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Artículos científicos

A Comparison of AHP and CODAS Decision-Making Methods for Preventive Maintenance in 3D Atom IV+ Machine

Una comparación de los métodos de toma de decisiones de la familia AHP y CODAS para el mantenimiento preventivo en la máquina de 3D Atom IV+

Uma comparação dos métodos de tomada de decisão das famílias AHP e CODAS para manutenção preventiva na máquina Atom IV+ 3D

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Abstract

Preventive maintenance (PM) of equipment is a critical concern for ensuring the effectiveness of a manufacturing system. This study proposes an integrated approach that employs the Analytic Hierarchy Process (AHP) and Combinative Distance-based Assessment (CODAS) of multi-criteria decision techniques. The methodology was found to address the PM equipment concerns related to the 3D Atom IV+ machine at the Instituto Tecnológico de Ciudad Juárez. The two multi-criteria techniques were compared based on the consistency of the results. The 3D Atom IV+ was identified as the most suitable critical elements. CODAS was preferred method for the 3D Atom IV+ machine of the PM process because of its consistent results, simplicity, and reduced information requirement from decision-makers compared to AHP. The methodology was able to identify the critical elements for preventive maintenance in a 3D Atom IV+ machine at Instituto Tecnológico de Ciudad Juárez using two MCDM methods, which was demonstrated in the case study. This study points out the comparison between two methods by developing a decision-making methodology that can find the critical elements for preventive maintenance in a 3D Atom IV+ machine.

Keywords: AHP, criteria weights, decision-making, MCDM, PM, 3D Atom IV+ machine,

Resumen

El mantenimiento preventivo (MP) del equipo es una preocupación crítica para garantizar la efectividad de un sistema de manufactura. Este estudio se propone un metodo integrado que emplea el Proceso Jerarquíco Analítico (AHP) y la Evaluación Combinada Basada en la Distancia (CODAS), pertenecientes a técnicas de toma de decisión multicriterio. Estos métodos se aplicaron para abordar las preocupaciones del MP relacionadas con la impresora 3D Atom IV+ en el Instituto Tecnológico de Ciudad Juárez. Las dos técnicas multicriterio se compararon con base en la consistencia de los resultados. Se identificó que la impresora 3D Atom IV+ para encontrar los elementos críticos en el equipo. Se favorece el uso de CODAS como el método preferente para la máquina 3D IV+ para su debido a sus resultados consistentes, simplicidad y menor necesidad de información por parte de los tomadores de decisiones en comparación con AHP. Se encontró que la metodología permite identificar los elementos críticos para el mantenimiento preventivo en una impresora 3D Atom IV+ en el Instituto Tecnológico de Ciudad Juárez utilizando dos métodos multicriterios, lo cual se demostró en el estudio de caso. Esta investigación se destaca la comparación entre dos métodos de toma de decisión (MCDM) mediante el desarrollo de una metodología que permitió encontrar los elementos críticos para el mantenimiento preventivo en una impresora 3D Atom IV+.

Palabras clave:, AHP, máquina 3D Atom IV+, MCDM, pesos críticos, MP, toma de decisiones.

Resumo

A manutenção preventiva (MP) do equipamento é uma preocupação crítica para garantir a eficácia de um sistema de manufatura. Este estudo propõe uma abordagem integrada que emprega o Processo Hierárquico Analítico (AHP) e a Avaliação Combinada Baseada na Distância (CODAS), pertencentes a técnicas de decisão multicritério. Estes métodos foram aplicados para abordar as preocupações do MP relacionadas com a impressora 3D Atom IV+ no Instituto Tecnológico de Ciudad Juárez. As duas técnicas multicritério foram comparadas com base na consistência dos resultados. Identificou-se que a impressora 3D Atom IV+ é útil para encontrar os elementos críticos no equipamento. É favorecido o uso do CODAS como o método preferencial para a máquina 3D Atom IV+ devido aos seus resultados consistentes, simplicidade e menor necessidade de informação por parte dos tomadores de decisão em comparação com o AHP. Constatou-se que a metodologia permite identificar os elementos críticos para a manutenção preventiva numa impressora 3D Atom IV+ no Instituto Tecnológico de Ciudad Juárez, utilizando dois métodos multicritérios, o que foi demonstrado no estudo de caso. Esta investigação destaca a comparação entre dois métodos de tomada de decisão (MCDM) através do desenvolvimento de uma metodologia que permitiu encontrar os elementos críticos para a manutenção preventiva numa impressora 3D Atom IV+.

Palavras-chave: AHP, impressora 3D Atom IV+, MCDM, pesos dos critérios, MP, tomada de decisão.

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Introduction

The effective preventive maintenance (PM) of equipment plays a pivotal role in manufacturing systems, as its absence can negatively affect productivity, quality, and operational costs. According to Estrada-Robles et al., (2022), PM not only supports system effectiveness, also boosts global competitiveness through optimized production processes and equipment usage, machine utilization effects, increasing production output, and control system flexibility. However, given the extensive range of available equipment, selecting critical equipment for a given production problem is challenging (Alsyouf, 2009; Atmani and Lashkari, 1998). Although PM plays a crucial role in designing effective preventive systems in manufacturing, studies on this subject are limited. As noted by Ayala and Woocay (2024), an inadequate PM can result in diverse negative outcomes, such as diminished quality, increased production costs, customer dissatisfaction, and higher maintenance expenses

In other hand, Ayağ and Özdemir, (2006) and Barba-Romero & Pomerol, (1997) studies in this domain often focus on machine selection. Other studies have proposed models and algorithms to address machine maintenance and operation problems in Flexible Manufacturing Systems (Bertolini & Bevilacqua, 2006; Bevilacqua & Braglia, 2000). Various studies have discussed equipment PM decisions (Caputo et al., 2013; Chan et al., 2001).

Many multi-criteria decision-making (MCDM) methods exist, with criteria weights models and the Analytic Hierarchy Process (AHP) being the most popular. According to Estrada-Robles et al., (2022); Ayala and Woocay, (2024); Kabir et al., (2013). The choice of MCDM method depends on the specific decision problem and requires a thorough understanding of the problem, feasible alternatives, possible outcomes, criteria conflicts, and data uncertainty levels.

