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# A novel methodology employed for ranking and consolidating performance indicators in holding companies with multiple power plants based on multi-criteria decision-making method

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ABSTRACT

A large international energy corporation owning power operations in several countries, including several generation plants as well as transmission and distribution units in Brazil's energy matrix, adopts for quite some time now the policy that performance monitoring should be left to each individual operation's management. This decentralized approach is viewed as undoubtedly having a number of managerial advantages, so much, so that it is currently in force and performance indicators are being established locally. This approach, however, has the basic disadvantage that quantitative comparisons are hard to make between operations, i.e., adequate tactical comparative assessment at corporate level, with immediate and potential unfavorable implications. Therefore, the present work undertakes to investigate the possibility of consolidating a comprehensive set of indicators capable of accommodating more possibilities of comparison between different power generation plants. The research also employs an effective ranking method in order to take as much managerial advantage as possible of the new body of identified indicators. An application example involving a set of selected indicators is presented.

## 1. Introduction

Due to the elevated costs incurred, effective asset maintenance in modern engineering systems such as large power generation plants involving the performance of highly expensive components, sensitive environmental requirements, as well as a number of other social and economic issues, including the increasing competition from new low-cost generation sources, constitute a major concern among interested parties. Particularly, chief executive officer considering the interests of shareholders, in every industry and country nowadays. This is certainly even more critical when one considers the challenges faced by large international groups with operations scattered over several different countries. For such large holding companies, therefore, being able to assess comparatively business units' performances at corporate level should be a prime and permanent point in the tactical agenda with a view to attaining strategically sustained success.

Due to the increasing realization of the importance of modern maintenance for keeping companies' operational costs within acceptable levels, the relevance and importance of effectiveness evaluation in maintenance activities is nowadays formally acknowledged by international documents, for instance [1,2], in addition to the works carried out by several authors such as [3–6]. Despite all that, however, there is also still a perception that adequate effectiveness evaluation is never a trivial task. As an example [7], expresses the opinion that 'performance measurement is failing organizations all around the world, whether they are multinationals, government departments, or non-profit agencies'.

When confronted with evaluations, managers must face at least one and frequently more than one difficult question. Often, they are led to argue about the applicability of the adopted criteria, particularly about the impact of results' disclosure on the opinion of certification organizations and regulatory agencies. It is also plausible to expect that they may wonder about the influence of evaluation results on clients' perception, and on peoples' motivation. It is even possible that they will question the fairness of their choices when the results of evaluations may have a bearing on the future of individuals such as employees and

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advisors, or companies such as suppliers and partners. Most often, however, they simply may not be confident enough about the adequacy of their evaluation methods and practices.

When the performance of several similar units belonging to one holding company must be evaluated, there is an almost natural tendency to perform such evaluations on an individual basis as if such units were independent business operations. This decentralized type of control is certainly considered a sound managerial approach by a number of business schools and will be found in many instances throughout the business world. When it comes to dealing with performance evaluation, however, although simpler and easier to carry out this approach has the basic disadvantage that quantitative comparisons are hard to be made between operations. As a consequence, the cross assessment of asset management results with a view to integrating efforts aimed at optimization and reduction of costs is generally not considered, at least not regularly performed. A less immediate but certainly potential repercussion is the fact that judgments when such comparisons become necessary on a higher business level, for instance when considering the updating of the portfolio by means of acquisitions, mergers, etc., may end up being made on a rather qualitative basis.

When considering a set of indicators for a single business operation it is not uncommon for both researchers and practitioners to have recourse to a list of the so-called world-class indicators as can be seen in the following literature review. In the present research, however, it was considered that such lists could be somewhat expanded in order to accommodate more possibilities of comparison between different power generation plants.

The objective of establishing any set of indicators is to provide management with a sound basis for business control. The authors therefore realized that in addition to the consolidation work initially envisaged, it would be advantageous to incorporate an effective ranking method in order to take as much managerial advantage as possible of the new proposed body of indicators. Therefore, as a contribution, this work presents an approach to consolidating standardized indicators for different business units, or even different companies in a group, after evaluation supported by a prioritization analysis.

In this paper, the authors question the more usual approach of assessing the maintenance performance of individual business operations even in the context of holding companies with multiple similar operations. Accordingly, this study employs a novel methodology that ranks and consolidates various maintenance performance indicators, thus allowing not only individual operation control but also adequate performance benchmark between different company power plants.

Finally yet importantly, this work intends to provide means of aligning energy dispatch requirements with the company's overall strategic objectives. Thus, despite the fact that there may already exist adequate indicators in use, it is convenient to derive common indicators and lead different units to adopt a corporative configuration with a set of consolidated indicators [8].

## 2. Literature review

### *2.1. Maintenance performance: the role of KPIs*

The idea of unifying maintenance performance indicators in the power generation industry has been with us for quite some time now, as shown by [9] who asserted that optimization of the maintenance strategy, enhancement of the maintenance efficiency and monitoring the performance are becoming the key attributes to ensure the survival of utilities in the energy market. Therefore, the need to collect relevant experience and suggest a consolidated system of performance indicators to measure the maintenance effectiveness was recognized by the Institute for Energy EC-JRC and research conducted aimed to suggest such a system.

Another author [10] brought up an essential point when handling KPIs, which is performance indicators are not defined in isolation; they should be the result of a very careful analysis of the interaction between the maintenance function with other organizational functions, and more importantly with the production function. They developed a conceptual framework that provides guidelines to select maintenance performance indicators, aligning maintenance goals with manufacturing strategy and corporate goals. This alignment among maintenance objectives with manufacturing and corporate objectives directed maintenance efforts towards its required performance and achieved better continuous improvement of the production equipment.

In other study [11] authors made a KPI assessment for planning and organizing delivery processes of industrial services. According to this study, KPIs need to fulfil some fundamental requirements: reflect and operationalize the overall objectives of the organization; be clearly defined and quantitatively measurable; be precise and not prone to manipulation; and be the cause of conscious decision. Based on such requirements a set of KPIs were implemented in their organization, helping both management and planning to identify the root causes for problems or inefficiencies.

An additional research [12] set out to provide an overview of research and development in the measurement of maintenance performance. Their focus was to determine how value could be created for organizations by measuring maintenance performance, examining such maintenance strategies as condition-based maintenance, reliability-centered maintenance, e-maintenance, etc. In other words, how to find frameworks or models that can be used to evaluate different maintenance strategies and determine the value of these frameworks for an organization. They concluded that, so far, the literature shows no attempts to create a framework or model linking two different maintenance strategies and comparing their effectiveness and efficiency. Nor has any attempt been made to link MPM frameworks with particular maintenance strategies such as the ones previously mentioned.

