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Prioritising Maintenance Work Orders in a Thermal Power Plant: A Multicriteria Model Application

Sidney Jose Meireles de Andrade [1], Plácido Rogério Pinheiro [2,*], Glauber Jean Alves Narciso [1], José Tarcisio Pimentel Neto [1], João Pedro da Silva Bandeira [1], Vinicius Sales de Andrade [1] and Cayo Cid de França Moraes [1]

[1] Porto do Pecém Geração de Energia S/A, Fortaleza 62674-906, Brazil
[2] Graduate Program in Applied Informatics, University of Fortaleza, Fortaleza 60811-905, Brazil
* Correspondence: placido@unifor.br

Abstract: Maintenance is one of the most rapidly expanding activities in the industrial environment, since its application is no longer limited to simple, regular fixes. In the case of thermal power plants maintenance is essential, since they only operate when the National Electric System Operator wants them to complement the production from renewable sources such as hydro, wind, and solar. To limit the frequency of failures that result in generation unavailability, the operation team performs daily inspections to evaluate the equipment's condition and the risks to the generating process. If an anomaly is found, the maintenance team will create service notes to address it. This research aims to demonstrate how the method Measuring Attractiveness by a Category-Based Evaluation Technique (Macbeth) can be applied to the development of a multiple-criterion model to support decision making in ordering the criticality of systems in thermal plant operational inspection routes to propose new methodologies for routine execution to increase the operation team's productivity. According to the results of the judgement matrix, the recommended ordering enabled a strategy for the performance of the current operational routes by redefining the criticality, periodicity, routing, and resources utilised, hence preserving the plant's reliability. According to the results, the proposed ranking will enable a new strategy for integrated maintenance planning, redefining the criticality of service orders according to the judgement based on criteria and subcriteria, thereby allowing the application of resources appropriately and focusing on what is more important to maintain the thermal power plant's continuity and operational safety.

Keywords: energy; thermal power plant; multicriteria methodology; operation and maintenance; reliability; Macbeth

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1. Introduction

In the business world, firms have been looking for ways to increase the efficiency of their internal operations to decrease costs and maximise resources. Managing their human capital and financial resources to maximise profitability is the most significant problem facing businesses in the current business environment.

Resources are the foundation of strategy, and distinct collections of resources produce competitive advantages that contribute to the production of wealth [1,2].

The effective management of these resources is crucial for survival and establishment in a global market where severe competition and a volatile economic climate produce an uncertain future.

A more competitive corporate market and rising consumer demand for top-notch products and services are characteristics of the modern global economy [3].

Businesses have had to look for new ways to run so that they can do well in the market. To achieve this, output was increased via technology and research money, which improved both technical and operational performance [4].

In the case of industrial plants, the utilisation of equipment that performs essential functions for production and whose failure can partially or entirely halt output is maximised. The top management has improved maintenance by implementing the best practices to achieve optimum equipment availability.

Maintenance is no longer only a repair department; it is now an integral component of the company's strategy for achieving its goals and objectives. Consequently, maintenance is becoming more significant, particularly in the most prominent organisations, where the growth in spending indicates the organisation's maturity and asset management strategy.

The main goal of any maintenance action is to make sure the system works and is available. Any maintenance procedure aims to ensure that the system is functional and accessible. This is accomplished by ensuring that the system is dependable and by keeping in mind that more maintenance planning is performed for essential equipment or systems to address any issues or unusual occurrences that may occur while they are in use.

Criticality analysis focuses on detecting the effect of equipment or system unavailability at a specific time by evaluating the interdependencies across processes, dependability models, parameter variations, and operational features of each process [5].

Furthermore, as noted in [6,7], under normal operating circumstances, the criticality of a system is not decided by a single component but rather by numerous linked pieces that are reviewed and studied based on their importance to the process.

Daily operational inspections of processes and systems at the Pecém Thermoelectric Power Plant are crucial for asset management and ensuring equipment and employees' generation and safety.

The observations enable the identification of early failures using the five human senses and serve as the basis for developing service notifications for maintenance with a wealth of information that will enable better agility and assertiveness in problem-solving by maintenance.

Maintenance has evolved into a critical sector for the survival and growth of any firm, since its effects directly influence the environment, performance, and safety of industrial activities [8]. Failure analysis has also evolved into a sophisticated approach for enhancing the system, the tools, and, eventually, the business [2].

On the other hand, Maintenance Planning and Control (MPC) seems to be present up until the present, and preventative maintenance is based on operating time [9,10]. Preventive maintenance was conceived to reduce equipment failure during production [11,12]. This describes the essential ideas of Reliability-Centred Maintenance (RCM), intending to implement it in age-based preventive maintenance of necessary equipment in thermal power plants.

Moreover, ABNT NBR 5462, Reliability and Maintainability (1994), defines maintenance as: "A mix of all technical and administrative operations, including supervisory activities, aimed to maintain or restore an item to a condition where it can perform a required function."

Analysing the maintenance history demonstrates that several strategies were created to ensure equipment and processes' availability, reliability, and maximum productivity, while minimising operating costs [13].

According to [14,15], preventive maintenance allows for comprehensive overhauls, restorations, and component replacements at each time interval or cycle. It is important to note that stopping the equipment is required for this procedure.

The emergency service is the entity that responds to equipment failure and seeks to restore it to service as soon as is feasible. Proactive maintenance operations act before equipment failure and can analyse the equipment's state to determine the optimal time for action. Temperature, electrical current, voltage, vibration, and wear thickness are examined in this evaluation [16,17].

This technique arose from the need to enhance the availability and productivity of industrial processes, which were hampered by frequent equipment failures [18,19]. Lastly, improvement efforts try to optimise the other strategies by analysing indicators, developing projects, outsourcing, and acquiring supplies.

Maintenance engineering was a paradigm shift compared to the others, since it is not a practical approach but rather technical support that tries to investigate and solve more complicated issues requiring more technical staff expertise. This enables the use and combination of technologies to increase productivity and facilitate the lives of those engaged in the manufacturing process [20].

Thermoelectric plants use the energy released by a particular material [21]. The primary systems of a fossil fuel thermoelectric plant are the boiler, turbine, and generator:

- A system for creating water vapour by combustion of an energy source within the boiler.
- A set of turbo-generators for generating electricity.
- The condensing steam system includes condensers, cooling towers, and make-up water pumps.
- The boiler water supply system includes feed pumps.