This article introduces an AHP and Combinative Distance-based Assessment (CODAS) approach for selecting PM critical elements of equipment and elucidates the implementation process in an 3D Atom IV+ machine as an example. The AHP and CODAS methods were employed to analyze the structure of the equipment selection problem and determine the criteria weights. Furthermore, this study examines how rankings change when criteria elements are weighted using the Saaty´s Method.

The contribution of this study lies in presenting a methodology for predicting additive manufacturing equipment PM using AHP and CODAS methods. This study proposes an MCDM methodology for identifying the principal PM critacal elements in a 3D Atom IV+ machine, offers an alternative weighting calculation based on literature review and expert judgment, and presents a novel research model illustrating hierarchical factors and their corresponding scoring values for establishing concrete strategies (Fraser et al., 2015). Combinative Distance-based Assessment represents a straightforward ranking method for both theoretical concepts and a good application, especially when compared to other methods utilized in multi-criteria approaches (Turskis, 2008). We employed of a CODAS MCDM method to find an appropriate PM critical elements for a 3D Atom IV+ machine at Instituto Tecnológico de Ciudad Juárez.

The CODAS method was utilized to assess strategic PM, offering applicability even in group decision-making scenarios. Their proposed methodology, incorporates thresholds furnishes complete ranking dispenses with preference functions, and encompasses concepts such as risk, uncertainty, and reliability using an interval valuations approach.

Researchers have explored the integration of AHP and CODAS to augment the capabilities of both techniques. In these integrated approaches, AHP was employed to analyze problem structures and determine criteria weights, whereas CODAS was used to compare the final rankings.

In this study, we introduced and applied AHP and CODAS methods to devise a PM strategy for 3D Atom IV+ machines in Mexico. A review of previous applications reveals that AHP and CODAS methods have been extensively utilized over the years, both independently and in conjunction with other techniques, and have garnered a reputation for reliability. Although the benefits of these methods for selection and ranking problems have been demonstrated by numerous researchers, their application to 3D Atom IV+ machines represents a novel endeavor in the additive manufacturing industry. The proposed methodology minimizes the amount of information required by decision-makers ensuring their final results using MCDM while maintaining simplicity. Some experts with 5 years of specializing in 3D machines were engaged in this study to assess criteria and alternatives. We proposed some research questions:

1. How could the AHP and CODAS method be addressed to determine the most critical elements for PM in a 3D Atom IV+ machine?
2. Could the AHP and CODAS algorithms be used to calculate all weighting values for all critical elements in a 3D Atom IV+ machine, integrating acquired judgment evaluation by experts?
3. Could the obtained results be compared for AHP weighting and CODAS ranking methods?

We look for a methodology utilizing AHP and CODAS for criterion weighting proposed in this study, which will be evaluated using our hypothesis:

"All weighting results for each criterion are based on the addressed methods of AHP and CODAS. To find the Consistency Ratio (CR) as per the Saaty´s method (Saaty,1980).

CR < 0.1, and compare CODAS ranking results.

This article comprises six sections:

1. Introduction: This section presents the problem under investigation.
2. Principles of AHP and CODAS
3. AHP and CODAS Approach
4. Theoretical Application of Proposed AHP and CODAS Techniques: A hypothetical application of the proposed AHP and CODAS techniques is discussed.
5. Comparative Results of AHP and CODAS methods.

6. Conclusions.

This section is divided into the following subsections: literature concepts review on PM equipment, MCDM method research, and identifying gaps concerning additive manufacturing equipment PM.

Critical Equipment for preventive maintenance

Critical equipment refers to those essential for continuous operations, vital not only for functionality but also for maintenance considerations. Given the competitive landscape and privatization of the additive manufacturing sector, ensuring a cost-effective and quality cost. Maximizing 3D machines uptime while minimizing costs is crucial to gaining a competitive edge. Effective maintenance practices are pivotal in achieving this objective. Therefore, prioritizing maintenance activities based on equipment criticality is crucial. Various methodologies have been employed by researchers to identify critical equipment. For instance, Bevilacqua and Braglia (2000) utilized a risk validation approach to categorize equipment problems by considering factors such as maintenance cost, availability, and MTBF. Other approaches, such as the System Efficiency Influence Diagram (SEID) technique, have also been employed to prioritize maintenance actions. The identification of critical equipment poses challenges, owing to the involvement of multiple criteria. Therefore, employing multi-criteria decision-making methods is essential for making informed decisions (Estrada-Robles et al., 2022; Bevilacqua and Braglia, 2000; Lin and Yang, 1996; Salonen, 2011).

MCDM Methods

Decision-making has been an important task in for humans for several years. Individuals make regular decisions in their daily lives. However, the evolving dynamics of business have placed growing emphasis on quantifiable decision-making. As problems become increasingly complex, decision-makers often encounter scenarios with numerous alternatives and multiple criteria. In such situations, utilization of multi-criteria decision-making (MCDM) methods is essential (Saaty, 1980; Standing et al., 2001; Sullivan et al., 2002; Peters and Zelewski, 2008; Pariazar, et al., 2008). Across all MCDM approaches, the primary objective remains consistent: to identify the optimal alternative or to rank a given set of alternatives.

The main steps involved in the MCDM process are as follows:

1. Defining criteria for system evaluation.
2. Generating alternative systems to achieve objectives.
3. Assessing alternatives based on the established criteria by experts.
4. Employing a standard multi-criteria analysis algorithm.
5. Selecting a preferred or optimal alternative.
6. If the initial solution is not satisfactory, proceed with again the analysis of the multi-criteria algorithm.

Multiple criteria decision-making (MCDM) methodologies offer an effective approach to aid decision-makers in selecting the optimal alternative across various criteria. To achieve a systematic solution, decision-makers utilize AHP and CODAS methods to operational procedures.