A further study [13] presented a critical analysis on how companies practicing world-class manufacturing have to modify their ways of measuring performance in their effort to reach manufacturing excellence. In other words, they purported that in order to achieve manufacturing excellence a manufacturing company must modify the methods of measuring and monitoring its performance. Accordingly, the paper proposed 15 measures of manufacturing performance that could be used as key performance indicators, contending that such measures are mostly process-oriented, emphasize non-financial performance, and incorporate the properties of effectiveness, efficiency, and adaptability.

Beginning with the statement that declining revenues and increasing regulatory obligations require hydro operators to focus on cost performance [14], stated to go on to say that benchmarking hydroelectric power plants is a valuable method to provide insights in O&M cost performance and that there are multiple benefits for hydropower operators when participating in an external benchmarking. Then, purporting that The O&M cost comparability of different hydropower plants was ensured by comprehensive cost driver analyses, they advance a methodology where Quantification of influence is done systematically for all KIPs and all cost types.

Authors [5] undertook in this study to identify relevant KPIs within the disciplines of both Manufacturing Planning and Control (MP&C) and Maintenance Management, with the objective of integrating them in order to avoid leaving out maintenance for strategic decisions in the organization. The resulting increased maintenance backlog due to unplanned maintenance activities, sub-optimal prioritizing of activities and unnecessary production downtime. The result was the improvement of the coordination between the Maintenance Management and MP&C activities with a view to reducing in the long run maintenance backlog level.

Purporting that establishing a useful set of maintenance KPIs depends on a company's maintenance objectives and is highly related to specific business contexts, strategies, processes, and systems, [22] present in their paper a new approach to selecting relevant maintenance

KPIs using a methodology based on the original ELECTRE I, which is a multi-criteria decision making method involving decision maker's preference information. According to the authors, the proposed methodology makes the decision process more explicit, rational, and efficient.

Asserting that maintenance is becoming increasingly important due to the new paradigms of production such as Lean Manufacturing, having a high impact on product quality and productivity and therefore on production costs and customer satisfaction [15], carried out a study aimed at identifying and analyzing the use of maintenance performance indicators adopted by companies of the industrial hub of Manaus in Brazil. Results showed that the use of performance indicators in the maintenance area is relatively low and is dependent on factors such as quantity of physical assets, maintenance staff size, adoption of total productive maintenance (TPM), and utilization of computerized maintenance management systems (CMMS). It was also found that the origin, whether local or international, influences the use and release of performance indicators by organizations.

According to [16] Maintenance Management is a crucial activity for improving efficiency in a facility. Within this process, maintenance work orders (MWOs) are used when tracking and solving any maintenance–related issues. However, actual information gathering procedures are often laden with inconsistencies or inaccuracies in the data. Accordingly, the paper describes a selection of KPIs that can be calculated using these MWO data elements, i.e., how the MWO elements can be assembled into indicators used for decision making and what decisions can be made with that type of KPI.

Since the pulp and paper industry is one of the five most energy-intensive industries world-wide [17], presented a study of the current level of implementation and operationalization of energy-related KPIs within this industry in Sweden. They outlined a unique methodological approach for evaluating the best practice levels of energy KPIs that is also potentially suitable for application in other industrial sectors. Existing drivers for and barriers to the development and implementation of energy KPIs are investigated, as well as the status of revising and monitoring energy KPIs. They concluded by saying that there is still vast potential for improvement.

A new methodology was proposed by [18] for the identification and selection of KPIs that identifies those technologies with a larger potential of insertion into the European Union (EU) energy matrix. The final list provided with 45 KPIs is used to assess the cost-benefit relation between projects that are related to smart grid development in isolated energy systems, providing the relevant stakeholders with a useful comparison among the proposed solutions. The selected performance indicators can be consolidated to provide higher-level results that can assess the overall performance of the solution, including even its general impact on society.

Considering that O&M performance is a critical issue, especially in developing countries and emerging economies [19], proposes an extensive 8 step procedure for preparing and implementing an O&M strategy where both the diagnosis is anchored in the evaluation of key performance indicators in step 1, and the overall performance will be monitored through key performance indicators (KPIs) in step 8. Besides, the final O&M strategy will include a clear definition of objectives based on KPIs. In addition, recommendations for benchmarking with other organizations are also included.

In line with the research on cost analysis of hydropower, options at non-powered dams carried out by the Oak Ridge National Laboratory for the US Department of Energy [20,21] stress the point that hydropower plants are one of the most convenient options for power generation. It goes on to state that the recent advances in Information and Communication Technologies (ICT) and in machine learning methodologies are seen as fundamental enablers to upgrade and modernize the current operation of most hydropower plants in terms of condition monitoring, early diagnostics, and eventually predictive maintenance. They also point out that very few works, or running technologies, have been documented so far for the hydro case and propose a novel Key Performance Indicator (KPI) recently developed and tested on operating hydropower plants. They conclude that in order to support the operation and maintenance tasks of plant operators the proposed KPI outperforms conventional multivariable process control charts.

### 2.2. Hierarchical Ranking of KPIs

Purporting that establishing a useful set of maintenance KPIs depends on a company's maintenance objectives and is highly related to specific business contexts, strategies, processes, and systems [22] present in their paper a new approach to selecting relevant maintenance KPIs. They use a methodology based on the original ELECTRE I, which is a multi-criteria decision-making method involving decision maker's preference information. According to the authors, the proposed methodology makes the decision process more explicit, rational, and efficient.

Authors [23] add that in order to prioritize KPIs by its importance this paper has presented an analytical hierarchy process (AHP) to simplify the decision-making process that includes qualitative and quantitative techniques and creates the possibility to decompose complicated problems into sub problems, simplifying the comparison of alternatives. Based on this method three KPIs were chosen as top ones out of thirteen KPIs selected initially. All thirteen metrics are important for the company to achieve its goals, but these three ones are more important and should have a closer follow up.

The Best-Worst method (BWM) represents a powerful tool for defining the criteria weighting coefficients, using proportions of the relative importance of the criteria in pairs based on the evaluation made by the decision makers. This method is strongly characterized by its flexibility and ease of application, which is expressed through the possibility of realistic processing of experts' preferences. At the same time, it offers the possibility of checking the consistency of the pairwise comparisons provided to ensure the rationality of the assessments, finding an optimal solution to determine the criteria weights in the decision-making process [24–27].

