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A new approach to integrating maintainability in design based on fuzzy logic: Case of disassembly, standardization and accessibility

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Abstract

Maintainability is an important design characteristic of a mechanical system, making various maintenance activities easier. Easily maintainable equipment gives industrialists a real advantage over competitors. Implementing such equipment is often complex and difficult for design engineers to take into account uncertainties and imprecisions at the design stage. There are several tools that can be used to assess maintainability, but these have been more developed as traditional tools. This article aims to propose a new approach to integrating maintainability into the design phase of mechanical systems based on fuzzy logic, which is built from human knowledge to support design engineers. Indeed, this method allows us to evaluate maintainability in the design phase according to its attributes, which are translated into linguistic variables. Our case study demonstrates the effectiveness of the method presented in this work during the design phase and evaluating maintainability based on attributes such as standardization, disassembly, and accessibility.

Keywords: Maintainability; Linguistic Variable; Fuzzy Logic; Attributes; System

1. Introduction

In today's globalized world, all mechanical systems must be highly efficient. This can only be achieved by improving system maintainability. Maintainability is defined as the probability that a faulty component or system can be restored within a specified time frame when maintenance is performed according to prescribed procedures. It is the ease with which a system can be maintained in order to isolate faults or their causes [1]. The issue of improving the maintainability of systems or equipment is becoming more important than ever because of the operating costs and accidents caused by incomprehensible maintainability design [2].

Engineering systems or products are important parts of the global economy, every year billions of dollars are spent to maintain and service various types of these systems worldwide, hence global competition and other factors force manufacturers to produce highly reliable, maintainable and safe systems [3]. The performance and technical and economic objectives required of production equipment or systems lead designers to take an interest in the types of system failures, but above all in the resulting consequences. The interest of manufacturers is increasingly oriented towards the maintainability of production means [4]. The objectives of industrial companies are to maximize profits. It is clear from this moment that any cause of production system shutdown is poorly perceived and can be the source of

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tensions between production stakeholders and business leaders. Hence, for their production lines, they consider systems or equipment that are very easy to maintain[5].

Man is often put in difficulty because of his imprecision and uncertainty when it comes to making decisions in the direction of maintainability.at the design phase (intrinsic maintainability) whose criteria are sometimes contradictory. Therefore, in order to find a solution to these concerns, our objective is the implementation of a method based on fuzzy logic for the improvement of the maintainability of mechanical systems in the design phase in order to make them more reliable and reduce their repair time (minimize downtime). From the various maintainability attributes discussed in the literature, this article will focus on three, which are: disassembly, standardization and accessibility.

2. Literature review

2.1. General information on maintainability

Reliability has long been considered, at the design stage, as a measure of system effectiveness. However, it has been proven to be an incomplete measure because it does not consider maintainability, which is another important aspect of system performance[6]. The life cycle cost of a system depends, to a large extent, on the maintainability of the system. Besides being a statistical concept, maintainability is a design parameter whose achievement is influenced by known elements and attributes[7].

2.1.1. Maintainability History

Maintainability refers to the measures taken during the development, design, and installation of a product that reduce maintenance hours, logistics costs, skill levels, and ensure that the product meets the requirements of its intended use. The precise origins of maintainability as an identifiable discipline are somewhat obscure, but in some ways, the concept dates back to the very beginning of the twentieth century. For example, in 1901, the Army Signal Corps contract for the development of the Wright brothers' airplane stipulated that the aircraft should be "simple to operate and maintain." [8]. In the modern context, the beginnings of the discipline of maintainability date back to the period between World War II and the early 1950s, when various studies conducted by the United States Department of Defense yielded surprising results[9],[10]

- A Navy study reported that during maneuvers, electronic equipment was operational only 30% of the time.
- The U.S. Army's Eighth Air Force, stationed in Britain during World War II, reported that only 30 percent of the heavy bombers stationed at an airfield were serviceable at any one time, and that the situation at other airfields was fairly similar.
- An Army study indicated that approximately two-thirds to three-quarters of the equipment was out of service or under repair at any given time.

2.1.2. Mathematical approach to maintainability M(t)

Maintainability can be characterized by its MTTR (Mean Technical Time to Repair) given by equation (1)

$$MTTR = \frac{\sum intervention\ time\ for\ n\ breakdowns}{number\ of\ breakdowns} \quad \ldots\ldots\ldots\ (1)$$

2.1.3. General information on fuzzy logic

Classical logic plays a huge role in various fields, its structure can be expressed as facts only with "true" or "false" which limits its scope in techniques and applications such as Artificial Intelligence, decision making with uncertain data, which want to imitate reasoning and the human mind. Fuzzy logic is designed precisely to solve this problem, to allow the characterization of elements in a "gradual" way. Our perception of the real world is permeated with concepts that do not have clearly defined boundaries, for example, much, tall, much taller than young, etc. are true only to a certain extent and they are false to a certain degree. These concepts can be called fuzzy or vague concepts, a human brain works with them, while computers cannot. Natural languages, whose level is much higher than programming languages, are fuzzy while programming languages are not[11].

2.1.4. History of Fuzzy Logistics

The beginnings of fuzzy logic appeared in 1940 when American researchers began to study the concept of uncertainty. In 1965,[12] introduced fuzzy set theory, he was then a professor at the University of California at Berkeley and became an internationally renowned automation engineer [13]. In 1973[14] publishes an article that mentions for the first time the term linguistic values, that is, the value is a word and not a letter. However, his reasoning principle inspired by human reasoning attracted Mamdani who was the first to introduce the notion of fuzzy logic in industrial regulation in

1974: the fuzzy regulation of a steam boiler[15]. Fuzzy logic was introduced in Japan in 1985 [16] by the Japanese researcher Sugeno, and Japanese companies understood its technical and commercial advantage.

- Ease of implementation;
- Solution of complex multi-variable problems;
- Robustness to uncertainties;
- Possibility of integrating expert knowledge.
- There are many applications in different fields. Here is a non-exhaustive list of some:
- Household appliances (washing machine, vacuum cleaner, pressure cooker, etc.);
- On-board automotive systems (ABS, suspension, air conditioning, etc.);
- Transportation systems (train, metro, elevator, etc.);
- Decision systems, diagnosis (medical, insurance).

