# MAINTENANCE STRATEGY SELECTION OF HYDRAULIC SYSTEMS IN THE STEEL INDUSTRY: A DESIGN SCIENCE RESEARCH APPROACH

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## ABSTRACT

The steel industry is a major global player in the world economy and significantly contributes to a country's development. Maintenance is indispensable for the productivity of steel industry assets. The growing use of high-precision operations in these organizations makes hydraulic systems a critical concern. Multi-criteria decision-making (MCDM) methods can facilitate decision-making, particularly with decisions about the best maintenance policies/strategies to be employed. The Analytic Hierarchy Process (AHP) is a consolidated and appropriate method for dealing with multiple factors and uncertainty. This research proposes a model to support decision-making for selecting a maintenance strategy for hydraulic systems in steel plants. The development of this model followed the Design Science Research (DSR) methodology, which has five stages. The main scientific contribution of this research is to demonstrate that the AHP allows a landscape with a qualitative approach regarding the maintenance strategy selection of hydraulic systems in the steel industry, which enables the development of a hierarchical framework that incorporates four maintenance strategies, criteria, and sub-criteria identified in the current literature. The criteria of cost, safety, reliability, quality, and feasibility were examined to determine the best maintenance strategy to be applied. Predictive maintenance was selected as the priority strategy, while safety was the criterion with the highest added value. The

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sensitivity analysis confirmed the robustness of the framework, showing that classifications remained stable even when the weights of the criteria varied.

**Keywords:** steel industry; maintenance; hydraulic systems; design science research; framework; AHP

## 1. Introduction

As Singh et al. (2023) point out, the steel industry is often vulnerable to the most challenging manufacturing conditions, such as wear, high temperature, erosion, and corrosive environments. Those conditions impact the operational performance of assets, resulting in production losses and maintenance costs.

Industries often face high production losses as they lack comprehensive maintenance systems. Therefore, organizations need to have an effective maintenance system and adopt the best strategies to ensure the process flows as smoothly as possible at the lowest possible cost. A correct maintenance strategy selection will reduce operational failures in assets, rework, and, consequently, costs. Different maintenance strategies have been proposed, each with advantages and disadvantages (Avakh Darestani et. al., 2022).

Hydraulic systems are extensively used in many industrial production processes. Within hydraulic systems, the reliability of each component provides the necessary support for overall system reliability. However, the complexity of the system design makes formulating a maintenance strategy challenging (Yang et al., 2024).

According to Torre et al. (2023), maintenance comprises an asset life management system, including technical and administrative activities. In an organization, maintenance planning significantly contributes towards minimizing operating costs. All maintenance strategies have strengths and weaknesses, and managers must make decisions with assertiveness.

According to Behnia et al. (2023), the selection of an effective maintenance strategy is essential for reducing costs, increasing operational efficiency, and ensuring process reliability with safety in organizations. In their decision-making, managers must select an effective maintenance strategy for a given process, comprising objectives, criteria, sub-criteria, and different alternatives, which is a multi-criteria decision making problem.

According to Patil et al. (2022), several approaches can be found in the literature for a suitable maintenance strategy selection, comprising mathematical models, classical and hybrid MCDM approaches, frameworks, and risk-based analysis approaches.

A broad range of MCDM methods exist, including the AHP method developed by Saaty (1974). This method offers significant advantages due to its application and flexible usage to assist in decision-making. Currently, the AHP remains the most widely used decision-making method in broad areas of business and scientific knowledge (Saaty & Vargas, 2001; Abdulgader et al., 2018; Canco et al., 2021).

Several studies emphasize the importance of efficient maintenance management, including Di Bona et al. (2021), Mattioli et al. (2020), Dai et al. (2019), and Shahin et al. (2018). In particular, Avakh Darestani et. al. (2022) state that the evaluation and ranking of maintenance strategies provides valuable insights into a company's strengths and weaknesses, serving as crucial inputs for strategic programming. Some authors like Patil et al. (2022), Ohta et al. (2018), Carpitella et al. (2021), Behnia et al. (2023), and Avakh Darestani et. al. (2022) address the selection of maintenance strategies in different industrial environments in their research; however, the current literature does not mention the selection of a maintenance strategy for hydraulic systems.

This research, in contrast to previous studies, presents an innovative study for the scientific community and the organizational environment, as it addresses new perspectives for selecting a maintenance strategy for hydraulic systems in steel mills. The application of the AHP method through the proposed framework focuses on achieving a robust solution for specialists who don't have specific skills in applying MCDM methods to aid decision-making.

Considering this context, the main goal of this research is to propose a model to support decision-making toward selecting a maintenance strategy for hydraulic systems in steel plants. The research question proposed for this research is as follows: How can the DSR approach contribute to developing an innovative framework for maintenance strategy for hydraulic systems in steel plants? This study contributes to the development of an innovative framework to support maintenance managers in decision-making in accordance with the desired level of service with the lowest possible risk, identifying the criteria and sub-criteria that meet the appropriate requirements for a critical assessment of the maintenance strategy for hydraulic systems management.

The DSR methodology is shown to be a suitable approach for this type of research since it presents tasks related to the combination of problems and opportunities with corporate values that focus on projecting results with the fewest possible defects, seeking to improve the maintenance management of hydraulic systems.

This study contributes to developing a resourceful framework that defines strategies to support maintenance managers in decision-making through the DSR methodology. The application of the AHP enables the development of a hierarchical framework that incorporates four maintenance strategies, criteria, and sub-criteria identified in the current literature.

## 2. Literature background

### 2.1 Steel industry

The steel industry is a crucial pillar of a country's economy, and its development significantly impacts overall economic growth. The steel production process consists of parallel processes, such as those occurring in the coking plant and sintering, as well as sequential processes, including the blast furnace, melt shop, casting, and hot mill (Chen et al., 2016).

Steel industries are considered technologically complex, but they are fundamental to supporting a country's development, generating around 40 million jobs worldwide (Torre, 2024). Steel consumption per capita significantly contributes to a country's economic growth. For these organizations, it is crucial to promote a continuous improvement culture of their processes concerning product development and research activities (Torre et al., 2024).

The steel industry plays a crucial role in economic development by supplying essential materials to various sectors, including construction, transportation, and defense. In this context, implementing effective maintenance strategies is vital for prolonging the lifespan of assets. This approach not only ensures sustainable operations but also leads to cost reductions, energy savings, and enhanced operational safety (Qin et al., 2022).

### 2.2 Maintenance

Maintenance plays a crucial and strategic role within manufacturing companies. The continuous operation of assets, often around the clock, results in a higher volume of maintenance activities. By enhancing machine availability and decreasing the likelihood of failure, manufacturing companies can effectively achieve their production goals (Lopes et al., 2020).

