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A ~~Model~~ model for ~~Aircraft Evaluation~~ aircraft evaluation to ~~Support Strategic Decisions~~support strategic decisions

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Abstract

In the contemporary air transport industry, many factors, such as environmental impact, service quality and comfort are becoming increasingly crucial. In this context, airlines and manufacturing companies can no longer consider air transport exclusively as a cost-oriented problem; thus, for airlines, the choice concerning the purchase of the aircraft is no longer a simple matter of minimizing operative costs, but rather a multi-attribute problem, characterized by a high complexity level in which a variety of factors play a pivotal role. Given this scenario, the aim of this paper is to propose a novel model for aircraft evaluation, based on the investigation of airlines' needs. The model is based on the two main approaches proposed in literature to address generic evaluation problems, Analytic Hierarchy Process and Fuzzy Set Theory, proposing a hybrid approach which combines some the strengths of the two methodologies. The usability of the hybrid model for the stakeholders of the air transport industry is investigated through an empirical study.

Keywords: AHP; Fuzzy Set Theory; Aircraft evaluation; Decision-making

1 Introduction

In the contemporary global market, the civil aviation industry is characterized by an ever increasing attention towards passengers' needs, service quality, comfort and environmental issues (~~Hope, 2005; Newson & Cairns, 2006;~~ Brindisi & ~~Concilio~~ Concilio, 2008; Hope, 2005; ICAO, 2013; Miyoshi & Mason, 2009; ~~ICAO, 2013~~Newson & Cairns, 2006). In this context, industry stakeholders (including airlines and aircraft manufacturing companies) can no longer consider the provision of air transport exclusively as a cost-oriented problem; consequently, airlines should select aircraft in such a way that they assure the best combination among costs, technical characteristics, passenger comfort, and environmental impact. On the other hand, large manufacturing companies, prior to the launch of capital intensive production programmes, have to clearly identify the set of characteristics that better satisfy airlines' requirements (Esposito & Passaro, 1997; Esposito & ~~Raffa~~ Raffa, 1994). The misalignment with respect to airlines requirements could jeopardize the success of new programmes and generate relevant financial losses (Esposito & Raffa, 2007; Ferreri, 2003).

Unsurprisingly, in recent years, the academic literature has been focusing on many aspects in terms of aircraft performances, besides the traditional ones. Several papers ~~analyse~~ analyze environmental impact from different points of views, by highlighting:

- the environmental impact of emissions and noise due to air traffic (Abeyratne, 2003; ~~Sen, 1997~~Armstrong, Allen, & Denning, 1997; Borken-Kleefeld, Berntsen, & Fuglestvedt, 2010; Price & Probert, 1995; Sen, 1997; Tsilingiridis, 2009);
- the social costs of aircraft noise and emissions (Brueckner & Zhang, 2010; Lu & Morrell, 2006; Schipper, 2004);
- strategies and goals of national and international organizations in reducing noise and emissions from air transport (Abeyratne, 2002; Girvin, 2010; Koblen, Szabo, & Krnáčová, 2013; Ott, 2007) and the economic impact and ecological effects of such strategies (Brueckner & Girvin, 2008; Vespermann & Wald, 2011);
- the proposal of new products, new technologies and new materials (such as new engines, alternative fuel, etc.) in order to reduce the negative environmental impact of the aviation industry (Dray, 2013; Frota, 2010; Haddad & Fawaz, ~~2013; Dray,~~2013).

Also, the amount of papers dealing with comfort and service quality issues is increasing, focusing on:

- the impact of airline service quality and comfort on passenger choices (Balcombe, Fraser, & Harris, 2009; Jiang, 2013; Martin, Roman, & Espino, 2008; Park, Robertson, & Wu, ~~2004; Park, Robertson, & Wu,~~ 2004, 2006; ~~Wojahn, 2002; Jiang, 2012;~~Pennig, Quehl, & Rolny, ~~2012;~~ 2012; Wojahn, 2002; Yang, Hsieh, Li, & Yang, 2012; ~~Zhang Y.,~~ Zhang, 2012);
- the attributes of the airline service quality (Babbar & Koufteros, 2008; Curry & Gao, 2012; De Jager, Van Zyl, & Toriola, 2012; Kim & Lee, 2009; Martin, Roman, & Espino, 2011; Wen & Yeh, 2010) and the customer-value drivers (Boetsch, Bieger, & Wittmer, 2011; Park, Robertson, & Wu, 2009);
- the evaluation of airline service quality (Chen & Chang, 2005; Cheng & Chang, 2006; Chou, Liu, Huang, Yih, & Han, 2011; Higgins, Lawphongpanich, Mahoney, & Yin, 2008; Liou & Tzeng, 2007; Pakdil & Aydin, 2007; Tsaur, Chang, & Yen, 2002);
- the effect of service quality on airlines' performance (Sim, Koh, & Shetty, 2006), the proposal of methods and strategies for improving airline service quality (Liou, Tsai, Lin, & Tzeng, 2011; Liou, Yen, & Tzeng, 2010; Maji, 2012);
- the important role of comfort in the interior design of airplanes (Brindisi & ~~Concilio~~ Concilio, 2008; Lee & Luengo-Prado, 2004; Vink, Bazley, Kamp, & Blok, 2012).

The extant literature suggests that, in the air transport industry, aircraft selection and evaluation issues have become a multi-attribute problem, characterized by a high complexity level in which a variety of quantitative and qualitative factors play a crucial role.

In this context, the aim of this paper is to propose a novel model for aircraft evaluation, based on the investigation of airlines' needs. This model considers not only traditional characteristics (operating costs and technical performance, such as cruise speed) but also a variety of features whose importance is strikingly increasing, such as environmental impact and aircraft interior quality. The proposed model can be useful both for airlines, in their process of selecting the most suitable aircraft for their fleet, and for manufacturing companies in their process of designing future aircraft.