The Analytic Hierarchy Process (AHP) has been widely used. AHP operates under the assumption that a complex problem can be defined as a hierarchical tree, consisting of an overarching goal and set of alternative factors. Typically, a decision problem is organized into three levels within the AHP framework. The levels represents: Goal-Criteria-Alternatives. These criteria are then applied to assess a predetermined a set of alternatives. Within each block of the hierarchy tree diagram, pairwise comparison matrices are calculated among elements to determine their relative importance, often incorporating both quantitative and qualitative considerations.

The versatility of AHP is reflected in its diverse applications. For example, AHP have been used to select the best maintenance strategies for the equipment and safety devices in industrial machinery. In many applicactions, AHP has been used to solve multi-criteria complex problems at various decision nodes and to prioritize load-shedding operations for industrial facilities. In many applications. AHP was used to calculate all weights for each criterion, which were then integrated into subsequent analyses using and ranking others MCDM methods. Its popularity can be attributed to its capability to effectively handle both tangible and intangible attributes.

Identified Gap from the Literature Reviewed

Extensive research has been conducted across various literature sources researching PM problems over the two decades, yet it is challenging to limited literature specifically addressing preventive maintenance for additive manufacturing 3D Atom IV+ machine through the utilization of AHP and CODAS methods.

In some researches for example**,** in Bevilacqua and Braglia (2000), using AHP process applied to MP strategy process, and in Alsyouf (2004), found a cost effective maintenance for competitive advantages. In other hand, in Atmani and Lashkari (1998), they found a model of machine tool selection and operation allocation in the flexible manufacturing system.

The Analytic Hierarchy Process

The methodology follows the analytic hierarchy process (AHP) as formulated by Saaty (1980), which has been widely employed in complex decision-making problems. A detailed structure adapted from Ayala and Woocay (2024) was used to describe the pairwise comparison matrices, normalization processes, eigenvector derivation, and consistency ratio calculations, as applied to the 3D Atom IV+ machine. According to practical industry recommendations (Sicnova, 2023). They design 3D machines, includes the development of the criteria used in the prioritization differents processes.

AHP aids decision-makers by offering a framework to efficiently assess and compare alternatives. This method employs a pairwise comparison matrix to evaluate alternatives across multiple criteria considering the best performance for each criterion.

AHP uses the fundamentals of decomposition of complex problems, comparative judgments by experts, and hierarchy composition using a tree diagram. particularly when multiple decision criteria are addressed and for arranging available alternatives in a preference order based on a rational system of quantitative comparisons. AHP relies on a robust yet straightforward theoretical foundation consists of three fundamental principles: Decomposition, Comparative Judgment, and Hierarchical Composition.

The AHP constructs hierarchy blocks starting from the initial problem as the foundation and progresses to criteria and alternatives at higher levels. This hierarchical diagram simplifies diverse objectives and goals into a strong score, enabling the selection of the alternative with the highest score for decision-makers. The comparison matrix employs a quantified value scale, and the comparative value scores are input into a judgmental matrix to facilitate the weight calculation. All weights are normalized by dividing the geometric mean of each criterion by the sum of the geometric means of all criteria using Saaty´s Method (1980).

The AHP method was developed using three fundamental algorithms: structuring the model, comparing all alternatives and criteria, and synthesizing all priorities. Initially, an unsolved decision problem was structured hierarchically and horizontally, breaking it down into interconnected decision elements (criteria and alternatives). The objectives, criteria, and alternatives are organized in a hierarchical structure into a diagram tree, typically consisting of at least three levels: overarching goals at the top, multiple criteria-defining alternatives in the middle, and decision alternatives at the bottom.

Once the problem is decomposed by experts and a hierarchy is established, the prioritization process begins with the relative importance of the criteria within each level. Pairwise comparisons commenced at the second level and were extended to the lowest level. All Criteria were compared pairwise (result values) within each level based on their respective levels of importance and specified criteria at a higher level.

In AHP, multiple pairwise comparisons adhere to a standardized comparison scale consisting of nine-point importance levels (Saaty,1980), as shown in Table 1.

Table 1. The nine-point intensity of importance scale and its description Saaty (1980)

Definition	Intensity of importance
Equally importance	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9
Intermediate	2,4,6,8

Source: adapted by Saaty, (1980)

The method's fundamental algorithms are as follows:

Algorithm 1: Decompose the entire problem into three levels:

1. Goal of the problem.
2. Judgment criteria and alternatives by experts.
3. Creation of a Hierarchy tree diagram.

Algorithm 2: Establish the Score scale for each criterion.

Algorithm 3: Calculate a Comparison matrix.

Algorithm 4: Convert the Comparison matrix into a normalized matrix

Let's consider ***X*** to represent the comparison matrix:

$\boldsymbol{X = [x_{ij}]}$, where ***i*** denotes equipment elements (***i = 1……… n)*** and ***j*** represents the criteria of the alternatives ***(j = 1….m).*** The normalized matrix derived from ***X*** can be obtained as

$$r_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}}, j = 1, 2, \ldots, m$$

Sum of r_{ij} column-wise and row-wise

Algorithm 5:

$CR = \{CR_j \mid j = 1, 2\ldots, n\}$ was considered as the criteria set. The output of the Pairwise Comparison Matrix among n criteria can be condensed into an $(n \times n)$ evaluation matrix A, where each element a_{ij} ($i, j = 1, 2\ldots, n$) represents the ratio of the criteria for all weights, as shown in Equation 1.

$$A = \begin{bmatrix} a_{11} & a_{12} \cdots & a_{1n} \\ a_{21} & a_{22} & a_{2n} \\ \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} \cdots & a_{nn} \end{bmatrix}, \text{ for } a_{ij} = 1, \; a_{ji} = 1/a_{ij}, \; a_{ij} \neq 0 \tag{1}$$