Maintenance stands out in asset management, focusing on availability, reliability, production levels, costs, and safety across various operating scenarios. Maintenance activities must be integrated and scheduled within the equipment's life cycle, considering the reliability characteristics needed for the specific systems. Maintenance cost minimization and asset availability are managed through a mathematical programming system (Carpitella et al., 2018).

A maintenance strategy outlines how an organization maintains the integrity and safety of its assets throughout their entire life cycle. It typically includes procedures for surveying and inspecting, repairing, maintaining, and renewing systems, subsystems, and components. In the quest for greater efficiency and reduced costs, researchers have developed several maintenance strategies over the years (Abbas & Shafiee, 2020).

Steel companies encounter various challenges across different sectors. For instance, inadequate maintenance management can adversely impact assets and labor. By employing MCDM methods, managers can effectively handle the decision criteria involved in the maintenance process (Depczyński et al., 2023).

Maintenance is crucial to the operational processes of steel plants. Hydraulic systems are among the most critical assets for the maintenance department because their failure can halt production entirely, leading to significant financial losses, severe environmental impacts, and potential safety hazards. Therefore, it is essential to implement appropriate maintenance measures for these systems (Torre et al., 2024).

According to Khan et al. (2021), hydraulic systems are often prominent in several common industrial applications, such as construction and manufacturing machinery. A failure in this kind of system can affect the operation of whole equipment or installations, which has a negative effect on the production process. Precise and timely fault diagnosis, coupled with appropriate corrective actions, can guarantee continuous operation, and increase the safety and reliability of the system. Adequate maintenance is vital for minimizing failure rates and extending the life of the equipment.

### 2.3 Types of maintenance

The existing types of maintenance differ according to the procedures used to manage an organization's assets. There are a broad range of different types of maintenance. For this research, we will consider the main types, such as autonomous, corrective, preventive, and predictive maintenance.

a) Autonomous maintenance
Recent advancements in Industry 4.0, machine learning, and digital twins have sparked a growing interest in implementing autonomous maintenance within organizations. This approach to maintenance has become a focal point in the industry due to the potential for automating operational processes. Autonomous maintenance can be defined as a system's ability to self-manage and operate independently; in other words, it refers to the capacity whereby a system operates in a self-controlled way (Khan et al., 2020). Autonomous maintenance is an integral part of Industry 4.0, as it emphasizes self-maintenance since it requires technology deployment. This strategy is often selected by organizations engaged in high-risk operations. As a result, the role of the maintenance operator is evolving to include oversight of improved monitoring systems (Di Bona et al., 2021).

b) Corrective maintenance
Corrective maintenance was primarily used in the 1940s, where its purpose was to address equipment failures after they occurred in order to restore normal operating conditions. This approach often interrupted the regular production plan, resulting in process losses. Additionally, because failures happen suddenly, this strategy can lead to untimely repairs and inefficient use of maintenance resources (Zhao et al., 2022). Corrective maintenance occurs after a component fails. Its primary goal is to restore the component as quickly as possible by repairing or replacing a piece of equipment or component that has been damaged (Mirhosseini & Keynia, 2021).

c) Preventive maintenance
Preventive maintenance takes place at predetermined intervals according to a previously developed plan designed to keep the system in working order based on historical data (He et al., 2018). Preventive maintenance is planned to enhance operational reliability and prevent equipment failures, especially given the significant economic investments required for the production workflow. Steel companies implement preventive maintenance strategies to replace equipment before it reaches the end of its useful life, thereby avoiding potential production losses (Sarda et al., 2021).

d) Predictive maintenance
Predictive maintenance identifies equipment issues early and efficiently, significantly benefiting the production sector. This maintenance approach is linked to Industry 4.0 and focuses on the condition of the equipment, following a set of activities with systematic

monitoring of variables that indicate equipment performance, playing a critical role in organizational effectiveness (Bajic et al., 2020).

Predictive maintenance is a strategy that improves equipment maintenance operations, ensuring the operational reliability of specific asset types in the industrial sector. It monitors factual information about plant assets, including their overall health, capacity, efficiency, and optimal maintenance policies, to determine when the system or machine might fail. (Shukla et al., 2022).

### 2.4 Design Science Research (DSR)

According to Chaudhuri et al. (2021), DSR enables researchers to actively engage in problem-solving and, at the same time, develop scientific knowledge. The basic idea of DSR is that new generic designs will have considerable practical importance. Knowledge gathering can be better crystallized and concretized using a DSR approach, focusing on enhancing the existing generic designs (Van Aken et al., 2016).

According to Goecks et al. (2021), the DSR methodology has been recognized as an effective research method in the scientific environment, comprising the development of an artifact/model based on experience and its demonstration, aiming at a solution to the proposed organizational objectives, which may include machines, the economy or society. The notoriety of this method stands out for eliminating the distance between theory and practice and for being a science that aims to solve specific problems.

Dresch et al. (2015) state that DSR would be responsible for developing and evaluating new systems by creating, recombining, or altering products/processes/software/methods to improve the existing conditions. This issue seeks to study, search, and investigate the artifact and its behavior, academically and organizationally. In this sense, it’s a rigorous process of designing artifacts for solving problems and evaluating and discussing the results (Lacerda et al., 2013).

DSR focuses on the prescriptive instead of the descriptive, i.e., attempts to prescribe processes more effectively. The DSR outputs are the artifacts evaluated as models, methods, or constructs (Lacerda et al., 2013; Manson, 2006). According to Kuechler and Vaishnavi (2012), the DSR follows the following five stages: awareness of a problem, suggestion, development, evaluation, and conclusion. Figure 1 demonstrates the DSR model proposed by Takeda et al. (1990), and improved by Kuechler and Vaishnavi (2008), according to Carstensen & Bernhard (2019).

