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CASE STUDY

Multi-criteria classification of spare parts in the steel industry

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ABSTRACT

Goal: This research addresses the critical challenge of evaluating spare parts inventory in the steel industry to enhance maintenance efficiency and reduce operational costs.

Design/methodology/approach: The study applies the Analytic Hierarchy Process (AHP), a widely recognized multi-criteria decision-making (MCDM) method, to develop a robust decision support system. A hierarchical structure of criteria and sub-criteria, along with alternatives (spare parts), was constructed based on an extensive literature review and validated through input from three maintenance and inventory management experts. The system was implemented in a Brazilian steel plant.

Results: The AHP-based framework systematically classified spare parts, emphasizing their criticality. Spare Parts 1 and 2 were categorized as Class B, scoring 0.6 and 0.56, while Spare Parts 3 and 4 were classified as Class A, scoring 0.82 and 0.83. These findings confirm the effectiveness of the AHP methodology in prioritizing spare parts for improved inventory management and decision-making. Sensitivity analysis validated the framework's robustness, demonstrating stable classifications across varying criteria weights.

Limitations of the investigation: While tailored to a Brazilian steel plant, the framework's scalability is evident. Limitations include its reliance on a specific context and the involvement of a limited number of experts, suggesting opportunities for broader validation.

Practical implications: The simplified AHP framework gives managers an accessible tool for classifying spare parts, eliminating the need for complex hybrid methods. It enables efficient decision-making, particularly in industries with high operational demands.

Originality: This research contributes a novel multi-criteria decision-making model for spare parts classification, significantly advancing maintenance efficiency and cost-effectiveness compared to traditional single-criterion approaches.

Keywords: Analytic hierarchy process; Multi-criteria decision-making; Inventory management; Steel industry; Spare parts classification.

1 INTRODUCTION

In a competitive market, industries often maintain low inventory levels to balance maintenance and ordering costs. A robust supply chain management strategy for spare parts is essential for ensuring operational efficiency and maintaining competitiveness (Silva & Fontana, 2020). The availability of spare parts is crucial for improving the efficiency of maintenance processes which, in turn, supports the organization's competitive advantage. However, managing inventory for high-quality spare parts presents significant challenges, as unscheduled breakdowns can lead to

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decreased asset availability and performance (Antosz and Ratnayake, 2019; Guevara-Rosero et al., 2023). A well-defined spare parts management strategy is vital to ensuring timely maintenance and replacement, minimizing stock management costs, and optimizing the utilization of organizational resources (Gao *et al.*, 2024). Inventory control is vital in industrial settings because providing the correct item in quantity at the right time can reduce costs while improving operational efficiency. Therefore, inventory planning requires careful attention from organizational management (Mallick *et al.*, 2019).

Spare parts are essential for sustaining equipment in continuous operation, minimizing downtime, and supporting maintenance activities. Life-cycle cost management plays a pivotal role, as it models, quantifies, and controls the costs of assets from design through disposal (Kulshrestha *et al.*, 2024). Since spare parts costs are closely linked to equipment life-cycle costs, managing them effectively is crucial for inventory control operations to prevent over-inventory and associated storage costs. Spare parts classification has become a standard practice for improving inventory management success (Hu *et al.*, 2018).

Maintenance is integral to operational processes in industrial plants, as equipment breakdowns can have severe consequences, including environmental disasters, personal accidents, and substantial financial losses. Hydraulic system breakdowns are particularly problematic, as they can halt production entirely, making maintenance departments critical in resolving these issues (Alenany *et al.*, 2021). Due to their versatility, hydraulic systems are widely used across industries. They are among the most critical assets requiring high operational availability, and ensuring their performance demands appropriate maintenance measures (Torre *et al.*, 2024).

Therefore, this study aims to develop an approach that optimizes the trade-offs between risks and service levels, specifically focusing on evaluating the criticality of spare parts for hydraulic systems in steel industries. In this context, our research question (RQ) is: How can we effectively assess the criticality of hydraulic spare parts in the steel sector? This research aims to create strategies that assist managers in decision-making by identifying the necessary criteria and sub-criteria for evaluating spare parts' criticality. This challenge is approached as a multiple-criteria decision-making (MCDM) problem. We utilize the Analytic Hierarchy Process (AHP), a well-established MCDM method developed by Saaty (1980), which has proven effective in addressing problems with multiple attributes, particularly within logistics and supply chain management (Khan *et al.*, 2018; Piprani *et al.*, 2020). The AHP organizes decision problems hierarchically, breaking them into objectives, criteria, sub-criteria, and alternative solutions. This structure aids decision-makers in understanding complex issues and facilitates informed decision-making (Elraaid *et al.*, 2024).

