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Fuzzy Approach for Maintainability Evaluation in the Design Process

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Abstract: The maintainability aspect of some complex products has a significant role during the life cycle; it is the design attribute determining the performance of various maintenance activities such as: inspection, diagnosis, repair, and replacement. If a product has poor maintainability, the maintenance activities which have to be performed on it during its life cycle are difficult, increasing the costs, and also the time required to accomplish the maintenance tasks. An early evaluation of maintainability during the design process may help the designers to make educated design choices, also from the maintenance point of view. In this article, we present a maintainability evaluation approach based on fuzzy logic; fuzzy linguistic variables are employed in order to represent and handle the design data available early in the design process. The main reason for employing fuzzy logic principles for maintainability evaluation is the imprecision and uncertainty generally characterizing the design data available at the beginning of the design process, when design specifications and requirements are subject to change and the description of the design is incomplete. The measure of the product maintainability or maintainability index might be expressed by a fuzzy numerical value computed as the weighted mean of the criteria values used for the evaluation.

Key Words: maintainability, evaluation, design, fuzzy.

1. Introduction

Maintainability is the design characteristic of a product determining the performance of various maintenance activities such as: inspection, diagnosis, repair, and replacement. Reduced maintainability of a product can largely influence the maintenance activities performed on it during its life cycle. If the maintenance activities are difficult to realize, then the time and the resources required will increase, also increasing the life cycle costs and diminishing the availability of the product. Maintainability is an important characteristic of some products, such as, complex systems that cannot be conceived as 'maintenance free'. For this type of product, integrating maintenance aspects early in the design stage by using a concurrent engineering approach is a good way to improve the maintainability and also to reduce the costs and time needed during product design.

Many important design decisions affecting the maintainability aspect of a future product are being made in the early stages of the design process, before the advent of detailed geometrical specifications. In order to evaluate the maintainability using known methods, such as digital mannequins or virtual reality, a detailed geometrical specification of the product is needed. This

type of evaluation can only be employed in the last design stages; however, an eventual design change needed in order to improve maintainability will largely increase the costs and will cause an important time delay.

The interest for increasing the maintainability of products is demonstrated by the reduction of life-cycle costs and by the increased lifetime of the products [1], (Figure 1).

In the context of concurrent engineering, maintenance requirements could be treated earlier in the design stages. A maintainability evaluation tool in this case could support concurrent decision-making made by engineers in order to obtain innovative designs while considering maintenance point of view.

In order to evaluate the maintainability of a product, the maintenance tasks needed to be performed during the service life and the maintenance logistics available for this purpose have to be defined. The definition of the maintenance tasks has to be coordinated with studies pertaining to reliability of the product. The maintenance tasks are initially defined using a FMECA (failure mode, effects, and criticality analysis), which reveals the parts that might need to be replaced during the service life of the product. The evaluation begins by selecting the appropriate maintainability criteria regarding the type of product, the maintenance strategy, and the design data available.

Maintainability evaluation during the design stages permits one to verify if the maintenance tasks can be accomplished with the available maintenance logistics

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Figures 6, 11 and 12 appear in color online: <http://cer.sagepub.com>

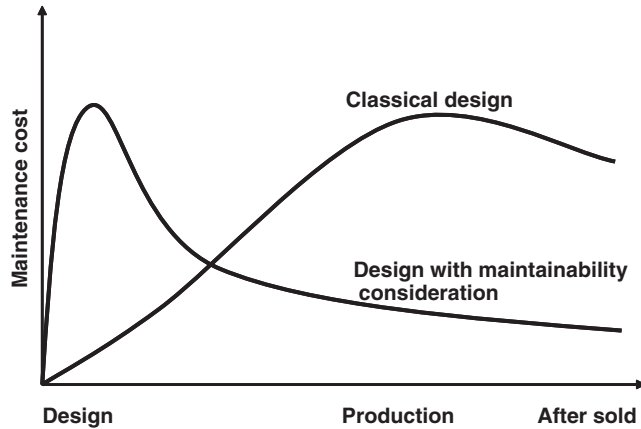


Figure 1. Maintenance cost.

and also to evaluate the performance of these tasks. If the maintenance tasks are difficult, or even impossible to be accomplished in the given conditions, then the designers will be provided with information and a maintainability index regarding the parts which need to be redesigned. The maintainability index can be useful to judge the maintainability of several design variants or to compare a new design with similar existing products.

2. Maintainability Evaluation

2.1 Existing Theories and Work

There are several approaches to evaluate the maintainability of a product at the design stage:

- Maintainability Design Checklists
- Maintainability evaluation using physical mock-ups
- Maintainability evaluation using digital mock-ups and virtual reality
- Maintainability evaluation using quantitative approaches.

