SELECTION OF INDUSTRIAL MAINTENANCE STRATEGY: CLASSICAL AHP AND FUZZY AHP APPLICATIONS

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ABSTRACT

The selection of a maintenance strategy is a decision often made with uncertainty or subjectivity. This decision involves the prioritization of critical factors since there are several factors to be considered simultaneously. Decision-making generally depends on subjective assessments from experts. To deal with multiple factors, Analytic Hierarchy Processes (AHP) is a well-established multiple criteria decision analysis (MCDA) method. This article presents an AHP application for the selection of a maintenance strategy by a real industrial plant. Four maintenance strategies are considered: Corrective Maintenance, Preventive Maintenance, Predictive Maintenance, and Proactive Maintenance. Decision criteria are cost, quality, safety, value added and viability. Then, incorporating the concepts of the fuzzy set theory, fuzzy AHP was applied to the same decision problem. In both applications, Corrective Maintenance was the strategy with the highest priority, and value added was the highest priority criterion. With the classical AHP application, some comparison matrices produced Consistency Ratios (CR) greater than 0.10, possibly generated by mistakes or misunderstandings from experts. However, the same result was obtained from fuzzy AHP and validated the result obtained from classical AHP application. The major contribution of the paper is the evidence that Fuzzy AHP may be a useful tool to solve the consistency problems in classical AHP applications.

Keywords: Analytic Hierarchy Process; consistency ratio; fuzzy set theory; maintenance strategy

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1. Introduction

Maintenance is the term used to address the way organizations try to avoid failures by taking care of their physical facilities (Slack, Brandon-Jones, & Johnston, 2016). The goal of maintenance is to ensure that physical items continue to do what their users want them to do (Moubray, 2000). Then, maintained items are expected to keep their functional capacity of operation. A maintenance strategy ensures the availability of equipment and facilities to allow production with reliability, safety, environmental preservation and adequate costs (Pinto & Nascif, 2014). There are different maintenance strategy alternatives, but, basically, the four main alternatives are:

- Corrective Maintenance (A1) is when the intervention occurs at the moment, or after, a failure occurs. The failure causes the equipment to be unavailable or have lower performance. Corrective maintenance can be planned, or not. Often, when unplanned, the intervention is immediate and without service preparation. When planned, the intervention team can be prepared to do the intervention.
- Preventive Maintenance (A2) is when the intervention is carried out as an objective to reduce or avoid the failure of the equipment. The interventions follow a previously prepared plan, and they are periodically carried out.
- Predictive Maintenance (A3) is when the intervention modifies parameters of performance. It prevents failures by means of various parameters, which aim for the continuous operation of the equipment for the maximum possible time.
- Proactive Maintenance (A4) is based on the frequency of occurrence of the failure. A history of these occurrences is made on the equipment and the information is used to determine the root cause of the failure. It generates actions related to the root cause of the failure, searching to increase the life of the equipment.

The selection of a maintenance strategy is a multi-criteria decision since it may involve an analysis of benefits, opportunities, costs and risks (Karpak, 2017). Additionally, this decision may also incorporate subjectivity and uncertainty. Analytic Hierarchy Process (AHP) and Fuzzy Set Theory (FST) may be applied to solve this decision problem.

The objective of this paper is to present a model for the selection of a maintenance strategy. Two models will be presented and applied in a real case: an AHP model and a FAHP (Fuzzy AHP) model. The next section presents the results from a bibliometric survey on AHP, FST and Maintenance. Results are compared in the conclusion section of the paper. Therefore, this paper has two major contributions which include: the theoretical or methodological contribution comparing results from two models (an AHP and a FAHP), and a practical contribution from the application of both models in a real case.

2. Literature review

Besides the multi-criteria decision nature of maintenance strategy selection, the literature combining AHP, FST and maintenance is very poor or, at least, incipient. A survey on the SCOPUS database with the keywords “AHP”, “Fuzzy” and “maintenance” resulted in 167 papers, as presented in Figure 1 (Elsevier, 2018). With a peek of more than 25 papers published in 2016, the average from 2007–2017 is 16.7 papers/year.