This manuscript comprises five sections. Following this introduction, the second section provides a comprehensive literature review on spare parts classification. The third section details the research methodology, focusing on the AHP. The fourth section presents and discusses the results. Finally, concluding remarks emphasize this study's findings and contributions.

2 LITERATURE REVIEW

The literature review was conducted through a systematic and exhaustive search of the Scopus and Web of Science (WOS) databases to identify contributions relevant to the field of multi-criteria decision-making (MCDM), specifically frameworks for spare parts classification in the steel industry. The search strategy utilized Boolean operators ("OR" and "AND") to combine keywords such as “AHP,” “analytic hierarchy process,” “decision making,” “MCDA,” “MCDM,” “multi-criteria,” “maintenance,” “inventory,” and “spare parts.” Searches were performed within the title, abstract, and keywords (TITLE-ABS-KEY) fields to ensure comprehensive coverage of pertinent studies (Table 1).

The inclusion criteria prioritized peer-reviewed journal articles written in English and published between 2014 and 2023. This timeframe was selected to encompass the most recent developments in the application of MCDM to spare parts management. Additionally, the selection was limited to journal articles to uphold methodological rigor, excluding conference proceedings, book chapters, and other non-peer-reviewed materials. Studies unrelated to industrial applications, particularly those centered on healthcare, education, or domains outside the scope of spare parts management, were excluded unless their methodological insights were transferable to the research context. Furthermore, duplicate records retrieved from both databases were systematically removed.

Table 1 - Documents in the Scopus and WOS databases

	"ahp" OR "analytic hierarchy process" OR "decision making" OR "mcda" OR "mcdm" OR "multi-criteria"		"maintenance"		"inventory" AND "spare parts"	
Year	Scopus	WOS	Scopus	WOS	Scopus	WOS
2014	46,707	34,726	31,525	25,425	88	66
2015	50,139	38,007	30,898	26,540	99	82
2016	53,312	41,693	32,500	27,475	59	62
2017	57,834	44,954	34,105	29,030	98	86
2018	64,059	48,793	35,810	30,274	95	80
2019	72,092	64,553	39,074	35,472	114	93
2020	79,645	70,430	41,419	37,144	116	85
2021	86,808	77,101	45,162	40,087	109	83
2022	89,445	77,613	46,461	39,042	97	86
2023	98,576	74,047	47,015	36,057	105	68
Total	698,617	571,917	383,970	326,546	980	791

Sources: www.scopus.com and www.webofscience.com

The comparative analysis revealed that Scopus offered broader coverage of the topic, with a larger number of relevant articles aligning with the thematic focus of this study. Consequently, Scopus was chosen as the primary repository, enabling consistency in data collection and analysis. From an initial dataset of 980 documents, 229 articles were identified as meeting the inclusion and exclusion criteria. The search query used for Scopus was as follows: (TITLE-ABS-KEY (AHP) OR TITLE-ABS-KEY (decision making) OR TITLE-ABS-KEY (analytic hierarchy process) OR TITLE-ABS-KEY (mcda) OR TITLE-ABS-KEY (mcdm) OR TITLE-ABS-KEY (multi-criteria) AND TITLE-ABS-KEY (maintenance) AND TITLE-ABS-KEY (inventory) OR TITLE-ABS-KEY (spare parts) AND PUBYEAR > 2013 AND PUBYEAR < 2024 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE,"j")) AND (LIMIT-TO (LANGUAGE,"English). The complete list of the 229 selected documents is publicly accessible in the repository at https://hdl.handle.net/11449/259746.

Figure 1 illustrates the subject area distribution of the 229 documents, with engineering dominating at 30%. Business, management, and accounting, representing less than 10%, highlight the potential for further management-focused research in this domain.