The suitable hierarchy for the prioritisation of problem resolutions to be addressed by the maintenance team during the daily operation of a thermal power plant is a success factor for the planning and scheduling of daily maintenance activities.

In this context, decision making is usually tricky in maintenance and operation. The strategy must be methodical, consistent, clear, and objective, since some of these problems are difficult, involve risks and uncertainties, and call for the contribution of several professionals. Thus, multiple-criteria decision-making strategies are advantageous [5].

The maintenance planning team concentrates and manages the management process of the resources available to be used by maintenance, such as people, materials, third-party services, truck resources, cranes, and scaffolding. This team has a backlog of maintenance activities, mostly service orders.

These are the results of the field inspection performed by the operator, who, using sensorial and detective inspection (the five human senses), records their observations in service notes, which are transformed into service orders after the maintenance team evaluates the problem and prepares the necessary resources to resolve it.

Examining daily operations, particularly those that, from the standpoint of the operation, represent emergencies owing to their severe threat to generation, safety, or the environment, is the purpose of the daily meeting. The frequency of declared emergencies is a maintenance indication, since it indicates that Engineering must review its maintenance plan or create one if none exists.

The maintenance organisation must manage and resolve production issues to remain competitive. Thus, it must be a reformed firm activity that is interwoven with the other operations and produces results, maximising solutions [6].

It is challenging for MPC to choose which activity should happen first, since there are so many locations, systems, and pieces of equipment and because each one is unique and significant in terms of the procedure, risks, and repercussions.

In this view, introducing a methodology that addresses Reliability-Centred Maintenance principles might contribute to optimising the operation and main operation of thermal power plants.

Operational inspection based on the definition of an order based on standards set by managers and technical teams has broad technical and academic relevance, contributing to the effectiveness, optimisation, and sustainability of power generation processes through a multicriteria model whose goal is to improve prioritisation routes.

Nevertheless, based on [5], the evaluation should not be very complex, as the observed differences are significantly more attributable to the variety of outcomes than to contradictions. The selected approach can be validated by meeting specific requirements. The Macbeth method in the problem at hand resulted from the decision maker's acceptance of the approach, which indicated that the questions posed to the decision maker were comprehensible and that the decision maker had trust in their answers.

In addition, the necessity of analysing the data's acceptability, the approach's use of its characteristics, and whether the conclusion supported the decision-making process was emphasised. The authors contend that the situation in question must be considered while selecting a multicriteria approach from those offered and using it in a particular situation. It will be essential to look at the situation, the goals of the decision, and the available information [22,23].

Moreover, according to [6], the choice of approach should be based on the evaluation of the selected criteria, the kind and accuracy of the data, and the decision maker's thinking style and problem-solving experience. Because there are several methods to performing a task, the outcomes may be unclear or even contradictory.

Combining brainstorming techniques with Web-Delphi research, this study describes the processes of structuring the multicriteria decision-making model. An interaction matrix was constructed and used as a foundation for future modelling after estimating the amount of change in the dependability of the affected after a specific failure of affecting components.

The proposed modified method for assessment of the optimal reliability of the system of a condensation thermal power plant provides a solid foundation for future work on its development and improvement of the assessed values' precision through the introduction of technical diagnostics and a modern information and management system [24,25].

In [26], the authors describe a multicriteria decision-making approach that integrates Markov chains with the multicriteria Macbeth to facilitate the best choice of combination of policies by employing the opinions of a multi-disciplinary decision group.

The suggested method considers the amount of professional approval of a specific choice. It also considers parameters linked to cost, care quality, and the effect of care coverage.

On the other hand, it offers a one-of-a-kind multicriteria system that helps ensure patients receive the best possible care. The model combines the Measuring Attractiveness by a Categorical-Based Evaluation Technique approach with Markov chains to calculate the predicted mean availability for various electric power distribution networks. The outcome is a comprehensive categorisation of the maintenance policies and activities (redundancy) to be implemented in power distribution networks [27].

In addition, Trojan and Marçal [28] categories maintenance types based on acceptable vocabulary and applicable criteria. The Electre Tri method was used to assess maintenance based on a multicriteria evaluation. The collected findings reveal a scientifically systematic pattern for these notions.

The operation of thermal power plants, which typically involve many systems, subsystems, and auxiliary equipment, has a high demand for monitoring and controlling processes, analysing failures, and implementing improvements and actions that increase reliability and, thus, reduce the failure rate. When considering operation and maintenance planning and Reliability-Centred Maintenance principles, it may be challenging to prioritise the criticality of an asset's component failures for operational monitoring [6].

The following label was defined as "prioritisation of maintenance service orders at thermal power plants", because this research aims to suggest an adequate prioritisation of service orders using a multicriteria decision support model to evaluate crucial factors to ensure the availability of a coal-fired power plant.

The remainder of the article has the following structure: Section 2 focuses on the research technique, its characterisation, and the structure and application stages required for classifying and ranking the monitored spots along the operational inspection routes. In addition, Section 3 describes the structure of the evaluation model, which includes the criteria and parameters for classifying and ranking monitored points. Moreover, Section 4 gives the computational results of the model's implementation. Section 5 closes with the application's results and discussions, followed by a conclusion.

2. Multicriteria Methodology

Regarding the objectives, the research is categorised as descriptive and exploratory since, according to [14], descriptive research uses traditional data collection methodologies, such as questionnaires and systematic observation. Thus, the survey describes the characteristics of a specific occurrence or establishes the correlations between variables. Exploratory research entails a review of the relevant literature and interviewing individuals with direct experience with the researched issue. Regarding methods, the research is bibliographic.

Typically, the evaluation question is solved by experts in thermal power plant operation and maintenance. The brainstorming approach to generate qualitative data is a creative tool that can be utilised in the research design phase to solve a troubling question.

According to [15], qualitative research can be conducted when there is an inextricable link between the target worlds and the problem approach. Therefore, the subjectivity of the topic, which cannot be quantified, reinforces the notion that everything is frequently quantified [29,30].

According to the results of the Macbeth approach's judgement matrix, the proposed ordering will allow the revision of the execution strategy of the current operational routes, redefining the criticality, periodicity, routing, and applied resources while retaining the plant's reliability.

This proposed approach explains the stages involved in generating the criticality ordering methodology due to the suggested adjustment to the current thermoelectrical inspection operational route strategy and the higher operation team productivity.

