based maintenance contract using cooperative and non-cooperative game approaches, also with one dimensional approach for failures, in order to maximize the expected total profit for both players.
Abapour et al. (2018) state that the challenges posed by deregulation and competition in the power industry, and fundamental changes in the control and operational structures of electric power systems require a strong tool for handling such issues. Game theory approach, which is defined as an analytical concept for dealing with the decision-making process in a variety of sciences, is vastly employed in dealing with power system problems. Accordingly, the basic foundations of game theory are introduced together with a brief definition of the main classifications of game theory, including cooperative games, dynamic games, evolutionary game theory and strategic games. In addition, a comprehensive review of the application of the game theory approach to the solution of electric power system problems is presented.
Pourahmadi and Dehghanian (2018) on their paper propose a promising approach for loss allocation in power distribution systems based on a cooperative concept of game-theory, named Shapley Value allocation. The suggested loss allocation approach is numerically investigated, the results of which are presented for two distribution systems and its performance is compared with those obtained by other methodologies. Despite the potential benefits of the Shapley Value approach, the authors concede that further simplifications may be needed for specific classes of problems to enhance the computational efficiency concerns.
Moghbeli et al. (2020) also purport that the generation maintenance scheduling (GMS) problem is one of the main issues in the restructured power system, due to its effect on the security risks and the profit of the generation company (Genco). Then, in order to consider the risk of GMS for producers, model the GMS problem from the perspective of producers employing non-cooperative game theory, and use the Nash equilibrium to determine the Genco's optimal strategy profile. Results are said to produce compatible outcomes for Gencos in a competitive market environment.
It can be seen that game theory has expanded indeed, and is now being used to deal with issues in many diverse fields, including several aspects of maintenance management and the solution of electric power system problems, which are of particular interest to the authors of this paper.

3. Methods and Materials

The hydropower units applied to the generation of electric energy have as fundamental peculiarity their gross dimensions, which makes the maintenance enforcement plans quite complex. Once established, it is expected that these plans will ensure the equipment an operational campaign exempted from unforeseen interruptions.
In general, asset managers seek full availability of their equipment and see maintenance plans as the key strategy for this purpose. In the energy generation and transmission environment, ensuring the availability of a turbine means ensuring that earnings are not interrupted, avoiding significant financial losses, especially preventing cities from suffering blackouts, which can mean costly penalties applied by regulatory agents.
This paper presents the application of the Max-min technique to the maintenance planning of a hydropower unit for overhaul maintenance optimization. Figure 1 shows the development and application steps of the proposed Game theory approach to maintenance decision making.

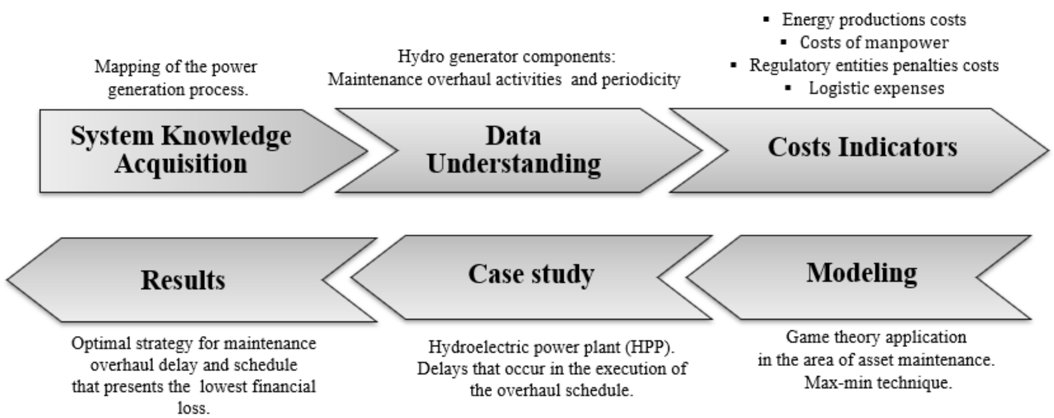

Figure 1. Game theory approach steps

This Game theory approach (Maxi-Min method) is applied in a real HPP maintenance overhaul planning, where delays are expected to occur and shows how the different strategies are evaluated and chosen in order to minimize the financial impact on the hydro generating business.