3. Methods

3.1. The steps in this process are as follows

- System parameters are selected and assigned values, which are then fuzzified;
- Definition of fuzzy inference rules (inference engine) for each maintainability criterion based on the parameters;
- Calculation of the average numerical value of each criterion based on its fuzzy inference rule;
- Convert this value to a fuzzy triangular number;
- Calculation of the weight of each criterion;
- Calculation of overall maintainability.

3.2. Choosing design parameters

During the design phase, the designer or manufacturer must collect information on the various parameters of the system. He must choose the parameters that will facilitate its maintainability.

3.2.1. For example, we can cite

- The connection type;
- Determination of the types of possible connections per connection;
- Determination of possible material types by bond and component;
- Definition of link positions.

3.2.2. Definition of linguistic variables

The term "linguistic variable" refers to an imprecise qualifier used to define a fuzzy set, which is a triplet (V, X, TV) defined by

- V denotes the name (eg, age, temperature, . . .);
- X represents the domain on which it is defined (eg, the set of integers, real numbers, . . .);
- TV, a finite or infinite set of fuzzy subsets of X characterizing V [14].

Linguistic variables are used to model imprecise or vague knowledge about a variable, whose precise value is unknown.

The main interest of fuzzy logic is to avoid a very artificial threshold effect when moving from one category to another: very naturally, fuzzy sets make it possible to represent the fact that when the cost of a product increases, it gradually (and not abruptly) goes from "reduced" to "reasonable", then to "high". Each linguistic variable will therefore be defined via a membership function associating with each cost c its degree of membership in the corresponding fuzzy set (set of "reduced", "reasonable" and "high" costs).

3.2.3. Definition of inference rules for each maintainability criterion

Fuzzy rule bases, in their general case, are therefore defined by membership functions on the system variables, and by rules that can be written textually or presented in a table. Each rule calls upon inputs and outputs that can be different.

The design and development of a fuzzy inference system requires the adoption of a structured approach to ensure a judicious choice of the different parameters of the system. The previous definitions are used to define human expert knowledge in a set of rules. These rules are based on a combination of elementary fuzzy propositions.

Fuzzy propositions are special cases of fuzzy expressions. For example, let two fuzzy propositions "*V is A*» using (V, XV, TV) and « W is B » using (W, XW, TW). Then, « V is A and W is B », « V is A or not W is B » are fuzzy expressions. The truth value of fuzzy expressions is obtained by applying the operators on the truth values of their operands. These expressions are therefore used to express the knowledge of human experts in fuzzy rules. A fuzzy rule is composed of a premise (or antecedent) and a conclusion (or consequence) and is of the form « IF premise THEN conclusion ». A premise is a fuzzy expression while a conclusion is a fuzzy statement of a different nature.

To perform an assessment of maintainability criteria, the attribute values are expressed here by the linguistic variables which are: "very satisfied", "satisfied", "a little satisfied", "average", "a little dissatisfied", "dissatisfied" and "very dissatisfied"[17]. For a good use of the inference rule, we must transform the value domains of each setting into linguistic variables (fuzzification), using the difficulty scores used in [18] and [19] (see table 1).

Table 1 Fuzzification of the value domains of system parameters

Design parameter	Value domain	Score	Interpretation	Linguistic variable
parameter 1	Value 1	Score 1	Interpretation 1	Variable 1
	⋮	⋮	⋮	⋮
	Value M_1	Score M_1	Interpretation M_1	Variable M_1
parameter 2	Value 1	Score 1	Interpretation 1	Variable 1
	⋮	⋮	⋮	⋮
	Value M_2	Score M_2	Interpretation M_2	Variable M_2
parameter 3	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮
parameter N	Value 1	Score 1	Interpretation 1	Variable 1
	⋮	⋮	⋮	⋮
	Value M_N	Score M_N	Interpretation M_N	Variable M_N

3.2.4. Definition of fuzzy numbers, membership functions and calculation rules

In the previous context, the attribute value is expressed by a linguistic variable, which cannot be calculated directly because it is not numeric and has not been normalized. We use a triangular fuzzy number to represent linguistic variables. The triangular fuzzy number is denoted, (V_i^a, V_i^b, V_i^c), where $0 \le V_i^a \le V_i^b \le V_i^c \le 1$.

- V_i^b is the most possible value of a linguistic variable;
- V_i^a is the lower bound;
- V_i^c is the upper limit.

The rules for the operation of the triangular fuzzy number are given in the following equations

Addition / Subtraction: $(\nu_i^a,\nu_i^b,\nu_i^c) \pm (\nu_j^a,\nu_j^b,\nu_j^c) = (\nu_i^a \pm \nu_j^a, \nu_i^b \pm \nu_j^b, \nu_i^c \pm \nu_j^c)$ .... (3)

- Multiplication: $(\nu_i^a,\nu_i^b,\nu_i^c)\,\mathbf{x}(\nu_j^a,\nu_j^b,\nu_j^c) = (\nu_i^a \times \nu_j^a, \nu_i^b \times \nu_j^b, \nu_i^c \times \nu_j^c)$ .... (3)
- Multiplication by a scalar: $\mathbf{k}\ \mathbf{x}\ (\nu_i^a,\nu_i^b,\nu_i^c) = (\mathbf{k}\nu_i^a, \mathbf{k}\nu_i^b, \mathbf{k}\nu_i^c)$ .... (4)
- Division by a scalar: $(\nu_i^a,\nu_i^b,\nu_i^c)\,/\,\mathbf{k} = (\nu_i^a\,/\,\mathbf{k}, \nu_i^b\,/\,\mathbf{k}, \nu_i^c\,/\,\mathbf{k})$ .... (5)

The triangular fuzzy number can reflect the fuzziness of the linguistic variable. Figure 1 shows the memberships of this linguistic variable. So, the triangular fuzzy number can be represented by a triplet (a, b, c) giving respectively the lower bound, the modal value and the upper bound of the fuzzy set. The indicators are generally expressed in % or ‰. Furthermore, for standardization purposes with fuzzy logic, we will choose them to be included in the interval [0 1].

Note that there are multiple possible forms of membership functions that are not piecewise linear (Gaussian, bell-shaped, sigmoid membership functions, etc.). It has often been shown in the literature that trapezoidal or triangular fuzzy numbers are nevertheless sufficient to encode most subjective data. We will base our analysis on triangular functions.