The results of the judgment matrix for the Macbeth method show that the proposed ordering would alter the execution strategy of the current maintenance schedule, redefining the criticality of each work order and deploying resources while retaining the plant's dependability.

Clarifying the stages involved in developing the criticality ordering technique is required in light of the suggested alteration to the current thermoelectrical maintenance work order strategy and the enhanced productivity of the maintenance team. The method development measures are depicted in Figure 1.

Initially, the most pertinent criteria and subcriteria for evaluating the criticality of equipment and systems were categorised. Due to the complexity of the evaluation and the impact of failures in the electricity generation process, the Delphi method was used as an investigation technique in two rounds during the second stage, where it was possible to create a ranking of criteria and subcriteria and obtain a higher level of specialist consensus.

The Delphi method is described as a means for building a collective communication process to allow a group of people to solve a complicated topic efficiently. As a result, Delphi is recognised as a technique for gathering knowledgeable expert views on a specific subject [17].

In addition, Delphi's capability for determining a specific expert's skills, abilities, or knowledge is emphasised. The Delphi implementation process is carried out in several steps. As depicted in Figure 2, an oval shape is usually used for a flowchart's start and stop steps.

The Delphi approach was implemented by developing and administering the primary questionnaire. Following this, a quantitative and qualitative analysis of the responses was conducted. The procedure continued with the second questionnaire, followed by replacement contemplation and growing closer to unanimity.

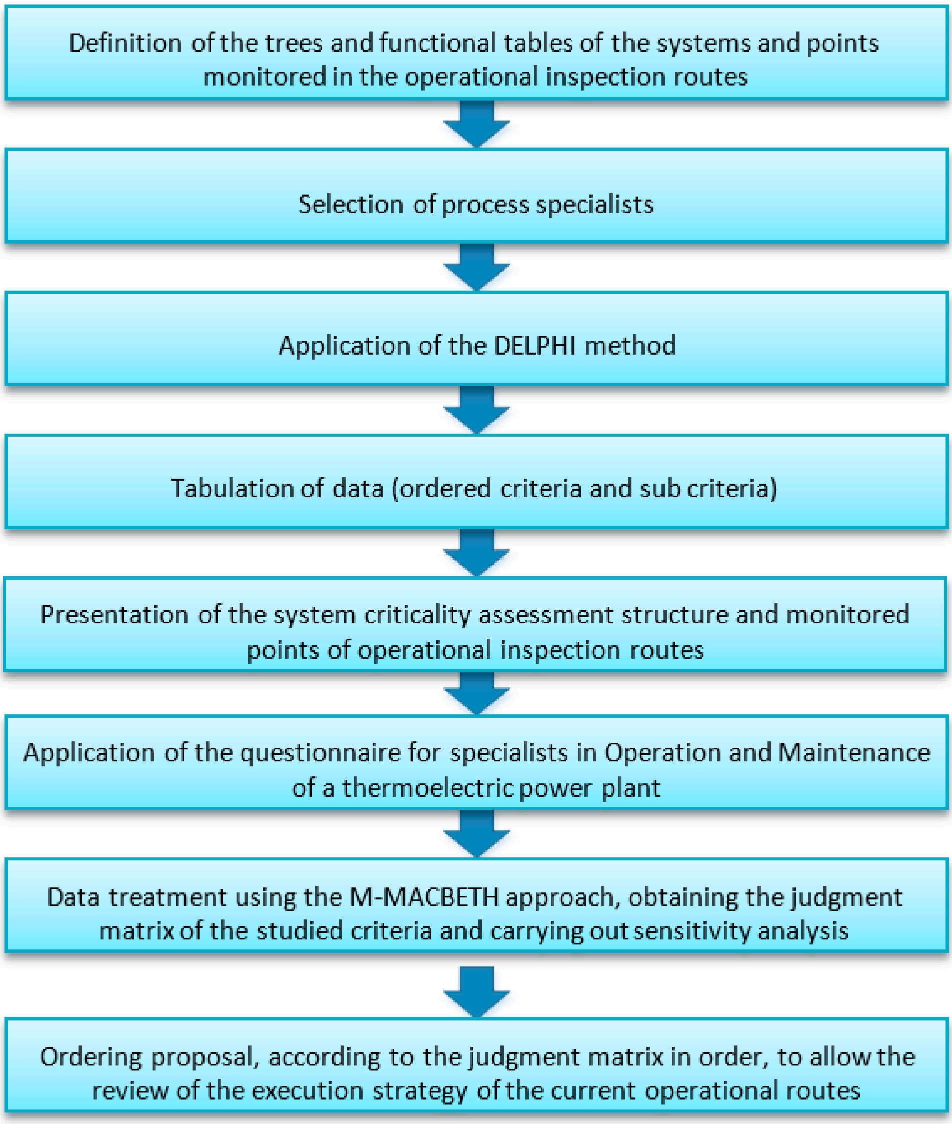

Figure 1. The method development measures. Own authorship.

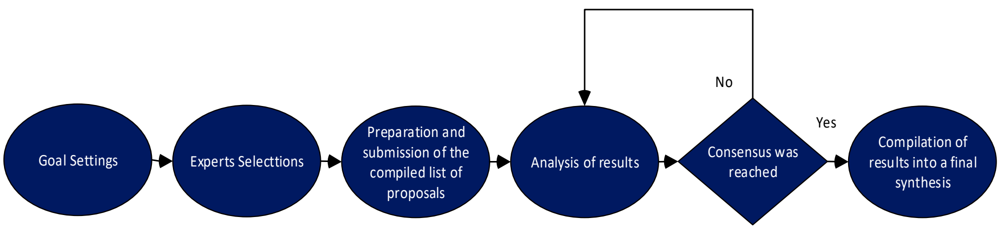

Figure 2. The generic process of a Delphi method. Own authorship.

3. Multicriteria Support to Decision Making

Regarding the multicriteria decision-making procedure, it is vital to comprehend the decision theory underlying the Multiple-Criteria Decision Analysis (MCDA) technique.

Considering the various views as a particular form of evaluation, decision making involving people's daily lives can be quite complex, resulting in a set of choices that may consider numerous opposing standards [28,29].

Multicriteria decision support methods are designed to evaluate increasingly complicated scenarios based on a distinct set of quantitative and qualitative indicators, including physical, financial, input, output, process, and outcome indicators, and can provide analysis support [30].