In matrix ***A***, $\boldsymbol{a_{ij}}$ denotes a positive value, where $\boldsymbol{a_{ij}}$ equals $\boldsymbol{1/a_{ji}}$, $\boldsymbol{a_{ii}}$ equals 1, and $\boldsymbol{a_{ij}}$ represents the user assessment of the relative significance of criterion ***i*** with respect to criterion ***j***. If ***i*** and ***j*** hold equal relative importance, $\boldsymbol{a_{ij}}$ equals $\boldsymbol{a_{ji}}$, and both are equal to 1, as shown in Equation 2.

$$\begin{array}{c|ccc} \mathrm{K} & A_1 & A_2 & A_3 \\ \hline A_1 & 1 & a_{12} \cdots & a_{1n} \\ A_2 & 1/_{a_{12}} & 1 & a_{2n} \\ A_3 & \vdots & \ddots & \vdots \\ & 1/_{a_{1n}} & 1/_{a_{2n}} \cdots & 1 \end{array} \tag{2}$$

The rankings of $\boldsymbol{a_{ij}}$ can be addressed as follows assumptions:

1) If criteria ***i*** and ***j*** are deemed equally important, the ranking is assigned as 1.
2) If criterion ***i*** is slightly more important than criterion ***j***, the ranking is three.
3) If criterion ***i*** is significantly more important than criterion ***j***, the ranking is five.
4) If criterion ***i*** is significantly strongly more important than criterion ***j***, the ranking is 7.
5) If criterion ***i*** is extremely more important than criterion ***j***, the ranking is 9.

Numbers 2, 4, 6, and 8 were used for intermediate comparisons.

Finding eigevector:

Thus, in the last algorithms of the process, mathematical equations were used to normalize and determine all weights for each matrix. All weights are represented by the right eigenvector ***(w)*** corresponding to the largest eigenvalue ***(λ_{max})***, as shown in Equation 3

$$\boldsymbol{A\ w = \lambda_{\max}\ w}$$

(3)

If the pairwise comparison matrix exhibits complete consistency, matrix ***A*** will have a rank of one and $\boldsymbol{\lambda_{\max}}$ equals ***n***.

$$A = \begin{bmatrix} \frac{a_{11}}{\sum_i a_{i1}} & \frac{a_{12}}{\sum_i a_{i2}} \cdots & \frac{a_{1n}}{\sum_i a_{in}} \\ \frac{a_{21}}{\sum_i a_{i1}} & \frac{a_{22}}{\sum_i a_{i2}} & \frac{a_{2n}}{\sum_i a_{in}} \\ \cdots & \cdots & \cdots \\ \frac{a_{11}}{\sum_i a_{i1}} & \frac{a_{12}}{\sum_i a_{i2}} & \frac{a_{1n}}{\sum_i a_{in}} \\ \frac{a_{n1}}{\sum_i a_{i1}} & \frac{a_{n2}}{\sum_i a_{i2}} & \frac{a_{nn}}{\sum_i a_{in}} \end{bmatrix}$$

It is important to note that the accuracy of the AHP results is directly linked to the coherence of pairwise comparison assessments. This coherence is determined by the relationship between the entries of matrix ***A:*** $\boldsymbol{a_{ij} \times a_{jk} = a_{ik}}$**.** The consistency index **(CI)** is formulated as in Equation 4

$$\mathbf{CI=(\lambda_{max}-n)/(n-1)} \qquad (4)$$

Subsequently, the final matrix ***R*** is computed to signify the weighting of the various criteria for the alternatives.

$$R= \begin{array}{c c} & \begin{array}{cccccc} w_1 & w_2 & \ldots w_J & & w_n \\ C_1 & C_2 & \ldots C_j & \cdots & C_n \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \\ A_i \\ A_m \end{array} & \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1j} & \cdots & r_{1n} \\ r_{21} & r_{22} & & r_{2j} & & r_{2n} \\ \cdots & & \cdots & & & \cdots \\ r_{i1} & r_{i2} & & r_{ij} & \cdots & r_{in} \\ r_{m1} & r_{m2} & & r_{mj} & & r_{mn} \end{bmatrix} \end{array}$$

The matrix dimension is R_{mxn}

The final Consistency Ratio (***CR)***, which determines whether the evaluations are consistent, was computed using the value (**CI)** and Random Index ***(RI)***, as shown in Equation (5).

$$\mathbf{CR = CI/RI} \tag{5}$$

where **RI** defines the Random Index, as shown in Table 2.

Table 2. The Random Consistency Indices

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: Saaty, 1980

If CR falls below 0.10, the eigenvectors can be used as relative weights to compute the weighted values assigned to each alternative. Consequently, the total weighted score and its corresponding rank are determined.

The threshold of 0.1 serves as the upper bound for the CR. If the final consistency index ratio surpasses this threshold, the evaluation process must be repeated to enhance the consistency.

CODAS (Combinative Distance-based Assessment)

This multi-criteria technique offers valuable and dependable solutions for addressing issues characterized by multiple error criteria and inaccuracies. The CODAS method finds applications across various disciplines and domains, particularly in decision-making scenarios in which information and knowledge are limited (Ghorabaee et al., 2016 and Fouladgar et al., (2012). By calculating the Euclidean Distance as the principal mathematical measure and taxicab distance as the second measure, this method calculates distances relative to the negative distance.

The CODAS method, developed by Ghorabaee, involves the following steps with adaptations to the original terms:

Step_1: Define the decision matrix, as illustrated below.

$$L=[L_{ij}]\{nxm\} = \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1m} \\ L_{21} & L_{22} & & L_{2m} \\ \vdots & & \vdots & \vdots \\ L_{n1} & L_{n2} & \cdots & L_{nm} \end{bmatrix}$$

Where Lij represents the value of alternative i in criterion j, with i ranging from 1 to n and j ranging from 1 to m.

Step _2: Problem Decomposition.

$$n_{ij=}\begin{cases} \dfrac{L_{ij}}{maxL_{ij}} & if\ j\ \in\ N_b \\ \dfrac{minL_{ij}}{L_{ij}} & if\ j\ \in\ N_c \end{cases}$$

where Nb and Nc represent the sets of benefit and cost criteria, respectively.