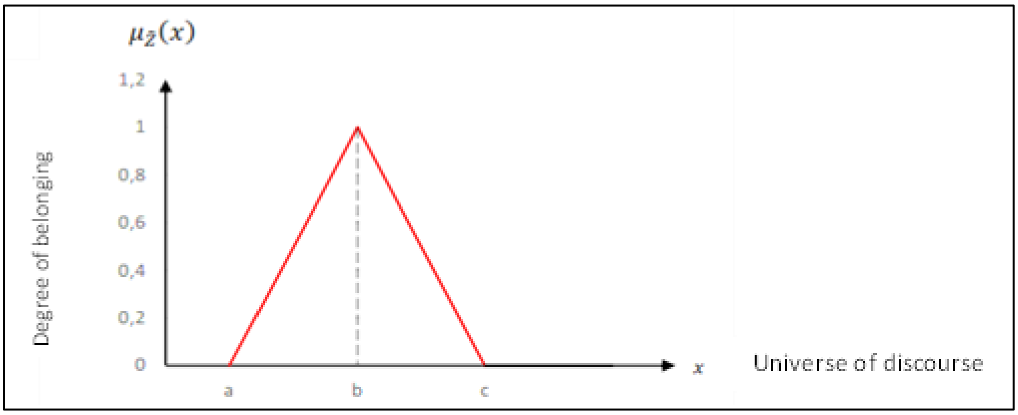

Figure 1 Membership function for a given linguistic value

According to the membership function, we can obtain the triangular fuzzy number corresponding to each linguistic variable.

- Let x be the universe of discourse, that is, a set of objects denoted x.
- The degree of membership in a linguistic value indicates to what extent an object x belongs to X, whereas in "crisp" sets (the term "crisp" is defined in contrast to fuzzy), objects either belong to the set or not.

Calculation of the global fuzzy number of each maintainability criterion for a multi-component system (efficiency function)

The process of evaluating each maintainability criterion based on the inference rule is given step by step as follows

- Calculation of the numerical value of each criterion by the following expression (6):

$$V = f(n_s, n_a) \qquad \text{.............} \quad (6)$$

Where,

- V is the numerical value of the criterion;
- n_a is the number of all inference rule results contained in each criterion's column;
- n_s is the number of elements that allow us to validate the result of a rule (a little satisfied, satisfied or very satisfied);

- $f(n_s,n_a)$ is the efficiency function, which describes the relationship between n_s / n_a and V.

$$f(n_s, n_a) = (n_s / n_a)^2$$

- Converting the numerical value of the criterion into a triangular fuzzy number

The membership function of the linguistic variable shown in Figure 1 can be expressed as follows:

$$\mu_i(X) = \begin{cases} \frac{X-a}{b-a}, if\ a \leq X \leq b \\ \frac{c-X}{c-b}, if\ b\ \leq X \leq c \\ 0, if\ not \end{cases} \quad \text{.......... (8)}$$

The conversion equation can be expressed as follows

$$(V^a, V^b, V^c) = \sum_{i-1}^{n} \mu_i(f(n_s, n_a)) x (V_i^a, V_i^b, V_i^c) \quad \text{..............(9)}$$

Where,

- μ_i is the membership function of the ith linguistic variable;
- (V_i^a, V_i^b, V_i^c) is the triangular fuzzy number of the ith linguistic variable;
- **n** is the number of membership functions.

3.2.5. AHP method for calculating the weight of maintainability criteria

The AHP (Analytic Hierarchy Process) method [20] is used to determine the weights of the three maintainability criteria (accessibility, disassembly and standardization) which are represented in Figure 2. Although the AHP method has the disadvantages of strict judgments and compensations between criteria, it fits perfectly to our study considering its flexibility for the assignment of priorities which is based on pairwise comparisons between the different criteria.

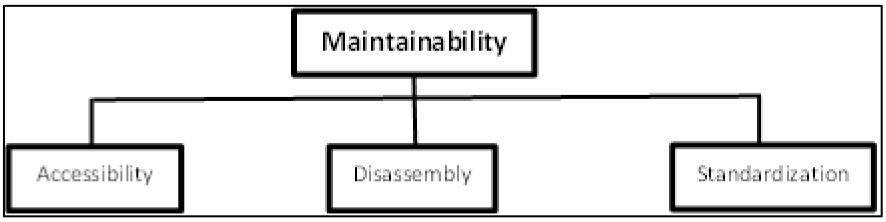

Figure 3 Maintainability criteria

The application of this method for calculating the weight of criteria takes place in four stages

Step 1 This step involves comparing the relative importance of the criteria based on [17]. This comparison is carried out by elements taken two by two in relation to the element of the higher level taking into account a numerical scale. Then, it is necessary to configure a reciprocal square matrix formed by the evaluations of the ratios of the weights (aij). Table 2 translates some rules for a verbal scale to a numerical scale [20].

To do this, we assume that aij is the value of the relative importance between elements i and j. Therefore, it represents the ratio between the weight relative to element i (Pi) and the weight relative to element j (Pj)

$$a_{ij} = \frac{p_i}{p_j} \quad \text{..........(10)}$$

Table 3 Judgments of the AHP method measurements [20]

Digital scale	Verbal scale
1	Equal importance of both elements
3	One element is a little more important than the other
5	One element is more important than the other
7	One element is much more important than the other
9	One element is absolutely more important than the other
2; 4; 6 ;8	Intermediate values between two judgments, used to refine the judgment

The different weights between the elements are represented in the following matrix form called the judgment matrix:

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{nn} \end{pmatrix} = \begin{pmatrix} 1 & \cdots & \frac{p_1}{p_n} \\ \vdots & \ddots & \vdots \\ \frac{p_m}{p_1} & \cdots & 1 \end{pmatrix} \quad \text{............(11)}$$

Step 2 This step consists of determining priorities by calculating the relative importance of each of the elements of the hierarchy from the evaluations obtained in the previous step. The relative importance of the different criteria is expressed by the values of the eigenvector normalized to 1 of matrix A. Thus, a new matrix B is determined.

$$B = \begin{pmatrix} \frac{1}{\sum_{i=1}^{n} a_{i1}} & \cdots & \frac{a_{1n}}{\sum_{i=1}^{n} a_{in}} \\ \vdots & \ddots & \vdots \\ \frac{a_{m1}}{\sum_{i=1}^{n} a_{i1}} & \cdots & \frac{1}{\sum_{i=1}^{n} a_{in}} \end{pmatrix} \quad \text{.........(12)}$$