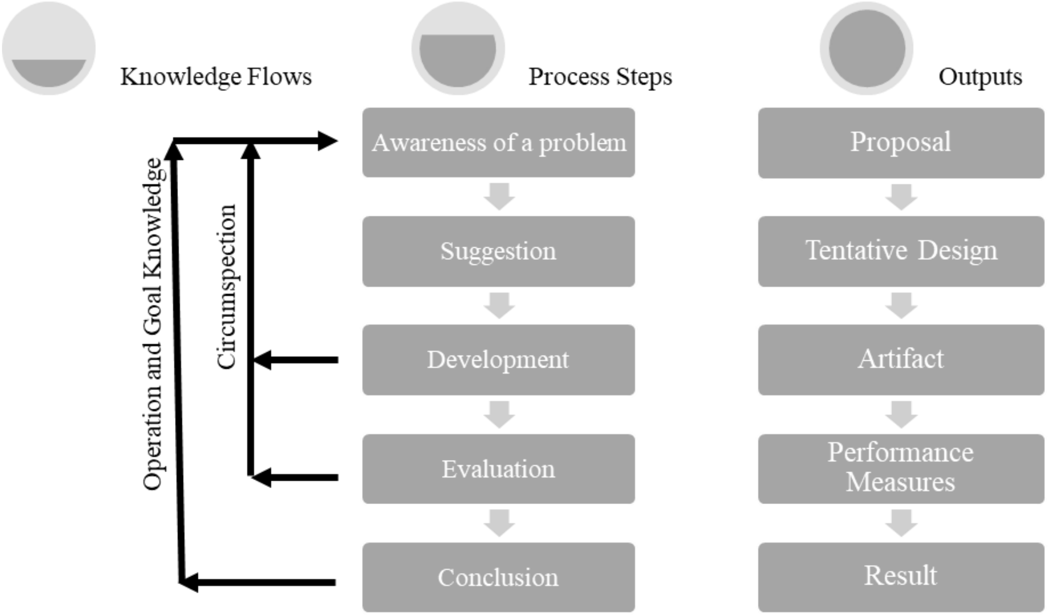

Figure 1 Procedure for the sequence of DSR

- Awareness of problem - The researcher becomes aware of a problem, possibly from industry, new technological developments, reading related disciplines, or other sources. Following this awareness, the researcher designs a formal or informal proposal for a research study (Kuechler & Vaishnavi, 2008). The research question is the result of this stage. At this point, attempts should be made to obtain as much information as possible relating to the context of the problem, along with searching pre-existing knowledge databases (Manson, 2006).
- Suggestion - The researcher can use previous knowledge to propose one or more artifacts that can solve the problem and improve the current situation (Dresch et al., 2015).
- Development - During this stage, the researcher will build one or more artifacts. The techniques used will vary widely, depending on the artifacts being constructed. Some examples of artifacts are algorithms with formal proof, software, and expert systems. The construction itself may not require any novelty beyond the state of practice, as the novelty is primarily in the design (Kuechler & Vaishnavi, 2008).
- Evaluation - This stage analyzes the artifact's behavior, which consists of the solution to the given problem. Testing is a prerequisite for understanding the processes that lead to the desired results. This stage can be supported by focus groups, experiments, or simulations (Goecks et al., 2021). The researcher evaluates the developed artifact from a theoretical overview by contextualizing a narrowly defined application (Chaudhuri et al., 2021).
- Conclusion - This stage aims to guarantee that the research can provide a reference for knowledge development within the practical and theoretical fields (Dresch et al., 2015).

## 2.5 AHP

According to Rashidi et al. (2017), the AHP is an MCDM method that uses a hierarchical structure and pairwise comparisons to prioritize criteria and/or sub-criteria. As the number of alternatives and/or criteria/subcriteria increases, the number of calculations for the comparison matrix also increases. This method involves decomposition, comparative judgments, and synthesis of priority. The AHP method developed by Saaty (1974, 1990) is a valuable tool for solving decision-making problems. The process begins by defining an overall objective. We will outline six steps for applying the AHP method in this research (Özcan et al., 2021; Kannan et al., 2021).

Step 1 - Define the problem by identifying criteria, sub-criteria, and alternatives to create a hierarchical structure.

Step 2 - Experts compare the criteria, sub-criteria, and alternatives based on their relative importance, called priority in the AHP method. The comparisons are based on the fundamental scale (Saaty, 1990), or simply the Saaty scale, as illustrated in Table 1.

Table 1
Saaty scale

| Values | Definition |
|---|---|
| 1 | Equal Importance |
| 3 | Moderate Importance |
| 5 | Strong Importance |
| 7 | Very Strong Importance |
| 9 | Extreme Importance |
| 2,4,6 and 8 | Intermediate Importance |

Step 3 – Each expert $k$ uses Table 1 and proposes its comparison matrix $\boldsymbol{A_k}$. The aggregate comparison matrix $\boldsymbol{A}$ consists of the geometric average of the $\boldsymbol{A_k}$ matrix components, for $k = 1, 2... K$, where $K$ is the number of experts consulted. The aggregation of individual judgments (AIJ) applies when the experts work in the same company (Saaty & Peniwati, 2013).

Step 4 - From the aggregated comparison matrix, we obtain the priority vector with the direct eigenvector $\boldsymbol{w}$ of $\boldsymbol{A}$, according to Equation 1, where $\lambda_{\max}$ is the maximum eigenvalue of $\boldsymbol{A}$.

$$\boldsymbol{A}\,\boldsymbol{w} = l_{\max}\,\boldsymbol{w} \tag{1}$$

Step 5 - The calculation of the $CR$ (consistency ratio) is given in Equations 2 and 3. In this context, $n$ represents the number of elements being compared, whether they are alternatives or criteria. The consistency index is denoted as $CI$, while the random consistency index is referred to as $RI$, which can be obtained from Table 2 and depends on the value of $n$.

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

Table 2
Random consistency index

| ***n*** | ***RI*** |
|---|---|
| 1 | 0 |
| 2 | 0 |
| 3 | 0.58 |
| 4 | 0.9 |
| 5 | 1.12 |
| 6 | 1.24 |
| 7 | 1.32 |
| 8 | 1.41 |
| 9 | 1.45 |
| 10 | 1.49 |

The *CR* should be less than 0.10. If the *CR* is greater than 0.10, the judgments must be revised.

Step 6 - Finally, the matrices are aggregated to establish local and global priorities, allowing for the best alternative selection.

## 3. Methodology

We conducted this research at a large Brazilian industrial plant in the steel market. The plant, located in Brazil's southeast region, has more than 20,000 employees and operates large-scale equipment such as sintering plants, blast furnaces, steelworks, continuous casting machines, hot and cold strip mills, and pickling plants. Hydraulic system maintenance management is a challenge in the steel industry. Given an identified problem, theoretical or practical, it is important to be aware of the consequences for the organization. It is also necessary to identify which objectives would be needed to consider the problem satisfactorily solved. Based on these implications, a systematic literature review was required to establish a framework. Focus groups could be used as an evaluation method for DSR, as they guarantee a more in-depth and collaborative discussion regarding the artifacts developed by the research (Lacerda et al., 2013).

### 3.1 Stages of the research

The stages of the research have been grouped into different steps for better monitoring and development. The steps comprise the DSR methodology, as shown in Table 3.