According to [31], multicriteria decision support approaches are versatile. Due to their ability to work with quantitative and qualitative characteristics, they can be utilised in various fields of knowledge:

1. Structuring: involves describing the issue, identifying the intended goals, and analysing the possibilities and repercussions.
2. Evaluation: develops a decision-making model by evaluating the significance of the stated criteria based on previously gathered data.
3. Recommendation: the application of the model proposed in the previous phase utilises the specified weighting of factors to support the conclusion. Following this, robustness and sensitivity studies are conducted.

The structuring of the model is also the first step in the process because it entails contextualising and identifying the issue, establishing the label, the Elementary Point of View (EPV), orienting the EPV, justifying the area, and developing maps of the relationships between means and ends, clusters, and Fundamental Points of View (FPV) and descriptors [32].

The third step is the model recommendation, which allows for final model consideration and creates resources for developing an action plan to aid in process improvement. The authors highlight in [33,34] that this phase fits as a support measure that aids decision making by enhancing confidence of decision making and aiding the decision maker in understanding the situation.

3.1. Macbeth Approach

Among the several methods utilised in multicriteria methodology for decision support, Macbeth is one of the most significant, since it permits the analysis of possibilities based on various criteria. This method is distinct from the others because it is based on weighted criteria, and the alternatives are qualitatively assessed [35].

In addition, from the authors' perspective, selecting a multicriteria method among those available and applicable to a particular case should be adapted to the issue at hand. Evaluation of the circumstance, decision objects, and accessible data will be crucial.

Choosing a strategy should be based on an assessment of the selected criteria, the kind and accuracy of the data, and the decision maker's thought process and problem-solving skills.

Notable is also the fact that the results can be dissonant or even contradictory as a direct result of having the opportunity to select from various approaches.

In addition, the evaluation should not be complicated, as the observed discrepancies are substantially more related to the diversity of results than conflicts, and specific criteria allowed for confirming the chosen technique.

The implementation of the Macbeth method in the problem of prioritising maintenance service orders in a thermal power plant resulted from the decision maker's acceptance of the method, which meant that they understood the issues brought to them and were confident in their responses.

In addition, up until this point, the requirement to evaluate the data's acceptability, its properties utilised by the approach, and if the result supported the decision-making process was emphasised. Secondary issues, such as M-Macbeth and Hiview, were also observed because they allowed greater integration with the addressed topic. Nonetheless, these writers concur that the multicriteria decision support technique offers multiple ways for it to be applied to various issues.

As per [36], "Macbeth makes use of a procedure that asks decision makers to verbally express the difference in attractiveness between two potential actions a and b (with a more attractive than b)".

Macbeth makes use of a semantic scale of attractiveness differences consisting of seven categories:

(1) C0—No difference in attractiveness (indifference).
(2) C1—Very weak attractiveness difference.
(3) C2—Weak attractiveness difference.
(4) C3—Moderate attractiveness gap.
(5) C4—Strong attractiveness difference.
(6) C5—Very strong attractiveness difference.
(7) C6—Extreme attractiveness difference.

The authors of [37] state that when ordinal scales are transformed into cardinal scales, the value zero corresponds to the neutral level, and the value 100 corresponds to the good level. The degree of variation in attractiveness between the levels above, below, or between the reference levels is determined using paired verification and the software M-Macbeth.

This software checks the trade-off rates, which determine the relative relevance of each model criteria and are also specified by the software's semantic judgement, assisting in achieving the desired outcomes.

When assessing alternatives based on many criteria, it may be difficult for decision makers to give a simple numerical value due to the influence of the criterion. Macbeth is a technique of semantic judgement in which the value functions are gained by evaluating the difference in attractiveness between two courses of action, always in pairs, making it more straightforward for the decision maker to conclude.

To maintain coherence by expanding the number of alternatives and criteria, Silveira [31] developed the M-Macbeth software, a computational tool that supports multicriteria judgments by analysing cardinal coherence in semantics and suggesting, if necessary, how to address it. After evaluating the variations in desirability, the computer constructs an ordinal value scale over the collection of possibilities through interactive means.

In constructivism, the guiding paradigm of the MCDA methodology, the decision-making process occurs through the interaction of the various actors involved in the creation of learning, considering the subjective characteristics of these actors, such as their objectives, values, criteria, culture, aspirations, intuition, and preferences, among others [29].

According to [34], the research objectives are partially descriptive and exploratory.

In this study, a qualitative and quantitative approach was used, as the qualitative characteristic was the participation of a group of specialists from the O&M areas who, through brainstorming, created criteria and subcriteria to prioritise the maintenance service orders, which were later validated and ranked by a larger group of specialists via a survey.

After the qualitative phase, the Macbeth decision support method, which allows the evaluation of options based on multiple criteria, was utilised based on the characterisation of a model of criteria and subcriteria derived from the participation of a larger group of participants from operation and maintenance in Brazil and Portugal, who evaluated the prioritisation of maintenance service orders.

The tool or process of brainstorming combines ideas with the release of imagination to stimulate creativity and innovation by associating ideas to solve a problem.

According to its originator, brainstorming is a conference to generate a list of ideas that seek a solution to a specific problem, which can then be reviewed and implemented [35].

After employing the brainstorming method with six professionals, we hoped to achieve relevance and consistency in the data collection phase. This research adds credibility by implementing a Web-Delphi-based research form with material from Brazilian and Portuguese experts.

The data for this scientific study were analysed and acquired using various methods, including bibliographic research, field observations, documentary research, electronic research, questionnaires, and interviews.

Based on the content of the bibliographies and documentary study of the theoretical references discovered in the problem, a literature review was conducted. A collection of journal papers, master's theses, books, and technical standards supported the study. Interviews were conducted with twenty-five professional experts in the operation and maintenance departments in coordination, management, and engineering roles.

Using the technique of brainstorming, the meeting participants discussed the relevance and application of the topic in the daily problems of routine maintenance work, relating the criteria and subcriteria for an efficient categorisation that is, in the group's opinion, the most relevant for an evaluation of criticality to prioritise the service by maintenance better, considering the effects that a failure can have on safety, the environment, and the process.

Based on the opinions of the O&M participants in Brazil and Portugal, as well as the evaluation and analysis of the responses received in the second cycle, a consensus was also sought regarding the criteria and subcriteria for maintenance work order prioritisation, as well as their respective weights. Thus, it will be feasible to determine the most significant and pertinent criterion and subcriteria for maintenance service order prioritisation.