This method has been used in a variety of real-world problems such as power systems, supply chain management, transportation, manufacturing, education, investments, airline, healthcare, banking, technology, etc. The Best-Worst method performs significantly better compared to other existing MCDM methods because: (1) it requires less comparison data and (2) it results in reliable values because it presents a consistency ratio to verify the reliability of the pairwise comparisons [24,26,28]. Based on the exposed reviews, the authors believed that, the use of the BWM would bring much better results in the decision method, since it takes the knowledge from maintainers in the power plant into the process, in order the have more accurate data to make their decision.

### 2.3. Individual versus consolidated KPIs

Considering the previous reviewed literature, Table 1 was drawn up listing cited papers opposite to their content as far as the scopes of KPIs are concerned, i.e., KPIs addressing individual operations versus corporate assessments.

It should be remarked that the World Bank in their above cited work, regarding different utility companies, suggest that 'it is imperative that the comparisons are made with similar utilities/plants and that the data are collected and analyzed in a similar fashion'. The also cited work of [14] in a similar way stresses the convenience of external benchmarking.

However, as can be seen in Table 1, there is certainly a gap in recent literature concerning the need to provide KPIs that could be used as internal corporate sources of benchmarking between operations or business units within the same holding group. Besides, studies aiming at internal corporate comparisons could not be found referring specifically to maintenance KPIs.

The above review led the authors to the conviction that, so far as

**Table 1**
KPI scopes in recent literature.

| Refs. | Industry | Consolidated Corporate KPI |
|---|---|---|
| Andersson and Thollander [17] | Paper production | No |
| Betti et al. [21] | Hydropower | No |
| Brundage et al. [16] | Manufacturing | No |
| Contri and Kuzmina [9] | Nuclear Power | No |
| Darestani et al. [3] | Manufacturing | No |
| Darestani et al. [38] | Recycling | No |
| Kumar et al. [12] | Manufacturing | No |
| Lindberg et al. [6] | Thermopower | No |
| Meier et al. [11] | Industrial services | No |
| Oliveira et al. [15] | Manufacturing | No |
| Muchiri et al. [10] | Manufacturing | No |
| Parmenter [7] | General application | No |
| Rodseth et al. [5] | Manufacturing | No |
| Sukarma and Azmi [13] | Manufacturing | No |

large corporations with several business units are concerned, there was not only a need for consolidating a comprehensive set of indicators capable of accommodating more possibilities of comparison between different power generation plants, but that this should be done employing an effective ranking method in order to take as much managerial advantage as possible of the new body of identified indicators.

Accordingly, this paper presents a new approach to selecting relevant maintenance corporative KPIs using a methodology that includes the application of an effective ranking method. Initially the methodology requires the definition of the most suitable KPIs to measure performance according to a company's maintenance objectives The proposed methodology, which involves decision maker's preference information, determines a ranking of most suitable indicators according to important criteria. To validate the methodology, an actual case study is presented employing the Best-Worst multi-criteria ranking method, which had already been successfully used by the authors in other applications.

## 3. Asset management and maintenance performance

Although a competent physical asset management (PAM) has always been of the essence for competitiveness and profit in any industry, with authors such as [29] sustaining the idea that it should be part of strategic management, in actual practice this fact has very often been overlooked by managers until quite recently. Hopefully not anymore after the appearance of the ISO 55000 [30] standard series where it is clearly asserted that a world-class asset management system is instrumental in building long-term resilience, achieving financial goals, and meeting regulatory requirements. Besides, it helps organizations to better formulate maintenance strategies, more precisely plan and carry out the upgrading, expansion or even replacement of existing infrastructure, determine capital investment, and allocate budgets. In other words, this standard series came to add value by providing managers with an agile framework to help connect asset management with the achievement of the respective organizational goals by incorporating the asset management system into core business processes [1].

In order to optimize the effectiveness of the asset management system, standard ISO 55001 [31] prescribes that the most appropriate methods of monitoring, measurement, and analysis should be identified, and that in addition to the need of evaluating and reporting on the effectiveness of processes for managing risks and opportunities, performance indicators should be developed to measure the effectiveness of the system. These measurements could be quantitative, qualitative, financial, or non-financial.

Considering the efficiency and effectiveness of asset management, Maintenance unquestionably stands out as one aspect of paramount importance. On the other hand, maintenance performance will be the result of those activities carried out in order to keep an item that has potential or actual value for the organization — part, component, device, subsystem, functional unit, equipment — i.e., any physical asset in a state in which it can perform its required functions, or restore it thereto. Moreover, maintenance performance can be expressed as an expected or attained result. As a matter of fact, standard ISO 55000 [30] defines performance as measurable result. Besides, it is clear that indicators are considered an appropriate means of evaluating maintenance performance, as demonstrated for instance by documents such as [1,2].

In order to assess maintenance performance, however, is important to bear in mind, as stated in standard [1], that maintenance performance is influenced by both external and internal factors. Examples of the former may be location; society culture; labor policies and costs; laws and regulations; technology availability; and environmental conditions. As for the latter, they may be related either to the organization such as scale; objectives and culture; or to the item proper such as criticality; scale and complexity; age; utilization rate; etc. Results are obtained by means of corrective, preventive, and predictive maintenance actions which require maintenance resources such as competence of direct and indirect people; labor internal and external; knowledge and information; spare parts and materials; tools and equipment; operational practices; supply and support services. Thus, in line with the prescriptions for the effectiveness of the asset management system, in order to monitor and assess the adequacy of maintenance performance it is necessary to establish adequate indicators, and their respective indices, capable of measuring the performance; comparing the performance versus the historical value of benchmarks; identifying strengths and weaknesses; and providing a solid ground for the control of progress and changes, as well as for the definition of strategies and the drawing up of action plans for improvements.

## 4. Best-Worst method (BWM)

The Best-Worst method (BWM) is a multicriteria decision method recently developed with the intent of efficiently ranking decisions where the decision maker chooses the best and the worst alternatives. A 1 to 9 scale is applied for the pairwise comparison between alternatives, analyzing the criteria related to their intrinsic particular aspects. It is a method that stands out for being easy to apply and for the performance of results, which are validated by the verification process of the assessments consistency [3,24,28,32].