Table 3
DSR stages

| Process steps | Outputs | Objectives | Phases | Demands |
|---|---|---|---|---|
| Awareness of problem | Proposal | Select an innovative theme, focusing on its relevance to the academic and organizational environment. | 1 | - Propose a model to support decision-making towards improving the maintenance management of hydraulic systems in steel plants |
| | | | 2 | - Bibliographic survey<br>- Select the articles most relevant to the topic in the Scopus database |
| Suggestion | Tentative design | Propose one artifact that can solve the problem and improve the current situation | 3 | - Conduct a brainstorming session to define the model to be handled.<br>- Selected model: maintenance strategy. |
| | | | 4 | - Identify the relevant criteria and sub-criteria for the proposed framework based on current literature |
| Development | Artifact | The techniques used will vary widely, depending on the artifacts being constructed | 5 | - Design a hierarchical structure<br>- Include the objective, criteria, sub-criteria and alternatives for the framework developed |
| Evaluation | Performance measures | Evaluate the developed | 6 | - Define MCDM decision-making |

| | | | | |
|---|---|---|---|---|
| | | artifact from a theoretical overview by contextualizing a narrowly defined application | 7 | - Conduct judgment of values by experts. |
| | | | 8 | - Apply the AHP method. |
| | | | 9 | - Evaluate consistency of the results. |
| Conclusion | Result | Guarantee that the research can provide a reference for knowledge development within the practical and theoretical fields | 10 | - Ensure results are consistent for the academic and organizational environment |

The first stage involves defining the theme, which relates to the management of maintenance for hydraulic systems. The second stage consists of conducting a bibliographic search in the Scopus database to follow the scientific method in addressing the researcher's formulated question. The third stage involves brainstorming to identify factors that influence the maintenance of hydraulic systems. The prioritized issue is the selection of maintenance strategies. The fourth stage involves identifying the criteria and sub-criteria relevant to the proposed framework, based on current literature. The fifth stage presents the hierarchical framework design, comprising the objective, criteria, sub-criteria, and alternatives for the item selected in the third stage. The sixth stage involved establishing the MCDM, where the AHP was chosen. The seventh stage focuses on the experts' judgment regarding these values. Experts evaluate criteria, subcriteria, and alternatives based on their relative importance, known as priority in the AHP. The comparisons rely on the fundamental scale or Saaty scale (Saaty, 1990). The eighth stage involves applying the AHP method, while the ninth stage focuses on consistently evaluating the results to achieve the proposed objectives. The tenth and final stage focuses on conclusions, emphasizing the consistency of the results within the academic and organizational environment.

## 4. Results and discussion

### 4.1 Awareness of problem

The possibility of improving hydraulic system maintenance management performance motivated the development of this research to acquire new knowledge and a deeper understanding of the operational challenges faced by maintenance managers.

In decision-making, models provide guidance regarding the method's application.

We chose the Scopus database for the bibliographic search because it has the largest collection of peer-reviewed literature. Given its extensive coverage of academic material, we consider it the most accurate, pertinent, and up-to-date research database available. We combined the Boolean operator "AND" with the words "maintenance strategy", AHP, Steel Industry, and Steel Plant. The adopted inclusion criteria were limited to articles published between 2020 to 2024, written in English, and focused on providing recent technological information through a bibliographic search. The exclusion criteria were articles not pertinent to the topic, objectives, and research question. With these criteria in mind, we found 97 articles as shown in Figure 2.

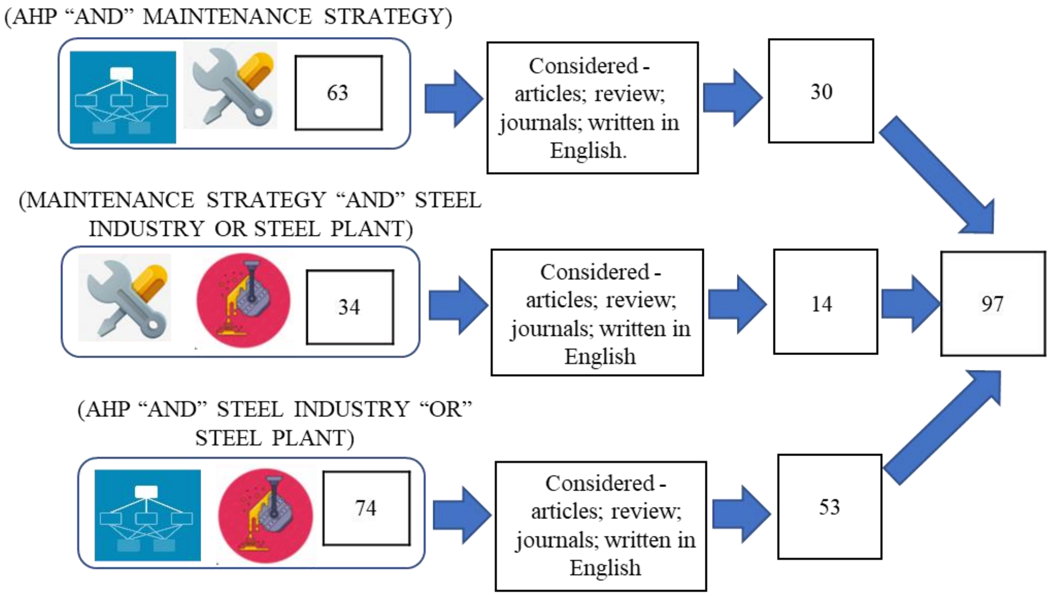

Figure 2 Article classification

The literature highlights some significant gaps in multi-criteria rankings for maintenance strategies. In particular, Avakh Darestani et. al. (2022) state that the evaluation and ranking of maintenance strategies provide valuable insights into a company's strengths and weaknesses, serving as crucial inputs for strategic programming.

### 4.2 Suggestions

We set up a committee by identifying specialists involved in maintenance engineering in the respective production area to check the crucial points of maintenance management of hydraulic systems from a diverse perspective regarding decision-making interests. The specialists considered for this project were from the maintenance engineering sector for hydraulic equipment, which is home to the most experienced professionals in this field. Their areas of expertise, professional roles, and years of experience are as follows:

Specialist 1 holds a Master's degree in metallurgical engineering and has 35 years of experience in the steel industry; Specialist 2 has a degree in production engineering and boasts 40 years of experience in the management and maintenance of hydraulic systems; Specialist 3 has a degree in mechanical engineering and has 15 years of experience in both the maintenance and project departments of hydraulic systems.

Brainstorming makes it possible to effectively identify the potential causes of a given problem, according to experts' opinions. The authors used this tool to improve a product's quality level by identifying the root causes of a decision problem (Siwiec & Pacana, 2021). A structured brainstorming session was held to identify the key issues and/or variables that influence the maintenance management of hydraulic systems. The evaluators assessed the proposals, and through a holistic view of hydraulic system maintenance management, Figure 3 shows insights from the brainstorming session.

The committee involved in this process operated as a focus group. According to Bauer and Gaskell (2017), a focus group consists of a transparent and accessible discussion in which all the issues involved are of common interest, and the exchange of opinions is founded on a rational argument. According to Rios et al. (2024), focus groups are conducted because of the need to include different perspectives and experiences of specialists, a necessity we address by involving experts from the maintenance department. Focus groups provide detailed feedback in the prototype development stages. In this context, the focus group method consisted of several phases involving a previously selected group of experts, carried out through meetings and workshops comprising a longitudinal approach and continuous improvement, with an average duration of 60 – 100 minutes. The iterations with experts in each phase included qualitative and quantitative analysis according to the framework under consideration.