3.2. Application Phase

The decision-making process in daily life is complicated by the need to consider various viewpoints and assess them depending on the problem's unique structure while addressing a problem. Thus, a set of potential solutions can be considered a collection of competing criteria [18,19].

This line of reasoning [20,21] demonstrates that a multicriteria decision problem is driven by the need to satisfy several frequently conflicting goals before deciding between two alternatives.

According to [6], public and private organisations' decision making relies on human activity, with managers' value judgement playing a vital role. Consequently, it is vital to address how the numerical representation of this value judgement is justified by integrating information technology into human decisions via decision-support techniques and tools.

Multicriteria decision support is a dynamic field of cutting-edge knowledge, and research strives to aid policymakers and negotiators by assisting them in problem-solving, allowing them to broaden their arguments and increase their capacity to learn and comprehend [22].

The goal of the multiple-criteria approach is to aid in complex decision making that demands the simultaneous analysis of numerous criteria and subcriteria, elucidating the relative value of each from the individual or group perspective of the evaluator. Mixed quantitative and qualitative data sets can be dealt with using a reasonable, justifiable, and explicable decision-making procedure [36].

With the criteria and subcriteria properly validated and ordered in the structuring phase and deemed the most important by the experts, a questionnaire was applied using reliability study techniques to define the trees and tables of the monitored systems and points of a thermoelectric power production process.

In addition, sixty-eight expert O&M professionals from plants of the EDP group in Brazil and Portugal participated via Google Forms to achieve a tighter consensus and collective ordering of the criticality of systems and points for evaluating a service order.

The data about the participant's responses were tabulated in Excel, shown in Table 1, from the model developed in the study, adapted by the author from [10], to generate input for the multicriteria model to perform the calculations of criteria and global evaluations, with sensitivity and robustness analysis.

The research data were analysed using the M-Macbeth method, which permits the quantitative transformation of qualitative judgments. The analysis will serve as a basis for configuring the M-Macbeth software to elaborate and apply the judgment matrix of the criteria studied.

With the criteria and subcriteria having been appropriately validated and deemed the most important and relevant by the specialists, a Web-Delphi questionnaire was applied, with the participation of approximately sixty-eight professionals from the Operation and Maintenance area of the Business with Units in the energy generation area of the EDP group in Brazil and Portugal.

Table 1. M-Macbeth scores. Source: own authorship.

Options	Global	Generation Impact	Redundancy Equipment	Occupation Safety	Environment	Cost Repair	MTTR	SLA—Attendance
All Upper	4	4	4	4	4	4	4	4
OSO9	3.09	4	3	4	1	3	4	3
OSO2	2.67	4	1	4	1	3	1	3
OSO3	2.59	4	3	3	1	3	1	3
OSO16	2.49	1	1	4	1	4	4	3
OSO8	2.49	4	3	4	1	3	4	3
OS10	2.44	4	3	1	1	3	4	3
OS1	2.43	3	3	1	1	4	4	3
OS13	2.11	1	1	4	1	3	1	3
OS6	1.93	1	1	4	1	1	1	3
OS20	1.91	4	3	1	1	1	1	3
OS18	1.86	4	2	1	1	1	1	3
OS7	1.67	3	1	1	1	1	1	3
OS4	1.63	1	3	1	1	3	1	3
OS12	1.46	1	1	3	1	1	1	1
OS15	1.37	1	1	1	1	1	1	3
OS5	1.34	1	3	1	1	1	1	2
OS19	1.31	1	1	1	1	1	1	3
OS14	1.29	1	1	1	1	1	1	3
OS11	1.2	1	3	1	1	1	1	1
OS17	1.09	1	1	1	1	1	1	1
All Lower	1	1	1	1	1	1	1	1
Weights:		0.1714	0.0571	0.2	0.2	0.1143	0.0857	0.1429

The form of the questionnaire model was structured as shown in the steps below:

1. Characterisation of the risks to people and the environment.
2. Characterisation of the risks to the process and consequent unavailability.
3. Generation of unavailability costs.
4. Maintenance costs.

According to an analysis by [37], the main difference between Macbeth and other multicriteria approaches is that it needs qualitative judgments about the differences in affinity between elements to calculate scores and weight the possibilities for each criterion.

Twenty-four questions were addressed in the questionnaire, and the interviewee had to select one of the options provided to provide an evaluation. These possibilities relate to their weights based on the categories of the ordinal semantic scale used by the Macbeth model.

The questionnaire findings were analysed using the Macbeth method, which permits the transformation of qualitative judgments into quantitative ones. The analyses served as the basis for parameterising the M-Macbeth software to generate the judgement matrix for each researched criterion and subcriterion.

The availability and dependability of equipment in a thermoelectric power plant is an essential success factor for organisations attempting to meet the contractual obligations outlined in energy auctions. In this context, maintenance is the process of performing the necessary actions to maintain or restore equipment or a system to a state in which it can perform the function for which it was designed, thereby reducing the failures that render equipment unavailable and allowing the generation process to continue without interruption or reduction in output.

A thermoelectric power plant's maintenance is crucial for maximising uptime and minimising breakdowns. In this sense, in addition to performing equipment maintenance, it is the maintainer's responsibility to develop proactive actions to ensure maintenance performance based on methods, techniques, and preventive plans derived from the planning and engineering processes to apply all the resources and tools that enable the continuous improvement of maintenance routines.

The backlog of maintenance service orders must be prioritised according to the criticality order of the systems, subsystems, and defects detected by the operation that comprises the backlog. This information must be known by those involved in the performance of maintenance.

Faced with the complexity of maintenance's definition, the risk factor that should be prioritised to evaluate the degree of impact and relevance to service these orders is the introduction of a multicriteria framework to support the decision. It is important to note that the risk factor (RF) examines the implications under various criteria, considering many different characteristics.

3.3. Model Building

Decision analysis is a systematic method for reasoning about complex problems and making wise decisions [38,39]. As can be seen, the process begins with identifying the decision context and understanding its objectives. These goals should be [40]:

a. Essential, considering the motivations and concerns of the decision problem.
b. Understandable, with unambiguous meaning.
c. Operational, allowing quantification and evaluation of performance.
d. Concise, considering as few goals as possible.
e. Preferably independent, meaning that the performance evaluation in one objective does not depend on the evaluations in the other.