The relative weight of an element i in column j of matrix B is calculated by the following equation

$$p_i^j = \begin{bmatrix} \frac{a_{1j}}{\sum_{i=1}^{n} a_{ij}} \\ \frac{a_{2j}}{\sum_{i=1}^{n} a_{ij}} \\ \vdots \\ \frac{a_{nj}}{\sum_{i=1}^{n} a_{ij}} \end{bmatrix} \quad \text{..............(13)}$$

Step 3: At the end of this step, we synthesize the priorities by calculating an overall evaluation score attached to each of the alternative solutions (Pig), and this, by applying the following equation:

$$P_i = \frac{1}{n}\sum_{j=1}^{n} p_i^j \qquad \text{............(14)}$$

Step 4: this last step, the consistency of the entire hierarchy is evaluated from an IC index (consistency index) given by the following formula:

$$IC = \frac{T_{c\,max} - K}{K-1} \qquad \text{..............(15)}$$

- With: K the number of elements compared and TC the average consistency value.

Similarly, a consistency ratio (RC) is defined and can be interpreted as the probability that the matrix B is randomly modified depending on the number of criteria and an index IA (random index).

$$RC = \frac{IC}{IA} \qquad \text{.............. (16)}$$

Table 3 Random Index Table [20]

Number of criteria	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
IA	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

According to [20], the assessments must be revised in the case where Rc exceeds 10%. The four steps thus presented allow us to arrive at the calculation of the weight of each criterion.

3.3. Fuzzy maintainability assessment

If each maintainability criterion value is better than "average", we believe the result is acceptable, then we can perform a comprehensive system maintainability assessment, otherwise, the design needs to be modified. We propose a comprehensive system maintainability assessment method based on a fuzzy weighted sum.

- Calculation of the overall system maintainability based on criteria.

The system maintainability value is also denoted by a fuzzy triangular number, which is expressed as

$$(v_s^a, v_s^b, v_s^c) = \sum_{i=1}^{n} p_i \times (v_i^a, v_i^b, v_i^c) \qquad \text{.............(17)}$$

Where,

- **n** is the number of maintainability criteria,
- (v_s^a, v_s^b, v_s^c) is the maintainability value of the system,
- (v_i^a, v_i^b, v_i^c) is the value (fuzzy number) of the ith maintainability criterion,
- $\mathbf{P_i}$ the weight of the ith maintainability criterion.

4. Results

Here we will present the results obtained after applying the process of the method described above, and then give their interpretations.

4.1. System parameters and their fuzzification

The exploitation of table 1 allowed us to obtain the results represented in table 4 below:

Table 4 Fuzzification of the millstone parameters

Design parameter	Value domain	Difficulty score	Interpretation	Linguistic variable
Location or positioning of the links	Flat surface	1	Easy access	satisfied
	Angular surface	1.6	Difficult to access, handling required	a little dissatisfied
	In a slot	2	Very difficult to access	dissatisfied
Tools for disassembly	Standard tools	1	Negligible torque effort	satisfied
	Specific tools	2	Low torque effort	medium
	Request special tools	3	Very high torque effort	dissatisfied
Link Visibility	Clearly visible	1	Surface attachment, spaced	Satisfied
	Hardly visible	1.6	Attachment pushed in, brought together	Medium
	Difficult to locate	2	Very deep, spaced attachment	Dissatisfied
Types of binding attachment	Wing head screw/nut	1	Easy handling	Satisfied
	Standard head screw/nut	1.4	Not easy to handle	Medium
	Pin	1.6	Handling a little difficult	A little dissatisfied

Table 4 allows us to transform the value domains of the system parameters into linguistic values for their fuzzification.

4.2. Determination of inference rules for maintainability criteria

Table 5 Inference rule for accessibility

Connection	Location	Visibility	Linguistic value of accessibility
Satisfied	Satisfied	medium	Satisfied
Satisfied	Satisfied	Dissatisfied	Dissatisfied
Satisfied	Satisfied	Satisfied	Very satisfied
Satisfied	A little dissatisfied	Dissatisfied	Dissatisfied
Satisfied	A little dissatisfied	medium	medium
Satisfied	A little dissatisfied	Satisfied	Satisfied
Satisfied	Dissatisfied	Satisfied	medium
Satisfied	Dissatisfied	Dissatisfied	Very dissatisfied

Satisfied	Dissatisfied	medium	A little dissatisfied
medium	Satisfied	Dissatisfied	Dissatisfied
medium	Satisfied	medium	A little satisfied
medium	Satisfied	Satisfied	Very Satisfied
medium	A little dissatisfied	medium	medium
medium	A little dissatisfied	Satisfied	A little satisfied
medium	A little dissatisfied	Dissatisfied	Dissatisfied
medium	Dissatisfied	Satisfied	medium
medium	Dissatisfied	Dissatisfied	Very dissatisfied
medium	Dissatisfied	medium	A little dissatisfied
A little dissatisfied	Satisfied	Satisfied	Very Satisfied
A little dissatisfied	Satisfied	Dissatisfied	Dissatisfied
A little dissatisfied	Satisfied	medium	A little satisfied
A little dissatisfied	Dissatisfied	medium	A little dissatisfied
A little dissatisfied	Dissatisfied	Satisfied	medium
A little dissatisfied	Dissatisfied	Dissatisfied	Very dissatisfied
A little dissatisfied	A little dissatisfied	Satisfied	A little satisfied
A little dissatisfied	A little dissatisfied	medium	A little dissatisfied
A little dissatisfied	A little dissatisfied	Dissatisfied	Dissatisfied