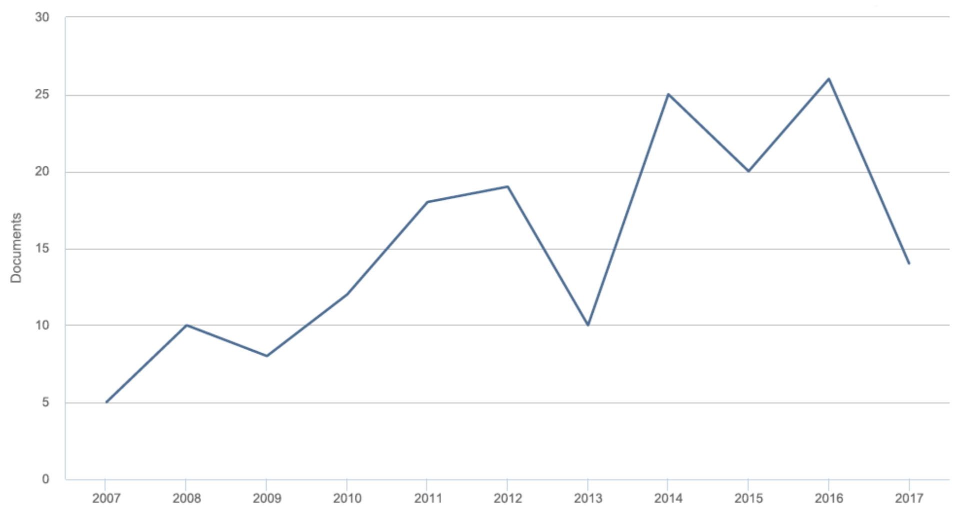

Figure 1 Publication numbers per year

Figure 2 presents the distribution by the countries of first authors for these papers. China is the leading country because of its large population and academic tradition as in almost every field of knowledge. Iran is a good surprise, appearing second along with other traditional countries.

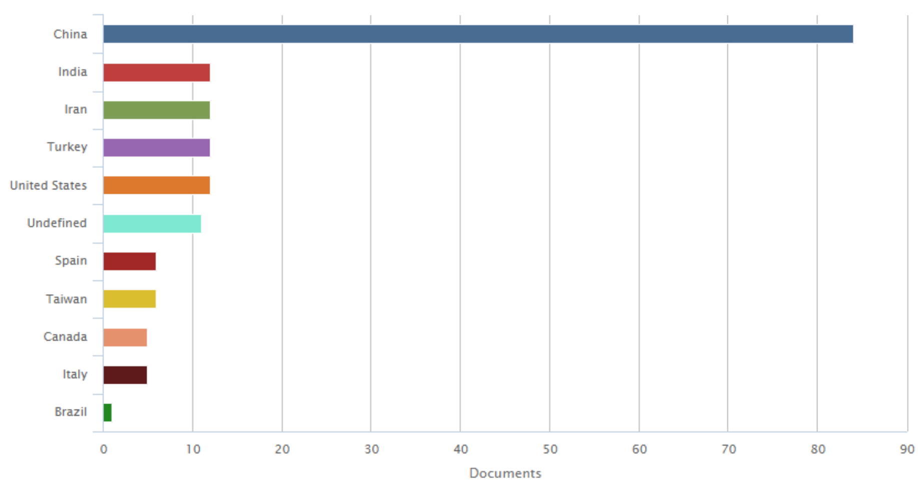

Figure 2 Publication numbers by country

Figure 3 presents paper distribution by research area. Engineering, Computer Science and Business Management, in this order, are the top areas.

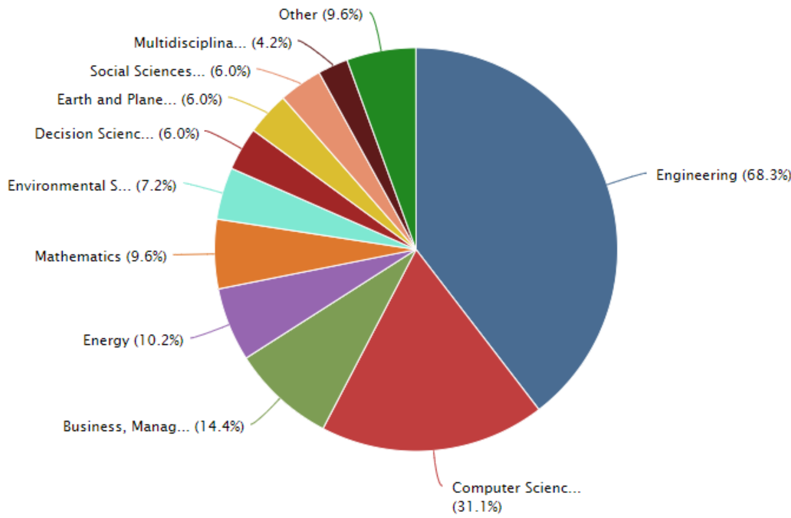

Figure 3 Publication percentages by research area

From the bibliometric research (Figures 1 to 3), there is a growing interest in the subject and an increasing number of citations of keywords AHP, Fuzzy AHP and maintenance, in the last years (Figure 4). Still, the number of papers in this area is low. So, the central question of this research is if the selection of maintenance strategies may be solved with multiple criteria decision analysis (MCDA).