Maintainability Design Checklists are being used in order to provide a summary of design review points for the maintainability assessment of complex systems. The checklists are structured into several categories which may include: ‘General Maintenance Reduction,’ ‘Design standardization features,’ ‘Design for physical accessibility,’ ‘Design for mechanical safety,’ etc. Each category is composed of several statements, the evaluator must verify the validity of those statements relative to the product being analyzed; the number of valid statements will give an indication concerning the maintainability of the product.

Table 1. Accessibility evaluation.

Value	Accessibility
1	All the parts are directly accessible and placed in the same area
0,8	All the parts are directly accessible and placed in different areas
0,6	Some parts are not directly accessible, but those parts are maintenance free
0,4	Some parts are accessible after disassembling a fast disassembling entity (a screw, etc.)
0	The majority of the parts is accessible by disassembling one or more entities

Maintainability evaluation using physical mock-ups is based on the use of physical models of the product in order to perform different maintenance tasks by using real tools and maintenance technicians. The evaluation shows the areas where maintainability could be improved, and allows some design changes. The disadvantages of this method are represented by the important time delay and costs induced by building the mock-up and also by the inflexibility of the physical mock-up.

Maintainability evaluation using digital mock-ups and virtual reality is based on the use of virtual (computer generated) prototypes of the product in order to perform maintenance tasks using virtual tools and maintenance technicians. Definition: ‘Virtual prototype, or digital mock-up, is a computer simulation of a physical product that can be presented, analyzed, and tested from concerned product life cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The construction and testing of a virtual prototype is called virtual prototyping (VP).’ This method is more easily integrated in the design process and reduces the time delay needed for the evaluation. The maintainability tasks are simulated using immersive and interactive virtual environments, virtual tools, and anthropometrically articulated representations of human beings [2,3,8]. The product’s model is usually an approximation of the exact virtual model created during the design process.

Maintainability evaluation using quantitative approaches involves several maintainability criteria in order to evaluate the maintainability of a system. One of the quantitative approaches is based on the use of tribology concepts in order to evaluate the maintainability of a mechanical system [9], the result is a ‘tribo-maintainability index.’ The evaluation may also be performed by assigning to each maintainability criterion, a numerical value between 0 and 1 using a table, like the one listed in Table 1 [4].

The numerical value for the maintainability index of the product is obtained by computing the weighted mean of numerical values of the criteria.

Another approach to maintainability evaluation is the Design for service-ability (DFS) [5], developed by researchers at the University of Rhode Island; this approach is based on observations of actual maintenance tasks, time, and the cost of service activities being used as quantifiers, the DFS is a part of the general concept of DFX (Design for X; X= Assembly, Manufacture, Disassembly, Recyclability, etc.). The goal of DFS is that, all of the system items could be accessed, maintained, or instantly replaced from the outside of the product. The DFA approach is pioneered by Boothroyd and Dewhurst, who conducted a series of studies on design for assembly, considering the assembly constraints during the design process [6]. In this approach, the product is analyzed according to various ‘ease of assembly’ criteria (symmetry, dimension, mating direction, number of parts, etc.); the result is a tabulated score used in order to compute a ‘design efficiency ratio.’ By using DFA, the estimated assembly time can be used as a guideline in order to improve the design, leading to the reduction of the final cost [7].

2.2 Fuzzy Multi-Criteria Maintainability Evaluation

In the first stages of the design process, the designer has to deal with the lack of information regarding the geometry of the future product, and so the evaluation of the product maintainability will contain a great deal of uncertainty. However, the degree of uncertainty which is linked with the data available to assess product maintainability will gradually diminish towards the end of the design process. The authors propose a methodology for evaluating maintainability starting in the conceptual design stage; the result is a maintainability index which can be used to acknowledge the maintainability of the future product. At this stage, the degree of confidence in the maintainability index is low, but it will increase to the end of the design process. In fact, more than a maintainability index, the authors also propose the designer to acknowledge the degree of confidence for the evaluation of a design solution. This is an original aspect, allowing a realistic comparison or classification of different design solutions from the maintainability viewpoint.

Fuzzy sets were initially proposed in 1965 by Zadeh [11] as a generalization of classical set theory. In classical set theory, for any set, every entity belongs to the set (has a membership of 1) or not (has a membership of 0). In a fuzzy set, elements can take varying degrees of membership between 0 (not at all in the set) and 1 (completely in the set); a membership function specifies the membership level of all elements in the set. In order to simplify the mathematical

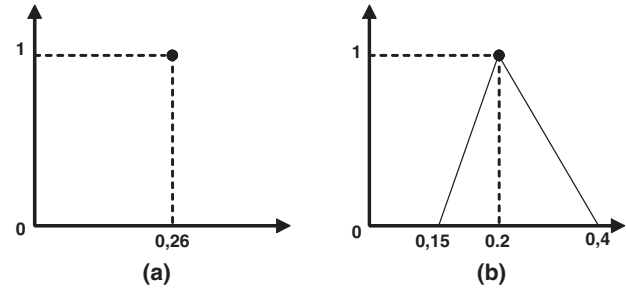


Figure 2. Difference between ‘crisp’ and ‘fuzzy’ numbers.

operations, triangular fuzzy numbers will be used in this article.