Table 6 Inference rule for dismount ability

Connection	**Location**	**Visibility**	**Tools**	**Linguistic value of dismount ability**
Satisfied	Satisfied	medium	medium	Satisfied
Satisfied	Satisfied	Dissatisfied	Dissatisfied	Dissatisfied
Satisfied	Satisfied	Satisfied	Satisfied	Very satisfied
Satisfied	A little dissatisfied	Dissatisfied	Dissatisfied	Dissatisfied
Satisfied	A little dissatisfied	medium	medium	A little satisfied
Satisfied	A little dissatisfied	Satisfied	Satisfied	Satisfied
Satisfied	Dissatisfied	Satisfied	Satisfied	A little satisfied
Satisfied	Dissatisfied	Dissatisfied	Dissatisfied	Very dissatisfied
Satisfied	Dissatisfied	medium	medium	medium
medium	Satisfied	Dissatisfied	Dissatisfied	Dissatisfied
medium	Satisfied	medium	medium	A little satisfied
medium	Satisfied	Satisfied	Satisfied	Very satisfied
medium	A little dissatisfied	medium	medium	medium
medium	A little dissatisfied	Satisfied	Satisfied	Satisfied
medium	A little dissatisfied	Dissatisfied	Dissatisfied	Dissatisfied

medium	Dissatisfied	Satisfied	Satisfied	A little satisfied
medium	Dissatisfied	Dissatisfied	Dissatisfied	Very dissatisfied
medium	Dissatisfied	medium	medium	A little dissatisfied
A little dissatisfied	Satisfied	Satisfied	Satisfied	Very satisfied
A little dissatisfied	Satisfied	Dissatisfied	Dissatisfied	Dissatisfied
A little dissatisfied	Satisfied	medium	medium	A little satisfied
A little dissatisfied	Dissatisfied	medium	medium	A little dissatisfied
A little dissatisfied	Dissatisfied	Satisfied	Satisfied	medium
A little dissatisfied	Dissatisfied	Dissatisfied	Dissatisfied	Very dissatisfied
A little dissatisfied	A little dissatisfied	Satisfied	Satisfied	Satisfied
A little dissatisfied	A little dissatisfied	medium	medium	medium
A little dissatisfied	A little dissatisfied	Dissatisfied	Dissatisfied	Dissatisfied
Satisfied	Satisfied	medium	Dissatisfied	A little dissatisfied
Satisfied	Satisfied	Dissatisfied	Satisfied	medium
Satisfied	Satisfied	Satisfied	medium	Satisfied
Satisfied	A little dissatisfied	Dissatisfied	medium	A little dissatisfied
Satisfied	A little dissatisfied	medium	Satisfied	A little satisfied
Satisfied	A little dissatisfied	Satisfied	Dissatisfied	A little dissatisfied
Satisfied	Dissatisfied	Satisfied	Dissatisfied	Dissatisfied
Satisfied	Dissatisfied	Dissatisfied	medium	Dissatisfied
Satisfied	Dissatisfied	medium	Satisfied	A little satisfied
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medium	Satisfied	Satisfied	Dissatisfied	A little dissatisfied
medium	A little dissatisfied	medium	Satisfied	A little satisfied
medium	A little dissatisfied	Satisfied	Dissatisfied	A little dissatisfied
medium	A little dissatisfied	Dissatisfied	medium	A little dissatisfied
medium	Dissatisfied	Satisfied	Dissatisfied	Dissatisfied
medium	Dissatisfied	Dissatisfied	medium	Very dissatisfied
medium	Dissatisfied	medium	Satisfied	A little satisfied
A little dissatisfied	Satisfied	Satisfied	Dissatisfied	A little dissatisfied
A little dissatisfied	Satisfied	Dissatisfied	medium	medium
A little dissatisfied	Satisfied	medium	Satisfied	Satisfied
A little dissatisfied	Dissatisfied	medium	Satisfied	A little satisfied
A little dissatisfied	Dissatisfied	Satisfied	Dissatisfied	A little dissatisfied
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A little dissatisfied	A little dissatisfied	Satisfied	medium	medium
A little dissatisfied	A little dissatisfied	medium	Dissatisfied	A little dissatisfied

A little dissatisfied	A little dissatisfied	Dissatisfied	Satisfied	medium
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Satisfied	Satisfied	Dissatisfied	medium	A little dissatisfied
Satisfied	Satisfied	Satisfied	Dissatisfied	Satisfied
Satisfied	A little dissatisfied	Dissatisfied	Satisfied	A little dissatisfied
Satisfied	A little dissatisfied	medium	Dissatisfied	medium
Satisfied	A little dissatisfied	Satisfied	medium	A little satisfied
Satisfied	Dissatisfied	Satisfied	medium	medium
Satisfied	Dissatisfied	Dissatisfied	Satisfied	A little dissatisfied
Satisfied	Dissatisfied	medium	Dissatisfied	A little dissatisfied
medium	Satisfied	Dissatisfied	Satisfied	medium
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medium	Satisfied	Satisfied	medium	Satisfied
medium	A little dissatisfied	medium	Dissatisfied	A little dissatisfied
medium	A little dissatisfied	Satisfied	medium	A little satisfied
medium	A little dissatisfied	Dissatisfied	Satisfied	A little dissatisfied
medium	Dissatisfied	Satisfied	medium	medium
medium	Dissatisfied	Dissatisfied	Satisfied	Dissatisfied
medium	Dissatisfied	medium	Dissatisfied	A little dissatisfied
A little dissatisfied	Satisfied	Satisfied	medium	A little satisfied
A little dissatisfied	Satisfied	Dissatisfied	Satisfied	medium
A little dissatisfied	Satisfied	medium	Dissatisfied	A little dissatisfied
A little dissatisfied	Dissatisfied	medium	Dissatisfied	Dissatisfied
A little dissatisfied	Dissatisfied	Satisfied	medium	A little dissatisfied
A little dissatisfied	Dissatisfied	Dissatisfied	Satisfied	Dissatisfied
A little dissatisfied	A little dissatisfied	Satisfied	Dissatisfied	A little dissatisfied
A little dissatisfied	A little dissatisfied	medium	Satisfied	A little satisfied
A little dissatisfied	A little dissatisfied	Dissatisfied	medium	Dissatisfied

For the fuzzification in % (of the type of link compared to the total number of links) in table 6 below we have

- From 0 to 30% corresponds to "dissatisfied
- From 30 to 70% corresponds to "medium"
- 70 to 100% corresponds to "satisfied".