As is well known, safe and sound decision-making constitutes a major and permanent concern for managers. It has been true in the past and more so in the present time of rapid change and fierce competition. Accordingly, there has been in the recent decades an intense quest for adequate methods capable of dealing with multiple different criteria, which may be and often are in conflict with each other, and still provide effective ranking decisions. Perhaps one of the most widely used methods has been so far Saaty's [33] analytical hierarchy process (AHP), certainly one of the pioneering works initially published in 1980. However, as pointed out by [34], AHP normally uses n (n-1)/2 comparisons to find the appropriate weights of the alternatives. When there are relatively large numbers of criteria, the comparisons will be increased and the process may become cumbersome and time consuming. On the other hand, BWM is a multi-criteria decision method that requires fewer comparisons. It is so because it uses only the best and the worst criteria for pair-wise comparison, i.e., the decision maker chooses the best and the worst criteria and two pairwise comparison vectors for the best and the worst criteria are provided by the decision maker. Thus, the method needs only 2n-3 comparisons, which makes it more expeditious and easier to use.

In this work, the BWM was used to identify the priority of performance indicators used in the management system for the industrial maintenance of hydropower plants based on plant assessment results. The example in ensuing item 6 shows the application of the method to 6 indicators. The application of the method was carried out according to the following steps [24,35–38] as follow:

**Step I.** List the variables (decision criteria) involved in the decision process.
**Step II.** Determine the most important criterion (BEST criterion) and the one with the least impact on decision (WORST criterion).
**Step III.** Use Saaty's 1 to 9 scale for the pairwise comparison of the preference of the BEST criterion over the other decision criteria, and to compare the preference of all the analyzed criteria with the WORST criterion.
**Step IV.** Obtain optimum weights ($w_1$*, $w_2$*, …, $w_n$*) for each analyzed criterion, an optimization system with Maximization e Minimization functions (MAX-MIN) must be built. This optimization system can be calculate using first Eq. (1), and then its linearization (simplification) obtained by means of the linear programming model presented in Eq. (2):

$$minmax_j\left\{\left|\frac{W_B}{W_j}- a_{Bj}\right|, \left|\frac{W_j}{W_w}- a_{jW}\right|\right\} s.t. \sum_{j=1}^{n} W_j = 1;\ W_j \geq 0\ \forall\ j \tag{1}$$

$$\min(\xi) s.t. \left|\frac{W_B}{W_j}- a_{Bj}\right| \leq \xi\ \forall\ j; \left|\frac{W_j}{W_W}- a_{jW}\right| \leq \xi\ \forall\ j; \sum_{j=1}^{n} W_j = 1;\ W_j \geq 0\ \forall\ j \tag{2}$$

Where:
$W_j$ are the optimal weights for the criteria ($W_1$*, $W_2$*, …, $W_n$*).
$W_B$ is the importance weight of the best criterion.
$W_W$ is the importance weight of the worst criterion.
The relation $aB_j = W_B / W_{jj}$ shows the evaluation of the best criterion in comparison with the others.

The relation $a_{jW} = W_j / W_W$ shows the evaluation of the others in comparison with the worst criterion; $a_{jW}$ indicates the preference of the criterion j over the worst criterion (W).

The solution of the linear programming of Eq. (2) provides the optimum criteria weights and the optimum value of the consistency ratio ξ*. This ratio indicates the consistency of parity comparisons made among criteria present in the decision process. A value close to zero denotes a high level of consistency.

**Step V.** Verify the consistency of the criteria weight attribution process by decision makers. The consistency rate (CR) is calculated by Eq. (3):

$$CR = \frac{\xi^*}{C.I.} \tag{3}$$

The consistency index (CI) is obtained using the maximum value of the coherence index (max ξ) and its correspondent random consistency index (CI) as shown in Table 2.

Adapted from [26].

Finally, the optimum weight for each criterion analyzed in the decision process is obtained.

## 5. Methodology flow chart

The methodology used in the study described in this paper for the consolidation of corporate indicators is illustrated in Fig. 1.

### 5.1. Indicator identification

As an initial activity of the method, all performance indicators that are used by the various plants of the corporation must be identified and classified. This phase shall be executed according to the following steps:

(a) Collect KPIs: All maintenance key performance indicators used individually by each one of the hydropower plants involved in the study must be identified and collected.
(b) Classify indicators: The identified existing indicators are classified according to their type, to wit: appropriation, referring to maintenance men-hour employment; efficiency, referring to the extent to which resources are well used for the intended task or purpose; and effectiveness, referring to the capacity of attaining planned results or objectives. A few additional indicators shall be suggested by the analyst in order to increase the completeness of the set of indicators and shall be classified according to their relevance to maintenance planning and execution.
(c) Compose tables: Indicators and respective indices are listed in comprehensive tables according to their respective classifications
(d) From this list, the more relevant maintenance indicators are selected to be scrutinized in the field interviews, according to expert knowledge considering business objectives and values. The objective being to consolidate them for all power plants and come up with a set of indicators that management can use to assess plants' performances and adopt benchmark lines for comparison.

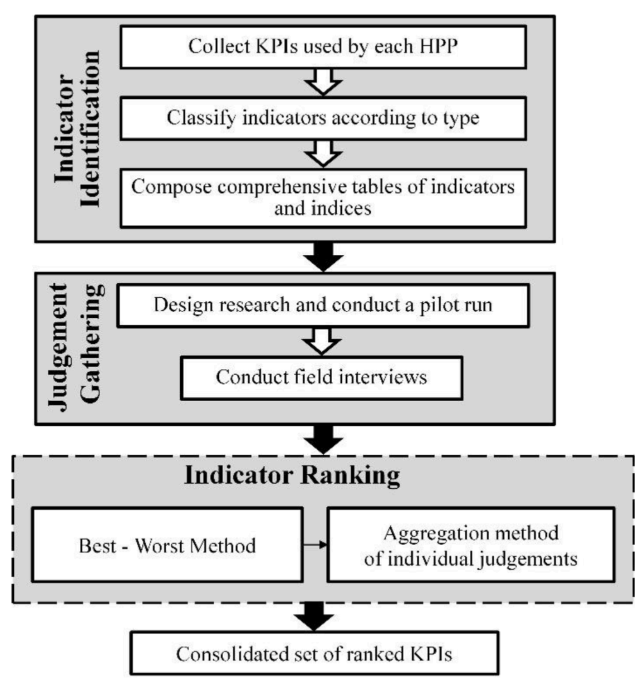


**Fig. 1.** Steps for the consolidation of corporate indicators.

**Table 2**
Consistency index (CI) values.

| $a_{Bw}$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| **CI** | 0.00 | 0.44 | 1.00 | 1.63 | 2.30 | 3.00 | 3.73 | 4.47 | 5.23 |

The objective of this first phase is to come up with a set of key performance indicators (KPI's) related to maintenance performance that may bring actual benefit to the management and operation of all the power plants involved in the study. Although concerned with the fact that an excessive number of indicators might be difficult to handle, the authors set out to establish a sufficient quantity thereof to allow adequate assessment of individual plant performance and at the same time provide the possibility of cross comparison between all the business operations. It is convenient to observe that maintenance indicators may be classified into two main categories:

(1) Maintenance indicators that bring out the effect of maintenance on business performance.
(2) Maintenance indicators relating directly to the physical assetś reliability and availability.

