Defining Maintenance Significant Items Based on ISO 55000 and AHP: A Hydropower plant case study

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Maintenance planning has become an increasingly difficult task as the complexity of equipment and systems evolves constantly. There are several techniques to determine critical system components which deserve greater attention in maintenance planning since they can significantly impact the results of organization. This paper proposes a novel framework for the determination of the maintenance significant items (MSI) based on ISO 55000 aspects and using the Analytic Hierarchy Process (AHP). The ISO 55000 series mainly aims to specify the requirements for the establishment, implementation, maintenance and improvement of a management system for asset management. In the proposed framework, ISO 55000 is used to support the criteria definition of the MSI evaluation. Based on four fundamental criticality aspects in asset management, such as safety, environmental impact, performance and compliance with regulations, nine criteria were chosen to analyze the items. Each component of the system was evaluated and ranked based on the scales criteria and through the use of the Analytic Hierarchy Process (AHP) method. Functional trees (FT) and Failure Mode and Effect Analysis (FMEA) of the components were previously developed to support criteria evaluations. The case study application consisted in an hydrogenerator of a Brazilian hydroelectric plant whose results showed the system's MSIs, supporting maintenance prioritization decisions and assisting in decision making regarding the achievement of the strategic objectives of the company.

Keywords: Maintenance Significant Items (MSI), Analytic Hierarchy Process (AHP), ISO 55000, Criticality analysis, hydro generators, asset management, maintenance planning, FMEA.

1. Introduction

In late industrialized countries, economic growth plans based on the implementation of large infrastructure projects are usual. These countries generally have their economy oriented mainly to primary products exportation, such as mineral and agricultural commodities. Brazil follows a similar path and, for much of the past sixty years, economic growth policies were based on infrastructure projects, such as hydroelectric power plants (Moretto et al. (2012)).

In fact, with a great hydroelectric potential, the country's energy expansion has been based for a long time on a model that highlights the predominance of hydroelectricity in the energy matrix. Even today, more than 65% of electricity is generated in hydroelectric power plants (Brazil (2018)).

Nevertheless, according to Alves (2014), Brazil exploits only about 25% of its hydric potential. Even so, Neves (2009) points out difficulties in expanding hydro power generation the country faces nowadays, especially related to financial resources and environmental regulations.

Accordingly, taking the current scenario, Falcetta (2015) consider a continuous need for complementing hydro power generation not only in hydrologically unfavorable years. However, as

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fossil energy sources appear to have an uncertain future and renewable sources survey still in development in Brazil, exploring the already installed hydraulic park is a matter of great importance, leading the available hydro generators reliability to a critical point.

At the same time, maintenance planning has become an increasingly difficult task as the complexity of equipment and systems evolves constantly. According to Bo (2015), maintenance for a long time was seen only as cost and therefore should be minimized. This context favored short-term decision-making against more detailed planning for the future. However, maintenance today is no longer a mere repair function to become one of the most important functional areas of the company (Tavares et al. (2015)).

In this way, there are several techniques to determine critical system components. These items deserve greater attention in maintenance planning since they can significantly impact the results of organization.

Maximizing investment returns on physical assets, while ensuring security and environmental preservation, is more critical than ever (Stanford, (2015)). Therefore, a new maintenance model is fundamental to guarantee the levels of availability and reliability required in organizations (Pilar et al. (2016)). With the publication of the ISO 55000 series for asset management in 2014, as result of an effort and global involvement, a response to the demand for standardization of physical asset management was formally available.

In this context, this paper proposes a novel framework for the determination of the maintenance significant items (MSI) based on ISO 55000 aspects and using the Analytic Hierarchy Process (AHP). The validation of the method is validated through a case study of a hydropower plant.

This paper is organized as follows: Section 2 presents a brief description about asset management and ISO 55000 series. Section 3 describes the AHP technique. Section 4 presents the proposed framework for defining MSI and its application on a hydrogenerator. Finally, Section 5 presents the authors conclusions about the proposed method and study case.

2. Asset Management and ISO 55000 Series

The evolution of industrial maintenance shows that current strategies differ in their focus on comparison to previous models (Bo (2015)). Influenced by asset management, formally developed from the 2000s with the PAS 55 and later with the ISO 55000 in 2014, maintenance is no longer seen merely as a repair force.