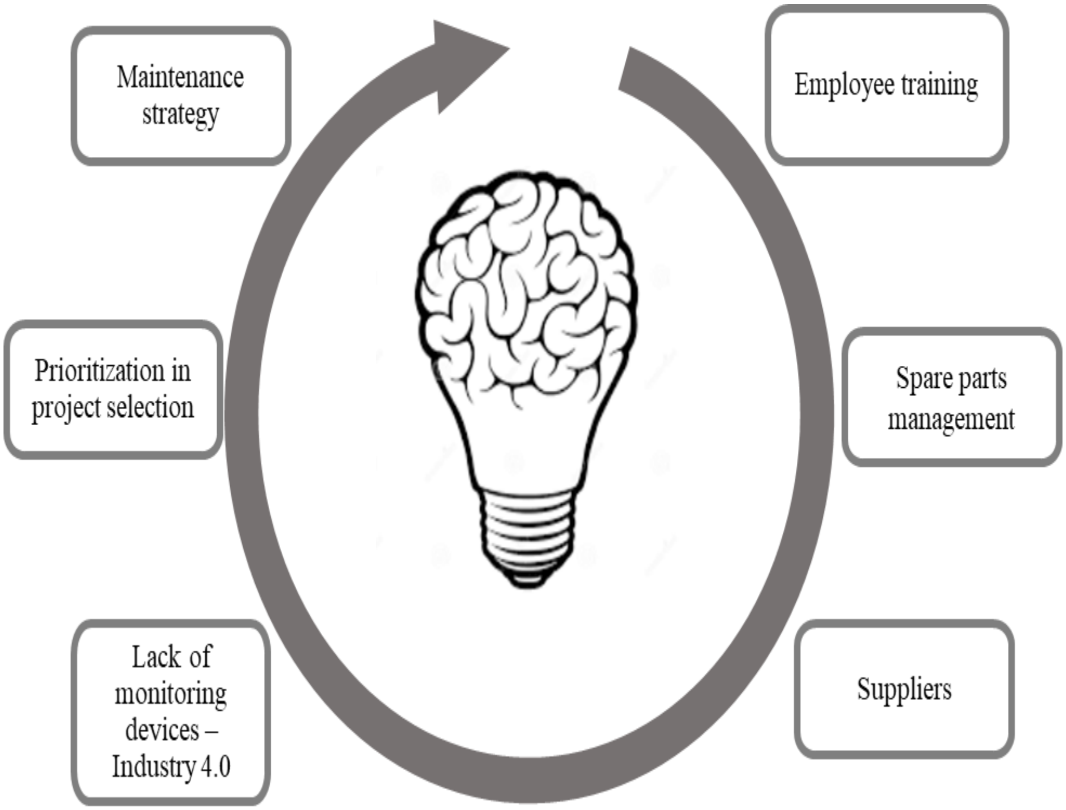

Figure 3 Brainstorming

The specialists participated in the brainstorming about the problems identified above, where the following considerations emerged:

- Maintenance strategy: A maintenance strategy is often a decision made with uncertainty. We consider this point as a key strategy for managing the maintenance of hydraulic systems.
- Project selection priority: Project prioritization sometimes also involves uncertainty, and prioritizing an organization's resources is fundamental to generating value.
- Lack of monitoring devices (Industry 4.0): This issue is of paramount importance due to the importance of monitoring the production process and an asset's performance; however, this issue is not a point of uncertainty.
- Supplier selection: In the steel industry, spare inputs for hydraulic systems require substantial attention, as these systems can pose risks to personal safety and the environment.
- Spare parts management: Spare parts inventory management generates uncertainty and becomes an item that requires substantial management attention.
- Training employees: Skilled professionals generate value for an organization, making it vital for the availability and reliability of assets. However, this item did not generate uncertainty.

A dedicated group of experts with extensive industrial experience prioritized the development of the framework for maintenance strategy selection. Although the experts have different duties, their opinions were considered equally since all are directly involved in maintenance management. There are several options for maintenance strategies, with the four main alternatives being autonomous maintenance, corrective maintenance, preventive maintenance, and predictive maintenance (Ge et al., 2017; Ohta et al., 2018). To determine the maintenance strategy to be implemented by the company, a criticality analysis was conducted. This analysis considered the four maintenance strategies. Consequently, data was gathered from current literature to establish the criteria for each maintenance strategy as it pertains to the maintenance of hydraulic systems.

a) Criteria and sub-criteria selection

The existing literature identified several key criteria that significantly influence the selection of maintenance strategies, such as safety, security, cost, reliability, availability, viability, and added value (Rahimi et al., 2014; Ge et al., 2017; Ohta et al., 2018; Carpitella et al., 2021). To determine the appropriate criteria for the maintenance strategy, we conducted a thorough analysis of the current literature, and the parameters such as cost, safety, reliability, quality, and viability, received approval from the committee of experts.

In economics, cost is defined as a metric that reflects the outcome of a process or the difference resulting from a decision (Ge et al., 2017). Safety in maintenance strategy refers to the measures taken to prevent unfavorable outcomes such as accidents, failures, and errors. It also involves managing known hazards to ensure they are kept at a manageable level, prioritizing the safety of the environment, the facilities, and individuals (Ohta et al., 2018). Reliability is defined as the probability of equipment functioning without failure over a specific period. It can be improved by reducing the frequency of failures (Patil et al., 2022). Quality is related to proper maintenance management, which enhances production quality and lowers costs. On the other hand, inadequate equipment maintenance management leads to breakdowns (Ohta et al., 2018). Viability is fundamentally connected to the effectiveness of a proposed strategy's implementation and its sustainability within the organization's existing Quality Management System (ISO 9001:2015).

The sub-criteria identified were selected from scientific articles and specific standards (ISO 4413:2022 and ISO 9001:2015). Verma et al. (2014) argue that lack of knowledge and noncompliance with standards are the primary causes of accidents in steel plants. Jocelyn et al. (2016) note that standards are essential for establishing proper maintenance practices Because maintenance activities inherently expose workers to significant risks. Additionally, Dindorf and Wos (2022) highlight that standards correlate with best practices for the operation and maintenance of hydraulic systems. This approach was aligned with the company's established goals and the operational conditions of the maintenance department. In this context, the experts chose the most suitable sub-criteria and assigned them to each criterion. Table 4 presents the selected criteria and sub-criteria along with the associated references.