Thus, it was appropriate that the set of KPI's should adequately contemplate both categories. A careful exam and discussion with local staff must be made in order to verify the types of assessment currently carried out in each individual plant, referring to the concepts of use, efficiency, and effectiveness, i.e., the indices used to express the relation between actual and planned inputs, or between used and available resources. The use indices express the relation between used and planned input items; efficiency indices the relation between output and input; while the effectiveness indices express the relation between actual and planned outputs, or between achieved and expected results.

It is also important to note that the identification of indicators supposes the existence of adequate means for either on or off-line monitoring of critical equipment and processes, i.e., for gathering, processing, and treating relevant data. Nowadays this undertaking is greatly facilitated by the ample availability of both hardware and software resources.

Summing up, it is convenient to say that indicators should be simple and practical, that is, easy to establish, to feed with data, and to understand. They must reflect reality as much as possible; therefore, their respective indices should be calculated as frequently as dictated by the best experience, using data from identifiable and reliable sources.

Table 3 shows the set of indicators (the corresponding indices of which are not shown for the sake of simplicity) and two indices considered in the present study identified according to their type of application, i.e., organizational (ORG), financial (FIN), or technical (TEC). This set of indicators can be considered the most suitable to be used by the board of directors to compare different power plants.

FIN indicators will provide corporate directors with a view of issues relating to the operational costs involved in attaining the desired maintenance performance. ORG indicators are meant to provide information about the degree of maintenance organization and planning required for achieving that goal. Finally, TEC indicators will give indication of the evolution of operational management proper.

**Table 3**
Set of considered indicators/indices.

| Indicator/index | Type | Indicator/index | Type |
|---|---|---|---|
| Emergency maintenance cost | FIN | Monthly mean repair time | TEC |
| Maintenance cost (corrective, preventive, predictive) | FIN | Unavailability for scheduled maintenance | TEC |
| Corrective maintenance appropriation | ORG | Unavailability for forced maintenance | TEC |
| Preventive maintenance appropriation | ORG | Maintenance cost | FIN |
| Predictive maintenance appropriation | ORG | Monthly availability | TEC |
| Planning capacity | ORG | Equivalent rate of forced unavailability | TEC |
| Solution capacity | ORG | Equivalent rate of scheduled unavailability | TEC |
| Solution capacity | TEC | ID – Availability index | TEC |
| Equipment health | TEC | FID – Availability Factor | TEC |
| Monthly failure rate | TEC | | |

### 5.2. *Judgement gathering*

The purpose of this phase is to assess what is considered important by the people who actually run the various plants as regards the set of indicators.

Interviewing is a popular way of gathering qualitative research data for pursuing in-depth information around a specific topic. It elicits detailed feedback from the field regarding the subject under study. Therefore, this step involves both the design of interviews and the choice of a method to be used later in order to rank the selected indicators.

#### 5.2.1. *Design research*

The research must be designed to gather information about the plant manager's opinion over the set of indicators. An adequate spreadsheet must be developed, and a pilot run was performed among members of the design team in order to both validate the calculation routine and decide the best way in which to conduct the field interviews.

#### 5.2.2. *Field interviews*

Then the field interviews with power plants' maintenance personnel must be conducted. The research questions and process were clearly articulated among the authors, keeping a clear focus on the intent of the questions, which in this particular case are the most appropriate indicators for assessing maintenance operational performance for all plants. Since interviews are used when there is, a need to understand in depth the opinions, behaviors and attitudes around a specific topic, in this study those of maintenance planners based on their daily experience in the power plant. It was decided that these interviews would be semi-structured, which means questions are predetermined, but the interviewer is free to ask for clarification.

As shown in Fig. 2, before conducting the interview with the experts from the power plants, a pilot interview was performed among the authors in order to gain experience, and go over practicing the interview methodology, comparing each best and worst indicator with all others and grading them accordingly. This was done to get feedback on the topic as well as the interview method.

In carrying out the analysis, the authors made use of the knowledge and opinion of experts from each power plant, that is, individuals with great experience when dealing with maintenance planning and execution in the sector under study. The objective was in fact to access the perspective of those who are endowed with a specific competence or relevant characteristic, collecting a useful amount of technical and behavioral details from their daily activities as maintenance leaders. These qualitative interviews were conducted jointly with the authors and a selected group of people, who were brought together to discuss the maintenance indicators and its importance for the maintenance activities.

### 5.3. *Indicator ranking*

The objective of this phase is to identify the priority of performance indicators to be incorporated into the management system.

#### 5.3.1. *Best-Worst method*

Indicators are ranked using the BWM with the results of field interviews carried out in the previous step.

#### 5.3.2. *Aggregation method of individual judgments*

KPIs priority position are obtained using the aggregation method of individual judgments explained and exemplified below in the case study.

This phase is detailed in the example to follow in the ensuing case study.