The three standards of ISO 55000 series (ABNT (2014a, 2014b and 2014c)) covers asset management in a broad spectrum but it is more important what asset management means for maintenance history. According to International Copper Association, (2015), asset management represents "a cultural shift in the strategic planning of companies that add to the traditional vision of products and customers to the vision of the assets and the value they are able to generate to the business"

According to Ihemegbulem et al. (2016), the ISO 55000 series is a detailed and comprehensive standardization that assists in the implementation of a physical asset management system in the organization. Although, the standard does not reveal what to do to manage physical assets, as like most other international management standards (Stanford, (2015)), the requirements guide to an alignment of the physical assets to organizational objectives.

For that, defining MSI, as critical asset that have the potential to significantly impact the achievement of the organizational objectives, contributes to strategic planning of maintenance department. In this context, the paradigm shift represents a long-term planning trend and reinforces the role of maintenance in business sustainability through asset management.

3. Analytic Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) is a multicriteria decision method developed by Saaty (1977), which relies on the judgment of specialists to obtain priority scales through pairwise comparisons of both criteria and alternatives.

Both AHP and its more generalized version, namely Analytic Network Process (ANP), have been used to determine MSI. Tang et al. (2017) have implemented AHP to help define MSI of a drilling pump system. Melani et al. (2018) determined the most critical components of a coal-fired power plant through ANP technique.

In this paper, AHP is used to determine MSI of a hydrogenerator based on ISO 55000's aspects and criteria. The AHP was implemented through five steps, described below. It is important to note that both the criteria and the components considered in the case study are described in Section 4.

Step 1: Construct a judgment matrix A, presented in Eq. 1, through pairwise comparisons among the criteria.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1k} \\ \vdots & \ddots & \vdots \\ a_{k1} & \cdots & a_{kk} \end{bmatrix} \tag{1}$$

In matrix A, k represents the number of criteria used and the element a_{ij} represents the relative importance of criterion i on criterion j, according to the scale of relative importance level presented on Table 1. Thus, the value of $a_{ij} = 1/a_{ji}$.

Table 1. The fundamental scale

Intensity of Importance	Definition
1	**Equal importance**
2	Weak
3	**Moderate Importance**
4	Moderate plus
5	**Strong importance**
6	Strong plus
7	**Very strong importance**
8	Very, very strong
9	**Extreme importance**

Source: Adapted from Saaty (1990).

Step 2: Perform a prioritization method by deriving a priority vector *w,* in Eq. 2, from the judgement matrix A.

$$w = \begin{pmatrix} w_1 \\ \vdots \\ w_k \end{pmatrix} \qquad (2)$$

where $w_i \geq 0$ and $\sum_{i=1}^{k} w_1 = 1$. The priority vector gives a weight w_i for each criterion considered. The prioritization method used in this study is the Row Geometric Mean Method (RGMM), where each element of vector w is calculated by Eq. 3 (Dong et al. (2010)).

$$w_i = \frac{\sqrt[1/k]{\prod_j^k a_{ij}}}{\sum_{i=1}^{k}\left(\sqrt[1/k]{\prod_{j=1}^{k} a_{ij}}\right)} \qquad (3)$$

Step 3: Check consistency of the judgement matrix A. For the RGMM method, this is done by calculating the Geometric Individual Consistency Level (GICL), in Eq. 4, developed by Crawford and Williams (1985).

$$GICL = \frac{2}{(k-1)(k-2)} \sum_{i<j} \left(\log(a_{ij}) - \log(w_i) + \log(w_j)\right)^2 \qquad (4)$$

Aguarón et al. (2003) provided the thresholds for GICL. When GICL<0.37 for k>4 (more than 4 criteria), for example, it is considered that the judgement matrix A is of acceptable consistency.

Step 4: If the calculated GICL is bigger than the thresholds, the judgement matrix should be adjusted, repeating steps 1 through 3 until the required consistency is satisfied.

Step 5: Calculate the final score of every system's component by the mathematical model presented in Eq. 5 (Tang et al. (2017)):

$$Component\ final\ score = \sum_{i=1}^{k} m_i w_i \qquad (5)$$

Where m_i is the normalized score given to the component for each criterion. This m_i score is based on scales ranging from 1 to 9 that are described in Section 4.