The model is based on two popular approaches proposed in literature to address evaluation problems, the Analytic Hierarchy Process (AHP) (Saaty, ~~1980; Saaty,~~ 1980, 2001) and the Fuzzy Set Theory (FST) (Zadeh, 1965), proposing a hybrid approach combining the main strengths of the two methodologies.

The usability of the model for the stakeholders of the air transport industry and its adaptability to contexts characterized by complexity, high technological level, and increasing requirements in terms of sustainability and environmental regulations, are investigated through an empirical study focused on regional transport aircraft.

The paper is organized in the following sections. Section 2 provides further information about the extant literature on evaluation models in the aviation industry. Then, in Section 3, the hybrid model is introduced and described. In Section 4, the proposed model is implemented and a case study related to the evaluation of three regional aircraft is analyzed and discussed. Finally, some conclusions are drawn.

2 Background

Since the 1960s, international air transport organizations and large aircraft manufacturing companies have developed accurate methodologies to calculate aircraft direct operating costs (AEA, 1985; Airbus, 1988; ATA, ~~1964; ATA,~~ 1964, 1967; Boeing, 1972). For many years direct operating costs (DOCs) and Net Present Value (NPV), that in turn includes DOCs, were the main two indicators being utilized in the aircraft evaluation process and in purchasing decisions.

Under this approach, Gibson and Morrell (2004) proposed the use of a variant of the well-documented adjusted present value (APV) concept and suggested a methodology for aircraft financial evaluation using Monte Carlo simulation and Real Option Analysis. Although this contribution has the merit of proposing a robust methodology, which overcomes the simple analysis based on DOCs or NPV, it addresses the evaluation exclusively from the financial point of view, thus neglecting issues related to quality and environmental impact.

In the early 2000s, a number of airlines introduced empirical multi-criteria procedures that included not only DOCs or NPVs, but also a number of indicators, such as speed, range and passengers' capacity (Ferreri, 2003). The weight of each criterion was identified on the basis of past experience or through heuristic decision-making procedures. Even today, many airlines use simple empirical multi-criteria procedures. In fact, despite the fact that the literature is rich of contributes suggesting a variety of tools to deal with multi-criteria problems, only few papers focus their attention on aircraft evaluation.

Among these, See et al. (2004) presented a multi-attribute methodology for selecting the best aircraft among a set of alternatives. Authors used the method of the hypothetical equivalents and inequivalents (Wu, 1996), basing their choice on three criteria: speed, range and number of passengers. This paper has the undoubted advantage of dealing with the problem of aircraft evaluation through a multi-criteria approach; nevertheless it neglects important criteria such as costs, aircraft interior quality and environmental issues. In addition, when the number of alternatives or the number of criteria increase, the proposed method becomes extremely farraginous and provided results are not easy to be interpreted.

Yeh and Chang (2009) proposed a fuzzy multi-criteria decision making algorithm. The evaluation process is based on three criteria (technological advances, social responsibility and economical efficiency), further articulated into eleven sub-criteria. For each criterion, the performance of each aircraft is evaluated through a fuzzy rating. The authors use a pair-wise comparison process to assess the weights among the three criteria, and between sub-criteria within each criterion. The crisp weights are translated into fuzzy numbers and then aggregated with the fuzzy rating of performances. The result is an overall fuzzy preference value for each aircraft type. The overall fuzzy preference value is then defuzzified to obtain a crisp preference value for each aircraft type. The proposed algorithm appears not easy to use. Nevertheless, it could be partially simplified avoiding the fuzzification of the crisp weights. In fact, the aggregation of the crisp weights with fuzzy performances provides overall fuzzy preference values that are highly correlated with the results of the proposed algorithm, revealing that fuzzification of weights could be an unnecessary complexification.

Gomes, Mattos Fernandes, and Mello (2012) proposed a fuzzy stochastic approach to the multi-criteria selection of aircraft based on the NAIADE method (Novel Approach to Imprecise Assessment and Decision Environments). The process of evaluation is based on three criteria (Financial, Logistics, Quality) further articulated in twelve sub-criteria (Acquisition Cost, Liquidity, Operating Costs, Range, Flexibility, Cruising Speed, Replacement Parts Availability, Landing and take-off distance, Comfort, Avionics, Availability, Safety). The output is the ranking of alternatives by means of an outranking procedure adapted from the PROMÉTHÉE method. The proposed method is conceptually simple. Nevertheless, as also authors underline, in the practical applications the mathematical calculations become complex and the analysis of alternative hard to evaluate and interpret.

In this context this paper proposes a novel model for aircraft evaluation, which aims to overcome the weaknesses of the previous models; specifically, coherently to the above-mentioned nature of the aircraft evaluation problem, the model should be based on a multi-criteria framework, including the most relevant categories for stakeholders in the civil aviation industry. Also, the usability of the model and its applicability to real-world decision-making should be ensured.

3 A ~~Hybrid Model~~ hybrid model for aircraft evaluation

The proposed model is based on the two main approaches suggested in literature to address evaluation problems, the Analytic Hierarchy Process (AHP) and the Fuzzy Set Theory (FST). In particular, our approach starts from the analysis of respective weaknesses and strengths of AHP and FST and proposes a hybrid model combines some of the positive features of the two approaches.

From the assessment of AHP and FST approaches, some positive and negative sides related to their usage emerge. Indeed, there are some distortions introduced by AHP and FST techniques in the perception, evaluation and computation respectively of performances and weights associated with criteria adopted in the evaluation process.

AHP models can significantly bias the evaluation of performances associated with the criteria due to the mechanisms that rule the conversion of qualitative judgements into numerical values (as illustrated in Bruno et al., 2012); this generally produces final rankings that tend to flatten the differences among alternatives themselves, causing then troubles to the decision-maker who cannot clearly identify the best solution. For these reasons, when AHP is adopted for performance evaluation, differences are not properly tracked and the ending outcomes of the model may appear significantly altered.