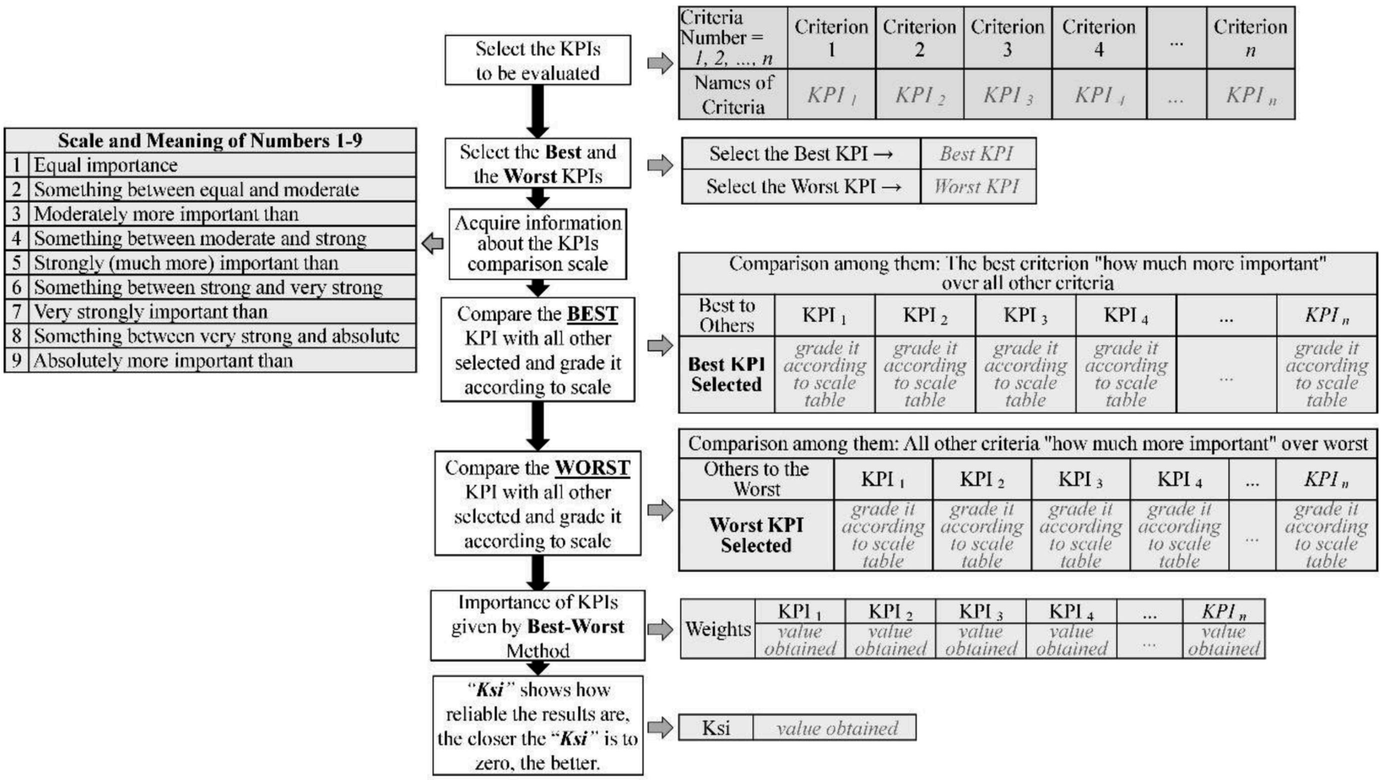


**Fig. 2.** Interview methodology flow chart.

### 5.4. *Consolidated set of indicators*

In this final phase, a concise set of KPIs must be selected with a view to providing top management with a sound and safe means of taking decisions at the corporate level, which constitutes a significant benefit provided by the application of the methodology.

## 6. Case study

### 6.1. *Methodology application*

Power plants investment must pay itself off within a certain period, as any business enterprise for that matter. With that in mind, in view of tight margins avoiding any kind of waste has become of the essence for the managers of such plants in the Brazilian energy matrix, and nowadays only a relatively small work force is available to run the activities needed to produce electricity. Therefore, maintenance planners need to be quite assertive when planning daily work tasks so time is spent in a manner conducive to achieving plant goals. This study is intended to be of help by proposing more representative maintenance indicators.

Table 4 shows the power plants involved in the study with their respective numbers of Kaplan turbine generating units and the required power output for each one. As can be seen, these run-of-river plants have a small number of turbines installed and the work force is very lean, so resources must be used wisely.

After collecting from these plants the maintenance indicators previously listed in Table 3, the research was developed with those indicators and applied to each one of the plants' maintenance engineers. However, for the sake of concision the design team selected the six indicators commonly used for the evaluation of maintenance performance shown in Table 5, for exemplifying the application of the next steps of the methodology in the present case study.

It is important to remark, however, that the application of the ranking method can be and in fact was made to all of the indicators in Table 3, not only to those in Table 5, with similar ensuing considerations.

The idea of the maintainers' interview was to find out from them those things that could not be directly observed on their daily work by the authors. In this way, the authors believed they could extract a very realistic information for this study. The outcome of the interviews provided results from both the pilot run and the plants' experts.

In order to obtain the optimum weight (percentage) of each maintenance key performance indicator (KPI), the BWM was applied interviewing 2 groups: Group 1 composed of experts and Group 2 of maintenance planning engineers. Table 6 shows the results for optimum weights obtained by the interviews involved in the study, and at the bottom of each group its corresponding standard deviation for the KPIs.

The KPIs priority position as regards their degree of monitoring importance was obtained using the aggregation by the geometric mean method for the obtained results. The geometric mean is more commonly used to aggregate the individual judgments (AIJ) where opinions are not equally important for the members of the experts' decision groups, since it satisfies the unanimity condition, homogeneity, and multiplicative

**Table 4**
Hydropower plants.

| HPP analyzed | HPP1 | HPP2 | HPP3 | HPP4 | HPP5 |
|---|---|---|---|---|---|
| Kaplan turbine generating units | 4 | 3 | 5 | 3 | 3 |
| Total power capacity (MW) | 700 | 452 | 902.5 | 374 | 219 |

**Table 5**
KPIs selected as examples.

| Indicator/index | Type |
|---|---|
| Equipment health | TEC |
| Monthly failure rate | TEC |
| Monthly repair rate | TEC |
| Unavailability for scheduled maintenance | TEC |
| Unavailability for forced maintenance | TEC |
| Maintenance cost | FIN |

**Table 6**
Optimum weight of (KPIs) obtained by the application of the BWM.

| Experts | Indicators Maintenance cost | Equipment health | Monthly failure rate | Monthly repair rate | Unavailability for scheduled maintenance | Unavailability for forced maintenance |
|---|---|---|---|---|---|---|
| Expert 1 | 0.039 | 0.416 | 0.121 | 0.121 | 0.061 | 0.242 |
| Expert 2 | 0.411 | 0.176 | 0.132 | 0.132 | 0.042 | 0.106 |
| Expert 3 | 0.16 | 0.128 | 0.107 | 0.463 | 0.036 | 0.107 |
| Expert 4 | 0.201 | 0.43 | 0.151 | 0.1 | 0.032 | 0.086 |
| Expert 5 | 0.426 | 0.098 | 0.098 | 0.197 | 0.033 | 0.148 |
| *Std. Deviation experts 1-5* | *0,150* | *0,144* | *0,019* | *0,134* | *0,011* | *0,056* |
| Planning Engineer | 0.256 | 0.128 | 0.342 | 0.128 | 0.103 | 0.043 |
| Planning Engineer | 0.082 | 0.184 | 0.122 | 0.184 | 0.306 | 0.122 |
| Planning Engineer | 0.066 | 0.265 | 0.403 | 0.031 | 0.059 | 0.176 |
| Planning Engineer | 0.077 | 0.333 | 0.231 | 0.154 | 0.051 | 0.154 |
| Planning Engineer | 0.05 | 0.358 | 0.209 | 0.139 | 0.104 | 0.139 |
| *Std. Deviation Planning Engineers* | *0,076* | *0,087* | *0,100* | *0,052* | *0,093* | *0,046* |

reciprocal property [39–41].