A triangular fuzzy number has a lower, upper, and modal value, and it is defined as follows:

A fuzzy number $M(l,m,u)$ on $R \in (-\infty, +\infty)$ is defined to be a fuzzy triangular number if its membership function $\mu_m : R \rightarrow [0,1]$ is equal to

$$\mu_m(x) = \begin{cases} \frac{1}{m-l}x - \frac{l}{m-l}, & x \in [l, m] \\ \frac{1}{m-u}x - \frac{l}{m-u}, & x \in [m, u] \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where $l < m < u$; l and u stand for the lower and upper values of the support of the fuzzy number M , respectively, and m for the modal value.

By using fuzzy numbers and sets, the designer has the possibility to represent a design variable using a preferred value and also a range of possible values which will quantify the uncertainty of the considered design variable. This will later permit one to define the degree of confidence for the maintainability evaluation.

Figure 2 shows the difference between a ‘crisp’ (a) and a ‘fuzzy’ (b) number:

Fuzzy numbers can be transformed into crisp values using ‘defuzzification’ procedures (actually in Figure 2 (a) = defuzzy(b)).

A Fuzzy Linguistic Variable [12] is characterized by a quintuple $\langle v, L, X, G, m \rangle$; in which v is the name of the variable, L is a finite set of linguistic terms $\{l_0, \dots, l_n\}$ describing v , whose values range over a universal set X of values of v ; G is a grammar for generating linguistic terms, and m is a semantic rule which assigns to each term $l \in L$ its meaning $m(l)$, which is a fuzzy set on X ; (i.e. $m(l) : T \rightarrow F(X)$).

The linguistic approach considers the variables participating in the problem, assessed by means of linguistic terms instead of numerical values [13].

Linguistic variables can have a hierarchical structure for their values with several levels of granularity, like the one in the Figure 3.

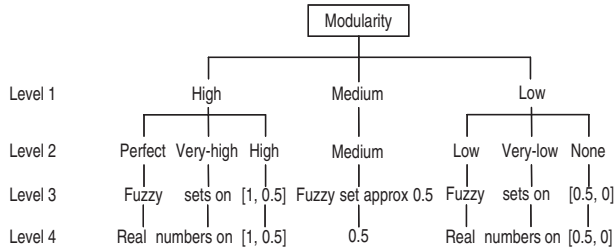


Figure 3. Hierarchy of values.

The level 1 provides a granularity containing three elements; the level 2, a granularity with seven elements; in level 3, the elements are fuzzy sets in the [0,1] interval; and finally, the finest granularity is obtained in level 4, where the elements are real numbers in the [0,1] interval.

If $L = \{l_0, \dots, l_n\}$ is the set of linguistic terms for a linguistic variable, then the term set needs to have the following properties:

The set have to be ordered: $l_i \geq l_j$ if $i \geq j$

$$\text{Max}(l_i, l_j) = l_i \text{ if } l_i \geq l_j$$

$$\text{Min}(l_i, l_j) = l_i \text{ if } l_i \leq l_j$$

For example, consider the term set of level 2:

$$L = \{l_0 = N, l_1 = VL, l_2 = L, l_3 = M, l_4 = H, l_5 = VH, l_6 = P\}$$

where: $N = \text{None}$, $VL = \text{Very Low}$, $L = \text{Low}$, $M = \text{Medium}$, $H = \text{High}$, $VH = \text{Very High}$, $P = \text{Perfect}$.

The term set can be transposed into fuzzy triangular numbers; the Figure 4 shows a possible domain for the term set:

The values for each term are:

$$N = (0, 0, 0.16), VL = (0, 0.16, 0.33), L = (0.16, 0.33, 0.5), M = (0.33, 0.5, 0.66), H = (0.5, 0.66, 0.83), VH = (0.66, 0.83, 1), P = (0.83, 1, 1).$$

Transposition of the term set into fuzzy triangular numbers is needed in order to compute mathematical operations such as addition, multiplication, etc.

The authors consider the fuzzy approach for maintainability evaluation to be appropriate in the beginning of the design process, since it allows a representation of the expert information in a more direct and adequate form and also because of the flexibility given by the linguistic variables whose various levels of granularity can represent design information from the beginning to the end of the design process [16].