Step_3. Calculate the normalized in the decision matrix with the following formula

$r_{ij} = w_j n_{ij}$

where w_j is the weight value of criterion j with $0 < w_j < 1$

Step_4. Determining the negative ideal solution

$ns = [ns_j]_{1xm}$

$ns_j = minr_{ij}$

Step_5. Compute the Euclidean distance (E_i) and Taxicab distance (T_i) of the negative idea solution alternatives

$$E_i = \sqrt{\sum_{j=1}^{m}\left(n_{ij} - ns_j\right)^2}$$

$$T_i = \sum_{j=1}^{m}\left|n_{ij} - ns_j\right|$$

Step_6. Preparation of the relative evaluation matrix

$$R_a = \lceil h_{ik} \rceil nxn$$

$$h_{ik} = (E_i - E_k) + (\varphi(E_i - E_k) * (T_i - T_k))$$

Then, $i= \{1, 2, . . . , n\}$ and τ shows a threshold function to recognize the equality of the distances of the two alternatives defined by

$$\varphi(x) = \begin{cases} 1 \quad if\ |x| \geq r \\ 0\ if\ \ |x| < r \end{cases}$$

The decision-maker has the discretion to assign the value of r, which falls within the parameter range of 0.01 to 0.05. The taxicab distance formula assesses the disparity between distances. In this study, r was set as 0.02.

Step 7. Calculate the assessment score of each alternative.

$$Hi = \sum_{k=1}^{n} h\,ik$$

Next, the evaluation score values of each alternative are determined by

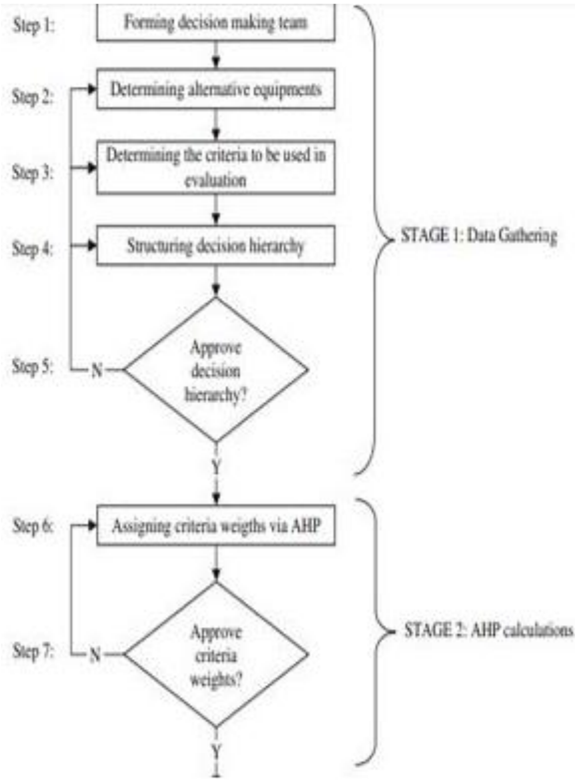
Step 8 Rank the alternatives according to the decreasing values of assessment.

AHP approach

The AHP methodology applied to the 3D Atom IV+ equipment preventive maintenance (PM) issue encompasses three process: (1) data on complex problems, (2) AHP computation results, and (3) decision-making by experts. Initially, within the data of the complex problem, alternative equipment elements options and the criteria for their evaluation were addressed, forming a decision tree hierarchy diagram. The decision hierarchy was validated by experts in decision-making. Subsequently, in the second objective, the criteria for the equipment elements PM are allocated weights using AHP. During this step, pairwise comparison matrices were constructed to ascertain all the criteria weights. Experts in the decision-making team provided individual assessments using the scale provided in Table 1 to establish values for the elements of pairwise comparison matrices. The comparison matrix, which served as the basis for calculating the criteria weights, was then derived. In the ultimate operation of this phase, the calculated weights of the criteria were ratified by the MCDM experts.

The priorities for PM equipment elements were determined by decision-making experts. Following endorsement of the functions of these elements, the best equipment element was selected in the final block of the proposed procedure based on expert rankings. A schematic of the proposed approach is shown in Figure 1.

Figure 1. The proposed AHP approach

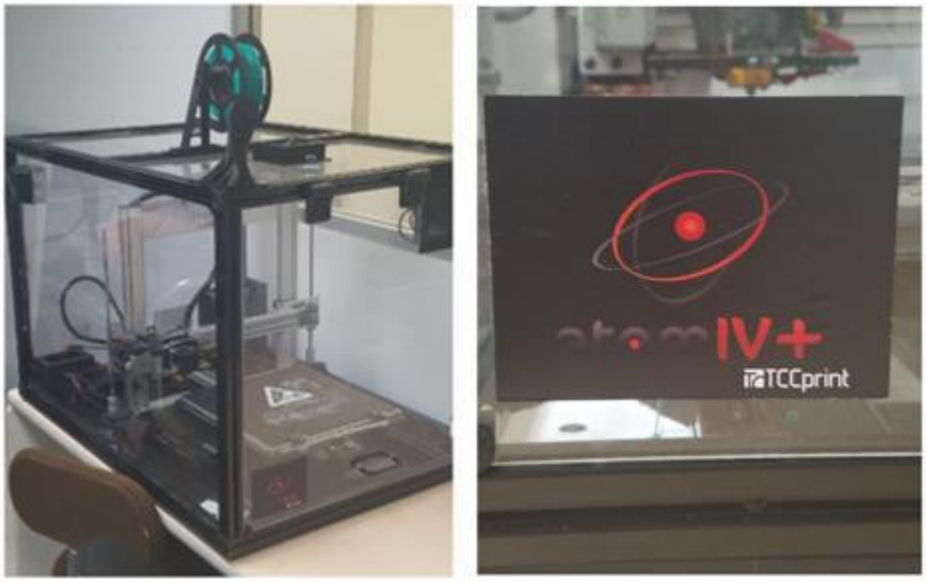


Reference by Saaty,1980

Application of the proposed research

To illustrate the proposed research, a 3D machine called Atom IV+ is shown in Figure 2. Consider a scenario in which an additive manufacturing laboratory at the Instituto Tecnológico de Ciudad Juárez (ITCJ) seeks to determine the most suitable maintenance strategy. Maintenance management systems offer a range of strategies, depending on the industry's requirements. These strategies typically fall into two primary categories: corrective and preventive. Corrective maintenance does not involve proactive maintenance until failure occurs. However, owing to tight operational budgets and intensifying competition, maintenance managers become increasingly inclined to implement dependable maintenance strategies. On the other hand, preventive maintenance involves preemptive maintenance actions undertaken before system failure to ensure the optimal performance of the system.