4. Game Theory Methodology Applied to Hydropower Plants Maintenance Planned Making-Decision: Case Study

Hydroelectric power generation is one of the industrial processes that require 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 the integrity of personnel as well as of material assets). This study was applied on the Kaplan hydro generator unit used in the energy generation system of a Brazilian hydroelectric power plant (HPP) located in the state of São Paulo (Brazil). This HPP has three Kaplan type hydro generator units with a total installed capacity of approximately 500 MW).
The HPP facility is composed of various industrial assets, including actuating devices, and automation systems, which produce electrical energy by the use of potential water energy. These main component assets are: dam, water intake gate, dam upstream, sluice gates, penstock, power house, hydro generator axis, turbine, speed governor, generator, suction tube (water discharge), elevator transformers, control room and downstream outlet. Figure 2 illustrates the HPP basic physical arrangement.

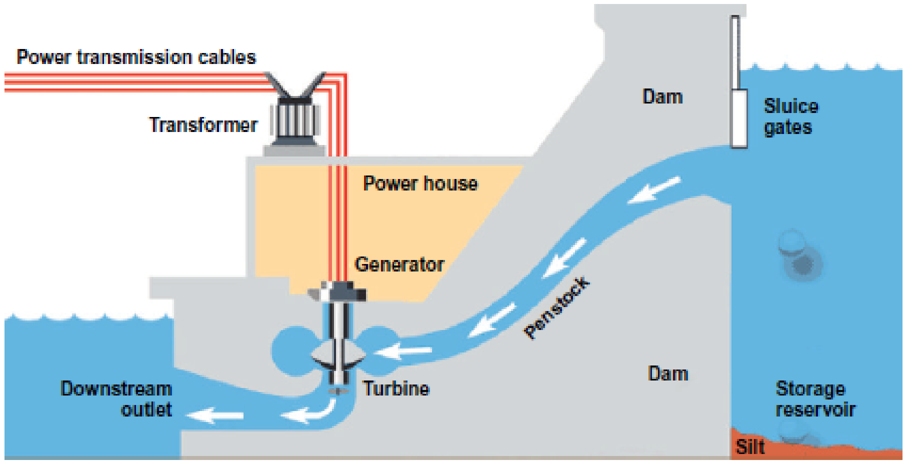

Figure 2. Electric power generation process
Source: Grigsby (2012) and Breeze (2014)

The hydro generator unit (GU) is responsible for transforming potential energy into kinetic energy, converting mechanical energy into electrical energy. The governor system controls the hydro generator's speed of rotation. The turbine, whose rotation is driven by the water mass, is connected directly to a generator to produce electricity. The generator converts the rotational movement of the turbine into electrical energy by electromagnetic induction. The energy generated has the appropriate voltage to be transmitted to the final consumer. (Grigsby 2012 and Breeze 2014).

Kaplan hydro generator units are designed to operate where a small head of water is involved; its turbines can be used in sites having a typical head range of 2–40 meters. A Kaplan hydro generator unit can be divided into three main systems: Speed governor, Turbine system, and Axis. Figure 3 illustrates the Kaplan hydro generator unit structure.

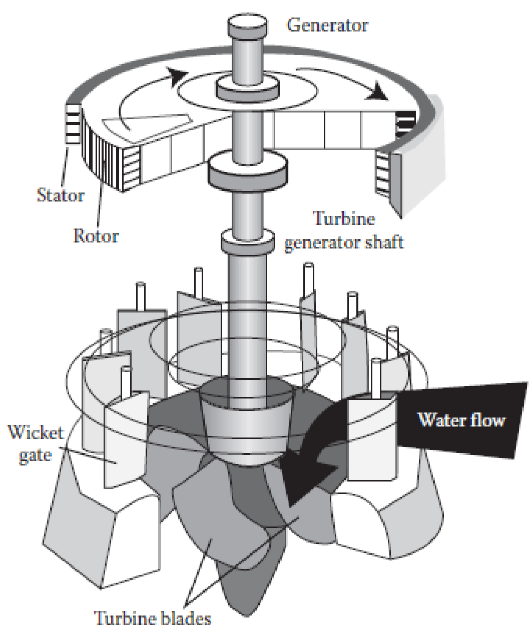

Figure 3. Diagram of Kaplan Hydro generator
Source: Grigsby (2012) and Breeze (2014)