Table 7 Inference rule for standardization

Connection	**Percentage**	**Tools**	**Standardization**
Satisfied	Satisfied	medium	Satisfied
Satisfied	Satisfied	Dissatisfied	A little satisfied
Satisfied	Satisfied	Satisfied	Very satisfied

Satisfied	medium	Dissatisfied	medium
Satisfied	medium	medium	A little satisfied
Satisfied	medium	Satisfied	Satisfied
Satisfied	Dissatisfied	Satisfied	A little dissatisfied
Satisfied	Dissatisfied	Dissatisfied	Dissatisfied
Satisfied	Dissatisfied	medium	Dissatisfied
medium	Satisfied	Dissatisfied	A little satisfied
medium	Satisfied	medium	A little satisfied
medium	Satisfied	Satisfied	Very satisfied
medium	medium	medium	medium
medium	medium	Satisfied	A little satisfied
medium	medium	Dissatisfied	A little dissatisfied
medium	Dissatisfied	Satisfied	Dissatisfied
medium	Dissatisfied	Dissatisfied	Very dissatisfied
medium	Dissatisfied	medium	Dissatisfied
A little dissatisfied	Satisfied	Satisfied	Very satisfied
A little dissatisfied	Satisfied	Dissatisfied	A little satisfied
A little dissatisfied	Satisfied	medium	Satisfied
A little dissatisfied	Dissatisfied	medium	Dissatisfied
A little dissatisfied	Dissatisfied	Satisfied	A little dissatisfied
A little dissatisfied	Dissatisfied	Dissatisfied	Very dissatisfied
A little dissatisfied	medium	Satisfied	Satisfied
A little dissatisfied	medium	medium	A little satisfied
A little dissatisfied	medium	Dissatisfied	medium

Tables 5, 6 and 7 show respectively the results of the criteria chosen according to the parameters of the systems based on the inference rule, since Table 5 has three input variables and each variable has three membership functions, so we have 27 rule possibilities for the accessibility criterion. Table 6 has 81 rule possibilities for the disassembly criterion and finally Table 7 has 27 rule possibilities for the standardization criterion.

Assignment of fuzzy numbers to linguistic values and their membership functions

Table 8 Triangular fuzzy numbers of each linguistic variable

Linguistic values	**Triangular fuzzy numbers**
Very dissatisfied	(0 ;0 ;0,1)
Dissatisfied	(0 ;0,1 ;0,3)
A little dissatisfied	(0,1 ;0,3 ;0, 5)
AVERAGE	(0,3 ;0, 5 ;0,7)
A little satisfied	(0,5; 0,7; 0,9)
Satisfied	(0,7; 0,9; 1)
Very satisfied	(0,9; 1; 1)

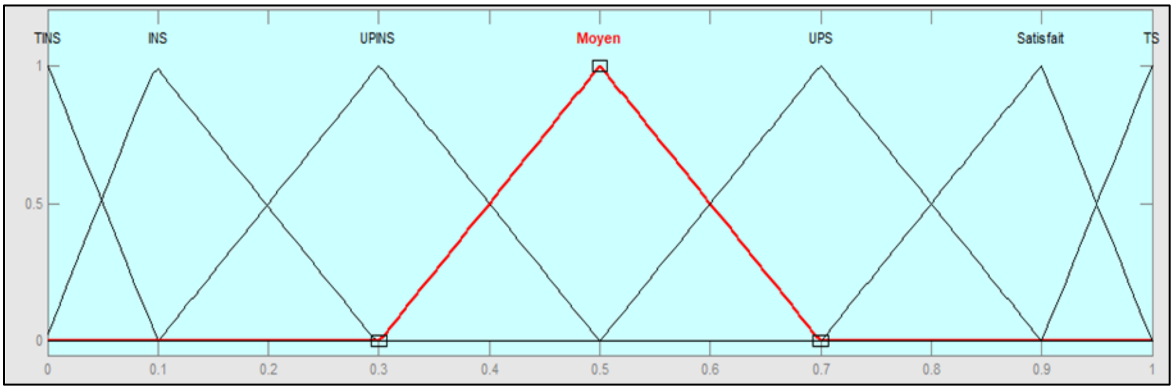

Figure 4 Membership function of the different inputs and outputs

With: TINS: Very dissatisfied; UPINS: A little dissatisfied; UPS: A little satisfied; TS: Very satisfied; INS: Dissatisfied.

Table 8 represents the fuzzy number corresponding to each linguistic variable and Figure 3 shows the memberships of each linguistic variable, where the abscissa axis carries the universe of discourse [0 1] and the ordinate axis represents the degree of membership of each linguistic value.

4.3. Calculation of the overall fuzzy number of each maintainability criterion

Here we will first calculate the numerical value of each maintainability criterion and finally we will convert it into a fuzzy number.

4.3.1. Calculation of the numerical value of each criterion

We will use the results of the inference rules in Tables 5, 6 and 7 to calculate the criteria : accessibility, disassemblability and standardization, validating the results that are above average.

According to equation 7 we will have

- Accessibility

$$v = \left(9/27\right)^2 = 0{,}11 \quad \text{............(18)}$$

- Demontability

$$v = \left(30/81\right)^2 = 0{,}14 \quad \text{............ (19)}$$

- Standardization

$$v = \left(15/27\right)^2 = 0{,}31 \quad \text{............ (20)}$$

4.3.2. Converting numeric values to fuzzy numbers

The membership functions of the linguistic values represented in Figure 3, which are expressed by equation (21), will allow us to convert the numerical values into triangular fuzzy numbers. According to equation (9), we will have

$$\mu_1(x)=\begin{cases}-10x+1 & 0\le x\prec 0.1\\ 0 & \text{Si non}\end{cases}\ ;\ \mu_2(x)=\begin{cases}10x & 0\le x\prec 0.1\\ -5x+1.5 & 0.1\le x\prec 0.3\\ 0 & \text{Si non}\end{cases}\ ;$$

$$\mu_3(x)=\begin{cases}5x-0.5 & 0.1\le x\prec 0.3\\ -5x+2.5 & 0.3\le x\prec 0.5\\ 0 & \text{Si non}\end{cases}\ ;\ \mu_4(x)=\begin{cases}5x-1.5 & 0.3\le x\prec 0.5\\ -5x+3.5 & 0.5\le x\prec 0.7\\ 0 & \text{Si non}\end{cases}\ ;$$

$$\mu_5(x)=\begin{cases}6.13x-1.13\ ; & 0.5\le x\le 0.7\\ -6.25x+3.13\ ; & 0.7\le x\le 0.9\\ 0 & \text{Sinon}\end{cases}\ ;\ \mu_6(x)=\begin{cases}5x-3.5 & 0.7\le x\prec 0.9\\ -10x+10 & 0.9\le x\prec 1\\ 0 & \text{Si non}\end{cases}\ ;$$

$$\mu_7(x)=\begin{cases}10x-9 & 0.9\le x\le 1\\ 0 & \text{Si non}\end{cases} \quad (21)$$