Figure 2. The 3D Atom IV+ machine research proposed.



Manufacturing Laboratory, ITCJ

Methodology

AHP was deemed most appropriate for our application because of its simplicity and versatility, clear Hierarchy, easy math calculations, expert judgments. In particular, AHP is the preferred method for problems that are amenable to hierarchical decomposition.

AHP analysis and results

The Analytic Hierarchy Process (AHP) is a decision-making method designed to choose one alternative from several given alternatives, consider multiple decision criteria, and rank these alternatives based on quantitative comparisons within a rational framework. AHP involves three fundamental steps (Standing et al., 2001, Sullivan, et al., 2002): problem decomposition, comparative judgments, and hierarchy composition.

The basic steps of AHP are as follows

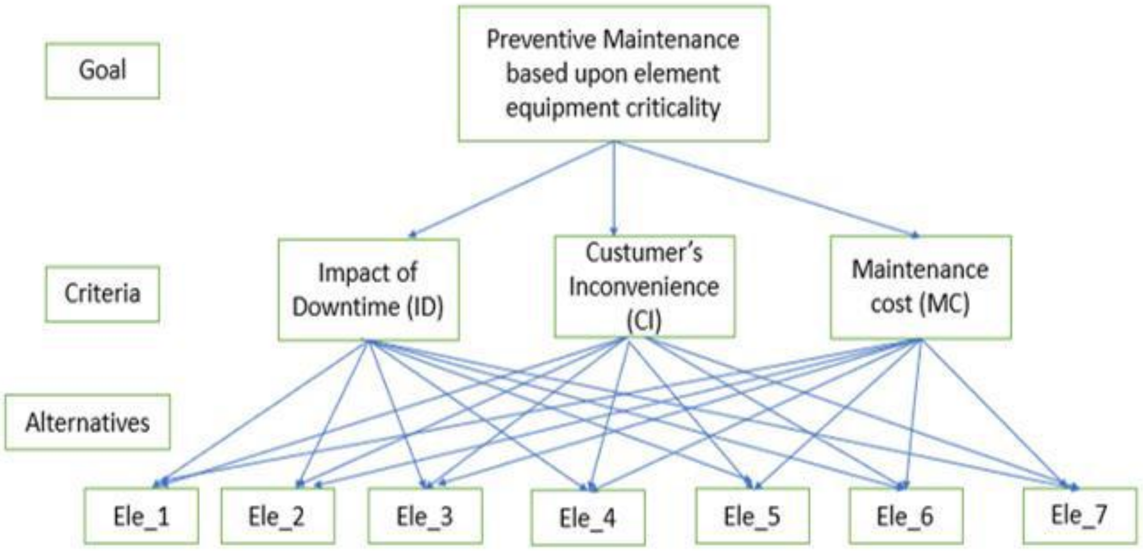
Step 1: Decomposition the problem into three diagram levels: the overall goal, judgment criteria, and alternatives, followed by the creation of a hierarchical structure. Figure 3 provides a visual representation of this hierarchy for our specific problem. In addition, we used a distinct equipment nomenclature in the diagram shown in Table 3.

Table 3. The Nomenclature of Equipment Elements on AHP Diagram

Code/Sensor	Element/System
E1	Axis_X
E2	Axis_Y
E3	Axis_Z
E4	Fan_Heat
E5	Temp_Nose_Feeder
E6	Temp_Base
E7	Feeder_Material

Source: created by the authors

Figure 3. The AHP Hierarchy Diagram of Critical Elements of Equipment 3D Atom IV+ machine.



created by the authors

Step 2: Criteria Definition.

Step 3: Matrix Construction.

Step 4: Convert the comparison matrix into a normalized matrix.

Step 5: Calculate the importance of all criteria through a pairwise comparisons matrix.

Steps 6 and 7: Define the consistency of the pairwise comparison matrix and compute the weights for all the criteria.

The problem and analysis of the 3D Atom IV+ machine

A considerable number of 3D Atom IV + machines are utilized in additive manufacturing at the Instituto Tecnológico de Ciudad Juárez (ITCJ), as shown in Figure 2, some of which are particularly pivotal from the manufacturing perspective. Therefore, implementation of preventive maintenance measures for these critical components is crucial. The following issues must be addressed

1. The inconvenience experienced by customers in the event of a failure.
2. The impact on downtime resulting from equipment failure.
3. The maintenance cost associated with the equipment.
4. Quality cost of the final product.

The objective of this study is to encompass all potential scenarios in the event of equipment failure. While the data for preventive maintenance will be hypothetical, the analysis of the issue holds significant importance and cannot be overlooked. Therefore, quantitatively obtaining these theoretical data is of paramount importance.

Formation of Scale for Scoring of Different Criterion

Three criteria were considered for criticality analysis. Each criterion was scored on a 1-9 Saaty´s scale rating, as detailed in Table 1.

1. ID_Impact of Downtime due to Equipment Failure: This criterion assesses the severity of downtime resulting from equipment failure. A Saaty´s scale rating from 1 to 9 was employed to encompass various potential impacts on downtime. Table 4 provides a comprehensive scale for this problem.
2. CI_Customer Inconvenience Due to Failure: Any equipment failure inevitably leads to losses because it may disrupt the supply of the required finished products to customers, causing inconvenience. To quantify the inconvenience experienced by customers, a scale was devised based on generation losses attributed to equipment failure. Table 4 outlines this scale.
3. MC_Maintenance Cost of the Equipment: Equipment failures necessitate maintenance activities to restore them to operational status, incurring associated costs. A scale was developed to account for the diverse range of potential maintenance costs based on the average expenses incurred for equipment maintenance. The scales used are listed in Table 4.