Hydroelectric power plants (HPP) are complex systems that require periodic maintenance, the level of the maintenance management organization will, therefore, greatly influence their operational performance. The hydro generating environment requires a high level of availability of generating units in order to avoid compensations,

interruptions and legal penalties from regulatory agencies due to power interruptions originating from unscheduled maintenance shutdowns. One way to prevent unexpected equipment downtime is to perform overhauls, which are long interventions for exams and repairs on parts that are inaccessible when the asset is in operation. An overhaul is a careful examination of disassembled parts of a generator turbine in order to detect failures in advance, making necessary repairs. In the environment of this study, overhauls last for about 45 days and happen every 12 years.
The case study proposed in this research concerns a group of partners who manage hydro generating sites and need to make decisions regarding delays that occur in the execution of the overhaul schedule at one of the generating units. The schedule for implementing this preventive program needs to be extended as some activities are taking longer than planned. However, the group of partners assesses the situation making sure that it is possible to reduce the delay time by increasing the size of the team that performs these activities. Then, the group proposes four possible solutions to be implemented that aim to solve the problem and are shown in Table 1. Each solution has its respective impact on the delay time and, consequently, financial consequences for the one plant that performs the asset maintenance and the one that provides human resources. Regarding the fourth option presented, this is called a hybrid choice, as it integrates the three previous options into one, bringing together local manpower, from the partner plant and hired as an outsourced contract for a determined period.

Table 1. Partner's options

Option	Solution Description	Impact (days)
1	Appropriation of local manpower	10
2	Borrowing manpower from partner's plant	7
3	Outsourced manpower	8
4	Hybrid manpower team (local + partner + outsourced)	4

As shown in Table 1, each option created by the field managers allows different impacts on maintenance duration, which means that the unit can be reconnected sooner or later depending on the option selected. It is easily observable that if only the third column "impact" in days is taken into account, row 4 of the table is the most advantageous. However, it is necessary to assess the financial impact generated by each type of solution presented by the team members. Financial costs include expenses with logistics and accommodation for people who need to be displaced from other operating units located in regions not close to the unit where maintenance is being carried out. For the option in which human resources are outsourced, there is a contractual cost that should be paid to the company providing the specialized service for carrying out the activities.
Aiming to assess the losses related to delays in carrying out the overhaul schedule of the generating unit, some variables are presented, as well as their formulas, many of which are well known in the power generation industry. This case study addresses a hydro generating plant with an installed capacity of 393 MWh, using 3 Kaplan generator turbines. The average annual hydro generation is 1944 GWh (Nogueira and Alarcón,2019) and this information is used as input data for the calculation of financial losses generated by delay in overhaul of the plant. The average power generated daily by the unit is obtained by equation 1.

$$\text{Average daily power output } = \frac{1944x10^3 MWh * 24h}{8760h} = 5{,}326\ MWh \tag{1}$$

Through the average daily hydropower output by the plant, it is possible to calculate the daily financial loss in the plant when it is not in full operation. Regarding the power price, the estimated value considered is 170 currency units per MWh and is applied in equation 2.

$$\text{Stoppage daily cost } = 5{,}326\ MWh * 170\ \frac{currency\ unit}{MWh} = 905{,}420 \tag{2}$$