The approach to predict the maintainability of a future product is based on the use of several maintainability criteria such as: ‘standardization’, defined as the degree in which standard parts are used in the

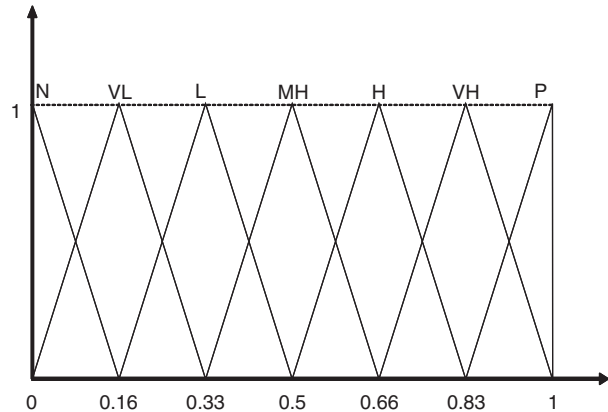


Figure 4. Domain for Level 2.

future product and ‘modularity’, defined as the degree in which modules are used; the criteria are chosen regarding the stage in the design process, the maintenance requirements, and the type of the product.

The proposed maintainability evaluation methodology can be decomposed into several stages which can be presented in the form of a diagram (Figure 5).

The evaluation begins with the selection of the relevant maintainability criteria considering the functional and maintenance requirements ($F_1, F_2, F_3, \dots, F_n$; $M_1, M_2, M_3, \dots, M_n$) as stated in the requirements list. The selection is made among more than 20 maintainability criteria [10] recognized by the majority of designers, and requires a maintenance expert or a maintenance expert system.

As the selected maintainability criteria (C_3, C_5, \dots, C_m) are not considered of equal importance, in the following, stage their corresponding weights (P_3, P_5, \dots, P_m) are computed starting from pairwise comparisons and with the help of a software application based on a ‘Monte Carlo’ algorithm. Another originality of the presented methodology is the use of a coherence index in order to assure the coherence of the weighting process.

The following stage is the evaluation of the maintainability index for each design solution proposed during the design process, the evaluation is conducted using the maintainability criteria and their respective weights previously determined.

In order to manage better the uncertainty of the design data used as input for maintainability evaluation, this approach proposes the use of linguistic variables and ‘fuzzy’ sets and numbers, instead of the ‘crisp’ values and sets generally employed. This is another original aspect allowing the ‘transfer’ of the design data uncertainty into the maintainability index in the form of a confidence index. The existing approaches cannot take into account the design data uncertainty, and therefore, their use is not appropriate at the beginning of the design process.

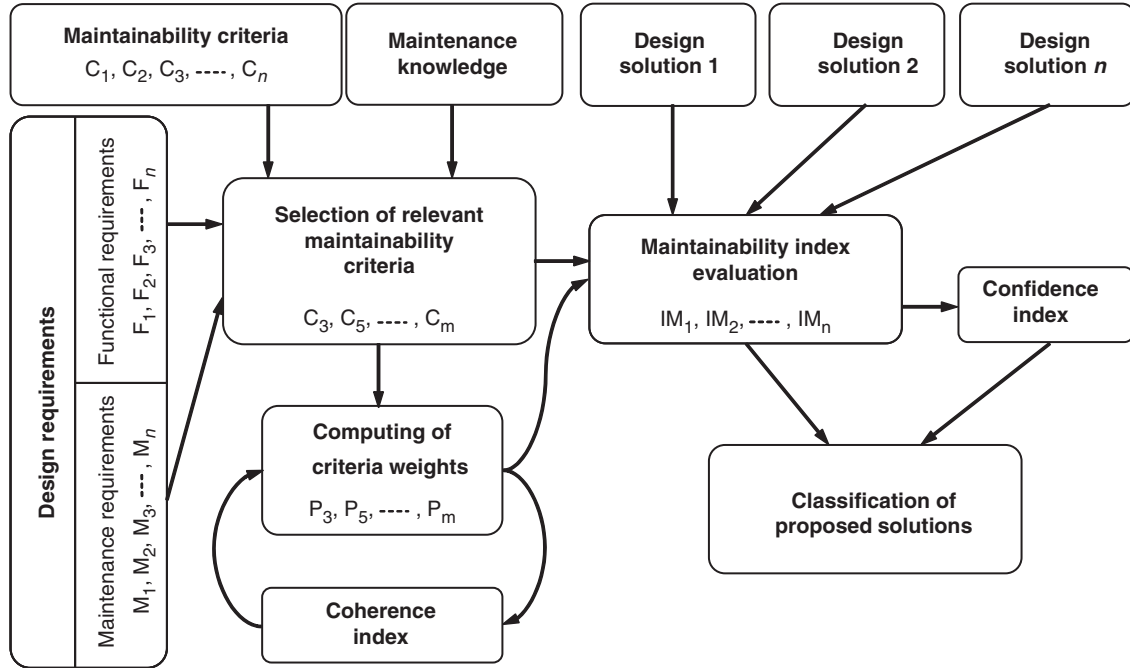


Figure 5. Fuzzy multi criteria maintainability evaluation.