4. Proposed Method

This paper proposes a novel framework for the determination of the maintenance significant items (MSI) using Analytic Hierarchy Process (AHP) and ISO 55000. This framework complies three sections, as presented in Fig. 1: Criteria definition (I), System study (II) and Criticality ranking (III).

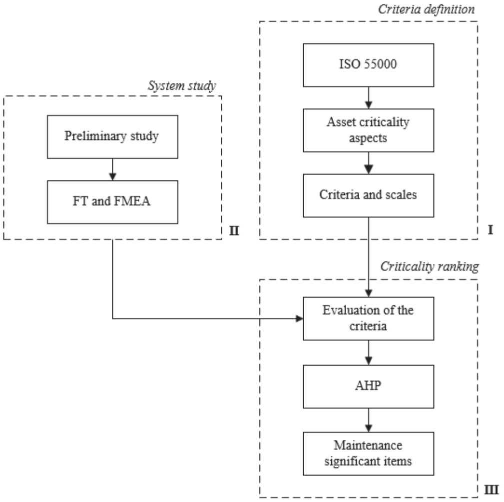

Fig. 1. Proposed framework for MSI definition

4.1 *Criteria definition*

The proposed method starts with the establishment of the criteria and scales for further evaluation. For that, the first section (I) was guided by ISO 55000 series due to its recently importance for maintenance.

According to the asset criticality in ISO 55000 standard, assets can be critical in safety, environmental or performance and may relate to legal, regulatory or statutory requirements (ABNT (2014a)). Thus, the evaluation criteria planned for MSI definition was based on these four aspects of criticality.

ISO 55001 requires for an asset management system that asset management objectives must be aligned, and consistent with, the organizational objectives (ABNT (2014b)). When the criteria that classify systems' criticality level are aligned with organizational objectives, managing critical asset contributes to achieving organizational goals.

Table 2. Criteria and scale description for MSI criticality assessment

#	Aspect	Criteria	Numerical classification based on a scale of …
s1	Safety	Safety classification	… safety impacts associated with system failure and conditions for maintenance.
s2	Safety	History of security events	… occurrence of undesirable safety events associated with the equipment in the last 5 years.
e1	Environmental	Environmental classification	… environmental impacts associated with system failure and conditions for maintenance.
e2	Environmental	History of environmental events	… occurrence of undesirable environmental events associated with the equipment in the last 5 years.
p1	Performance	Reliability	… failure rate scale of the equipment in the last 5 years.
p2	Performance	Maintainability	… time-of-return of the system, including mobilization time and time to repair.
p3	Performance	Health assessment capacity	… monitoring capability associated with the condition of the equipment.
p4	Performance	Maintenance compliance	… compliance of maintenance plans of the equipment in the last 6 months.
r1	Regulatory	Impact on availability	… impact scale of the equipment failure availability and energy generation.

In this paper, the annual integrated reports analysis was used to identify the company's organizational objectives. Thus, combining the organizational objectives of the case study organization under the four criticality aspects, nine criteria were defined for MSI assessment as presented in Table 2.

A numerical classification (grade) based on a scale from 1 to 9 for each criterion was developed for the evaluation of the systems. Table 2 also shows the description of each criterion for assigning the grades.

4.2 *System study*

The System study section (II) consists of parallel activities of systems in analysis' understanding. It aims to support the researchers and those involved in the criticality evaluation of the systems since understanding systems is critical for an adequate MSI criticality assessment.

Initially, a preliminary study was done on the case study, a hydropower plant, in order to understand the operational context and main systems. Finally, functional trees were elaborated allowing the understanding of the interfaces of the equipment and system in the site and FMEA methodology was used to identify failure modes in order to complement the system study.

4.3 *Criticality ranking*

In the Criticality ranking section (III), the framework proposed evaluate the nine criteria defined, use the AHP method for ranking the systems and, finally, list the MSI according to higher score prioritization.

5. Case Study

In this paper, the proposed framework was applied to a 198 MW installed hydropower plant composed of 4 Kaplan turbine generating units (GU1 to GU4) as the case study for MSI determination.