When FST approaches, instead of AHP, are applied for dealing with criteria performances, the distortions illustrated above are almost eliminated. Indeed, in FST models, the qualitative scale defined for each criterion is not treated as a flat scale, as membership functions are defined for each one of the levels. In this way, a fuzzy variable is associated with each crisp numerical value of the indicators related to the evaluation criteria. This fuzzy variable keeps track of the degree of membership of the measured value to each defined qualitative range; hence, biases introduced by AHP approaches are almost overcome.

On the other side, from an accurate investigation on FST models, and in particular on their application in real-world practice, some other shortcomings can be highlighted. When decision-makers are inquired to state judgments about the weights associated with different criteria, a flattening/overestimating effect of weights assessment is triggered. Firstly differences between levels of importance of criteria are lost and then lots of criteria are overestimated. This happens for the uncontrolled decision-makers propensity to judge criteria importance equally high or very high for all the factors considered when absolute qualitative judgments are inquired. When AHP is applied for weights determination, the drawbacks illustrated above are overcome thanks to pair-wise evaluations between criteria that allow detecting even little differences perceived by decision makers about importance assigned to different criteria.

Therefore, AHP-based models appear relevantly suitable for weights determination, meanwhile for performance evaluation they lead to some biased results; FST-based models, instead, seem to be very suitable for performance estimations, but, on the other side, they introduce some distortions in the weights assessment process as well. For this reason, we propose a hybrid model which combines the methodology to determine criteria weights typical of the AHP approach with performance estimation drawn from a FST based model. In particular, the use of FST (through the use of linguistic scales) in the performance evaluation process could be very beneficial in this case, as experts conducting the evaluation process may not be able to estimate, in a precise way, different nuances in performance levels; therefore, it may be important to use methods that capture the imprecision, rather than to use crisp scales.

In the literature there are several proposals of Fuzzy-AHP models for dealing with problems in many different fields (Buyukozkan, 2012; Calabrese, Costa, & Menichini, 2013; Chen & Chao, 2012; Ertay, Kahveci, & ~~Tabanli 2011;~~ Tabanli, 2011; Lee, Nha Le, Genovese, & Koh, 2011; ~~Calabrese, Costa, & Menichini, 2013;~~ Li, Liu, & ~~Chen~~ Chen, 2012; Shaw, Shankar, Yadav, & Thakur, 2012; Zeydan, Colpan, & ~~Cobanoglu~~ Cobanoglu, 2011). All these papers propose the "fuzzification" of the AHP through the adoption of a fuzzy pair-wise comparison matrix (see also, for instance, Abdullah & Najib, 2014; Abdullah & Zulkifli, 2015; Cho & Lee, 2013; Ishizaka & Nguyen, 2013; Rezaei, Fahim, & Tavasszy, 2014). In this process, they practically insert the Fuzzy Logic within the core of the AHP methodology. As stated by Saaty and Tran (2007), the result is a contamination of the AHP with the Fuzzy Logic that implies a higher computational complexity (involving the calculation of eigenvalues, eigenvectors and consistency ratios) and a more complex framework, which increases the difficulties in the phase of implementation and reduces them usability in the practical applications, as also results interpretations may become more difficult. Moreover, the fuzzification of pair-wise comparison matrix is unnecessary since the matrix in itself is able to catch the nuances of the judgements (Barbarosoglu & Yazgac, ~~1997;~~ 1997; Cheng, Chen, Chang, & Chou, 2007; Eagan, 1999; Narasimhan, 1983; Nydick & Hill, ~~1992; Saaty,~~ 1992; Saaty & Tran, 2007; ~~Soukoup,~~ Soukup, 1987).

It is also worth to notice that several adaptations of decision support models based on a combination of Fuzzy Logic and AHP have been applied to deal with evaluation problems in the aviation industry ~~(Aydogan, 2010)~~ (Aydogan, 2011) and aeroengine health assessment (Wang, Fan, & Wang, 2010); however, the combined application of the two methodologies for the aircraft evaluation problem is a novel contribution.

Moreover, differently from what is illustrated in the literature, the hybrid model proposed and assessed in this paper combines the procedure for deriving criteria weights typical of the AHP approach with performances drawn from a FST approach. In other words, the model we propose does not contaminate the AHP with FST (and ~~vice versa),~~ vice versa), while keeping the two approaches separate and using each of the two for its respective strengths. In this way the computational complexity of the Fuzzy-AHP application is reduced, and the practical application is facilitated. While Fuzzy Set Theory and AHP are well established methodologies, their application in the way proposed in this paper represents another contribution, as, to the best of our knowledge, has not been proposed in similar studies.

The implementation of the model is characterized by the following steps (Fig. 1).

Step 1. The starting point of the hybrid approach is represented (as in the case of the AHP and FST-based approaches) by the identification of airlines' needs.

Step 2. After the identification of airlines' needs, the characteristics of the formal model are then defined in terms of evaluation criteria, sub-criteria, alternatives and decision makers.

Step 3. Once criteria and sub-criteria have been identified, these ones, along with alternatives and decision makers, are arranged according to a hierarchical scheme, as prescribed by the AHP approach.

Step 4. The determination of the weights is performed following an AHP approach; in particular, after the definition of the hierarchical scheme, the relative importance of evaluation criteria and sub-criteria at each level of the hierarchy is evaluated through the pair-wise comparison method according to Saaty (1980) scale reported below:

1: Equal importance of two elements

3: Moderate importance of one over another

5: Strong or essential importance

7: Very strong or demonstrated importance

9: Extreme importance

Within this framework, *2, 4, 6, 8* are utilized to keep track of intermediate values, while reciprocals are utilized for inverse comparisons (Saaty, 1980).