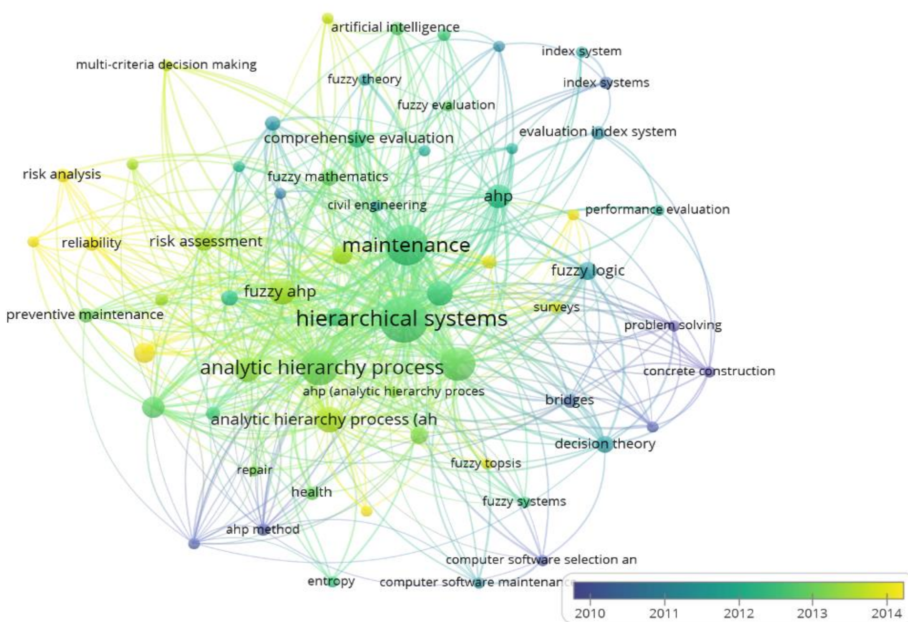

Figure 4 Citations in the last 10 years

3. Methodology

3.1. Classical Analytic Hierarchy Process

The name AHP was given because of its use of hierarchies to make multi-criteria decisions (Saaty, 1977; Saaty, 1980; Saaty, 1991). As in Figure 5, the top level has the decision objective, in our case, the selection of a maintenance strategy. In the bottom level, there are the decision alternatives, in our case A1 to A4, which were previously introduced.

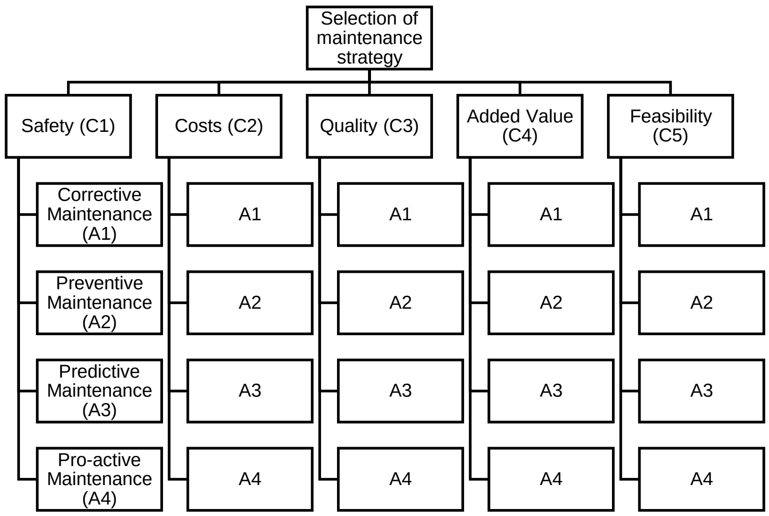

Figure 5 Multi-criteria selection of maintenance strategy

The criteria C1,…,C5 were identified from the literature of maintenance selection and they were utilized in the case presented in the next section (Ge, et al., 2017;W ang, Chu, & Wu, 2007). That is, this set of criteria was approved by a manager from a real industrial plant. Briefly, these are the concepts expressed by each criterion:

- Safety (C1): The required safety levels have increased lately. For maintenance strategy, it represents the conditions that deter undesirable results, such as accidents, failure, mistakes, and so on. It also refers to the controllability of reducing known threats to an acceptable level, both in terms of personal safety, and plant safety or even in terms of environmental safety.
- Costs (C2): Maintenance costs must not exceed acceptable limits. Costs do differentiate a process and have direct influence on the incomes.
- Quality (C3): Proper maintenance management brings a better quality of production and cost reduction, while a poor maintenance management of the equipment leads to the breakdown. This causes the need to invest in repair and perhaps in replacement, thus translating into a high cost, and may also affect other sectors. When it comes to production, poor maintenance management can lead to loss of production and product quality.
- Value added (C4): In the economic area, value added is the difference between the final and initial price to produce a given product. In the maintenance area, value added means all the benefits and returns of maintenance activities. Generally, the higher the value added, the more return will be obtained with a

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greater effectiveness of maintenance and with less entry of services or products. The most relevant factors are inventories of spare parts, loss of production and identification of failures.

- Feasibility (C5): It is applied to determine whether the maintenance strategy is suitable for the system. According to the different requirements of works and techniques for maintenance strategies, the feasibility criteria can be divided into two relevant evaluation factors. First, labors which includes when managers and maintenance staff prefer the maintenance strategies that are easy to implement and understand. Second, the technique reliability, still under development, which is condition-based maintenance and predictive maintenance that may be inapplicable for some facilities.

One important AHP assumption is the independency between alternatives and criteria. As a matter of fact, in practice, a manager may decide to implement more than one maintenance strategy, combining them, for different equipment. This is a limitation of this work. We will consider the maintenance strategies as independent of each other, or else, mutually exclusive and collectively exhaustive (Lawrence & Pasternack, 2013).

In AHP, priorities for both sets of criteria and alternatives are obtained with the right eigenvector **w**, for a comparison matrix **A**, as in Equation 1, where $\lambda_{\max}$ is **A**'s maximum eigenvalue.

$$\mathbf{A}\,\mathbf{w} = \lambda_{\max}\,\mathbf{w} \tag{1}$$

For fully consistent matrices, that is, if we have $a_{ik}=a_{ij}a_{jk}$, $\lambda_{\max}=n$ (Saaty, 1977). Otherwise, $\lambda_{\max}>n$. As, close as $\lambda_{\max}$ is to n, the more **A** may be considered consistent. The consistency index $CI=(\lambda_{\max}-n)/(n-1)$ is a better measure for the consistency since it also considers the matrix order, n (Saaty, 1980). The consistency ratio $RC=CI/RI$, where RI is a random index, with an upper limit of 0.1 is the most applied consistency parameter.

For the comparison matrix presented in Table 1, we have $\lambda_{\max}\approx3.04$, $CI\approx0.02$ and $CR\approx0.04$, which are acceptable.

Table 1
Pairwise comparisons of three criteria

	Criterion 1	Criterion 2	Criterion 3	Priority
Criterion 1	1	3	5	64%
Criterion 2	1/3	1	3	26%
Criterion 3	1/5	1/3	1	10%

Let us suppose that the decision-maker is quite confident with the comparison between Criteria 1 and 2. However, he is not sure about Criterion 3. Then, he considered different values to compare this criterion with the other ones. However, in the original AHP, he can only provide one value. Table 2 presents another comparison matrix with new values, in bold, for the uncertain comparisons in Table 1. For Table 2, $\lambda_{\max}=3$, $CI=CR=0$, that is, this is a fully consistent matrix.

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Table 2
New pairwise comparisons of three criteria

	Criterion 1	Criterion 2	Criterion 3	Priority
Criterion 1	1	3	**3**	60%
Criterion 2	1/3	1	**1**	20%
Criterion 3	**1/3**	**1**	1	20%

Comparing Tables 1 and 2, the priorities have changed a little. Criterion 1 still has the highest priority, a little less than 2/3. However, Criteria 2 and 3 are now tied. That is, Criterion 3's new priority is twice the older priority. With FST, both priorities may be considered, or better, both sets of comparisons may be used.

3.2. Fuzzy Analytic Hierarchy Process

A fuzzy set *A* in *X* is characterized by a membership function $f_A(x)$ which associates each point in *X* a real number in the interval [0, 1] (Zadeh, 1965). FST literature has a rich history, including Type 2 fuzzy sets, Interval-valued fuzzy sets, intuitionistic fuzzy sets, fuzzy multisets and more recently, hesitant fuzzy sets (Kahraman, Oztaysi & Onar, 2016).