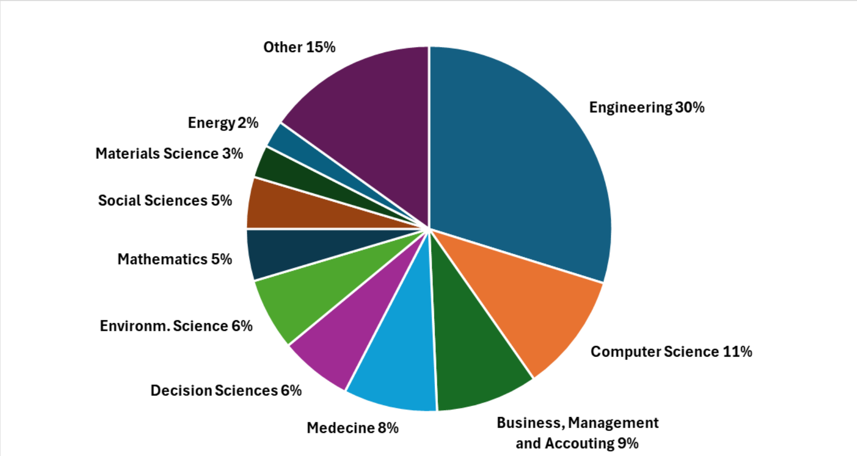

Figure 1 - Publication by subject area of 229 most relevant documents.
Source: www.scopus.com

Figure 2 shows the top 10 contributing countries, with the United States leading with over 45 documents. Notably, no Latin American countries appear in the distribution, underscoring a significant regional research gap, which this study aims to address.

The literature review revealed substantial gaps in multi-criteria frameworks for classifying spare parts criticality. Antosz and Ratnayake (2019) emphasized the potential of AHP in integrating cost and availability criteria for improved spare parts management. Similarly, Mindt *et al.* (2022) proposed a hybrid framework combining qualitative and quantitative approaches to optimize spare parts provision. Ghuge *et al.* (2022) explored trade-offs in spare parts management, highlighting the balance between storage costs and the risk of shortages. Despite these contributions, existing studies lack comprehensive application of multi-criteria frameworks tailored to the steel industry.

This research, in contrast, contributes to the field by presenting an innovative multi-criteria decision-making framework designed explicitly for classifying hydraulic spare parts in steel industries. The framework, developed collaboratively by researchers from two South American universities and tested in a Brazilian steel plant, extends traditional approaches by incorporating broader managerial criteria. It enhances cost-effectiveness and provides valuable implications for addressing operational challenges in other steel industries. Moreover, this study represents a novel contribution to international literature, bridging the regional gap and advancing managerial perspectives in spare parts classification.

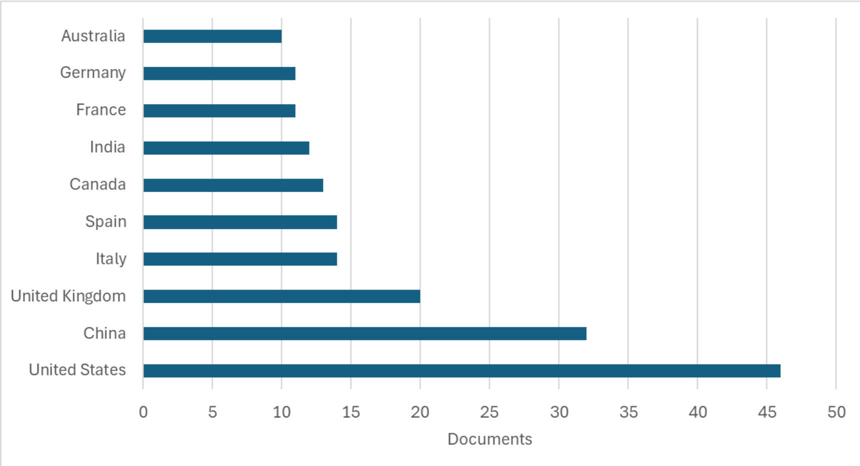

Figure 2 - Publication by country of 229 most relevant documents.
Source: www.scopus.com

2.1 Criticality and management of spare parts

Asset availability and reliability directly influence production line productivity, making effective maintenance critical. Spare parts availability is particularly vital, as organizations prioritize establishing robust inventory control policies to ensure maintenance efficiency (Ilgin, 2019). Traditional spare parts evaluations often focus on economic factors, which may fail to capture their true criticality. A more comprehensive assessment of critical spare parts ensures better alignment with inventory control policies (Gong *et al.*, 2022). Spare parts inventory management research is classified into three key categories: forecasting, inventory management strategies, and spare parts classification. The literature presents diverse techniques for spare parts analysis, which fall into quantitative methods (e.g., analyzing spare parts data) and qualitative methods (e.g., managers' expert opinions) (Ferreira *et al.*, 2018).