Table 4
Selected criteria and sub-criteria

| Criteria | Sub-criteria |
|---|---|
| Cost (W1)<br>(Rahimi et al., 2014; Ge et al., 2017; Ohta et al., 2018; Carpitella et al., 2021) | Spare parts (W11)<br>(Ge et al., 2017; Carpitella et al., 2021) |
| | Labor (W12)<br>(Carpitella et al., 2021) |
| Safety (W2)<br>(Rahimi et al., 2014; Ge et al., 2017; Ohta et al., 2018; Carpitella et al., 2021) | Environment (W21)<br>(Rahimi et al., 2014; Ge et al., 2017; Ohta et al., 2018; Carpitella et al., 2021) |
| | Staff (W22)<br>(Rahimi et al., 2014; Ge et al., 2017; Ohta et al., 2018; Carpitella et al., 2021) |
| | Asset (W23)<br>(Rahimi et al., 2014; Ge et al., 2017; Carpitella et al., 2021) |
| Reliability (W3)<br>(Rahimi et al., 2014; Ge et al., 2017; Carpitella et al., 2021) | Spare parts availability (W31)<br>(Ohta et al., 2018; Ge et al., 2017; Carpitella et al., 2021) |
| | < MTTR (Average time for repair) (W32)<br>(Carpitella et al., 2021) |
| | Training (W33)<br>(Rahimi et al., 2014; Ge et al., 2017; Carpitella et al., 2021) |
| | Failure analysis (W34)<br>(Ohta et al., 2018; Ge et al., 2017; Carpitella et al., 2021) |
| Quality (W4)<br>(Ohta et al., 2018) | Specialized labor (W41)<br>(Ohta et al., 2018) |
| | Appropriate spares (W42)<br>(ABNISO 9001:2015)<br>(ISO 4413:2022) |
| | > MTBF (Mean time to repair) (W43)<br>(Carpitella et al., 2021) |
| Viability (W5)<br>(ISO 9001:2015) | Trend of market (W51)<br>(ISO 9001:2015) |
| | Modernization of equipment (W52)<br>(ISO 4413:2022) |

### 4.3 Development

To employ the AHP method, a hierarchical tree was developed containing one objective, six criteria, fourteen sub-criteria, and four alternatives, as shown in Figure 4.

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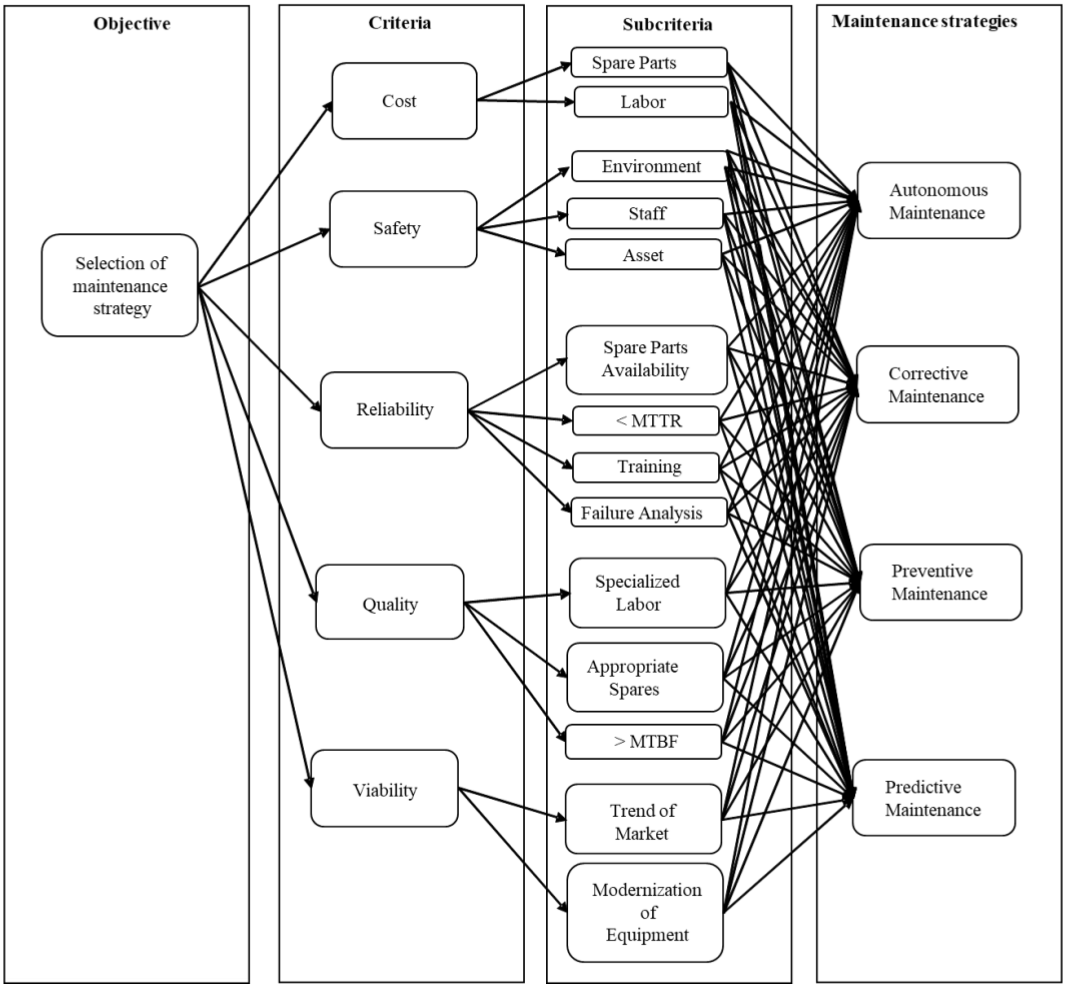

Figure 4 Hierarchy for AHP application

### 4.4 Evaluation

We chose the AHP method as it provides a comprehensive and rational procedure for modeling a decision problem, representing and quantifying the variables involved, and aiming for agile understanding by all those involved. In addition to being the most widely used method for MCDM, this method can be applied in an operational environment since the organization does not need to purchase specific software. We used Microsoft Excel software to apply this method, using alternatives, criteria, and sub-criteria according to the proposed framework.

In order to apply the AHP method, three maintenance engineering experts were interviewed and they assigned values for each variable according to the Saaty scale as follows: one matrix in relation to the objective, five matrices in relation to the criteria, and fourteen matrices in relation to the maintenance strategy alternatives.

Table 5 presents the comparisons made by the three experts between the criteria and the objective of this study.