2.3 The Criteria Weighting Stage

The evaluation process begins by selecting the relevant maintainability criteria regarding the type of product, the maintenance strategy, and the design data available.

Often, several criteria have to be considered for the maintainability evaluation and weights need to be assigned to these criteria (the difficulty starts with three or four criteria); in order to simplify this weighting process, the analytic hierarchy process (AHP) will be used to compute the weights for maintainability criteria.

There are several methods known as the ‘analytic hierarchy process’ derived from the original AHP [14,15] which allows us to find a set of weights for n criteria starting from a number of pairwise comparisons between the relative weights of two criteria. The comparisons can be made by one or several evaluators which will fill the matrix (2).

$$M = \begin{pmatrix} c_{11} & \cdot & \cdot & c_{1n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & c_{ij} & \cdot \\ c_{n1} & \cdot & \cdot & c_{nm} \end{pmatrix} \quad (2)$$

where: $c_{ij} = p_i/p_j$; $i, j = 1, \dots, n$, with p_i and p_j respectively representing the relative weights of the ‘ i ’ and ‘ j ’ criteria. The comparisons matrix is reciprocal if $c_{ij} = 1/c_{ji}$; $i, j = 1, \dots, n$ and in this case only $n(n-1)/2$ pairwise comparisons are needed. In general, the set of the

resulting weights is not unique (except the case of a coherent matrix), and it varies according to the AHP method used.

Once the comparisons matrix has been filled, an algorithm can be applied in order to compute the weights values; also in the case of an incoherent matrix (in practice it is often the case), a coherence index can also be computed in order to evaluate this incoherence. The coherence index is computed as the mean distance between the pairwise comparisons and the criteria weights.

The authors have developed a software application based on a ‘Monte Carlo’ algorithm which computes the weights for several criteria; the following image (Figure 6) presents the prototype of a software application in the case of weighting three maintainability criteria.

The chosen maintainability criteria are inputted in the C1, C2, and C3 fields; then the evaluator will make the pairwise comparisons (relative weights C1/C2, C1/C3, and C2/C3) between criteria.

The pairwise comparisons can be made using the fuzzy linguistic variable defining the weight with a term set composed of five linguistic terms ($L = \{l_0 = \text{Much less important}, l_1 = \text{Less important}, l_2 = \text{Equal importance}, l_3 = \text{More important}, l_4 = \text{Much more important}\}$), or by inputting the relative weights directly in C1/C2, C1/C3, and C2/C3 fields.

The program will display the computed weights and also the coherence index (the mean distance between the computed weights and the pairwise comparisons). This simple software application can be easily developed

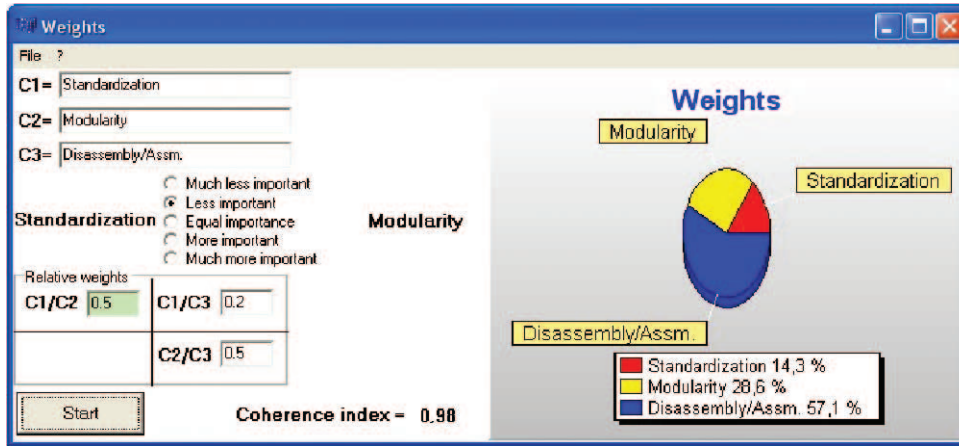


Figure 6. Software application for three criteria.

in order to compute the weights for more than three criteria and is also possible to integrate it into a larger maintainability evaluation tool.

As a perspective, the authors will attempt to give some rules of know-how in order to advise the designer in the weighting process. These rules will take into account, for instance, the aim, the quantity, and the general context for using the product. It is possible to integrate these rules into an expert system in order to advise the designer during the maintainability evaluation process.