To build the evaluation model, Bana e Costa [41] emphasised the following steps:

(a) Defining the problem label.
(b) Identification of the actors involved in the evaluation process.
(c) Identification of the evaluation elements (criteria).
(d) Building the value tree.
(e) Construction of the descriptors.
(f) Construction of value functions.
(g) Determination of replacement rates (weights).

3.4. Label Definition

The purpose of this study can be attained by determining the primary and secondary criteria for ranking the criticality of systems on the operational inspection routes of thermal power plants from the perspective of operation and maintenance specialists.

3.4.1. Identification of the Actors

In constructing the model, some actors participate directly or indirectly in the decision-making process, which can be divided into two categories: actors and interveners. The actors are not directly involved in the decision-making process but will be affected by the decision and can exert pressure on the intervening party. Interveners consist of three types of actors:

(a) Decision makers—have the power to make decisions.
(b) Representatives—represent the decision makers by designation.
(c) Facilitators—the expert who leads the decision or assessment process.

Given the above, to establish the most suitable model for the study, the following actors were considered:

(a) Agents: These are the plant's maintainers, responsible for maintenance and inspection activities.
(b) Decision makers: These are specialists in O&M of thermal power plants who have technical knowledge about the criticality and impacts of failures in the plant's systems and subsystems and participated in the construction of the model.
(c) Facilitator: Author of the dissertation.

3.4.2. Identification of the Evaluation Elements: Evaluation Criteria

The basis for the evaluation process is supported by a set of steps to identify the evaluation elements:

(a) Identification of the EPV.
(b) Construction of cognitive Maps.
(c) Identification of the FPV.

According to [41], the identification of the EPV is necessary for the subsequent construction of the cognitive map so that the FPV can be identified.

The steps of EPV identification and cognitive mapping were performed by applying the Web-Delphi tool with the experts who work in O&M of coal-fired power plants, as detailed in the following:

FPV 1—Operational aspects;
FPV 2—Safety and environment;
FPV 3—Maintenance.

After the definition of the FPVs, the due decompositions were performed, creating the EPV, the basic structure of the multicriteria evaluation model [38]. Notably, the stakeholders validated the decomposition of the FPVs (criteria) and the EPVs (subcriteria) in the Web-Delphi survey:

FPV 1—Operational aspects

EPV 1.1—Operational availability.
EPV 1.2—Equipment redundancy.

FPV 2—Health, safety, and environment.

EPV 2.1—Occupational safety impact.
EPV 2.2—Environmental impact.

FPV 3—Maintenance.

EPV 3.1—Average repair costs.
EPV 3.2—Mean time to repair (MTTR).
EPV 3.3—The service of the maintenance team within a deadline (SLA).

3.4.3. Building the Value Tree

With the definition of the basic structure of the evaluation model, the value tree was created, consisting of the elements indicated below, duly represented in Figure 3.

(a) A strategic goal (green colour).
(b) Three FPVs or criteria (orange colour).
(c) Seven EPVs or subcriteria (gray colour).

Figure 3 presents a Macbeth tree built for the research's multicriteria model object. The nodes below the initial node (global) correspond to the point of view that experts considered most relevant to ordering the criticality of systems, subsystems, and monitored points.

3.4.4. Descriptors

After defining the FPVs (three) and EPVs (seven), to measure potential actions, it is necessary to construct a criterion [41,42]. The criterion consists of two tools: a descriptor and a value function.

The descriptors promote understanding of what will be measured, and the value function shows information related to the difference in attractiveness between the NI of the descriptors.

A descriptor corresponds to a set of NI, reporting the performance of potential operations for each FPV [31]. In this study, four NI were used, one for each descriptor.

In descending order, the level of impact was ranked by preference: the most attractive ones correspond to the best-performing actions, and the least attractive ones correspond to the worst-performing actions.

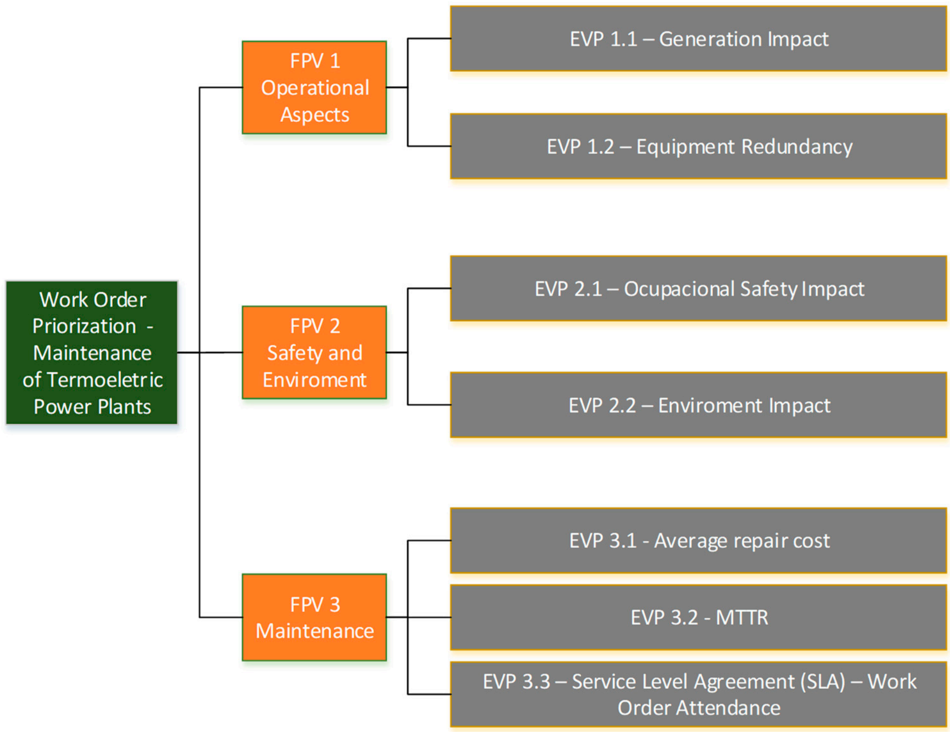

Figure 3. Value tree of the multicriteria evaluation model. Source: own authorship.

In the present study, each possible state of the descriptor was associated with an impact level Nj, where j corresponds to the descending order of the decision maker's preference, i.e.,:

1. N4—Impact level with the highest attractiveness (upper limit).
2. N3—Impact level with immediately lower attractiveness.
3. N1—Impact level with the lowest level of attractiveness (lower limit).