Table 5
Judgment of criteria by experts

| **E1** | **W1** | **W2** | **W3** | **W4** | **W5** | **E2** | **W1** | **W2** | **W3** | **W4** | **W5** | **E3** | **W1** | **W2** | **W3** | **W4** | **W5** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **W1** | 1 | 0.33 | 0.20 | 0.14 | 3 | W1 | 1 | 0.20 | 0.33 | 2 | 1 | W1 | 1 | 0.20 | 0.20 | 4 | 3 |
| **W2** | 3 | 1 | 0,33 | 0.20 | 5 | W2 | 5 | 1 | 3 | 3 | 5 | W2 | 5 | 1 | 3 | 5 | 7 |
| **W3** | 5 | 3 | 1 | 0.50 | 7 | W3 | 3 | 0.33 | 1 | 4 | 3 | W3 | 5 | 0.33 | 1 | 5 | 5 |
| **W4** | 7 | 5 | 2 | 1 | 7 | W4 | 0.50 | 0.33 | 0.25 | 1 | 3 | W4 | 0.25 | 0.20 | 0.20 | 1 | 2 |
| **W5** | 0.33 | 0.20 | 0.4 | 0.14 | 1 | W5 | 1 | 0.20 | 0.33 | 0.33 | 1 | W5 | 0.33 | 0.14 | 0.20 | 0.50 | 1 |

Table 6 shows the aggregate comparisons for the three experts. The Safety (W2) criterion and Reliability (W3) criterion have the highest priority, which corresponds to the requirements of a maintenance strategy for hydraulic systems applied to the steel sector.

Table 6
Aggregate priority of criteria

| Aggregate | W1 | W2 | W3 | W4 | W5 | Priority |
|---|---|---|---|---|---|---|
| W1 | 1 | 0.24 | 0.24 | 1.05 | 2.08 | 10.65% |
| W2 | 4.22 | 1 | 1.44 | 1.44 | 5.59 | 35.31% |
| W3 | 4.22 | 0.69 | 1 | 2.15 | 4.72 | 31.94% |
| W4 | 0.96 | 0.69 | 0.46 | 1 | 3.48 | 16.43% |
| W5 | 0.48 | 0.18 | 0.21 | 0.29 | 1 | 5.67% |

For the aggregated comparison matrix shown in Table 6, we obtained $l_{\max}$ using the sum vector and the normalized eigenvector, where the multiplication matrix shown below in matrix 4 is calculated.

$$l_{\max} = [10.87; 2.80; 3.35; 5.93; 16.87].\begin{bmatrix} 0.657 \\ 2.179 \\ 1.971 \\ 1.014 \\ 0.350 \end{bmatrix} \approx 5.15 \tag{4}$$

The CI was calculated according to Equation 5:

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} = \frac{(5.15-5)}{(5-1)} = 0.037 \tag{5}$$

The CR was calculated according to Equation 6:

$$CR = \frac{CI}{\mathrm{IR}} = \frac{0.037}{1.12} = 0.033 \qquad (6)$$

For the aggregated comparison we obtained $l_{\max}$ = 5.15, $CI \approx 0.037$ and $CR \approx 0.033$. Therefore, the judgments do not need to be revised, as the CR is below 0.10. As a result, the safety and reliability criteria were found to have the highest priority. The experts then compared the sub-criteria according to their relative importance in the criterion.

Specialists then compared the sub-criteria according to their relative importance in the criterion. Table 7 illustrates the aggregate comparisons for the Cost criterion (W1). The local priority was obtained by normalizing the right eigenvector of the comparison matrix. The global priority was obtained by multiplying the local priority of the sub-criterion by the priority of the criterion, in this case, 10.65%.

Table 6
Aggregate priority of the sub-criteria under the Cost criterion

| Cost | W11 | W12 | Local | Overall |
|---|---|---|---|---|
| W11 | 1 | 1.65 | 62.28% | 6.63% |
| W12 | 0.61 | 1 | 37.72% | 4.02% |

For the aggregate comparison matrix presented in Table 6, a consistency analysis was not necessary because for n = 2; therefore, CI = RI = CR = 0. Consequently, the judgments do not need to be revised. The comparisons of the sub-criteria were repeated according to the relative importance of each criterion, which is shown in Tables 7 –10.

Table 7
Aggregate priority of the sub-criteria under the Safety criterion

| Safety | W21 | W22 | W23 | Local | Overall |
|---|---|---|---|---|---|
| W21 | 1 | 0.38 | 3 | 27.46% | 9.7% |
| W22 | 2.62 | 1 | 5.00 | 61.89% | 21.85% |
| W23 | 0.33 | 0.20 | 1 | 10.64% | 3.76% |

Table 8
Aggregate priority of the sub-criteria under the Reliability criterion

| Reliability | W31 | W32 | W33 | W34 | Local | Overall |
|---|---|---|---|---|---|---|
| W31 | 1.00 | 4.38 | 4.22 | 1.71 | 48.19% | 15.39% |
| W32 | 0.23 | 1.00 | 0.33 | 0.28 | 7.77% | 2.48% |
| W33 | 0.24 | 3.00 | 1.00 | 0.63 | 16.63% | 5.31% |
| W34 | 0.58 | 3.56 | 1.59 | 1.00 | 27.40% | 8.75% |

Table 9
Aggregate priority of the sub-criteria under the Quality criterion

| Quality | W41 | W42 | W43 | Local | Overall |
|---|---|---|---|---|---|
| W41 | 1.00 | 3.56 | 3.30 | 63.05% | 10.36% |
| W42 | 0.28 | 1.00 | 0.79 | 16.83% | 2.76% |
| W43 | 0.30 | 1.26 | 1.00 | 20.12% | 3.31% |

Table 10
Aggregate priority of the sub-criteria under the Viability criterion

| Viability | W51 | W52 | Local | Overall |
|---|---|---|---|---|
| W51 | 1.00 | 0.69 | 40.95% | 2.32% |
| W52 | 1.44 | 1.00 | 59.05% | 3.35% |

The values show that the sub-criterion with the highest added value for the Cost criterion (W1) is Spare parts (W11), the sub-criterion with the highest added value for the Safety criterion (W2) is Staff (W22), the sub-criterion with the highest added value for the Reliability criterion (W3) is Spare parts availability (W31), the sub-criterion with the highest added value for the Quality criterion (W4) is Specialized labor (W41); finally, the sub-criterion with the highest added value for the Viability criterion (W5) is Modernization of equipment (W52). The sub-criteria of Spare parts and Spare parts availability are relevant to stock management, indicating that these items are paramount. On the other hand, Specialized labor and People safety show that hydraulic systems assets require specialized management and maintenance. The Modernization of equipment demonstrates that these assets are continually undergoing evolution. Subsequently, analogous matrices were filled in by the experts, where they compared the alternatives according to each sub-criterion, resulting in the decision matrix shown in Table 11.