Several widely adopted inventory classification methods include ABC (*always*, *better*, and *control*), FSN (*fast*, slow-moving, and *non-moving*), HML (*high*, *medium*, and *low*), SDE (*scarce*, *difficult*, and *easy*), and VED (*vital*, *essential*, and *desirable*). These methods have been tailored for various applications, such as optimizing purchasing or storage processes to minimize costs (Lestari *et al.*, 2019). The ABC Analysis, or Pareto Analysis, is the most common quantitative technique, grouping inventory into high (Class A), moderate (Class B), and low (Class C) priority levels based on demand values (Mehdizadeh, 2020). However, this method has limitations, necessitating additional criteria for a more nuanced classification. Managers must define the number of criteria and assign an appropriate weight to each (Ilgin, 2019; Mor *et al.*, 2021; Pérez Vergara *et al.*, 2020). VED Analysis evaluates spare parts based on their criticality to the main product's functionality. Items that cause complete process shutdowns, especially when no backup is available, are classified as vital (Mor *et al.*, 2021). Combining ABC and VED analyses through multi-criteria classifications can further enhance service levels (Cardós Carboneras *et al.*, 2021).

Criticality is an essential dimension of spare parts management (Ayu Nariswari *et al.*, 2019). Key criteria for assessing spare parts criticality typically include equipment importance, failure probability, replacement time, suppliers' availability, technical specifications, and maintenance requirements. Antosz and Ratnayake (2019) categorize these criteria into logistics (e.g., supplier availability, lead time, cost) and maintenance requirements (e.g., replacement time, failure frequency, and equipment category).

Table 2 summarizes the logistics and maintenance criteria, sub-criteria, and attributes relevant to spare parts criticality assessments.

Table 2 - Multiple criteria for spare parts criticality

Criterion	Sub-criterion	Attributes
Logistics	Economics	Price, stocking strategy, and stock-out implications
	Replenishment	Lead time and ordering policy
	Suppliers	Proximity, responsiveness, and uniqueness
Maintenance	Equipment	Criticality of the equipment, life cycle stage, and repairability
	Failures	Frequency of failure and predictability
	Operations	Availability of technical information, maintenance policy, operation time, and responsiveness

Source: Adapted from Alenany *et al.* (2021).

3 METHODOLOGY

Multi-Criteria Decision Making (MCDM) is widely applied across various research areas to analyze conflicting decisions and provide optimal solutions for diverse problems (Campos *et al.*, 2021). Such problems often require thorough evaluation as organizations strive for higher productivity, improved quality, and reduced cost. MCDM encompasses two main components: Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM). MADM addresses problems with a limited number of alternatives, whereas MODM deals with larger or infinite alternative sets (Ohta *et al.*, 2020; Rahman *et al.*, 2021). This research employs MADM, as the decision problem involves a small, finite set of alternatives.

The study was conducted in a steel industry located in southeastern Brazil, which employs over 10,000 workers. The plant operates large-scale equipment such as blast furnaces, hot and cold strip mills, and casting lines. Determining the criticality of spare parts in such an environment poses challenges, as spare parts may hold varying criticality levels depending on maintenance and logistics priorities. To address this, spare parts were arranged hierarchically, and quantitative and qualitative criteria were combined to frame the research problem. Quantitative analyses leveraged existing data on spare parts characteristics, while qualitative analyses incorporated expert judgments based on experience and domain knowledge to identify the most critical spare parts accurately. The study engaged three experts: two engineers from the maintenance engineering department and one analyst from the stock management and materials planning department. All experts were equally involved in maintenance management, ensuring balanced contributions to the evaluation process.

The research process comprised multiple steps, including defining the research theme, conducting a bibliographic survey, creating a hierarchical structure, selecting the MCDM method, eliciting expert judgments, applying the AHP, assessing consistency, and drawing conclusions. The methodological flow is presented in Figure 3.