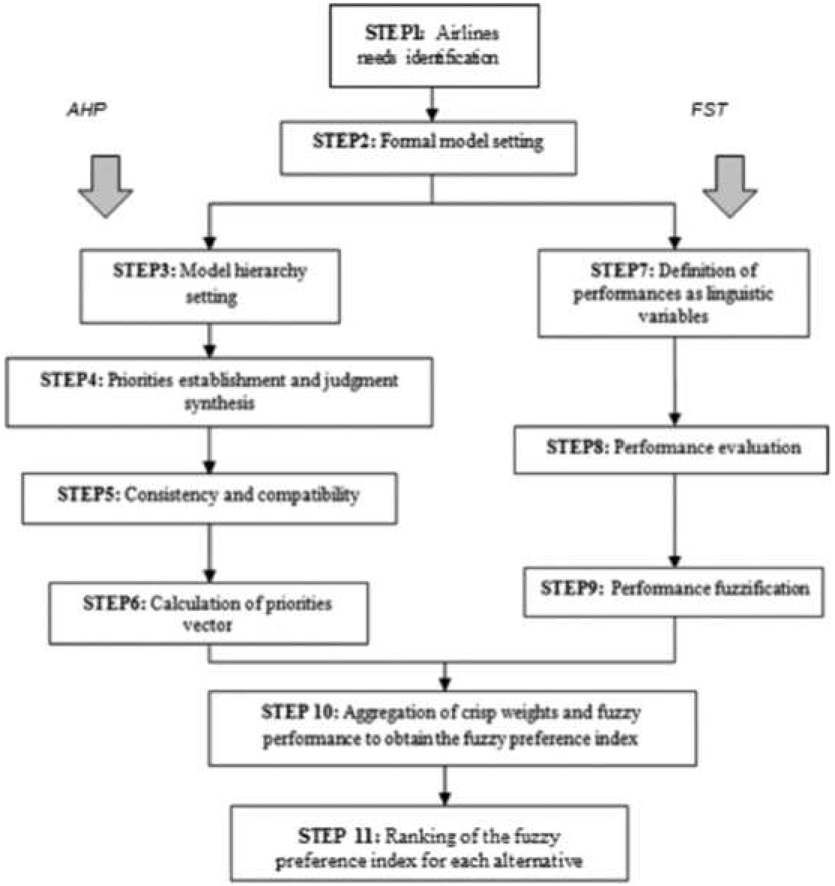

Fig. 1 Hybrid approach (step by step).

Step 5 (From here onwards, the indentation should be back to normal.). Consistency of the obtained pair-wise comparison matrices is then verified according to Saaty (1980) procedure. For each pair-wise comparison matrix of dimension *n*, this is done, by extracting the maximum eigenvalue $\lambda_{\max}$ and computing the Consistency Index (CI) as:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Then, the computed CI is compared to the Random Index (RI), representing an average CI for a huge number of randomly generated matrices of the same order, to obtain the Consistency Ratio (CR) as:

$$CR = \frac{CI}{RI}$$

Typical values for RI depending on the dimension of the matrix *n* are reported in Table 1. Values of CR lower than 0.1 indicate an acceptable level of inconsistency in the pair-wise comparison matrices, that can be therefore utilized for the extraction of the weights.

Step 6. Once consistency has been proved, the final pair-wise comparison matrices are then ~~utilised~~ utilized to derive a coherent vector of priorities corresponding to criteria weights, by extracting from each of them the eigenvector associated with the maximum eigenvalue and ~~normalising~~ normalizing its components (Saaty, 1980).

Step 7. For the sake of performance evaluation, a FST based approach is proposed; in particular, criteria performances are defined as linguistic variables on five qualitative levels: *Very Poor* (VP), *Poor* (P), *Medium* (M), *Good* (G), *Very Good* (VG). Thereafter, the five qualitative levels are translated into fuzzy numbers. In particular, the membership functions of the fuzzy numbers representing the terms VP, P, M, G, VG associated with the linguistic variable performance are evaluated by a direct estimation method (Watanabe, 1979). The range where the trapezoidal membership function assumes maximum value (equal to 1), is defined as the range corresponding to the intersection of the judgments collected from multiple decision makers; the border values (where the trapezoidal membership function assumes values equal to 0), instead, are ~~labelled~~ labeled on the extreme values of the range given by the union of the judgments collected from them.

Step 8. Performance evaluation is then conducted. This step consists of a measurement process of indicators associated with criteria and sub-criteria, through an appropriate data collection process.

Step 9. Performances are then fuzzified, by translating numerical values given by indicators into fuzzy numbers. In this case the numerical values measured for each criterion are compared to the corresponding term set of linguistic variables. The output values for membership functions are combined according to the inferred weights of the members through a fuzzy weighted operator. The result of this procedure is a fuzzy number translating the crisp value measured for a specific couple criterion-alternative. This procedure has to be applied for all the criteria (and related sub-criteria) of the hierarchy.

Step 10. As depicted in Fig. 1, fuzzy performances and crisp weights need to be combined to get the final vendor rating. The issue here is represented by the intent to pick the fuzzy aggregation operator in a way to avoid to spread the entropy related to fuzzy numbers when they are combined. Fuzzy weighted mean operator is judged as the most suitable one to adopt for weights, performances and combined aggregation since it is a convex composition of several fuzzy sets with coefficients which indicate the 'percentage' of a given set in the aggregation. It allows combining fuzzy variables in a simple way, not requiring time expensive or complex calculations, and resembling human decision making.

Step 11. The ranking of trapezoidal fuzzy numbers representing the score associated with the different alternatives represents the last step associated with hybrid model implementation. It appears fundamental to ~~utilise~~ utilized the final fuzzy scores of alternatives for profiling a final rank of the alternatives, in order to identify the best one, as this is an important component of the decision process. According to the review performed by Abbasbandy and Hajjari (2009), more than 30 fuzzy ranking indices have been proposed, although a heated debate has been developing about the counter-intuitiveness and absence of discrimination capability of many of these methods. According to the seminal work of Bortolan and Degani (1985), each ranking method involves some losing of information; still, nowadays, there is a lack of a golden choice that allows the identification of a universally accepted ranking methodology (Abbasbandy & Hajjari, 2009; Kaufmann & Gupta, 1988); Brunelli and Mezei (2013) have proven that rankings may differ significantly depending on the adopted methodology.