The geometric mean is a central tendency measure. It is defined as the nth root of the product of a set of elements, the root index being the number of multiplied terms. Using the geometric mean, the assessment aggregation is calculated as in Eq. (4):

$$GM = \sqrt[n]{x_1 * x_2 * \ x_3 *, \ \ldots, \ x_n} \tag{4}$$

Where:

*GM* - is the geometric mean;

*n* - is the root index; $x_1$, $x_2$, $x_{3, \ldots,} x_n$ - are the elements used to calculate the geometric mean.

With the geometric mean application, the individual judgments are synthesized in a decision matrix. Table 7 shows the optimum weights for KPIs obtained by the aggregation of the individual assessments of each member of the groups involved in the maintenance and engineering of the HPPs.

By means of the aggregation of assessments, the priority of monitoring importance for the KPIs, for each group of experts, is shown in Table 8.

It should be noted that no indicator in Table 8 was equally ranked by experts and maintenance planning engineers. Here, however, since the exemplified indicators were purposefully chosen to reflect maintenance operational performance, it was suggested that priorities provided by group 2 should be taken into consideration by managers at operational level, except perhaps the low priority attributed to the maintenance cost that, as is well known, constitutes in practice a main concern at top management level, and for this reason can hardly be taken lightly at any level down to the shop-floor, except perhaps for very short periods of time and exceptional conditions.

The results obtained through the interviews and the application of the decision-making method showed differences in priority between the two groups. Since these plants belong to the same business unit, it is reasonable to consider that such differences in priorities should not exist among these plants. Consequently, based on the study's results, the managers of each plant should disseminate this information to their teams and begin to unify priorities. As pointed out before, this will bring better alignment among all plants regarding the company's strategic objectives. Fig. 3 presents a comparison of repair times and monthly failures between two power plants of the holding company.

**Table 8**
Final result for the prioritization of KPIs by monitoring importance.

| KPIs | Priorities Group 1 | Priorities Group 2 |
|---|---|---|
| Equipment health | 1st | 2nd |
| Maintenance cost | 2nd | 6th |
| Monthly repair rate | 3rd | 4th |
| Unavailability for forced maintenance | 4th | 3rd |
| Monthly failure rate | 5th | 1st |
| Unavailability for scheduled maintenance | 6th | 5th |

Maintainability is the measure of how easily and rapidly a piece of equipment can be restored to operational status following a failure. It is associated with equipment design, installation work, adequacy of maintenance procedures, and availability of personnel with required knowledge and skills. In the charts of Fig. 3, real data were extracted from two hydropower plants having the same sort of equipment.

When examined individually, indicators' figures suggest that for both HPP-1 and HPP-2 repair time seems to be satisfactorily stable all over the year. The sharp reduction as of November in HPP-1, as well as the lower values in the beginning of the year for HPP-2, relate more to particular conditions of plant operation than to the efficiency and effectiveness of maintenance actions proper. In addition, when considered in isolation monthly failures in HPP-1 appear to show a very favorable behavior with a considerable decline in the second semester, and in HPP-2, the situation will be deemed very satisfactory.

These would probably be the views of the respective managers when assessing their distinct plants. However, when indicators' figures are put together and compared at corporate level the ensuing analysis will certainly lead to somewhat different considerations.

**Table 7**
Results for individual aggregation of Expert Groups' assessments.

| Individual Assessment Aggregation | Indicators Maintenance cost | Equipment health | Monthly failure rate | Monthly repair rate | Unavailability for scheduled maintenance | Unavailability for forced maintenance |
|---|---|---|---|---|---|---|
| Optimum final weight Aggregation Group 1: Experts | 0.1853 | 0.209 | 0.1204 | 0.171 | 0.0394 | 0.1283 |
| Optimum final weight Aggregation Group 2: Maintenance Planning Engineers | 0.0881 | 0.2368 | 0.2411 | 0.1092 | 0.0998 | 0.1146 |

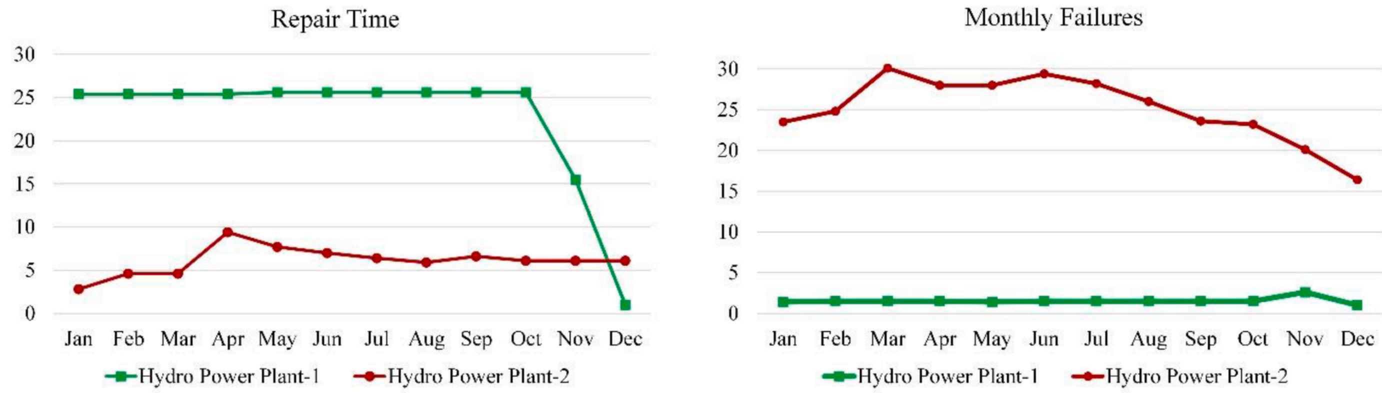


**Fig. 3.** Comparison of indicators for two HPPs.

It is visible that one plant (HPP-1) spends more time repairing its failures than the other plant. Thus, although without further investigation it is not entirely possible to discard the fact that repairs, tests may be more carefully done, and procedures more properly followed in HPP-1 than in HPP-2, the comparison provides ground to suppose that there seems to be room for improvement to bring down the repair time in the latter plant.