Regulatory entities that inspect and control the entire national energy generation and transmission system are responsible for applying the penalties provided by law for non-compliance with the agreed quantity of energy produced (Nogueira and Alarcón,2019). According to Brazilian Ministry of Mines and Energy (2007) and De Castro et. al. (2017), the established penalty varies according to the installed power of the plant and the history of recurrences, and for this case the value of the penalty applied for the act of delay will be considered regardless of the duration period. The partner plant that supplies the manpower absorbs financial costs caused only by the possible increase in operational unavailability that starts from 0.5% (normal operation) and reaches 1.0% (when reductions occur in the staff), being the daily loss calculated by equation 3.

$$\text{Estimated costs of manpower sharing } = 905{,}420 * 1.0\% * 24h = 217{,}300 \tag{3}$$

The plant requesting this resource pays the expenses of the maintenance team related to logistics such as accommodation, in addition to the overtime charges. The daily expenses associated with the receipt and accommodation of each member of the partner plant are presented by equations 4 to 6. It is assumed that the team's accommodation is done in the plant's own facilities where the renovation is carried out, therefore not requiring transfer allowances to and from the plant. The cost of overtime is calculated assuming 50% more than the cost of normal hours and a daily amount of 4 overtime hours performed daily by each member of the external team, in addition to the 8 normal hours, totaling 12 hours of work on each impact day.

$$\text{Acommodation } = daily\ accommodation\ rate * impact\ (days) \tag{4}$$

$$\text{Logistic Expenses } = round\_trip\ transfer\ cost\ (air) \tag{5}$$

$$\text{Overtime Costs } = 1.5 * hourly\ wage * 4 * members \tag{6}$$

In the situation in which it is decided to enter into an outsourced labor contract, the total daily cost per head is indicated. Aiming to make calculation routines simpler, the same wage cost is assumed for own employees and for externals and, therefore, the same hourly wage value is used. The logistics and accommodation costs of the outsourced team are also paid by the company that carries out the renovation. The company hired to provide human resources and the partner plant can offer 10 members each to complement the overhaul plant's reinforcement team. Therefore, as shown in table 2, the daily financial losses generated by each day of delay (impact) are established.

Table 2. Daily financial losses

Daily financial losses (Source)	**Description**	**Value ($)**	**Supported by equation(s)**
Provider Plant	Manpower sharing	217,300	(3)
Overhaul Executing Plant	Manpower transfer/ accommodation/ overtime costs	19,920	(4) to (6)
Overhaul Executing Plant	Outsourced Contract Costs	20,836	-
Overhaul Executing Plant	Loss of profit	905,420	-
Overhaul Executing Plant	Penalties from Regulators	323,571	-

As previously informed, table 2 is dimensioned based on the daily losses that occur in the two generating plants. However, the estimate depends on the strategy chosen by the maintenance and operation managers, shown in table 1, culminating in different impact days. In order to complement the previous tables, table 3 shows the total financial losses of each plant in each option, enabling the implementation of the game theory method. Below, table 3 presents the values of financial losses for each available option.

Table 3. Total financial losses based on strategy chosen

Strategy	**Option**	**Impact (days)**	**Loss amount**	
			Provider Plant ($)	**Executing Plant ($)**
Appropriation of local manpower	1	10	108,650	9,576,971
Providing manpower from plant partner	2	7	1,521,106	6,800,951
Outsourced manpower	3	8	108,650	7,733,626
Hybrid manpower team (local + partner + Outsourced)	4	4	869,203	4,108,279

Table 3 shows that depending on the strategies chosen, there are different losses for both power plants. However, for the provider plant, option 1 and 3 show an identical loss and lower than the others. It occurs because this unit is exempt from displacing its maintenance team and this allows it to obtain losses related to 0.5% of inherent unavailability as previously discussed. When the executing generating plant is observed, its losses are different for every strategy chosen by the management team. This is due to the fact that their losses are directly related to the delay time in days (impact) variable, which is a multiplier factor for all losses listed in Table 2, with the exception of the legal penalties. Thus, aiming at the application of game theory, the information in table 3 was arranged in order to represent a game in which the provider plant and the executing plant are the players.
The game scheme is illustrated in table 4. Conventionally, in tables that display games with the possible moves of the participants and their rewards, in each option shown in table 4, the value of the left and right refer to the reward of the provider plant and the executing plant respectively. As the case study in this paper is concerned with financial losses, here awards refer to losses. Therefore, the lower the reward value obtained by the player the better the result will be for this competitor.