Table 1 Random Index values.

n	1	2	3	4	5	6	7	8
R.I.	0	0	0.52	0.89	1.11	1.25	1.35	1.40

Within ranking methods, defuzzification techniques provide a way to associate a crisp real number to fuzzy sets, in such a way that a ranking can be developed by utilizing a simple ordering relation. These specific techniques can be classified in three main categories (Saletic, Velasevic, & Mastorakis, 2002): distribution techniques, maxima techniques, area techniques. Distribution and area techniques are suggested for use in fuzzy controllers; the maxima techniques are suggested for use in general fuzzy expert systems and fuzzy decision-making systems (Saletic et al., 2002), mainly for the low computational complexity which characterizes them. Therefore, since the main purpose of the step is to provide a simple and straightforward ranking to industrial decision-makers, maxima technique (and, in particular, the Middle of Maxima defuzzification method) are judged as the most suitable to profile the final ranking of the alternatives.

4 Empirical ~~Study~~study

To test and to verify the usability of hybrid model in the air transport industry, in this section an empirical study involving three regional aircraft is illustrated.

Step 1. The *identification of airlines needs* is performed considering the case of Air Italy, an Italian airline, which was interested to select aircraft to be purchased within a set of three candidates: Bombardier CRJ1000 (first flight 2008), Sukhoi SSJ100 (first flight 2008), and Embraer ERJ190 (first flight 2004).

Step 2. The *formal model setting* was focused on the definition of the characteristics of the model, identifying the evaluation criteria capable of better representing the airline's requirements. In this case the evaluation criteria were derived merging some insights coming from the literature with Air Italy requirements. The overall set of provided criteria (including economic performance, technical performance, aircraft interior quality, and environmental impact) was then discussed and articulated in specific sub-criteria (including operating cost, aircraft price, cruise speed, autonomy, seat comfort, cabin luggage compartment size, environmental pollution, and noise); for each sub-criterion, specific indicators were defined and normalized in a range from 0 to 1 (as reported in Table 2).

Step 3. Collected criteria and related sub-criteria were organized in homogeneous groups by interviewees involved in the aircraft evaluation process. The output of such gathering is the hierarchy of criteria indicated in Fig. 2.

Step 4. Table 3 reports the pair-wise matrix that is the result of the focus group meeting with the Airline decision makers. It represents the priority establishment between the criteria at the first level of the hierarchy according to the Saaty's (1980) scale. A similar procedure was followed also for the other elements in the hierarchy.

Step 5. The principal eigenvalue ~~$(\lambda$~~ (λ_{max}) of the matrix reported in Table 4 was computed to evaluate the consistency index (CI). Then, the latter was matched with random index (RI) to derive the consistency ratio (CR). As reported in Table 3 the final consistency ratio was equal to 0.023, which is less than the threshold (0.1) needed to assure consistency. A similar procedure was followed also for the other elements in the hierarchy.

Step 6. Once the consistency of the matrix had been verified, the final priority vector was obtained (Table 4). The eigenvector associated with the principal eigenvalue ~~(λ~~(λ_{max}), was calculated and normalized to obtain the final priority vector. Its components, as indicated in Table 5, correspond to the weights associated with the variables at the first level of the hierarchy.

Following the same procedure, the weights associated with the other variables of the hierarchy were extracted obtaining the final results depicted in Fig. 3.

Step 7. An example of *definition of performances as linguistic variables* is reported in Figs. 4a and 4b. Through the direct estimation method, qualitative ranges associated with five levels (very poor, poor, medium, good and very good) were defined. Fig. 4a reports the direct estimation process (based on judgments collected from four experts) for the qualitative performance level *Good* under the criterion Speed. It can be seen as the intersection and the union of the four judgements represent, respectively, the core and the support of the fuzzy number. Results of the same process applied to the other performance levels for the same criterion are reported in Fig. 4b.

Step 8 and Step 9. An example of performance fuzzification is reported with reference to the criterion *Cruise Speed*. Fig. 5 shows that, starting from the crisp numerical performances measured trough specific indicators associated with the sub-criteria reported in the hierarchy (which, in this case is equal to 0.40, for the CRJ1000), this performance is then fuzzified by comparing its crisp numeric value to the term set of the linguistic variables defined for that criterion.

The fuzzy numbers corresponding to crossed membership functions, combined with the inferred weights through a fuzzy weighted operator allow obtaining the final fuzzy number representing the performance of the alternative CRJ1000 for the sub-criterion *Cruise Speed*. This same “fuzzification” method was applied to get fuzzy numbers representative of the performances of the criteria belonging to the last level of the hierarchy and also of all the respective sub-criteria, which were directly measured to evaluate the score for each aircraft evaluated.

Step 10. Crisp weights and fuzzy performances were aggregated across the hierarchy, according to the *aggregation of crisp weights and fuzzy performances to obtain the fuzzy preference index* through the weighted fuzzy operator (see Figs. 6–8).

Step 11. Finally, in adherence to the *ranking of the fuzzy preference index for each alternative* step, the fuzzy numbers representative of the aircraft rating were defuzzified adopting the middle of maxima (MoM) defuzzification method. Results are reported in Table 6.

Table 2 Criteria, Sub-criteria and indicators.