During the system study phase and development of functional trees, each generating unit was divided into eight sections, as shown in Table 3. This configuration enables to create a standard taxonomy and drill down the hydropower plant. As example, Table 3 describes Id first level with a x since it represents the generating unit level number (1 to 4), followed by the section level number.

Table 3. Sections of each generating unit

Id	Criteria definition
x.1	Draft tube
x.2	Turbine
x.3	Electrical connection
x.4	Generator
x.5	Shaft
x.6	Excitation system
x.7	Speed governor
x.8	Draft tube

For better comprehension of the system study, Fig. 2 exemplifies the functional tree for turbine section of generating unit 1. These functional diagrams of the plant supported the researchers in the understanding of the plant and in the identification of failure modes by the FMEA.

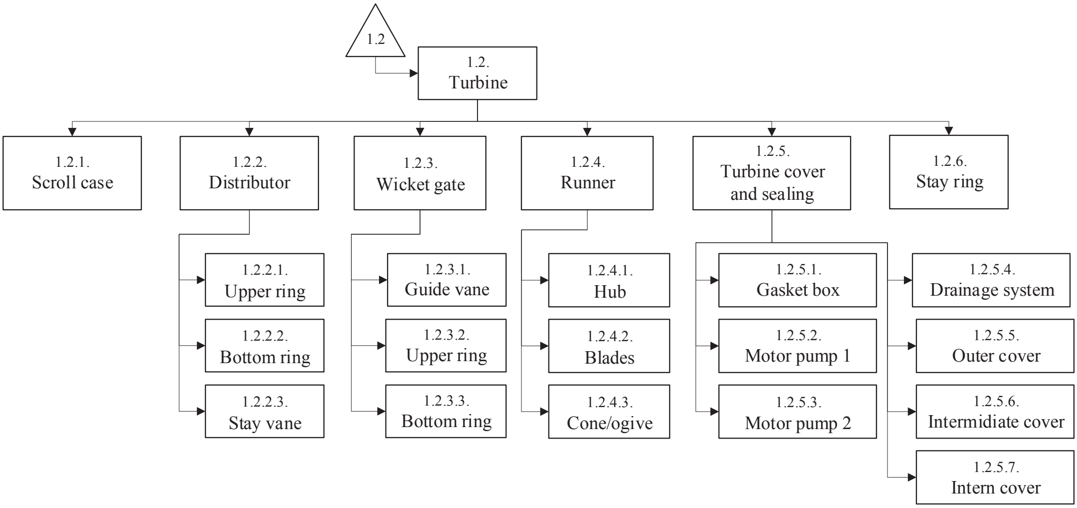

Fig. 2. Functional tree for Kaplan turbine of a generating unit

The FMEA process for an equipment and a subunit is exemplified in Table 4 which shows that the tool was only used for failure mode, causes and potential effects analysis. As the application of FMEA to the MSI definition framework aims to familiarize the participants with the equipment in order to base the evaluation of criticality criteria, not all FMEA aspects, for example RPN or recommended actions are applied

For AHP method prioritization, all items of hydropower plant functional hierarchy were evaluated according to the nine criteria and numerical scale (1 to 9). Table 5 presents, as example, turbine section of a generating unit evaluated in the case study. The criticality criteria are presented by its id according to Table 1.

Table 4. FMEA for equipment and subunit application for system study

Id	Item	Function	Failure modes	Potential failure effects	Potential causes
1.2.1.	Scroll case	Conduct water from the penstock to the distributor	Excessive turbulence in the hydraulic flow	1) Loss of efficiency of the turbine, leading consequently to the loss of efficiency in the electric generation	a. Cavitation
1.2.2.1.	Upper ring (distribuitor)	Support the stay vanes	Component rupture	1) Damage to the wicked gate and distributor 2) Inaccurate water flow control 3) Possible machine stop	a. Fatigue crack propagation
					b. Material with mechanical characteristics in non-compliance with design specifications
					c. Low torque/loose fasteners
			Loose fasteners	1) Damage to the wicked gate and distributor 2) Inaccurate water flow control 3) Possible machine stop	a. Fatigue crack propagation
					b. Material with mechanical characteristics in non-compliance with design specifications
					c. Low torque/loose fasteners
			Misalignment or plastic deformation	1) Damage to the wicked gate and distributor 2) Inaccurate water flow control	a. Low torque/loose fasteners
					b. Improper mounting