Table 11
Aggregated priority of the alternatives

| **Strategy** | **W11** | **W12** | **W21** | **W22** | **W23** | **W31** | **W32** | **W33** | **W34** | **W41** | **W42** | **W43** | **W51** | **W52** | **Overall** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Autonomous** | 16% | 24% | 45% | 47% | 74% | 23% | 20% | 34% | 53% | 35% | 29% | 22% | 62% | 100% | 40% | |
| **Corrective** | 31% | 21% | 13% | 12% | 11% | 100% | 24% | 13% | 9% | 25% | 17% | 11% | 11% | 11% | 29% | |
| **Preventive** | 58% | 75% | 66% | 100% | 86% | 92% | 100% | 66% | 29% | 41% | 88% | 63% | 51% | 22% | 72% | |
| **Predictive** | 100% | 100% | 100% | 67% | 100% | 75% | 46% | 100% | 100% | 100% | 100% | 100% | 100% | 62% | **86%** | |

The decision matrix shows that the predictive maintenance strategy has the highest added value, with 43%, which is significant compared to the other results. As a result, this maintenance strategy should be a priority. Regarding the preventive and autonomous maintenance strategies, some managers had doubts about the outcome. The results show that the preventive maintenance strategy prevails over the autonomous maintenance strategy. The reason behind these results is the importance of a specialized workforce to manage and maintain these assets. The corrective maintenance strategy had a very low added value, which indicates such maintenance should be avoided. These figures support predictive techniques as fundamental to the availability, reliability, and safety of assets related to hydraulic systems. Thus, we can expect to avoid production losses that cause injury to the steel industry. Hydraulic systems are vulnerable to failure during operation, which can result in decreased system efficiency, lower operational performance, and safety hazards. Deploying an efficient maintenance strategy with proper management and precise system monitoring guarantees reliable system operation. Organizations are increasingly adopting advanced monitoring techniques to customize maintenance strategies. Predictive maintenance has become a promising solution for manufacturing industries, where the performance of hydraulic systems is paramount (Noura et al., 2024).

A sensitivity analysis was performed to evaluate the robustness of the results by systematically varying the criteria weights and observing their effects on the selection of maintenance strategies. Figure 5 illustrates the results of the sensitivity analysis, showing the performance of alternatives with dynamic criteria weights regarding the attribute W1 (Cost). The study revealed two distinct ranking scenarios based on changes in criteria weights. For weights of up to 80%, the ranking was as follows: Predictive, Preventive, Autonomous, and Corrective. However, when the weights exceeded 80%, the ranking changed to Predictive, Preventive, Corrective, and Autonomous. These findings demonstrate the stability of the proposed strategy selection under varying conditions.

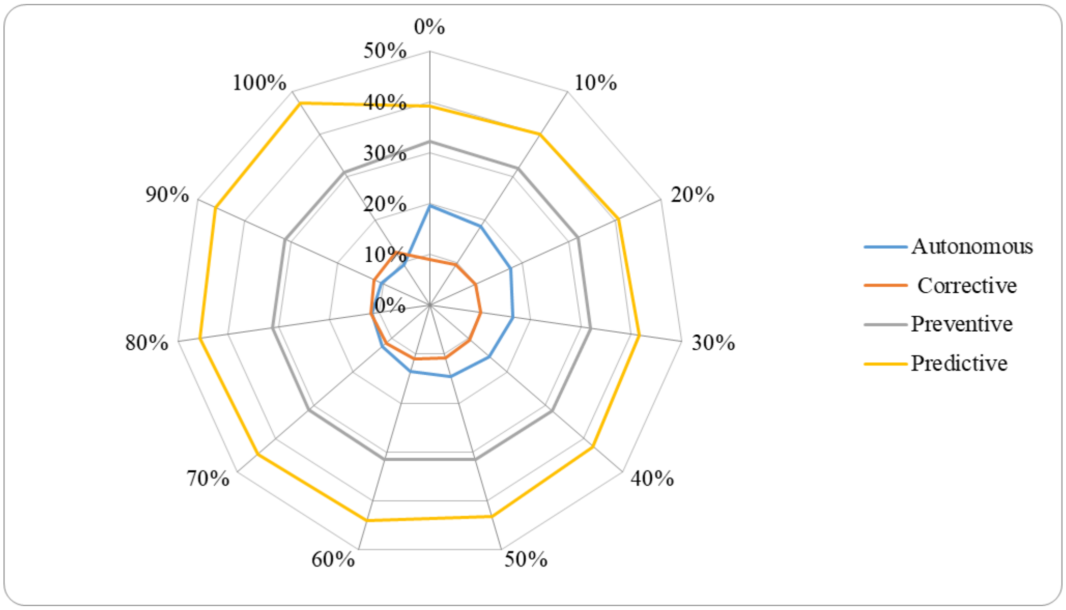

Figure 5 Performance sensitivity analysis of alternatives

### 4.5 Discussion of results

Promoting interactions between an organization and academia optimizes engagement, cooperation, and knowledge sharing, thus encouraging technological development and innovation environments.

a) Results of the research from a theoretical perspective
Through a literature review, the main criteria and sub-criteria relevant to the framework developed were identified to meet the premises of the proposed problem. The primary limitation of this study is its restricted scope, as the framework development and validation were based solely on data and specialist opinions gathered from the maintenance area of a single organization within the steel industry. Based on the technical analysis conducted by the maintenance management department of the studied organization, it is evident that the most suitable method for addressing the research question and achieving the outlined objectives is DSR. This method is particularly effective due to its theoretical approach, which is tailored for specific contexts and aids in decision-making while minimizing risk.

b) Results from the organizational environment perspective
With the proposed framework, managers can devise strategies to navigate the increasingly demanding and competitive challenges in the industrial sector. In this context, we developed a protocol based on established parameters to guide users in implementing appropriate maintenance strategies for this type of asset. The AHP method is highly valuable because of its widespread application and established effectiveness, offering substantial support to managers in decision-making. Many specialists had never applied the AHP in practice before, and its implementation sparked curiosity and learning within the maintenance department of the organization.

## 5. Conclusion

Selecting an appropriate maintenance strategy increases equipment availability and reduces an organization’s maintenance costs. The proposed framework effectively identified the prioritization of various maintenance strategies. The results indicated that safety and reliability were the top priorities. The priority order of the maintenance strategies was as follows: predictive maintenance, preventive maintenance, autonomous maintenance, and corrective maintenance. The latter, in particular, was found to provide very low added value, suggesting that it should be avoided for hydraulic systems. In this regard, predictive maintenance was prioritized for hydraulic assets.

This approach enables real-time monitoring of hydraulic systems through sensor utilization, thus increasing the response time for troubleshooting. As a result, equipment downtime is reduced, ultimately increasing the value delivered to the end customer. Through this research, the main goal of proposing a model to support decision-making toward selecting a maintenance strategy for hydraulic systems in steel plants was achieved. The proposed framework is a valuable tool for decision-making and will aid in resource optimization for industry managers. Furthermore, the sensitivity analysis confirmed the framework’s robustness, demonstrating steady performance under different criteria weights and providing decision-makers with confidence in its application.

Concerning the proposed research question, it was demonstrated that the DSR approach contributes to developing an innovative framework for the maintenance management of hydraulic systems in steel plants, which becomes fundamental for assertive decision-making. For future studies, we suggest exploring additional MCDM techniques, such as Fuzzy Set Theory or Multi-Attribute Utility Theory, to determine the results between some alternatives. The proposed methodology can also be applied to other business sectors, including finance, human resources, and production.

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