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Evaluating military training aircrafts through the combination of multi-criteria decision making processes with fuzzy logic. A case study in the Spanish Air Force Academy

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ABSTRACT

The combination of Multi-Criteria Decision Making (MCDM) processes with Fuzzy Logic can be efficiently applied to solve decision problems with criteria differing in nature. This combination is used in the present work to solve a real world decision problem of interest for the Spanish Air Force, specifically, the selection of the best military training aircraft based on a set of criteria. This decision problem involves, on one hand, quantitative or technical criteria (service ceiling, endurance, etc.) and, on the other hand, qualitative criteria (human factors, flying and handling qualities, etc.) based on the experience of a set of senior pilots and flight instructors of the Spanish Air Force collected via surveys. In order to extract information from the expert surveys, the MCDM process was combined with fuzzy logic. The Analytic Hierarchy Process (AHP) was used to obtain the weights of the criteria and, through the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), the alternatives were evaluated. This work is a preliminary study of the training aircraft alternatives proposed by the Air Staff and the Logistic Support Command of the Spanish Air Force. These alternatives were chosen based on operational criteria which are detailed in the work. As a result of the decision process used, the best alternative was shown to be the Pilatus PC-21 aircraft.

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1. Introduction

When an Air Force needs to select a training aircraft, decision-making is a crucial intellectual activity involved in the process, as in some stages of aircraft design [34]. Generally, in the decision-making process for these problems, a large number of key and different criteria are involved. Therefore, it is advisable to use tools for their resolution such as Multi-Criteria Decision Making (MCDM) processes, whose use is widespread nowadays in the military [23] and aerospace fields [45], as well as in other research disciplines [18,41].

In addition, the criteria for the optimal choice of a training aircraft exhibit different nature, including quantitative criteria (service ceiling, stalling speed, endurance, etc.) as well as qualitative criteria (human factors, flying and handling qualities, etc.). Thus, in order to solve this optimization problem, the application of any of the known MCDM methods as the Analytic Hierarchy Process (AHP) [40], the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [22], the ELimination Et Choix Traduisant la REalité (ELECTRE) method [39], etc., must be combined with fuzzy logic [19,21,27,50] with the aim of being able to perform the extraction of knowledge and solving the proposed problem.

Several examples of the application of the MCDM in the military field can be found in the scientific literature. In the 90s, some weapon systems were evaluated using ranking fuzzy numbers with AHP [8], a methodology also exploited by the United States Army to manage organization in peacekeeping force design in Bosnia [35]. Nowadays, this methodology has proven to be a useful tool, e.g., for determining the size of the USA destroyer fleet in case of an armed conflict in the Korean peninsula during 2015 [12].

From the point of view of aircraft selection, the AHP methodology has been used to evaluate combat helicopters [9], as well as the quality in combat aircrafts maintenance tasks [48]. Regarding the TOPSIS method, it has been used to evaluate training aircrafts in China [46]. A combination of the two aforementioned methodologies has been used to determine the efficiency of combat aircrafts [47].

From the perspective of the Spanish Air Force (SPAF), the Air Staff (EMA) and the Logistics Support Command (MALOG) are the main decision-makers. These groups will adopt a decision based on several operative, politics, strategic, and economics viewpoints. Nevertheless, it is advisable to make a preliminary assessment

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taking into account both the most significant technical criteria and the experience of important advisory groups such as senior test pilots and flight instructors of the SPAF.

The aim of this work is the selection of the best military training aircraft among several alternatives found on the current aircraft market. This problem will be faced by using the AHP methodology to obtain the weights of the criteria that influence the decision, and the TOPSIS method to evaluate the different alternatives. Furthermore, these two methods will be combined with fuzzy logic due to the existence of qualitative and quantitative criteria.

The rest of this paper is structured as follows. In Section 2, the methodologies used for obtaining the weights of the different criteria and for carrying out the evaluation of alternatives are described. Section 3 presents a real world training aircraft selection problem currently faced by the Spanish Air Force Academy (SPAFA), and the optimum result obtained with the proposed methodology. Finally, Section 4 collects the conclusions reached, as well as possible future research lines.

2. Methodology

On countless occasions, human beings must select, among several alternatives, the one they think is the best option. A decision problem arises when, in response to a proposed situation, there are two or more alternatives from which, individually or collectively, it is necessary to choose one of them or, at least, sort the preferences. Typically, decision-making processes are based on the knowledge and the experience of the decision maker in similar situations which occurred before. Nevertheless, it is not common to use any methodology or tool to assist in the decision making process, such as the valuable MCDM tools, whose use for military and aerospace problems has been introduced in Section 1.