Table 4. Score table for the Equipment elements (experts ratings)

Code/Sensor	Element/System	ID	CI	MC
E1	Axis_X	2	8	4
E2	Axis_Y	2	8	3
E3	Axis_Z	2	8	5
E4	Fan_Heat	6	4	2
E5	Temp_Nose_Feeder	8	7	9
E6	Temp_Base	9	7	2
E7	Feeder_Material	3	9	2

Source: created by the authors

The Problem Analysis

Numerous functional components are present in 3D Atom IV+. We identified several crucial elements of this equipment that directly influenced its performance when failures occurred. The criticality of these equipment elements requires a thorough analysis. Table 4 presents the scoring tables, formulated for this study. Additionally, for the analytical results, we used the AHP scale of Saaty outlined in Table 1.

The methodology and associated algorithms have been described previously. The analysis was performed as follows:

Step 1: Normalization Process

Step 2: The scale for each criterion is defined. Table 6 presents the scale of the four criteria.

Step 3: A comparison matrix is constructed based on a defined scale. Table 3 presents the requisite comparison matrices for all alternatives.

Step 4: The comparison matrix is transformed into a normalized matrix. The conversion processes are listed in Table 5.

Tabla 5. The Normalized Matrix Obtained from the Comparison Matrix

Final Rank of PM equipment elements by AHP Saaty´s Method for 3D Atom IV+ machine									
Code/ Sensor	Element/System	ID	CI	MC	Impact of downtime (ID)	Custumer's Inconvenience (CI)	Maintenance Cost (MC)	W_Score	Rank
E1	Axis_X	2	8	4	0.0625	0.1568	0.1481	0.1017	7
E2	Axis_Y	2	8	3	0.0625	0.1568	0.1111	0.1009	6
E3	Axis_Z	2	8	5	0.0625	0.1568	0.1851	0.1055	5
E4	Fan_Heat	6	4	2	0.1875	0.0740	0.0740	0.1466	3
E5	Temp_Nose_Feeder	8	7	9	0.2500	0.1372	0.3333	0.2177	1
E6	Temp_Base	9	7	2	0.2812	0.1372	0.0740	0.2066	2
E7	Feeder_Material	3	9	2	0.0937	0.1764	0.0740	0.1187	4

Source: created by the authors

Step 5: Importance Weighting

The process is elucidated using an actual pair-wise comparison matrix through the following steps:

Table 6. Pairwise comparison matrix of criteria

A		ID	CI	MC
C	ID	1	4	8
	CI	1/4	1	5
	MC	1/8	1/5	1

Source: created by the authors

Step 6: Consistency Assessment

Compute the product of the values in each row of matrix $\boldsymbol{A}$ by taking the n_{th} root of the product in the mathematical operation, where n represents the dimension of matrix $\boldsymbol{A}$. Subsequently, the calculated roots are summed. Each root was normalized using the sum to derive the value of each eigenvector, as listed in Table 7.

Table 7. The Eigenvector analysis

	ID	CI	MC	3rd Root	Eigenvector
ID	1.000	4.000	8.000	3.556	0.549
CI	0.2500	1.000	5.000	1.967	0.303
MC	0.125	0.200	1.000	0.668	0.103
			Total	6.472	1.000

Source: created by the authors

Step 7: Final Weight Calculation

Involves the multiplication of each row of the comparison matrix by the corresponding eigenvector column, similar to matrix multiplication. For each of the three rows, the computation yielded values of 3.556, 1.967, and 0.668.

In step _d the values obtained in step c were divided by their corresponding eigenvectors to determine the respective values of λ. The average of these three λ values provided λ_{max}, where $\lambda_{max}=3.194$.

Step _e: Compute the Consistency Ratio Index value of the (CI) using the following formula:

$CI = (\lambda_{max} - n)/ (n - 1)$

which for $n=3$ results in a value of 0.0546.

In step_f the Consistency Index Ratio value of the (CIR) is computed by dividing the value of the (CI) by the Random Index value of the (RI), which was equal to 0.0418 in this case. Saaty's Random Index (RI) values are provided for various judgment orders in Table 2. If the (CIR) value was less than 0.10, the judgment was considered consistent.

Finally, in step 7 because the value of (CIR) is less than 0.10, the eigenvectors can be utilized as the relative weights of the criteria for calculating all weighted values.

The values for each alternative are computed to determine the total weighted score and their respective ranks. Tables 8 and 9 present the final ranks of AHP and CODAS.

Table 8. The Final Rank of PM 3D Atom IV+ machine by the AHP Method

Final Rank of PM equipment elements by AHP Saaty´s Method for 3D Atom IV+ machine									
Code/ Sensor	Element/System	ID	CI	MC	Impact of downtime (ID)	Custumer's Inconvenience (CI)	Maintenance Cost (MC)	W_Score	Rank
E1	Axis_X	2	8	4	0.0625	0.1568	0.1481	0.1017	7
E2	Axis_Y	2	8	3	0.0625	0.1568	0.1111	0.1009	6
E3	Axis_Z	2	8	5	0.0625	0.1568	0.18518	0.1055	5
E4	Fan_Heat	6	4	2	0.1875	0.0740	0.07407	0.1466	3
E5	Temp_Nose_Feeder	8	7	9	0.2500	0.1372	0.3333	0.2177	1
E6	Temp_Base	9	7	2	0.2812	0.1372	0.0740	0.2066	2
E7	Feeder_Material	3	9	2	0.0937	0.1764	0.0740	0.1187	4

Source: created by the authors

The Result by CODAS for the 3D Atom IV+ Machine

Table 9. The Final Rank of PM 3D Atom IV+ machine by CODAS Method

Reference	Code	Critical elements	Weighted	Ranking
4	Ele7	Feeder_material	1.5030	1
8	Ele5	Temp_Nose_Feeder	6.6110	2
6	Ele6	Temp_Base	12.6152	3
5	Ele4	Fan_Heat	32.6046	4
3	Ele3	Motor_Z	43.2256	5
2	Ele2	Motor_Y	45.5324	6
1	Ele1	Motor_X	57.0330	7

Source: created by the authors

Results

These results are intriguing for our analysis. It is widely acknowledged that Temp_Nose_Feeder plays a pivotal role in the 3D Atom IV+. The AHP method was confirmed as the most crucial component, ranking first with a weighted score of 0.2177, as shown in Table 8.