3.4.5. Value Functions (VF)

According to [38], semantic judgement is the most suitable method for developing a value function, since it can assist decision makers in determining their preferences when evaluating various actions from a particular perspective. In this context, utilising a Categorical Base Evaluation Technique to measure attractiveness is appropriate.

Moreover, according to [43,44], a semantic matrix containing the differences in attractiveness is constructed based on the semantic categories, and decision makers must select one of the categories included in the ordinal scale used by Macbeth based on the pairwise comparison of the NI of the same descriptor.

According to [31], alternatives are always compared in pairs by qualitatively evaluating the difference in attractiveness between them and selecting one of the Macbeth categories or several hesitations or divergence categories. When the evaluator submits qualitative evaluations and inputs, the software automatically verifies their consistency and suggests their elimination if inconsistencies are detected.

For a matrix of judgments to be consistent, it must be possible to deduce from them scores such that the following take place:

1. Equally attractive options obtain the same score;
2. A more attractive option obtains a higher score;
3. Suppose the difference in attractiveness between two options (e.g., strong) is more significant than the difference in attractiveness between the other two options (e.g., medium). In that case, the option should be scored so that the difference between

the scores of the two options is that the first two scores are more remarkable than the other two (ordinal consistency conditions).

According to [38], the value function and attribute consistency must be determined. Otherwise, if a discrepancy exists in the system of linear equations, the programme will suggest that it needs to be corrected.

In addition, the consistency of the judgement is automatically evaluated during the weight determination process, as it is during the definition of the value functions. The M-Macbeth software provides various solutions when judgments are conflicting. Ultimately, the decision maker must review and validate the derived weights to ensure they reflect their perspective.

4. Results

The case study illustrates the use of decision analysis to maintain service orders, which reflect genuine issues identified by the operations team and entered into the management system. These events should be attended to and addressed by the maintenance staff. These service orders for the systems and subsystems of a thermal plant must be analysed using objective criteria developed from the O&M team's learned knowledge to maximise resources and increase maintenance team efficiency.

In this context, it is necessary to prioritise and select activities based on their significance to the process and the potential impact of a failure on the generation to establish service strategies so that the planning instructs the maintenance execution team to perform these activities in the order in which they were prioritised.

The study was organised along three axes, denoted by the acronym FPV. In addition, to improve measurement accuracy, each axis was subdivided into three EPVs, for a total of seven, based on the multicriteria assessment model created for this research. A simple additive value model was used to evaluate each intervention option.

This model measures each possible intervention option of overall attractiveness/benefits for later selection. Equation (1) defines the simple additive value model.

$$V(a) = \sum_{i=1}^{n} \lambda_i v_i(a), \quad (1)$$

where

V(a)—is the global score of option a;
λ_i—is the weight of criterion i;
v_i (a)—is the partial score of option and in criterion i.

The value functions and weights corresponding to the $v_i(a)$ and variables were constructed and determined using the Macbeth method. In Equation (1), an application of a result value function is shown. Impacts on power production were defined as the performance descriptor of the criteria about the effect of a load curtailment failure or shutdown of producing units and failing to satisfy contractual obligations (availability contract). More considerable influence was put on power generation, incurring contractual penalties owing to poor availability, a more critical requirement for reliability-focused maintenance procedures to predict failures, and as a result, a higher priority for monitoring and attractiveness.

According to [44,45], using the Macbeth approach, it is possible to define VFs that measure the attractiveness of each performance level. These numerical functions result from qualitative judgments about the differences in attractiveness reported by the decision maker.

During this process, the M- Macbeth software automatically checks the consistency of the judgment, noting any inconsistencies detected and suggesting ways to resolve them. Once the judgment matrix is filled in, M- Macbeth can create the VFs.

Due to their knowledge, experience, and average time working at a power plant thermoelectric plant (eight years on average), the O&M specialists among engineers and specialised technicians who worked on structuring the model helped overcome the first barrier of the research, which was the ordering of the performance levels and the definition of the value functions that are the semantic judgment made by decision makers to determine their preferences in the process of evaluating potential actions from a given perspective, from the pairwise comparison of the impact levels of the same descriptor. This task depends on human activity, where the value judgments of those involved play a fundamental role and the contribution of the professionals interested in the validation of the weights were obtained to ensure they reflect the opinion of the ten specialists. The survey involving other professionals from Brazil and Portugal ratified the results, resulting in a list of criteria and subcriteria ordered and weighted as to the degree of impact.

Table 1 shows the M-Macbeth window with the results obtained by applying the multicriteria model to prioritise the service orders of the central systems and subsystems of the power plant thermoelectric plant as the sample. The results show that considering the twenty-five O&M specialists (decision makers) that participated in the research and answered the questionnaire, in the order of priority for maintenance service orders, according to the model, the most engaging activities are according to the decreasing order of prioritisation. The failure indicated by OSO9, "11HNC11AN001—check electrical actuator of fan ID B", corresponds to a case where there is a high impact on a failure event in the following:

(a) Generation impact.
(b) Occupation safety.
(c) Medium time to repair.

Consequently, the suggested monitoring order corresponds to what the decision maker believes should be performed to maintain the reliability of the plant. As can be seen, the approach taken in this study incorporated the decision maker's objectives and identified which subsystems and monitored points are most attractive. Each subsystem or monitored point's unique (global) cumulative benefit may be assessed thanks to the assessment method.

Figure 4 illustrates how the methodology evaluates each monitored subsystem or point's individual cumulative (global) benefit. Following the global score value on both axes, the less time until (OS17) and the greater the work order priority (OS9) for maintenance attendance are based on the OS17 and OS9 values, respectively.

We emphasise the sensitivity and robustness analysis, an M-Macbeth supported technique, as the key impediment in constructing and deploying the multicriteria model. Moreover, this allows us to assess how much the model's suggestions vary when the weight of criteria is tweaked.

Simultaneously, the proportionality connections between the other weights are maintained to establish what possible inferences may be taken from the model when local and global data are modified.

The model's uncertainties were developed using a collaborative effort to evaluate how well the model functions. A 5% uncertainty level was considered for the criteria occupational safety impact, impact on power generation, environmental impact, and asset impact, whereas a 2% uncertainty level was considered for the remaining criteria.