Table 5. Criticality criteria evaluation for turbine section of a generating unit

		Criticality criteria								
Id	**Description**	**s1**	**s2**	**e1**	**e2**	**p1**	**p2**	**p3**	**p4**	**r1**
1.2.	**Turbine**	7	1	5	1	2	9	9	1	9
1.2.1.	**Scroll case**	7	1	3	1	1	7	9	1	9
1.2.2.	**Distributor**	7	1	3	1	1	9	9	1	9
1.2.2.1.	Upper ring	7	1	3	1	1	9	9	1	9
1.2.2.2.	Bottom ring	7	1	3	1	1	9	9	1	9
1.2.2.3.	Stay vane	7	1	3	1	1	9	9	1	9
1.2.3.	**Wicket gate**	7	1	3	1	1	7	9	1	9
1.2.3.1.	Guide vane	7	1	3	1	1	7	9	1	9
1.2.3.2.	Upper ring	7	1	3	1	1	7	9	1	9
1.2.3.3.	Bottom ring	7	1	3	1	1	7	9	1	9
1.2.4.	**Runner**	7	1	5	1	1	7	7	1	9
1.2.4.1.	Hub	7	1	5	1	1	7	7	1	9
1.2.4.2.	Blades	7	1	5	1	1	7	7	1	9
1.2.4.3.	Cone/ogive	7	1	5	1	1	7	7	1	9
1.2.5.	**Turbine cover and sealing**	7	1	1	1	2	3	5	1	9
1.2.5.1.	Gasket box	7	1	1	1	2	3	5	1	9
1.2.5.2.	Motor pump 1	7	1	1	1	2	3	5	1	9
1.2.5.3.	Motor pump 2	7	1	1	1	2	3	5	1	9
1.2.5.4.	Drainage system	7	1	1	1	2	3	5	1	9
1.2.5.5.	Outer cover	7	1	1	1	2	3	5	1	9
1.2.5.6.	Intermidiate cover	7	1	1	1	2	3	5	1	9
1.2.5.7.	Intern cover	7	1	1	1	2	3	5	1	9
1.2.6.	**Stay ring**	7	1	5	1	1	7	9	1	9

After completing the evaluation of the criteria for all items of the functional hierarchy trees, the criticality ranking step applies the AHP method for MSI definition.

Following the steps established in section 3, the judgment matrix was developed through pairwise comparisons between the previously defined criteria and is presented in Table 6. In this judgment matrix, it is possible to see, for example, that the safety classification criterion (s1) is considered to be "strongly more important" than criterion history of security events (s2). That's why the value of element a_{12} in Table 6 is 5, considering the fundamental scale presented in Table 1.

Once the judgment matrix was developed, the priority vector was obtained and is presented in Table 7. It is possible to see, in Table 7, that the criterion s1 (safety classification) is considered the most important in the criticality ranking.

To verify if both the priority vector and the judgment table are consistent, the GICL was calculated. The value obtained for GICL was 0.0976, which is lower than the threshold of 0.37 determined by Aguarón et al. (2003) and, therefore, it can be considered that the application of the AHP is consistent.

Table 6. Judgement Matrix

	s1	s2	e1	e2	p1	p2	p3	p4	r1
s1	1	5	3	9	5	5	9	7	5
s2	$\frac{1}{5}$	1	2	3	3	3	5	3	2
e1	$\frac{1}{3}$	$\frac{1}{2}$	1	5	3	3	7	5	3
e2	$\frac{1}{9}$	$\frac{1}{3}$	$\frac{1}{5}$	1	2	2	3	2	1
p1	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{2}$	1	1	5	3	$\frac{1}{5}$
p2	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{2}$	1	1	5	3	$\frac{1}{5}$
p3	$\frac{1}{9}$	$\frac{1}{5}$	$\frac{1}{7}$	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{5}$	1	$\frac{1}{3}$	$\frac{1}{7}$
p4	$\frac{1}{7}$	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$	3	1	$\frac{1}{7}$
r1	$\frac{1}{5}$	$\frac{1}{2}$	$\frac{1}{3}$	1	5	5	7	7	1

Table 7. Priority Vector

#	**Criteria**	**Priority Vector**
s1	Safety classification	0.359
s2	History of security events	0.146
e1	Environmental classification	0.161
e2	History of environmental events	0.063
p1	Reliability	0.053
p2	Maintainability	0.053
p3	Health assessment capacity	0.018
p4	Maintenance compliance	0.030
r1	Impact on availability	0.116

The last step of AHP application was then implemented to obtain the MSI. Table 8 presents the MSI for the hydropower plant as the main result of the framework and objective of this paper application. Since the hydropower plant has a big quantity of sections, systems, equipment and subunits in its functional trees, this tables presents only the top important items, selected by sorting the 10% of higher AHP scores.