On the other hand, the charts reveal that the number of failures in HPP-2 is certainly very high when compared to those in HPP-1. Therefore, unlike the benevolent consideration of a favorable situation in the above isolated analysis, now it becomes evident that the causes for such failures must be carefully investigated and removed, including the fact that the low figures for repair time might actually mean that repairs are not being performed effectively.

It is also interesting to note that another point learned from this study is the lack of KPIs standardization among power plants of the same organization. When all plants implement the same sort of KPIs, benchmarks can be used and lessons learned shared among them to improve maintenance actions through the use and comparison of adequate common KPIs.

Previously, each plant would consider important certain KPIs and not others. The objective of this study was to promote homogeneity of assessment among all plants. Therefore, all the KPIs included in the paper were already used by some plant within the holding company and considered adequate and effective.

### 6.2. Sensitivity analysis

A sensitivity analysis was carried out by varying the grades of the 'Monthly failure rate' indicator, placed in the fifth position according to the assessment by group 1. This choice was due to the large discrepancy between assessments by groups 1 and 2 for this same indicator.

The objective of this sensitivity analysis was to evaluate how much variation was necessary in the grades of group 1 in order to move the 'Monthly failure rate' from fifth to first position, same as in group 2. Accordingly, experts' grades in group 1 were varied. A minimum variation of four points in each grade was required for the 'Monthly failure rate' indicator to reach first position. Table 9 shows results.

**Table 9**
Sensitivity analysis results.

| **Sensitivity Analysis** | | | | |
|---|---|---|---|---|
| | | | **4 points variation in grades** | |
| **KPIs** | **Priorities Group 1** | **Priorities Group 2** | **Priorities Group 1** | **Priorities Group 2** |
| Maintenance cost | 2nd | 6th | 3rd | 6th |
| Equipment health | 1st | 2nd | 2nd | 2nd |
| ***Monthly failure rate*** | ***5***th | ***1***st | ***1***st | ***1***st |
| Monthly repair rate | 3rd | 4th | 4th | 4th |
| Unavailability for scheduled maintenance | 6th | 5th | 6th | 5th |
| Unavailability for forced maintenance | 4th | 3rd | 5th | 3rd |

It is interesting to remark that those values for standard deviations in Table 6 are very close to the ones determined in the sensitivity analysis. The standard deviation calculated for results after the variation of group 1 experts' grades was equal to 0.018. This considerably low value, together with the large amount of variation required to shift the chosen indicator's position from fifth to first during the sensitivity analysis, seem to indicate the soundness of the experts' assessments in this study. Discrepancies in assessment, therefore, are rather due to the expected differences in perspective between groups composed of experts in different levels of activity, as was expected from the onset by the authors.

In other words, the variation required for moving 'Monthly Failure Rate' was considerably larger than the small differences in standard deviations in each group. This fact suggests a high degree of consistency within each group, as opposed to the large variation between groups.

### 6.3. Further comments on costs and benefits

As is usual to do when envisaging or proposing any new management measure, before structuring the present consolidation methodology the authors carried out a judicious discussion about the cost-benefit aspects involved in the practical adoption of what was going to be proposed.

Additional costs would be caused by both the collection and processing of new data. The former aspect, however, would at most require a minor rearrangement of the broad data collection already done in all considered generation plants, transmission, and distribution units, particularly due to the need to provide information to satisfy the requirements for management planning, including logistics, and operation. Furthermore, most of the data used to estimate the proposed indicators are usually collected by power plants aiming at providing information required by the Brazilian Electrical System Operator.

Since all the considered generation plants, transmission, and distribution units possess up-to-date operational ERP systems, the latter aspect mentioned above would also cause negligible additional costs.

As for the benefits, by time of the conclusion of the present work it was not possible to obtain a quantitative assessment thereof. However, the authors believe that based on information gathered on the previously presented literature review as well as the practical qualitative assessment by managers provide ample support for the convenience and advantage of implementing a more encompassing and therefore more reliable set of homogeneous KPIs. The use of this set of indicators may also support the standardization of industrial asset management practice in all plants in accordance with ISO 55.000 precepts. Based on those indicators the holding may not only optimize the preventive maintenance planning of the assets of the power plants but also optimize the acquisition process of critical spare parts. The improvement of those processes may reflect an increase of operational efficiency of the assets.

## 7. Concluding remarks

Maintenance key performance indicators (KPIs) vary according to the organization, its goals, strategies, and action plans. The measurement of performance is important because it identifies existing gaps between current and desired performance and shows in which direction the organization is going, signaling the health of processes or activities. The idea behind collecting data and calculating KPIs is to measure and assess the performance of the organization. Then to analyze how effectively the measured aspects are behaving over time and what needs to be done in order to improve the planning and the operation of the organization. Useful KPIs drive reliability growth while guiding for improving the effectiveness and efficiency of maintenance.

Many attempts have been made to deal with the development and implementation of effective key performance indicators that can create value for organizations. It includes how to align the local maintenance function strategies in several plants with the grand organizational strategy and keep an effective communication in the group, and as a result reduce throughput time and improve coordination between maintenance managements by giving the proper attention to the right KPIs.

The present paper proposed a method to rank key performance indicators (KPIs) in multinational power organizations, and showed an example involving just six of such indicators related to maintenance operational performance, i.e., those particularly meaningful for plant maintenance personnel. Certainly this "operational bias", has led plant representatives, namely plant maintenance engineers, to have ranked Maintenance Cost as the least important one based on their daily experience, due to the urgency of getting equipment up and running as soon as possible to meet energy supply contracts. Having in mind the same limitation, they identified Failure Rate and Equipment Health as the most important, considering that the less the equipment fails the better the availability of the equipment to meet the energy demands. On the other hand, the experts as outside viewers kept a broader perspective and were concerned with all aspects, having thus selected Maintenance Cost as the more important KPI. This observed discrepancy only reinforces the paper's basic proposal, to wit: the need for alignment between local and corporate strategies by means of adequately ranked KPIs. The actual advisory work was carried out considering simultaneously all the identified indicators and indices considered as KPIs.

This paper has focused its study on the KPIs used in maintenance. However, the authors would suggest the extended application of the method to financial and operational KPIs or, for that matter, to any other area's indicators where it may also be convenient to align them among the power plants, with the objective of following the same strategies for all plants.

## Declaration of Competing Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

## Data availability

Data will be made available on request.

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