Discussion

Experts in thermal power plant operation and maintenance participated crucially through research methodologies, brainstorming, and Web-Delphi. They contributed positively to identifying the criteria and subcriteria, allowing the development of the value tree through a multicriteria model, evaluating the criticality, and defining the ordering of the systems, subsystems, and monitored points.

With the funds generated by the research, it will be feasible to apply well-grounded human-agent strategies and to direct the specific expectations of the operation and maintenance team, creating the circumstances for substantial benefits.

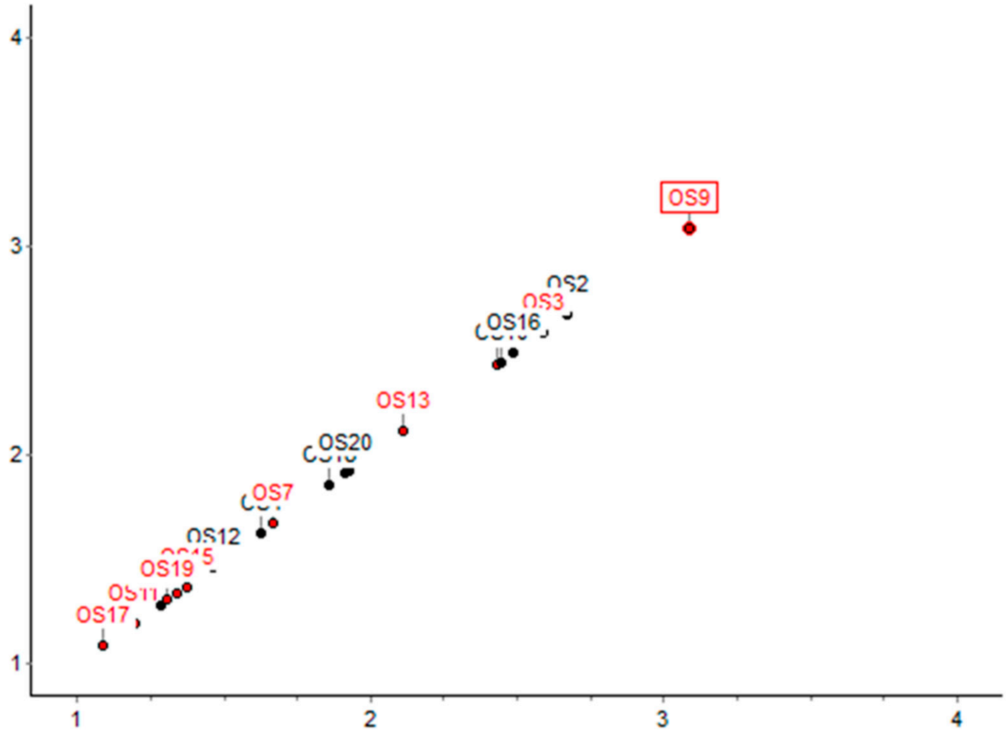

Figure 4. M-Macbeth with the findings of the review of the prioritising service orders. Source: own authorship.

The study was restricted to ranking service requests according to their importance. Because they are typical installations for thermoelectric plants that are a component of the thermodynamic Rankine power cycle and because they all represent a substantial decrease in the assessment proposal, the core systems of the equipment in the designs were utilised as an example.

The weight sensitivity analysis evaluates potential changes to the global ranking of proposals if, for example, the relative weights of individual criteria (or subcriteria) are changed while the proportional weights remain unchanged.

The sensitivity analysis was considered separately for four service orders (OS-9, OS21, 0S3, and OS16) that, in the opinion of experts, have greater excellent global attractiveness in terms of the criteria of impact on workplace safety, impact on energy production, impact on the environment, and on-time maintenance team service, which is given more weight.

After the procedure, a sensitivity analysis was conducted to examine the model's sensitivity to weight changes and the effects of these alterations. Using the M-Macbeth software, the sensitivity analysis was conducted interactively. Despite the study, the decision maker determined that no modifications were necessary.

Applying well-founded human-agent strategies and directing the clear expectations of the operation and maintenance teams will be possible with the money raised by the study, setting up the conditions for significant gains.

Other computational results in applying the Macbeth method can be applied to developing a multiple-criteria model to support decision making in ordering the criticality of systems in operational inspection routes of thermal power plants [46,47].

In addition, in [48,49], the findings of the judgement matrix and the ordering suggestion enabled a strategy for the execution of the present operational routes by redefining criticality, periodicity, routing, and resource application, hence preserving the plant's dependability.

This is limited to evaluating the criticality of the boiler system's subsystems and monitored points. These represent thermoelectric plants categorised under the Rankine thermodynamic cycle and constitute a substantial portion of the assessment proposal.

5. Conclusions

This study was conducted to demonstrate the application of a multicriteria model approach employing the Macbeth method and the computational tool M-Macbeth for efficiently prioritising the maintenance service orders for the service by maintenance of these service orders of the thermal power plant, which is a multiple-choice decision problem. A structured strategy should view the many decision-making criteria as a complex problem [50].

Maintenance activities in thermal power plants are crucial for ensuring a low failure rate and high availability of a generating unit within regulatory-agency-established limits. Executing these activities within a Planned Proactive Maintenance Program structured in a manner that begins with the detective inspection of the operation team will generate positive impacts, such as high operational reliability of systems and equipment, lower maintenance costs, and shorter repair times.

The maintenance planning method might be changed so that it now considers the risk element, thanks to the suggested ranking. This is because, as the Macbeth assessment matrix demonstrates, it was validated that the weights and criteria are adequate for their intended use, which is already increasing the plant's dependability.

As a result of the research findings, it was possible to use well-grounded management practises and direct the maintenance staff to the service orders that the model indicated had the highest priority, resulting in higher maintenance productivity and effectiveness.

Compared to other studies, the significant addition of this research is the application of the technique to a collection of service orders currently in the backlog of maintenance at a thermoelectric power plant instead of merely to a part of the system or subsystem.

It is suggested that more research needs to be conducted on the other systems and subsystems of an average thermal power plant and the creation of specialised management tools in this field. In thermal plant operational inspection, other approaches for ranking the criticality of systems include many criteria [51,52]. The study's most pressing problems include incorporating artificial intelligence and machine learning principles to gather requirements, making dynamic determinations of criteria and subcriteria, and integrating the model with integrable systems [53].

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