2.4 The Maintainability Index Evaluation Stage

In the first stages of the design process, the numerical values for maintainability criteria might be obtained using analogies with similar existing products. The evaluator (maintenance expert) can express the evaluation for a criterion using a linguistic variable which can be translated using the term set transposition into a fuzzy number between 0 and 1 (0 means that the product does not satisfy the criterion, and 1 for the ideal case). For example, the numerical value for ‘standardization’ criterion might be the triangular fuzzy value (0.15, 0.2, 0.4) (standardization index) which means approximately 0.2, but no less than 0.15 and no more than 0.4 (Figure 2(b)).

The numerical values for the maintainability criteria may also be obtained by using a virtual simulation of the maintenance task for which an evaluation is required. If the virtual simulation is performed using a Digital Mock Up (DMU) module integrated into a CAD system, then the concurrent design is facilitated, the maintenance expert and the structural designer share the same resources, and they can easily exchange information and feedback.

The numerical value for the maintainability index (IM) is computed using the weighted mean of the

numerical values for each maintainability criterion that is being used, (Equation 3).

$$IM = \frac{\sum_{i=1}^n a_i \cdot I_i}{\sum_{i=1}^n a_i} \tag{3}$$

IM – maintainability index; *a_i* – the weight of the ‘*i*’ criterion; *I_i* – the numerical fuzzy value for the ‘*i*’ criterion.

The result is a fuzzy number which expresses the maintainability of a proposed design solution. If a comparison of two or more design solutions is required, then a confidence index is being calculated. If IM is the maintainability index of a design solution, then a probability area *A_{IM}* can be defined as $A_{IM} = \int_l^m \mu_m(x) dx + \int_m^u \mu_m(x) dx$, where $\mu_m(x)$ is the membership function of IM (Figure 7).

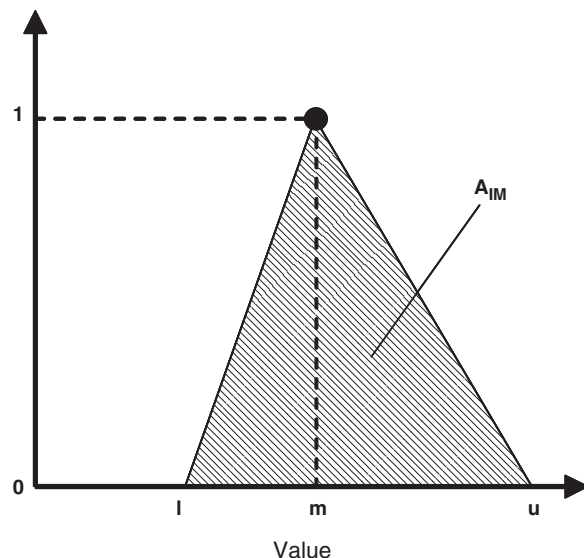


Figure 7. The probability area.

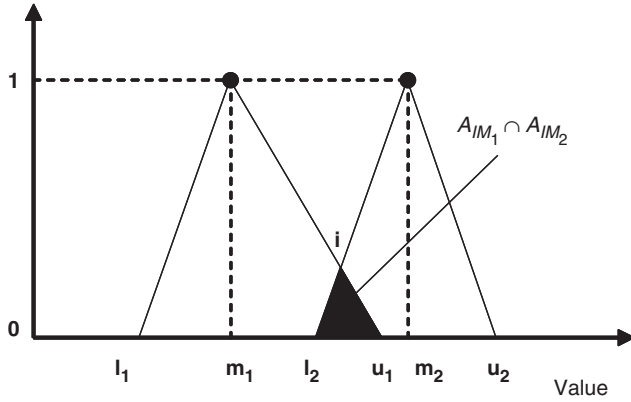


Figure 8. Intersection of the probability areas.

If IM_1 and IM_2 are the maintainability indexes of two design solutions, then the confidence index for the evaluation IC_2 is defined as (Equation 4):

$$IC_2 = 100 - \frac{A_{IM_1} \cap A_{IM_2}}{A_{IM_2}} \cdot 100 \quad (4)$$

Where $A_{IM_1} \cap A_{IM_2}$ is the intersection of the probability areas A_{IM_1} and A_{IM_2} (Figure 8).

The confidence index can be computed for any type of membership function using the following equation:

$$IC_2 = 100 - \frac{\int_{l_2}^i \mu_{m_2}(x) dx + \int_i^{u_1} \mu_{m_1}(x) dx}{\int_{l_2}^{m_2} \mu_{m_2}(x) dx + \int_{m_2}^{u_2} \mu_{m_2}(x) dx} \cdot 100$$

2.5 Example

Following the methodology presented above, we present an example of fuzzy maintainability evaluation using three evaluation criteria: ‘Standardization’, ‘Modularity’ and ‘Disassembly/Assembly’. The evaluation was applied in the case of redesigning an existing product, a micro-motor (Figure 9).