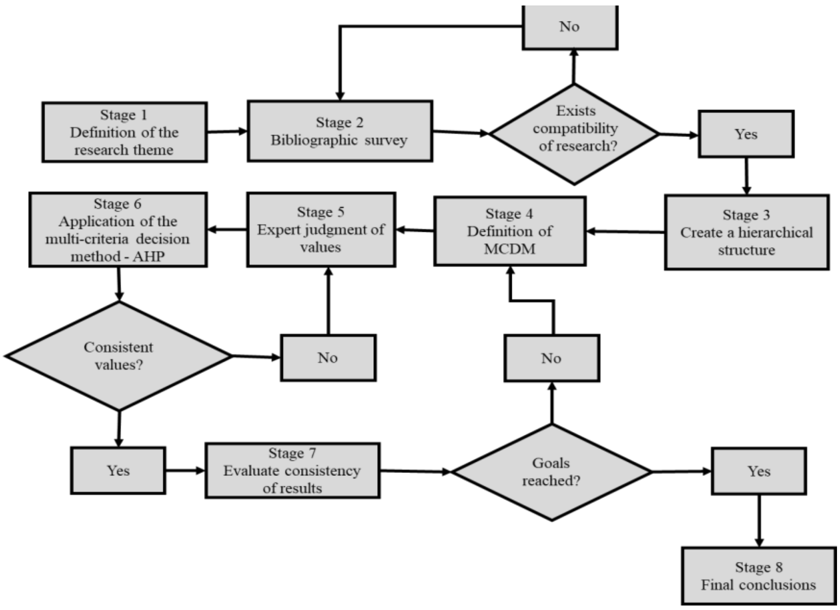

Figure 3 - Flowchart of the methodological approach
Source: The authors themselves.

The AHP, developed by Saaty (1974, 1977, 2013), is one of the most widely applied MCDM methods in both scientific and business domains (Abdulgader et. Al., 2018; Canco *et al.*, 2021; Gonzalez-Urango *et al.*, 2024). Identifying criteria and sub-criteria related to a management problem depends on the perspectives and experiences of experts. AHP's structured framework minimizes variability in expert evaluations and promotes transparent decision-making (Unver and Ergenc, 2021). AHP has been successfully applied across fields such as industry, investment, engineering, finance, logistics, product design, education, and policy-making (Sahin, 2024). This method was chosen for its comprehensive modeling of decision problems, which allows for effective representation and quantification of variables. Importantly, AHP is operationally accessible, as it does not require specialized software and can be implemented using widely available tools like Microsoft Excel.

In inventory management, AHP has demonstrated its utility in diverse applications. For example, Pérez Vergara *et al.* (2020) combined AHP with ABC analysis to improve distributed decision-making while Sales *et al.* (2020) employed the AHP for risk assessment in inventory management. Ghuge *et al.* (2022) developed a framework related to the spare part segmentation for additive manufacturing by applying the AHP method, and, Yunwen *et al.* (2022) used it to evaluate civil aircraft spare parts. However, research addressing hydraulic systems inventory management remains scarce, underscoring the novelty of this study.

Applying the AHP framework determined the levels of significance and consistency among criteria, enabling a more objective assessment of the problem. The decision problem was structured hierarchically in the first step, with the objective at the top, criteria, and sub-criteria in the middle, and alternatives at the bottom. In a hierarchical model, the elements appear in levels, and the elements at the lower level require consideration of the elements at the higher level. First, criteria must be pairwise compared regarding the decision objective (Saaty, 2013). Next, sub-criteria must be compared against their criteria. Alternatives were then evaluated against the sub-criteria. Figure 4 displays an example of a hierarchy model.

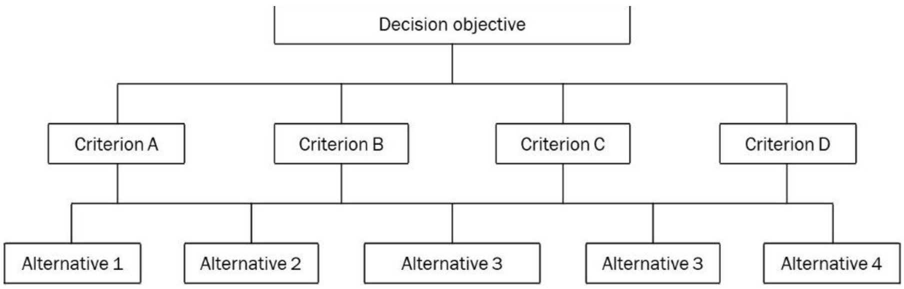

Figure 4 - Hierarchy model with four criteria and five alternatives
Source: The authors themselves.

Figure 5 presents the hierarchy model tailored for this study, incorporating criteria and attributes refined by the Brazilian steel plant's managers. The attributes listed in Table 2 were kept, but the managers regrouped them into three criteria. Then, the equipment's criticality was elevated from sub-criterion to criterion level.