Based on the membership functions of equation 21, we can have the fuzzy triangular numbers. From equations 8, 21 and 9, we will have:

- Converting the numeric value of accessibility to a fuzzy number

$$(\nu^{a},\nu^{b},\nu^{c}) = 0,1\times(0;0,1;0,3)+0,3\times(0,1;0,3;0,5)=(0.03,0.1,0.18) \quad (22)$$

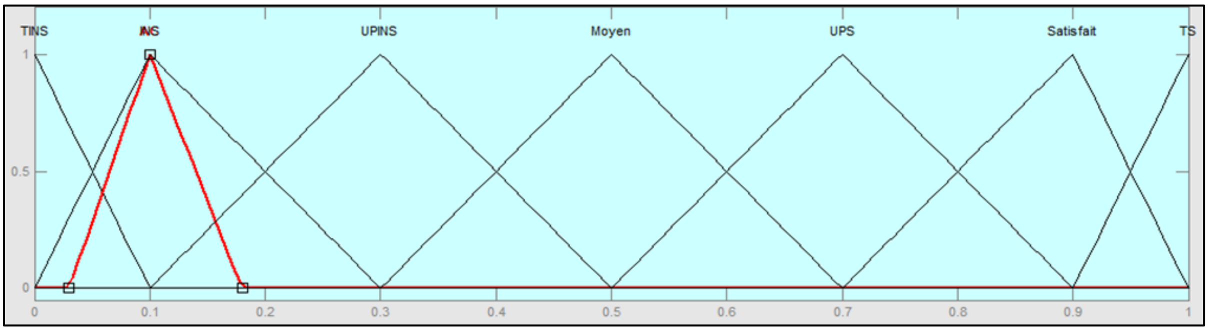

Figure 4 Accessibility membership function

- Converting the numeric value of disassembly to a fuzzy number

$$(\nu^{a},\nu^{b},\nu^{c}) = 0,1\times(0;0,1;0,3)+0,3\times(0,1;0,3;0,5)=(0.03,0.1,0.18) \quad (23)$$

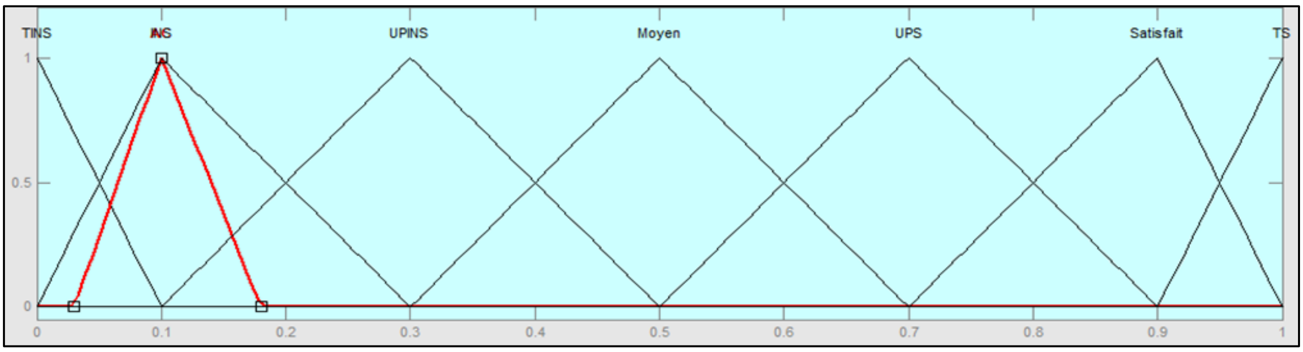

Figure 5 Membership function of disassemblability

- Converting the numeric value of Standardization to fuzzy number

$$(\nu^{a},\nu^{b},\nu^{c}) = 0,3 \times (0,1;0,3;0,5) + 0,5 \times (0,3;0,5;0,7) = (0.18,0.34,0.5) \quad (24)$$

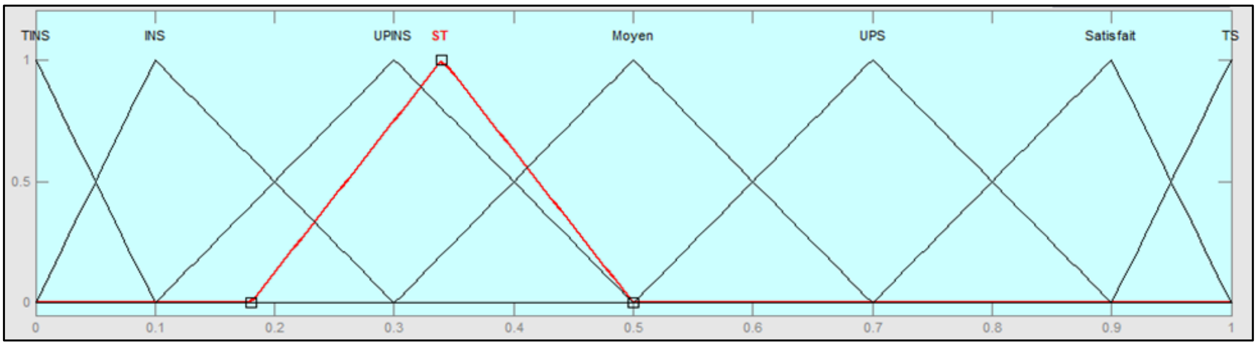

Figure 6 membership function of standardization

Here we find that accessibility and disassembly are located between somewhat dissatisfied and dissatisfied, while standardization is located between somewhat dissatisfied and average.