The weights for each criterion have been computed following the methodology described in the Section 2.3. After comparing the relative importance of the criteria, the computed weights are:

$$a_{Std} = 0.143; \quad a_{Mdt} = 0.286; \quad a_{D/A} = 0.571$$

The authors have considered a maintenance operation consisting of changing the two radial ball bearings sustaining the crankshaft. This maintenance operation was simulated using the DMU module found in CATIA V5 and a set of virtual maintenance tools.

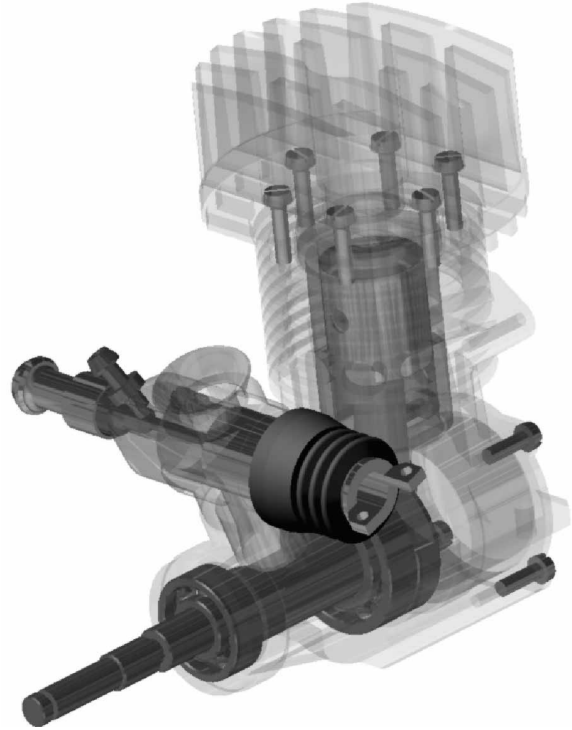


Figure 9. Micro-motor.

In the original design, in order to replace the ball bearings, an almost complete disassembly of the motor is required.

For the original design, the maintainability criteria have been evaluated as follows: ‘Standardization’ – High; ‘Modularity’ – Low; and ‘Disassembly/Assembly’ – Low.

Those evaluations can be translated into fuzzy triangular numbers using the term set transposition:

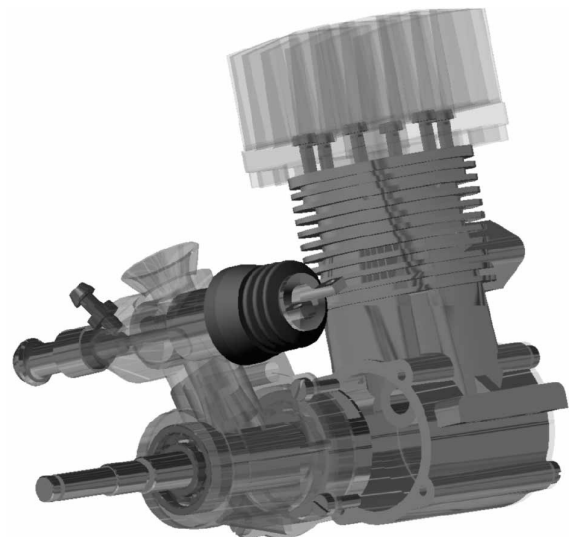


Figure 10. Redesigned micro-motor.