2.1. The statement of a decision problem

Any MCDM can be expressed by means of five elements $\{C, D, r, \prec, I\}$, where:

1. $C = \{C_1, C_2, \ldots, C_m\}$ is the set of criteria that allow the comparison of the alternatives from specific points of view.
2. $D = \{D_1, D_2, \ldots, D_n\}$ is the set of feasible alternatives for the decision-maker, and from which the decision-maker must choose one.
3. $r : D \times C \to R$ is a function which for every decision D_i and every criterion C_j gives a value such that $(D_i, C_j) \to r(D_i, C_j) = r_{ij}$. Once the sets of criteria and alternatives have been chosen, a measure of the effect produced by each alternative with respect to each criterion is needed. By means of linguistic terms, the decision-maker represents the goodness of an alternative with respect to a criterion; different values of r can be represented by means of a matrix called the *matrix of decision making*.
4. $\prec$ is the decision-maker's relation of preferences. A coherent decision-maker is assumed, therefore he should try to maximize his profits or, at least, minimize his losses. In this case the decision-maker needs to obtain the best alternative according to the considered criteria.
5. I is certain information about the criteria, which in this study will be linguistic. The decision-maker gives linguistic information about the importance for each criterion.

Particularly, in this study, the sets C and D are finite, this fact will avoid convergence and measurability problems.

2.2. Linguistic variables and fuzzy sets

2.2.1. Linguistic variables

Most of the time, the decision-maker is not able to define the relative importance of the criteria or the goodness of the alternatives with respect to each criterion in a quantitative way. In these situations, approximate measures or quantities can be used as in [13,31]. Another way to overcome this problem is by applying the concept of fuzzy sets introduced by Zadeh [50]. Such fuzzy logic can be applied through linguistic variables [51].

A *linguistic variable* [52,53] refers to a variable whose values are words or sentences in a natural or artificial language. In general, the evaluation of judgments by means of linguistic terms is easier for the decision-maker than trying to quantify them. In these cases, using fuzzy numbers is more appropriate than using real numbers for evaluating the assessments.

2.2.2. Fuzzy sets

In this study, linguistic variables will be identified with fuzzy sets [5,24,26]. Fuzzy set theory was developed to deal with vague, imprecise, and uncertain problems [50]. It has been used as a modelling tool for complex systems that can be controlled by humans but are difficult to define precisely [26]. Within this formulation, a collection of objects (universe of discourse) X is related to a fuzzy set A described by a membership function f_A with values in the interval $[0, 1]$.

$$f_A : X \to [0, 1]$$

Thus A can be represented as $A = \{f_A(x) \mid x \in X\}$. The degree with which x belongs to A is the membership function $f_A(x)$. In this work, triangular membership functions, related to triangular fuzzy numbers (a, b, c), will be used. The interested reader can find a detailed description of these numbers, as well as the arithmetic operations on them, in [27]. An approach for defuzzification after applying the MCDM can be found in [17].

2.3. Analytic Hierarchy Process (AHP)

This MCDM tool, developed by Saaty [40], is a pairwise comparison method that attempts to estimate the impact of each one of the alternatives in a set on the overall objective of a hierarchy of criteria.

For the defined set of criteria $C = \{C_1, C_2, \ldots, C_m\}$, let's denote their actual weights by "$w_1, w_2, \ldots, w_m$". The matrix of pairwise comparisons "$A = [a_{ij}]$" collects an expert's preference between individual pairs of alternatives "i" and "j", i.e., a_{12} is the relative importance (in the opinion of the expert) of C_1 to C_2. Consequently, the elements "a_{ij}" can be considered as estimators of the ratios "w_i/w_j". According to Saaty [40], the elements $a_{ij} \in [1/9, \ldots, 1, \ldots, 9]$, are positive and satisfy the reciprocity property: $a_{ij} = 1/a_{ji}$ $(i, j = 1, 2, \ldots, m)$. Obviously, the elements on the main diagonal are $a_{ii} = 1$.

In case of using linguistic variables and fuzzy numbers, as in this work, elements "a_{ij}" are fuzzy numbers. Table 1 presents the linguistic decision-maker's preferences in the pair-wise comparison process used in this study.

Once the matrix A is obtained, the vector of weights is the eigenvector corresponding to the maximum eigenvalue λ_{max}. This vector of weights allows the quantification of the importance of the different criteria.

Additionally, the maximum eigenvalue can be used as a measure of the consistency of the expert's preferences arranged in the comparison matrix. The consistency index (CI) is given by $\mathrm{CI} = \lambda_{max} - m/(m-1)$. If the expert shows some minor inconsistency, then $\lambda_{max} > m$. Additionally, Saaty [40] proposes the following measure of the consistency ratio: $\mathrm{CR} = \mathrm{CI}/\mathrm{RI}$, where RI (random

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