Table 4. Evaluation of the four strategies using Game Theory

Provider Plant	**Executing Plant**	
	Appropriation of local manpower	**Outsourced manpower**
Providing manpower	Option 2 1,521,106 6,800,951	Option 4 869,203 4,108,279
Does not provide manpower	Option 1 108,650 9,576,971	Option 3 108,650 7,733,626

The game strategy used is to maximize the results of the columns and minimize the results of the rows. This strategy is known as Max-min. The results used for applying the Max-min are those obtained by the player who is in the table line. Hence, table 5 is shown and then 4 questions needed to be answered as part of the process of this method.

Table 5. Max-min implementation

Provider Plant	Executing Plant	
	Appropriation of local manpower	**Outsourced manpower**
Providing manpower	Option 2 1,521,106	Option 4 869,203
Does not provide manpower	Option 1 108,650	Option 3 108,650

- 1 - What is the lowest reward for each column?
- Answer: Option 2 and Option 4
- 2 - What is the highest reward between these 2 rewards?
- Answer: Option 4
- 3 - What is the highest reward in each row?
- Answer: Option 4 and Option 3
- 4- What is the lowest reward between these 2 rewards?
- Answer: Option 4

According to the Max-min method, option 4 is considered the most advantageous from an organizational point of view for those responsible for coordinating hydro generating plants. Hence, in addition to using local manpower, maintenance managers must choose to request labor from the partner plant, and sign a labor outsourcing contract, i.e., carry out a hybrid system of human resources and execute the entire overhaul schedule with a delay of only 4 days.
Therefore, the following conditions were met in this case study: $maxi_{min}$ columns = $mini_{max}$ rows. When this occurs in a combination of strategies, it can be said that the balance of the game has been achieved. Given the combination of strategies above, this is called a cell point.

5. Results and Conclusion

An application of game theory in the area of asset maintenance was presented in this paper. The theory was concerned with a delay problem in the overhaul schedule of the assets of a power generating plant. Then, under four types of possible strategies, a process of interaction between two power plants, which simulated two associate managers or players belonging to a business group, was modeled in order to verify the lowest possible financial loss to members among the options available for the solution of the overhaul schedule execution problem. The interaction between the players concerned the sharing of labor as a way to reduce the delay time of the overhaul. The game was then set up in a table containing the respective losses for each option presented. The viability of the players' strategies was assessed using the Max-min method in order to maximize the results of the columns where the overhaul plant was located and to minimize the results of the lines where the plant providing human resources was located. The result of the simulation of the game helped managers in decision making, showing that the best option is to share labor with the partner plant and also establish an outsourcing contract complementing the staff. The decision indicated by the method pointed to the lowest financial loss for the group of associate managers and a delay of only 4 days in the renovation schedule.

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Alécio Julio da Silva is a Mechanical Engineer graduated in 2007 and is currently Master degree student at the University of São Paulo (USP). He has professional experience in the maintenance sector of the Railways and Beverages industry. His research activities are centered on: expert systems supported by Artificial Intelligence applied in the prognosis/ diagnosis of equipment failures and IA algorithms integrated with IoT technologies.

Marjorie Maria Bellinello is a full Professor at Department of Mechanical and Maintenance Engineering of Federal University of Technology - Paraná (UTFPR). She is author and co-author more than 20 publications on national and international journals (International Journal of Engineering Trends and Technology, Cahiers Agricultures, Brazilian Journal of Business, Annals of Agricultural and Environmental Medicine), book chapters and conferences proceedings. Dra Bellinello has participated as Researcher in many national and international projects at the University of São Paulo (USP), Politechnical University of Marche (UNIVPM),) and Notthingham University. The focus of her research is industrial maintenance management, decision-making theory, decision support systems, intelligent manufacturing, risk assessment methodologies, reliability and maintenance engineering, human reliability, production systems optimization and work ergonomics.

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