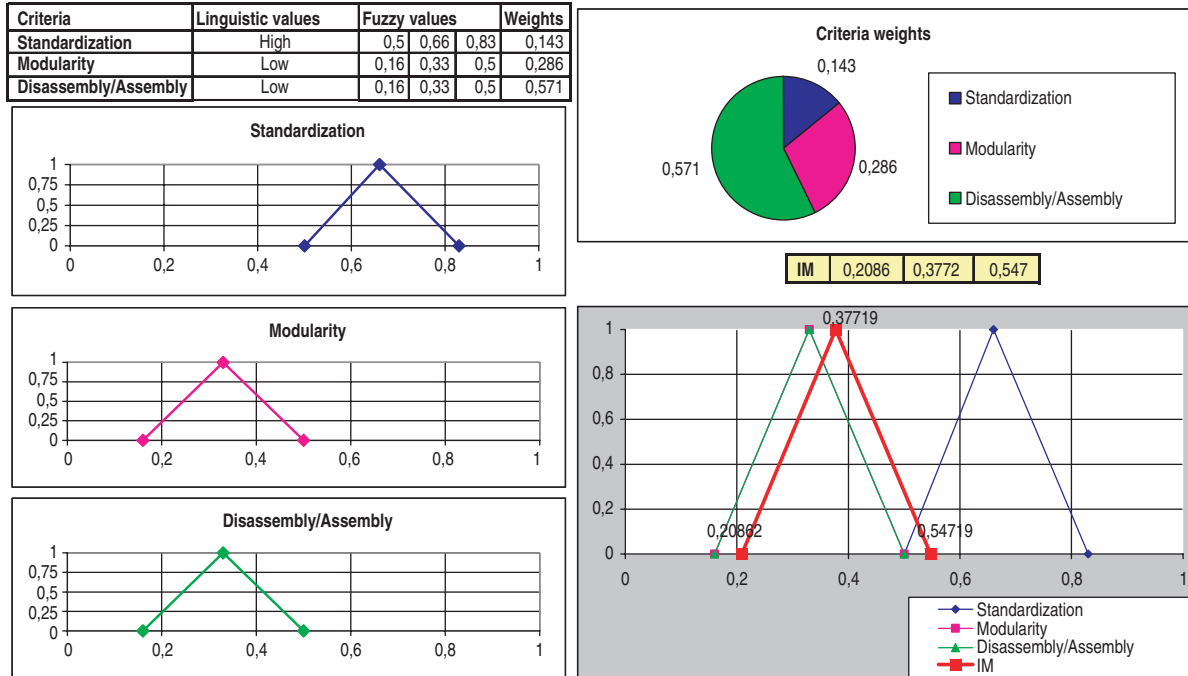


Figure 11. Fuzzy maintainability evaluation tool.

$$I_{Std} = [0.5, 0.66, 0.83];$$

$$I_{Mdt} = [0.16, 0.33, 0.5];$$

$$I_{D/A} = [0.16, 0.33, 0.5].$$

The redesigned version of the motor has the carter divided into two bodies, in order to facilitate the accessibility to the ball bearings; and so it is no longer necessary to also disassemble the piston, cylinder, and cylinder head (Figure 10).

In the case of the redesigned motor, the maintainability criteria have been evaluated as follows:

‘Standardization’ – High;

‘Modularity’ – Medium;

‘Disassembly/Assembly’ – Medium.

These evaluations can also be translated into fuzzy triangular numbers using a term set transposition:

$$I_{Std} = [0.5, 0.66, 0.83];$$

$$I_{Mdt} = [0.33, 0.5, 0.66];$$

$$I_{D/A} = [0.33, 0.5, 0.66].$$

In order to facilitate the evaluation process, an evaluation tool which computes and displays the fuzzy value for the IM has been developed (Figure 11).

The evaluator must input the values for the maintainability criteria and their corresponding weights

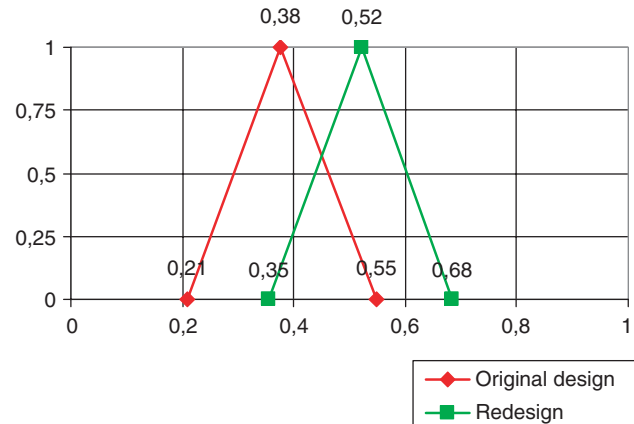


Figure 12. Fuzzy maintainability index comparison.

(criteria values can be introduced as linguistic values or directly as triangular fuzzy numbers).

The result of the evaluation for the original design is the fuzzy value $IM_o = (0.208, 0.377, 0.547)$ (this means that the maintainability index is approximately 0.377, but no less than 0.208 and no more than 0.547, following the triangular characteristic function) (Figure 12).

In the case of the redesigned motor, the maintainability index value is $IM_r = (0.354, 0.523, 0.684)$ (Figure 12).

Then the confidence index of the evaluation is $IC_r = 66.7\%$.

The confidence index can be improved if the probability areas of the maintainability indexes IM_1 and IM_2 are decreased.

3. Conclusions

The authors have developed a maintainability evaluation method that can take into account the maintenance constraints from the beginning of the design process, whereas, traditionally at this stage maintenance is often disregarded.

This method provides the designer with information regarding the maintainability of the product being designed, in the form of a maintainability index.

The designer can use this methodology to acknowledge maintenance constraints (issued from maintainability criteria) during the design process in order to improve the design; it can also use the maintainability and confidence indexes to choose between several design variants from the maintainability point of view.

The use of linguistic variables and fuzzy numbers facilitates the evaluation process and allows the use of data containing an important amount of imprecision and uncertainty.

The fuzzy approach for maintainability evaluation might support concurrent decision-making made by engineers in order to obtain innovative designs, also according with the maintenance point of view.

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