The proposed framework has defined MSI according to criticality aspects of ISO 55000 series evaluation and AHP multicriteria method. The definition of MSI for an organization is an important step in resource management and maintenance policies prioritization.

Table 8. MSI definition-based criticality AHP rank

Id	Description	Score	Rank
9.2.	Dam	0,0068170	1
9.4.	Spillway	0,0068170	2
4.7.2.3.	Kaplan mechanism	0,0059415	3
1.1.2.	Trash rack	0,0059250	4
2.1.2.	Trash rack	0,0059250	5
3.1.2.	Trash rack	0,0059250	6
4.1.2.	Trash rack	0,0059250	7
9.6.	Reservoir	0,0058717	8
1.7.2.3.	Kaplan mechanism	0,0058067	9
2.7.2.3.	Kaplan mechanism	0,0058067	10
3.7.2.3.	Kaplan mechanism	0,0058067	11
9.5.	Intake	0,0054208	12
1.8.3.	Draft tube	0,0054126	13
2.8.3.	Draft tube	0,0054126	14
3.8.3.	Draft tube	0,0054126	15
4.8.3.	Draft tube	0,0054126	16
1.2.6.	Stay ring	0,0053075	17
2.2.6.	Stay ring	0,0053075	18
3.2.6.	Stay ring	0,0053075	19
4.2.6.	Stay ring	0,0053075	20
1.2.4.	Runner	0,0052924	21
2.2.4.	Runner	0,0052924	22
3.2.4.	Runner	0,0052924	23
4.2.4.	Runner	0,0052924	24
5.1.	Voltage transformer 7TR1	0,0052059	25
5.2.	Voltage transformer 7TR2	0,0052059	26
5.3.	Voltage transformer 7TR3	0,0052059	27
5.4.	Voltage transformer 7TR4	0,0052059	28
1.1.3.	Penstock	0,0051778	29
2.1.3.	Penstock	0,0051778	30
3.1.3.	Penstock	0,0051778	31
4.1.3.	Penstock	0,0051778	32
3.2.3.	Wicket gate	0,0048133	33
1.2.2.	Distributor	0,0047667	34
2.2.2.	Distributor	0,0047667	35

Although in the same plant maintenance policies are usually replicated to similar equipment, the result of this work highlighted that systems of one generation unit may have different criticality from the others. As an example, one can identify the Distributor (3.2.3.) of the GU3 that is among the items with the highest score, unlike the others Distributors. Also, it is evident that the Kaplan mechanism of GU4 (4.7.2.3.) Is significantly more critical than the others.

According to ISO 55001 requirements, the organization shall define the asset portfolio covered by the scope of the asset management system (ABNT (2014b)). However, it does not specify how this selection should be made. The framework of this work, for presenting a systematic and generic method to define the most important items for maintenance of any structure, can be a proposal to meet the requirements of the asset management standard.

6. Conclusions

The present work proposes a novel framework for the MSI determination based on ISO 55000 aspects and using AHP as multicriteria method. For that, a three-section method was developed and validated with a hydropower plant case study.

The framework aims highlights the most significant items for maintenance planning according to the criteria evaluation and AHP application. With the results, maintenance strategy could prioritize system which are critical for the organizational objectives.

The study case application showed the framework to be consistent as a tool for MSI determination once it presents a criticality ranking for maintenance decision and it's quite simple to perform, even in complex systems. As suggested, this framework also can be extended as a tool for asset portfolio definition since ISO 55001 requires to define the critical assets for an asset management system implementation.

Finally, it is expected that the results of this work will contribute to maintenance and asset management research and the diffusion of multicriteria prioritization method, aiming to increase reliability and optimize maintenance planning.

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