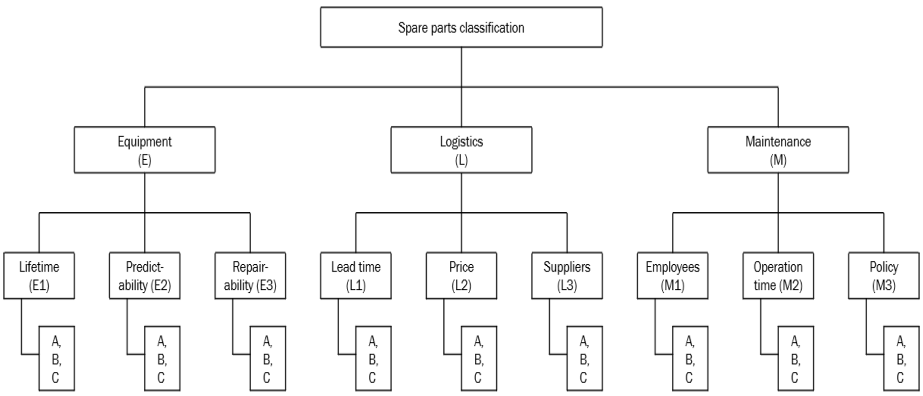

Figure 5 - Hierarchy model for spare parts classification
Source: The authors themselves.

Experts used the fundamental Saaty scale (Table 3) to assign relative importance to criteria and sub-criteria, which formed the basis for prioritization.

Table 3 - 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

Source: Adapted from Saaty (1980).

In the AHP, each expert k constructs a comparison matrix A_k. The aggregate comparison matrix A is obtained through aggregate comparison of the matrices A_k, for $k = 1, 2... K$, where K is the number of experts consulted. These individual matrices are aggregated into a single comparison matrix $\boldsymbol{A}$ using the geometric mean, as recommended by Saaty and Peniwati (2013). The eigenvector $\boldsymbol{w}$ of A, as representing the relative priorities, is calculated using Equation 1, where λ_{max} is A's maximum eigenvalue (Saaty, 1977).

$$\boldsymbol{A}\,\boldsymbol{w} = \lambda_{max}\,\boldsymbol{w} \quad (1)$$

The aggregation of individual judgments (AIJ) is indicated when the experts work in the same company (Saaty, 2013).

The consistency of judgments is evaluated using the Consistency Index CI and the Consistency Ratio CR, calculated using Equations 2 and 3.

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

The random consistency index RI can be obtained in Table 4 as a function of n.

Table 4 - Random Index

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

Source: Adapted from (Saaty, 1980).

The consistency ratio CR is a better measure since it compares CI with a random index RI according to Table 4, which can be calculated according to Equation 3 (Saaty, 1980).

$$CR = \frac{CI}{RI} \quad (3)$$

Consistent matrices have $\lambda_{max} = n$, then $CI = 0$, and $CR = 0$. Inconsistent matrices have at least one comparison, resulting in $\lambda_{max} > n$. It is pertinent that CR does not exceed 0.1. If $CR > 0.1$, judgment revisions are required.

A limitation of AHP stems from the necessity for pairwise comparisons. Research shows that the human brain can effectively compare a maximum of about seven elements, plus or minus two (Miller, 1956; Saaty and Ozdemir, 2003). Consequently, using the traditional AHP method, the maximum number of alternatives can be compared is nine. However, this limit can be extended through the use of absolute measurement, where alternatives are not compared in pairs but are instead evaluated against established standards or ratings (Saaty, 1986).

This research adopts absolute measurement because there may often be more than nine spare parts to be classified. Table 5 presents the ratings for Classes A, B, and C based on various attributes. As mentioned, Class A includes spare parts that require the most attention from inventory managers, followed by Class B (*intermediate priority*) and Class C (*lower priority*). The ABC Classification method allows for the management and categorization of inventory at different levels according to its value to the organization (Demiray *et al.*, 2024). Per the Pareto Principle, spare parts are assigned scores of 1, 0.80, and 0.20 for Classes A, B, and C, respectively.

Table 5 - Comparisons and weights of the criteria

Attribute	Ratings
Employees	A: Outsource expertise
	B: From other areas of the company
	C: Staff from the area
Lead time	A: More than 90 days
	B: 31 to 90 days
	C: Up to 30 days
Lifetime	A: Up to 1 year
	B: 1 to 3 years
	C: Over 3 years
Maintenance policy	A: Corrective
	B: Preventive
	C: Predictive
Operation time	A: More than eighteen hours a day
	B: Eight to eighteen hours a day
	C: Less than eight hours a day
Predictability of failure	A: Low
	B: Medium
	C: High
Price	A: Over US$10,000
	B: US$5,001 to US$10,000
	C: Up to US$5,000
Repairability	A: Over 8 hours
	B: 2 to 8 hours
	C: Less than 2 hours
Suppliers	A: Only one
	B: Two or three
	C: More than three

Source: The authors themselves.