Criteria	Sub-criteria	Indicator	Pre-normalization range
Economic performance	Unit operational costs	Cost per passenger per NM on a typical 300 NM route	[0.098; 0.158]
	Aircraft price	Purchasing price in M$	[30;60]
Technical performance	Cruise speed	Maximum speed in KTS	[400; 500]
	Autonomy	Maximum range in NM	[1000; 3500]
Aircraft interior quality	Seat comfort	Square meters per passenger	[0.51; 0.75]
	Cabin luggage compartment size (kg)	Kilograms of overhead baggage per passenger	[5;10]
Environmental impact	Environmental pollution	kg $CO_{2\text{-eq}}$ per passenger emitted on a 300 KTS route	[40; 79]
	Noise	EPNdB measurement in critical stages	[250; 280]

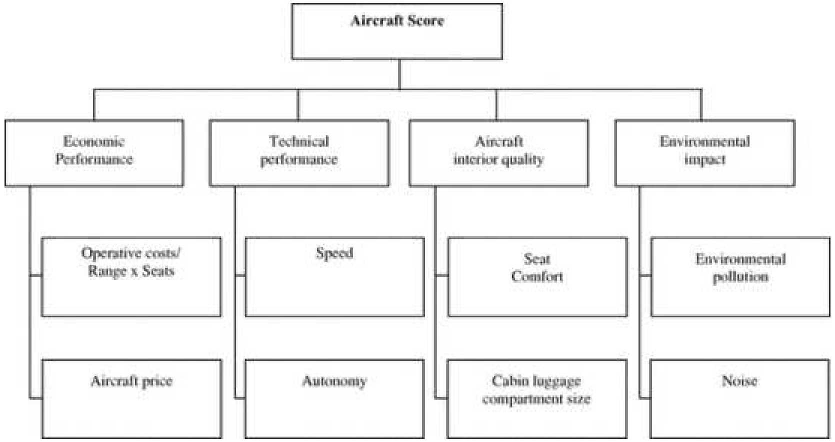

Fig. 2 Hierarchy of criteria.

Table 3 Pair-wise comparison matrix.

Vendor rating (This should read "Aircraft Score")	Economic performance	Technical performance	Aircraft interior quality	Environmental impact
Economic performance	1.00	5.00	5.00	5.00
Technical performance	0.20	1.00	1.00	2.00
Comfort	0.20	1.00	1.00	2.00
Environmental impact	0.20	0.50	0.50	1.00

Table 4 Principal eigenvalue, consistency index and consistency ratio.

	Vendor rating (This should read "Aircraft Score")
λ_{max}	4.061
CI	0.020
RI	0.890
CR	0.023

Table 5 Priority vector.

Priority vector
0.62
0.15
0.15
0.09

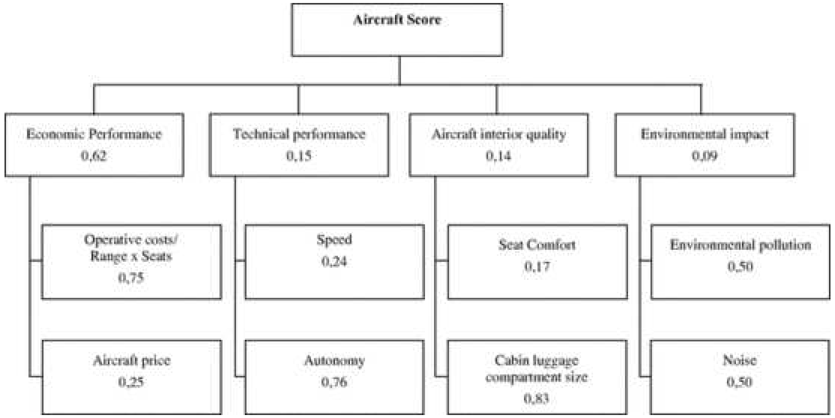

Fig. 3 Weights associated with evaluation criteria.

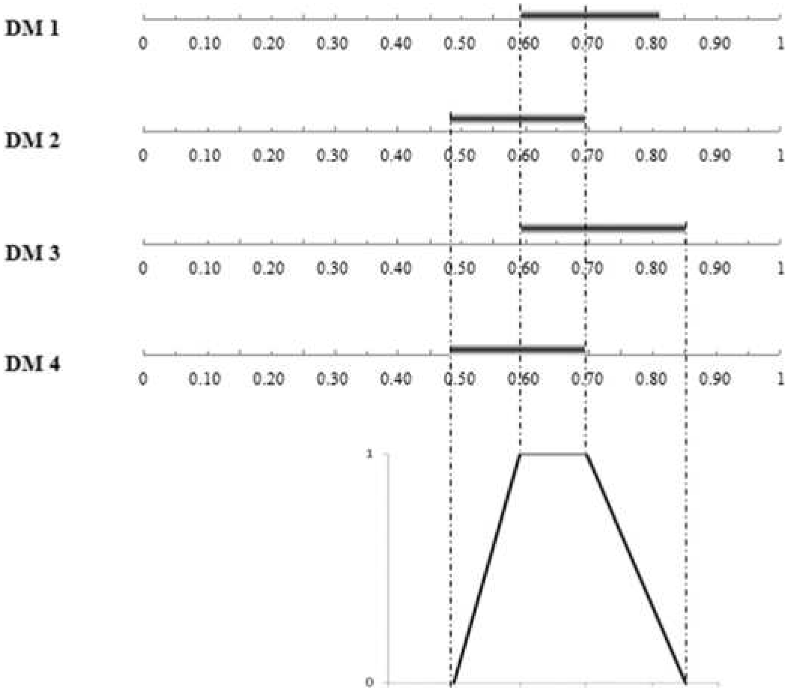

Fig. 4a (It would be better to have a better balance of text and figures, by including figures exactly where specified in the submitted version of the manuscript.)Direct estimation for the qualitative performance level “Good” for the criterion “Speed”.