The AHP multi-criteria analysis coupled with expert judgment serves as a means to pinpoint the most significant factors shown in Table 3 and Table 4, establishing a systematic approach that supports a maintenance strategy tailored to the 3D Atom IV+ machine.

The computed scoring values, derived from AHP using weight calculation methods, yield consistency ratio values exceeding 0.10 CR according to Saaty's method, aligning seamlessly with the predefined objectives and research inquiries.

Furthermore, the factors identified in the MCDM analysis, as shown in Table 8, encompass the score values and rankings that harmonize with the advocated PM outlined in Figure 3. This framework streamlines the identification of the requisite PM type for formulating specific strategies according to the requirements of an enterprise.

By employing the CODAS methodology, it was possible to pinpoint the primary elements of the PM in the 3D machine hierarchy using the AHP elements weights. The findings revealed notable consistency across both methodologies, with an element of significant relevance shared almost equally with critical components (Table 10).

Table 10. Comparison of the final rank results

Method	Element/system	Rank
AHP	Temp_Nose_Feeder	1
	Temp_Base	2
	Fan_Heat	3
CODAS	Feeder_Material	1
	Temp_Nose_Feeder	2
	Temp_Base	3

Source: created by the authors

Discussion

The Analytic Hierarchy Process (AHP) was used for multi-criteria decision making in the 3D Atom IV+, which allows structuring complex problems into a hierarchy composed of objectives, criteria, and alternatives. The research focused on pairwise comparisons of the elements, which facilitated the assignment of relative priorities based on both qualitative and quantitative judgments. AHP is particularly useful for integrating intangible and tangible criteria, transforming subjective judgments into numerical values using Saaty's scale, and ensuring logical consistency through the calculation of the consistency index. However, one of the challenges of AHP is the potential inconsistency in comparisons, which may require adjustments and revisions to maintain the validity of results, especially when the number of criteria and alternatives is high.

On the other hand, the CODAS method is a multi-criteria technique based on Combinative- distance Assessment that evaluates alternatives by considering both Euclidean distance and taxicab distance, in relation to an ideal solution. CODAS stands out for its computational simplicity and its ability to handle criteria with different units of measurement, which facilitates comparative evaluation in contexts where the alternatives have heterogeneous characteristics. Unlike AHP, which is based on subjective judgments to establish priorities, CODAS uses distance measures to determine the order of preference, which can reduce subjectivity and improve objectivity in the ranking of alternatives.

In the comparison of both methods for obtaining critical elements for the 3D Atom IV+, AHP offered a clear hierarchical structure and a rigorous approach to the valuation of qualitative criteria, making it ideal for situations where experience and expert knowledge are fundamental for decision-making. CODAS, on the other hand, was suitable for scenarios where quantitative data is available and a quick, objective evaluation based on proximity to the ideal solution is sought. However, CODAS may be less intuitive for users without experience in multi-criteria analysis, while AHP requires considerable effort to ensure consistency and avoid bias in judgments.

Finally, the choice between AHP and CODAS depends on the context of the problem, the nature of the criteria, and the availability of data. AHP is preferable when expert judgments and a detailed criteria structure are required, while CODAS is useful for quick and objective quantitative assessments. The integration or combination of both methods can also be explored to leverage the strengths of each and improve the quality of multi-criteria decision-making.

Conclusion

The greatest advantage of this type of analysis is its ability to provide a comprehensive view of the problem through multiple criteria, ensuring a well-rounded assessment that encompasses all factors using AHP and CODAS methods. Consequently, the analysis yields significantly improvements were observed results. This appears of such an analysis conducted for 3D Atom IV+ machine equipment using the AHP method developed by Saaty, effectively addressing all identified gaps at ITCJ using the actual research..

Upon conducting a comparative analysis of factors with all hierarchy critical elements calculated using criterion weights for AHP, Table 8 indicates that Temp_Nose_Feeder emerged as the most crucial factor when considering all individual critical elements in 3DAtom IV+ machine within the overarching classifications.

The primary contribution of this research, particularly concerning preventive maintenance strategies, involves presenting a methodology employing AHP and CODAS to aid additive manufacturing companies and researchers in identifying relevant factors for 3D Atom IV+ machine preventive maintenance at ITCJ. This facilitates the allocation of resources to strategies that enhance competitiveness while mitigating costs. The utilization of n-expert judgment proved pivotal, enabling the assignment of importance to pertinent criteria in both AHP and CODAS method. For future endeavors, it is suggested to (1) explore alternative MCDM approaches for calculating weighting values through n-expert judgment and (2) integrate machine learning techniques to analyze the primary factors affecting PM in the 3D Atom IV+ machine at ITCJ:

(a) Using another MCDM method to calculate the weighting values through n-experts judgment, and subsequently, an analysis of the scoring and ranking values was obtained.

(b) Implementing machine learning to analyze the factors identified in our research.

Future research

For future research, the following aspects are proposed:

(a) Use other multi-criteria decision-making methods to calculate the weighting values through n-experts judgment (TOPSIS, VIKOR, MOORA).

(b) Implement a study with neural networks for these additive manufacturing equipment.

(c) Develop user interfaces that indicate the wear behavior of the critical elements (sensors) during operational cycles through a new reasearch. Additionally, future studies should include additional criteria for uncontrolled variables such as humidity, noise, temperature, and vibration using neural networks.

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