The ratings are based on expert opinion (Table 5), which considers the organization's maintenance system. This data source relates to the records of hydraulic systems maintenance.

4 RESULTS AND DISCUSSION

Three experts from the Brazilian steel plant were identified for their expertise in spare parts management and consulted for the AHP application. These experts provided individual pairwise comparison matrices using the Saaty Scale (1–9) (Saaty, 2013), which were aggregated using the geometrical mean as recommended by Saaty and Peniwati (2013). Table 6 presents the aggregate pairwise comparison matrix and the resulting weights for the criteria. All pairwise comparison matrices showed consistency ratios below the acceptable threshold of 0.1, ensuring the reliability of judgments.

Table 6 - Comparisons and weights of the criteria

Criterion	E	L	M	Weight
Equipment (E)	1	3	1.59	50%
Logistics (L)	1/3	1	0.33	14%
Maintenance (M)	0.63	3	1	36%

Source: The authors themselves.

Following the criteria evaluation, the experts assessed the attributes associated with each criterion. Table 7 presents the weights for these attributes and their overall contribution, calculated by multiplying attribute weights with their respective criterion weight from Table 5.

Table 7 - Weights of the attributes

Criterion	Attribute	Weight	Overall
Equipment	Lifetime (E1)	27%	13.5%
	Predictability of failure (E2)	62%	31.0%
	Repeatability (E3)	11.5%	5.5%
Logistics	Lead time (L1)	17%	2.4%
	Price (L2)	15%	2.1%
	Suppliers (L3)	68%	9.5%
Maintenance	Employees (M1)	20%	7.2%
	Operation time (M2)	17%	6.1%
	Maintenance policy (M3)	63%	22.7%

Source: The authors themselves.

The attributes with the highest overall weights are predictability of failure (E2) at 31% and maintenance policy (M3) at 22.7%. These results underline their critical influence on the steel industry's spare parts classification for hydraulic systems. The experts then evaluated four spare parts (Parts 1 to 4) against the attributes, as shown in Table 8.

Table 8 - Multiple criteria classes of four spare parts

Spare part	E1	E2	E3	L1	L2	L3	M1	M2	M3
1	C	B	A	A	A	B	B	B	C
2	A	C	B	B	B	C	A	C	B
3	B	A	A	C	C	B	A	C	B
4	C	A	A	A	A	A	C	A	A

Source: The authors themselves.

Table 9 summarizes the overall scores and classifications of the spare parts, applying the Pareto 80/20 distribution.

Table 9 - Overall classes of four spare parts

Spare part	Overall	Class
1	0.60	B
2	0.56	B
3	0.82	A
4	0.83	A

Source: The authors themselves.

Spare Parts 1 and 2 were classified as Class B with scores of 0.60 and 0.56, respectively, while Spare Parts 3 and 4 were classified as Class A with scores of 0.82 and 0.83. Notably, in a mono-criterion ABC analysis based solely on price, the classifications for Spare Parts 2 and 4 would have remained unchanged (Class B and Class A). However, despite its lower price, the multi-criteria approach classified Spare Part 3 as Class A due to its high predictability of failure, emphasizing the importance of incorporating multiple criteria.

Sensitivity analysis was conducted to assess the robustness of the results by systematically varying criteria weights and observing the effects on spare parts rankings. Figure 6 illustrates the sensitivity analysis results of the alternatives' performance with dynamic criteria weights concerning the attribute L2 (Price). The sensitivity analysis revealed three distinct ranking scenarios based on changes in criteria weights. For weights up to 34.85%, the ranking was 4, 2, 1, 3 (Class A, Class B, Class B, Class A). For weights between 34.85% and 72.68%, the ranking remained 4, 1, 2, 3 (Class A, Class B, Class B, Class A). Above 72.68%, the ranking shifted to 1, 4, 2, 3 (Class B, Class A, Class B, Class A). These results demonstrate the stability of the proposed classification under varying conditions.