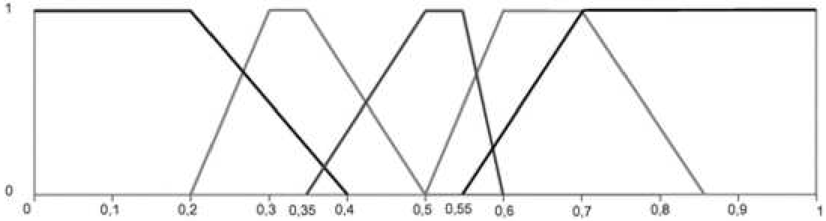

Fig. 4b Definition of performance as linguistic variable for the criterion “Speed”.

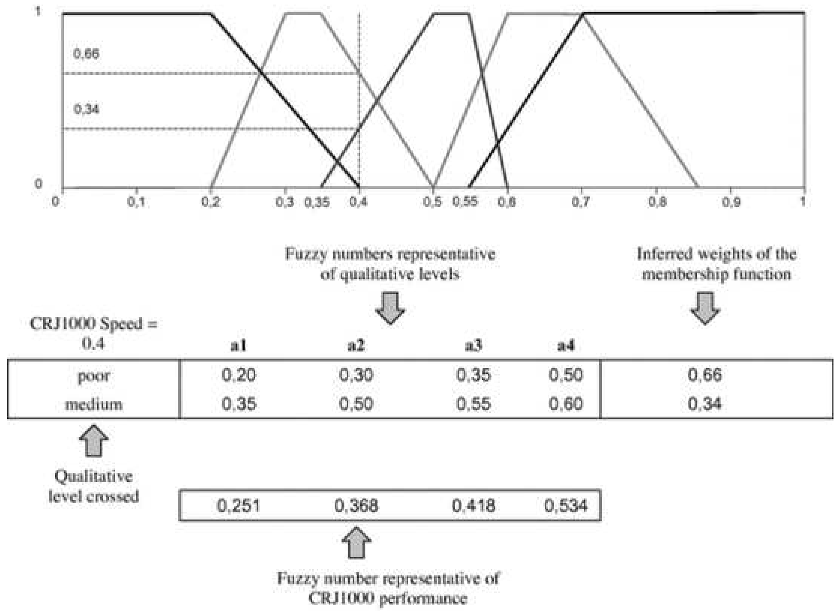

Fig. 5 Performance evaluation and fuzzification for the criterion “Speed”.

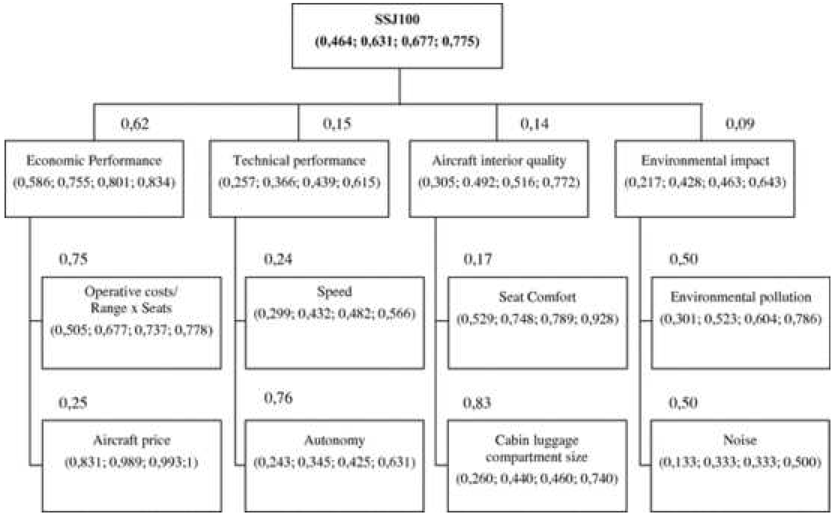

Fig. 6 Application of the model to the alternative Sukhoi SSJ100.

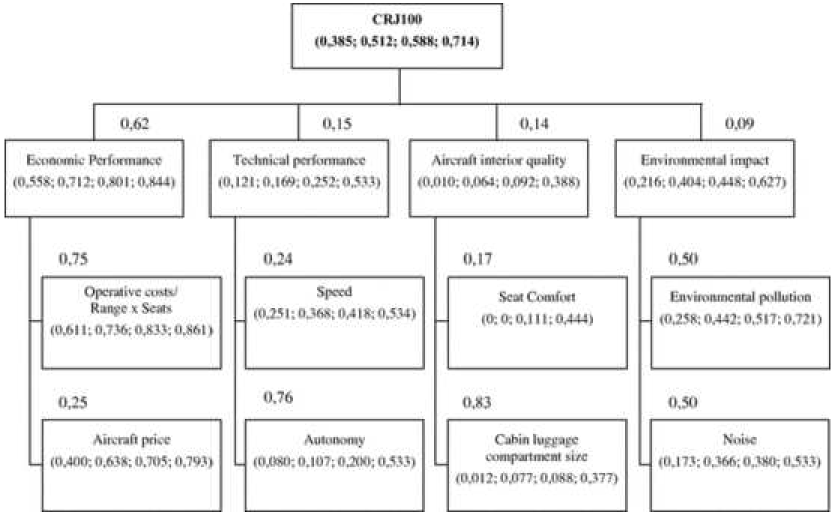

Fig. 7 Application of the model to the alternative Bombardier CRJ1000.