Triangular fuzzy sets (TFS) are common membership functions used in engineering (Pedrycz, 1994). A TFS is often represented by a vector (l, m, u), being m the modal value, that is $f_A(m)$=1, and l and u being the lower and upper limits, or $f_A(l)$= $f_A(u)$=0.

Table 3 presents a comparison matrix completed with TFS. Note that if $a_{ij}=(l_{ij}, m_{ij}, u_{ij})$, then $a_{ji}=1/a_{ij}=(1/u_{ij}, 1/m_{ij}, 1/l_{ij})$ (van Laarhoven & Pedrycz, 1983). Priority vector **w** was obtained according to Equation 2 (Chang, 1996).

$$w_i = \left(\sum_{j=1}^{n} l_{ij},\quad \sum_{j=1}^{n} m_{ij},\quad \sum_{j=1}^{n} u_{ij}\right)\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{1}{u_{ij}},\quad \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{1}{m_{ij}},\quad \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{1}{l_{ij}}\right) \quad (2)$$

Table 3
Fuzzy pairwise comparisons of three criteria

	Criterion 1	Criterion 2	Criterion 3	Priority
Criterion 1	(1, 1, 1)	(1, 3, 5)	(3, 5, 7)	(.22, .60, 1.52) → .78 → 59%
Criterion 2	(1/5, 1/3, 1)	(1, 1, 1)	(1, 3, 5)	(.10, .29, .82) → .40 → 30%
Criterion 3	(1/7, 1/5, 1/3)	(1/5, 1/3, 1)	(1, 1, 1)	(.06, .10, .27) → .15 → 11%

We can see more similarity between priority vectors from Tables 1 and 3 than Tables 2 and 3 or Tables 1 and 2. In all tables, Criterion 1 has the highest priority. In Tables 1 and 3, Criterion 2 has the second priority and Criterion 3 has the lowest. One important observation is that Table 3 mixes information from Tables 1 and 2. For the decision maker, there is a feeling that no information needs to be discarded.

4. Application

4.1. Classical Analytic Hierarchy Process

For this study of AHP application, three senior maintenance managers from a global manufacturer of industrial components serving primarily the railroad, vehicular and construction located in Southeastern Brazil were interviewed. This is a typical industrial plant located in the state of Sao Paulo. This plant is a Tier 2 player in the Brazilian rail supply chain, manufacturing structural components for trains, tractors, excavators and heavy machines from multinational groups located mainly in the states of Sao Paulo and Rio de Janeiro.

Table 4 presents the pairwise comparisons on the criteria from the experts, aggregated by geometric mean (Saaty & Peniwati, 2013). We have $\lambda_{max} \approx 5.77$, $CI \approx 0.19$ and $CR \approx 0.17$, which are not acceptable since $CR > 0.10$. Comparison matrices with CR higher than the upper limit represent an alert that comparisons may be not logically connected. After a discussion with experts, the priority vector presented in Table 4 was accepted. That is, criteria Value Added (C4) and Quality (C3) have the highest priority, which is reasonable in the highly competitive heavy steel industry market.

Table 4
Pairwise comparisons of criteria to maintenance strategy selection

Criterion	C1	C2	C3	C4	C5	Priority
C1	1	4.77	0.29	0.18	2.57	15%
C2	0.21	1	0.24	0.18	1.67	7%
C3	3.45	4.17	1	0.48	5.66	30%
C4	5.56	5.56	2.08	1	2.33	41%
C5	0.39	0.60	0.18	0.43	1	8%

Table 5 presents a decision matrix. The priorities in this matrix were obtained from comparison matrices of alternatives regarding each criterion aggregated from individual matrices according to every expert. For C1 and C4, the bolded consistency ratios were greater than the upper limit. This inequality was mainly due to difference in the opinions obtained from expert interviews.

Table 5
Local and overall priorities for maintenance strategies

Strategy	C1 (15%)	C2 (7%)	C3 (30%)	C4 (41%)	C5 (8%)	Overall
Corrective (A1)	38%	52%	47%	54%	36%	48%
Preventive (A2)	47%	32%	19%	25%	14%	26%
Predictive (A3)	6%	7%	21%	12%	30%	15%
Pro-active (A4)	9%	9%	13%	9%	20%	11%
CR	**0.17**	0.04	0.07	**0.20**	0.10	0.24

The overall consistency ratio was below the upper limit, so the results are acceptable. However, the judgement values for the two criteria should be reviewed.