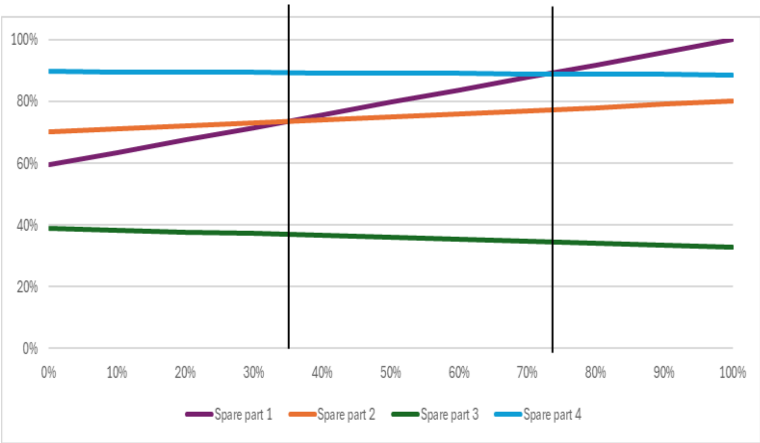

Figure 6 - Performance sensitivity analysis of alternatives
Source: The authors themselves.

The inventory management of spare parts for hydraulic systems in the steel industry addresses uncertainties related to high-quality spare parts, directly impacting asset availability and performance. This study provides decision-makers with a reliable method for classifying spare parts by applying a structured framework with objectives, criteria, sub-criteria, and alternatives.

This research advances spare parts classification by introducing theoretical background and managerial insights into the criticality assessment of hydraulic spare parts, particularly in the steel industry (Antosz and Ratnayake, 2019; Muniz *et al.*, 2021). Unlike prior studies, which often hybridize AHP with fuzzy sets or other MCDM methods (Asmara and Kusumah, 2021; Gong *et al.*, 2022; Ilgin, 2019), this study demonstrates the practicality of a simplified AHP framework. This approach balances methodological rigor and accessibility, making it suitable for personnel without specialized technical skills.

This study underscores the utility of the AHP framework in addressing the criticality assessment of spare parts for hydraulic systems, offering a structured and intuitive decision-making approach. The analysis emphasizes the significance of integrating multiple criteria, particularly those with the highest weights, such as predictability of failure and maintenance policy, in shaping inventory decisions. Moreover, the sensitivity analysis affirms the framework's robustness, demonstrating consistent performance under varying criteria weights and giving decision-makers confidence in its application. These findings illustrate the practicality of the AHP method in streamlining spare parts management and its potential to serve as a foundation for developing tailored solutions in related domains. Future applications may benefit from leveraging this approach to align operational goals with sustainability initiatives or to address emerging challenges such as digital transformation and resource optimization in industrial processes.

5 CONCLUSION

This study addressed the decision-making problem of spare parts inventory management for hydraulic systems in the steel industry. The research objective was to evaluate the criticality of spare parts using a systematic and efficient approach. Through applying the Analytic Hierarchy Process (AHP), four spare parts with low turnover were classified, providing actionable insights for inventory management.

The AHP method proved efficient, eliminating the need for hybrid or more complex MCDM techniques, such as Fuzzy Sets or Multi-Attribute Utility Theory. The simplicity of the AHP allowed for effective problem-solving without additional computational burdens, demonstrating its accessibility for practical applications. Furthermore, the method effectively resolved the decision problem: spare parts were classified into Classes A, B, and C using a multi-criteria ABC analysis. This classification framework offers scalability; if additional spare parts were analyzed under the same criteria weights, their classification could be automated, enhancing operational efficiency and decision-making accuracy.

This study advances the literature by presenting a novel application of AHP to the criticality assessment of spare parts in hydraulic systems, a domain with limited prior research. The research framework underscores the influential role of criteria such as predictability of failure and maintenance policy, which contribute significantly to decision-making. Additionally, this approach demonstrates the practicality of addressing spare parts criticality through a structured and straightforward methodology without requiring specialized technical skills or proprietary software.

Certain limitations should be acknowledged. While the framework was tailored to hydraulic systems in the steel industry, its design offers flexibility for adaptation to other industrial contexts. The study engaged three highly qualified experts whose insights were instrumental in developing the framework. However, involving a larger or more diverse group of experts could further validate and refine the framework. These considerations present opportunities for future research, including adapting the framework to additional industries and integrating broader expert perspectives.

Future studies could refine the proposed AHP-based framework by exploring variations such as AHPSort, the Analytical Network Process, or the Neural Network Process to enhance its adaptability and robustness in different contexts. Incorporating tools such as questionnaires into the methodological process could provide richer input data, enhancing the framework's transparency and reliability. Additionally, varying the criteria weights or rating scores could improve the expert system's flexibility when applied to new industrial settings. Beyond spare parts management, this framework could be extended to other decision-making processes, such as forecasting sales, manufacturing planning, or resource allocation, broadening its applicability across diverse operational environments.

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