4.4. Calculation of the weights of each maintainability criterion

- The pairwise comparison matrix of maintainability criteria
- From equation 11 we will have

Table 9 Criteria Judgment Matrix

Maintainability criterion	Accessibility	Disassembly	Standardization
Accessibility	1	3	6
Disassembly	1/3	1	4
Standardization	1/6	1/4	1

- Normalization of the pairwise matrix of maintainability criteria
- From equations (12) and (14), we will have:

Table 10 Normalization matrix

Maintainability criteria	Accessibility	Disassembly	Standardization	Weight
Accessibility	0.667	0.706	0.545	0.639
Disassembly	0.222	0.235	0.364	0.274
Standardization	0.111	0.059	0.091	0.087
Sum	1.5	4.25	11	1

- Calculation of the consistency index (CI) of the entire hierarchy

Table 11 The value of average coherence

Weight of criteria	**0.639**	**0.274**	**0.087**				
Criteria	**Accessibility**	**Disassembly**	**Standardization**	**Total**	**Weight of criteria**	**Total/Weight**	**Tcmax**
Accessibility	0.639	0.822	0.522	1.983	0.639	3.103	3.054
Disassembly	0.213	0.274	0.348	0.835	0.274	3.047	
Standardization	0.107	0.069	0.087	0.262	0.087	3.011	

- From equation (15), we have

$$IC=\frac{0.054}{2}=0.027 \quad \text{............ (25)}$$

- Calculation of the consistency ratio (CR)
- From equation (16), we will have

$$RC=\frac{0.027}{0.58}=0.047 \prec 0.1 \quad \text{............ (26)}$$

Since the result of the consistency ratio obtained is less than 10%, we can conclude that the weight values calculated with equation (14) must be validated. From which we have the following vector

$$P=\left[0.639,0.274,0.087\right]$$

Table 12 Maintainability criteria with their different weights

Maintainability criteria	**Fuzzy values**	**Weight**
Accessibility	(0.03;0.1;0.18)	0.639
Disassembly	(0.03;0.1;0.18)	0.274
Standardization	(0.18;0.34;0.05)	0.087

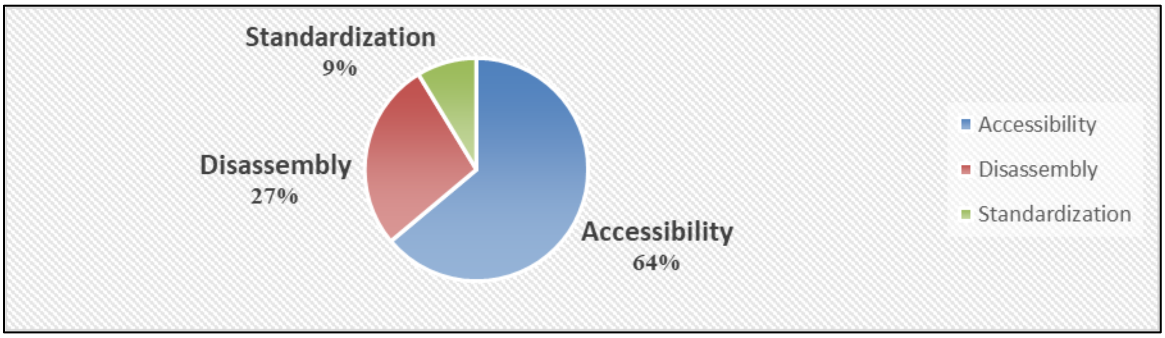

Figure 7 Distribution of criteria weights

4.5. Calculation of maintainability

4.5.1. From equations (17) and (8), we will have

$$(v_s^a, v_s^b, v_s^c) = 0.639(0.03, 0.1, 0.18) + 0.274(0.03, 0.1, 0.18) + 0.087(0.18, 0.34, 0.5) = (0.034, 0.121, 0.208) \quad (28)$$

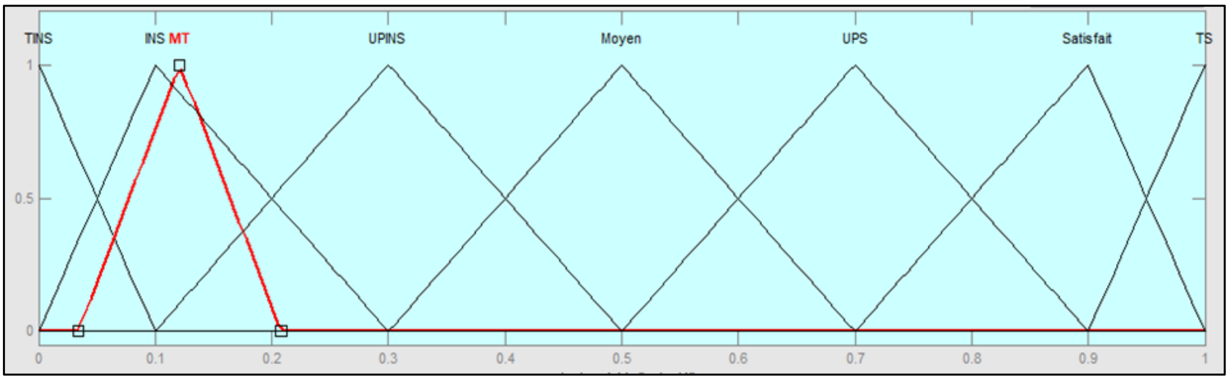

Figure 8 Maintainability membership function

The result obtained indicates that the maintainability is located between the linguistic values very dissatisfied and dissatisfied. With this method we can return to readjust the parameters of the system by integrating in the design phase the combinations of the inference rules resulting in the linguistic value higher than average (a little satisfied, satisfied or very satisfied) to improve the result of the maintainability obtained in order to facilitate the maintenance of the system. While the methods used in the literature, for example [21] et [22] do not allow to express the settings of the system in fuzzy logic, then to return to readjust on these to improve the maintainability if necessary, but just allows to calculate the maintainability index to compare the maintainability of two or more systems.

5. Conclusion

This article explored how fuzzy logic, which can be an artificial intelligent technique, can be used to integrate maintainability into the design of mechanical systems. The main goal was to introduce a methodology for influencing system design parameters to ease maintainability, then also to make a choice among the various most influential maintainability criteria and to use inference rules to evaluate the state of each criterion based on the chosen parameters. To achieve our objective, we used inference rules to calculate the numerical values of accessibility, disassembly and standardization before converting them into fuzzy linguistic numbers. Then, we used the AHP (Analytic Hierarchy Process) method to calculate the weight of each criterion. The fuzzy linguistic numbers and the weights obtained are used to calculate the maintainability of the system. We found that the linguistic value of the maintainability obtained is between very dissatisfied and dissatisfied. Moreover, we observed that, to improve this maintainability we must integrate into the design only those combinations of inference rules that have results in fuzzy linguistic value above the average (i.e. a little satisfied, satisfied and very satisfied).

As perspectives for this work, it would be important to combine neural networks with fuzzy logic (Neuro-Fuzzy), to increase input and output parameters to have more precision. Because in our case we only used 3 parameters for accessibility, standardization and 4 for disassembly. It would also be necessary to optimize input parameters by a programmable algorithm.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflicts of interest regarding the publication of this paper.

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