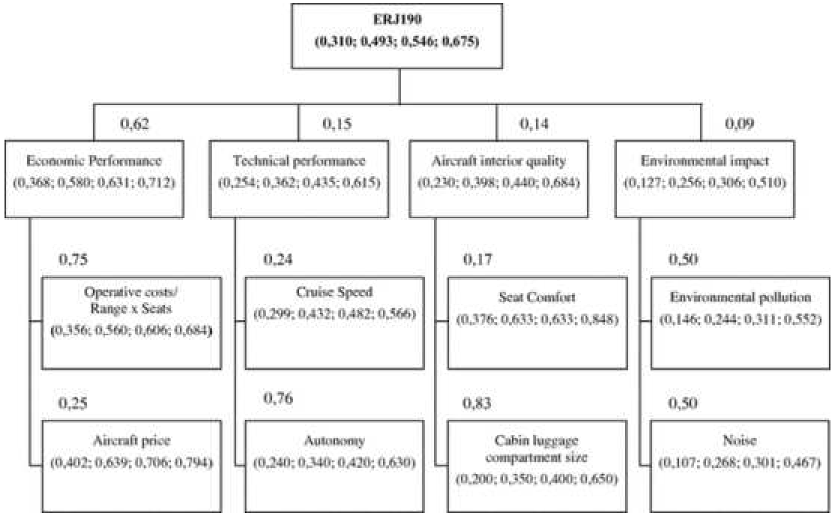

Fig. 8 Application of the model to the alternative Embraer ERJ190.

Table 6 Aircraft final score.

Aircraft	Fuzzy rating	Crisp score
Sukhoi SSJ100	(0.464; 0.631; 0.677; 0.775)	0.637
Bombardier CRJ1000	(0.385; 0.512; 0.588; 0.714)	0.550
Embraer ERJ190	(0.310; 0.493; 0.546; 0.675)	0.506

Table 6 shows that the Sukhoi SSJ 1000 has a higher score than Bombardier CRJ1000 and Embraer ERJ190. The practical relevance of the hybrid approach does not consist only in its usefulness as an evaluation system but rather in the opportunity to adopt it as a strategic tool by both airlines and manufacturing companies. Airlines may use the model to clearly identify their own requirements and ask to manufacturer to modify specific characteristics to better satisfy their own needs. Vice versa, manufacturers may use the model in the phase of design for better meet the airlines requirements.

For example, the Embraer ERJ190 appears to be the aircraft with the lowest score. However the analysis of the performances (Fig. 8) provides useful suggestions to the manufacturer about how it could be possible to gain positions in the ranking, mainly by increasing the value of the criterion *Operating costs*, which is definitely lower than the one reported by other aircraft and whose associated weight is considerably high (0.75). If Embraer engineers are able to re-design a new version of the ERJ190 aligning operating costs towards an average value of the performances estimated for the other competitors (Table 7), ERJ190 could increase its overall rating from 0.506 to 0.596 in such a way to become second instead of last in the new ranking.

Table 7 Hybrid model application as strategic tool to better improve aircraft rating.

Aircraft	Operating costs	Updated operating costs
Sukhoi SSJ100	(0.505; 0.677; 0.737; 0.788)	
Bombardier CRJ1000	(0.611; 0.736; 0.833; 0.861)	
Embraer ERJ190	(0.356; 0.560; 0.606; 0.684)	(0.558; 0.707; 0.785; 0.820)

5 Conclusions

In this paper a model for aircraft evaluation has been proposed. The model includes four criteria (economic performance, technical performance, aircraft interior quality, and environmental impact) and eight sub-criteria (aircraft price, operative cost, cruise speed, autonomy, seat comfort, cabin luggage compartment size, noise, and environmental pollution). The model framework is articulated in eleven steps and it is based on a hybrid approach that uses both the Analytic Hierarchy Process and the Fuzzy Set Theory. The AHP approach is ~~utilised~~ utilized for criteria weights determination because it ensures to keep track of the differences between importance associated with diverse criteria thanks to pair-wise evaluations between them; the FST approach, instead, is adopted to deal with aircraft performances because it allows representing the vagueness associated with criteria evaluation and indicating the “nuances” of airlines perceptions about aircraft performances without losing information. In this way the proposed model overtakes some AHP and FST weaknesses and combines some of their strengths.

The proposed model also overtakes weaknesses of previous models dealing with aircraft evaluation. Differently by Gibson and Morrell (2004) and See et ~~al~~al. (2004), the hybrid model includes a variety of criteria in line with the new requirements of airlines, such as seat comfort, cabin luggage compartment size, noise, and environmental pollution. Compared with models from Yeh and Chang (2009) and Gomes et al. (2012), the hybrid model has a lower level of computational complexity, which facilitates its practical application.

The model has been tested starting from the requirements of an Italian airline (Air Italy) and considering three potential candidates (Sukhoi SSJ 1000, Bombardier CRJ1000, and Embraer ERJ190) to be selected for enlarging the airline’s fleet.

The results of the model implementation highlight how the practical relevance of the hybrid approach does not consist only in its usefulness as an evaluation system but rather in the opportunity to adopt it as a strategic tool. In particular, airlines may use the model both *ex-ante*, in order to clearly identify their own requirements, and *ex-post*, in order to choose the aircraft that better fits to their requirements; manufacturers operating in global markets may use the model both *ex-ante*, for meeting, in a better way, airlines’ requirements, and *ex-post*, for comparing their own aircraft with those of competitors to propose new models or modified versions of old models.

Further researches could be addressed at extending the model towards a multi-stakeholder perspective, in which not only the airline point of view is considered but also the one of other players in the civil aviation industry. In this way, the model could become a strategic tool for detecting preferences misalignment and gaps in the industry, leading to interesting considerations. Future studies will also address the issue of the actual usability of such model, by deploying more real-world case studies reflecting on further issues arising from its implementation.

Also, the methodological framework could be further developed, by introducing a specific module for performance aggregation and ranking determination based on the use of well-established techniques (such as, for instance, outranking methods, TOPSIS); the integration of the model in a dynamic decision support system could be also proposed.~~(Aydogan, 2011; Cheng et al., 2007; Jiang, 2013; Lee et al., 2011; Yang et al., 2012).~~

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Highlights

- This paper presents a novel multi-criteria decision-making model for aircraft evaluation.
- The model is based on a combination of Analytic Hierarchy Process and Fuzzy Set Theory.
- A variety of criteria aligned to contemporary airlines' requirements is included.
- The model overcomes limitations of existing approaches proposed to deal with the problem.
- A real-world empirical study testifies the usability and usefulness of the model.

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