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4.2. Fuzzy Analytic Hierarchy Process

The same experts were invited to fuzzify their comparisons. That is, every previous comparison was assumed as a modal value for a triangular fuzzy set. Lower and upper values were added with their review. Table 6 presents fuzzy pairwise comparisons on the criteria from the expert interviews, aggregated by geometric mean. We have $\lambda_{low}\approx5.07$, $CI_{low}\approx0.02$ and $CR_{low}\approx0.01$, $\lambda_{med}\approx5.77$, $CI_{med}\approx0.19$ and $CR_{med}\approx0.17$ and $\lambda_{hig}\approx7.43$, $CI_{hig}\approx0.61$ and $CR_{hig}\approx0.54$, where $CR_{low}\approx0.01>0.10$ is acceptable, but CR_{med} and CR_{hig} are not acceptable.

Table 6
Fuzzy pairwise comparisons of criteria to maintenance strategy selection

Criterion	C1	C2	C3	C4	C5
C1	(1, 1, 1)	(4.25, 4.75, 4.95)	(.30, .35, .45)	(.15, .25, .25)	(3.25, 3.45, 3.75)
C2	(.20, .21, .24)	(1, 1, 1)	(.15, .25, .25)	(.15, .35, .40)	(1.04, 1.71, 2.31)
C3	(3.45, 4, 4,55)	(3.70, 4.17, 4.76)	(1, 1, 1)	(.34, .48, .62)	(5.17, 5.74, 6.18)
C4	(5.00, 5.56, 6.25)	(5.00, 5.26, 6.25)	(1.61, 2.08, 2.94)	(1, 1, 1)	(2.16, 2.33, 2.47)
C5	(.33, .39, .49)	(.43, .58, .96)	(.16, .17, .19)	(.40, .43, .46)	(1, 1, 1)

Table 7 presents priority vectors for the criteria with AHP and with FAHP. Vectors are very close, with the same ordinal vector: [3, 4, 2, 1, 5]. That is, C4 has the highest priority in both applications and it is followed by C3, C1, C2, and C5.

Table 7
Priorities of criteria to maintenance strategy selection

Criterion	AHP	FAHP
C1	15%	22%
C2	7%	8%
C3	30%	33%
C4	41%	32%
C5	8%	5%

Table 8 presents a new decision matrix. Priorities were obtained from fuzzy comparison matrices of alternatives regarding each criterion aggregated from individual matrices according to every expert. Bolded priorities are higher than the values in the previous decision matrix (Table 5).

Table 8
New local and overall priorities for maintenance strategies

Strategy	C1 (22%)	C2 (8%)	C3 (33%)	C4 (32%)	C5 (5%)	Overall
Corrective (A1)	**45%**	52%	27%	48%	**39%**	40%
Preventive (A2)	39%	30%	12%	**33%**	14%	26%
Predictive (A3)	6%	6%	9%	10%	28%	9%
Pro-active (A4)	9%	**12%**	**52%**	9%	19%	**24%**

The results from both classical AHP and FAHP were quite similar. The plant must adopt Corrective Maintenance as a maintenance strategy.

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5. Conclusions

MCDA is widely used when the decision problem has social, economic, technical and political factors that need to be meticulously evaluated in a globalized world where an organization must produce the maximum, with more quality in less time and minimum cost. Classical AHP and Fuzzy AHP models were applied and compared in a case study to solve the problem of maintenance strategy selection in an industry. Despite the convenience of classical AHP in manipulating the criteria for decision making, imprecision and lack of definition may cause inaccurate judgments with conventional approaches. To fill this gap, Fuzzy AHP has a greater advantage in capturing the imprecision of human thought and contributing to a structured resolution. Moreover, in the case under study, in both models, Corrective Maintenance (A1) was the strategy with the highest priority and value added (C3) was the criterion with the highest priority. This goes against the principles of evolution of maintenance to reach World Class Maintenance, where it seeks to minimize costs and combat the lack of maintenance effectiveness. We can also observe that some pairwise comparison matrices in the classic AHP produced consistency ratios (CR) higher than recommended (CR> 0.10), which was possibly generated by errors or misunderstandings in the judgment of the specialists. However, even with these adverse results, the work showed that the MCDA could be used in the selection of a maintenance strategy.

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