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Economic and Environmental Sustainability for Aircrafts Service Life

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Abstract: Aircrafts are responsible for a significant environmental impact mainly due to the air pollution caused by their motors. The use of composite materials for their production is a way to significantly reduce the weight of the structures and to maximise the ratio between the payload weight and the gasoline consumption. Moreover, the design phase has to consider the cost of different operations performed during the aircraft service life. During the entire life cycle, one of the main costs is the maintenance one. In the current literature, there is a lack of knowledge of methods for maintenance cost estimation in the aircraft industry; moreover, very few environmental assessment methods have been developed. Thus, the aim of this paper is to define a new method to support the aircraft design process; both the environmental and the economic dimensions have been included with the purpose of assessing the aircraft sustainability during its service life. A green index has been identified mixing the maintenance cost and an environmental parameter with the aim of identifying the greenest solution. A final practical application shows the feasibility and the simple application of the proposed approach.

Keywords: aircraft industry; aircraft sustainability; green design; maintenance cost

1. Introduction

In the last years, the environmental situation has forced the entire world to focus its attention on the green dimension and, in general, on the three pillars of sustainability. Thus, every company and sector are adapting their business considering a new vision and preserving the quality of the environment. In 2003, a study by Upham et al. started to point out the environmental impact in the aircraft industry, considering several factors that influence the aircraft service life [1]. In the following years, other researchers underlined the aircraft service effects on society and they studied the linked economic aspects, mainly due to the depopulation of the areas near the airports [2–4].

In such a context, the use of composite materials in the aerospace industry is becoming a very important topic because of several reasons, but all related to one main issue, i.e. the reduction of the aircraft's structural weight [5]. The weight reduction has a great influence and plays a relevant role in the air pollution caused by aircrafts [6]. In fact, for years such a factor has been considered one of the most significant contributors to sustainability [7]. At the same time, several problems have to be considered, in particular the management of possible structural damages due to such materials [8]. The designer therefore needs to find a suitable trade-off between the air pollution reduction and the economic considerations linked to the maintenance costs. Moreover, the decision-making process needs to consider the classical variables related to the mechanical resistance, including economic and environmental variables for a complete green evaluation.

The current literature presents a huge lack of information on tools or methods for the sustainability evaluation in the aerospace industry, while in other sectors, such as the maritime or railway sector, there are many methods to be applied to the problem of sustainability [9,10]. In the past, several methods have tried to estimate the lifecycle costs (LCC) of an aircraft, but all of them require specific input data that are typically not available during the early design stage [11,12]. Such a gap has been faced by Heller et al. who consider the concept of similarity indicators in order to estimate the costs of a future product; the approach has been tested in the civil aircraft industry, but it does not address environmental sustainability [13]. Ameli et al. proposed a design tool based on mathematical programming to evaluate the life cycle cost and environmental impact of complex new products, such as automobiles, ships and aircraft [14]. The model minimizes the manufacturer total cost during the entire life cycle, including supply, transportation, production and end-of-life treatment costs; moreover, a constraint checks the environmental suitability of the configuration. However, the model does not consider nor assess the sustainability of the new solution during its usage stage.

As introduced, very few authors proposed methods for the aircraft sustainability assessment to apply during the design phase. Starting from such consideration, the first open issue is to find a quantitative way to estimate the future economic and environmental performance of an aircraft. From here, there is a need of a decisional tool, a green decision support method that can help the designer to take the suitable solution, considering all the relevant decision factors. The aim of this paper is to define a new procedure to support the aircraft design process, able to evaluate both the environmental and the economic dimensions with the purpose of assessing the aircraft sustainability during its service life. It is well known that the aircraft maintenance cost strongly influences the economic performance of a fleet, being the largest component of the total operation cost, excluding the fuel cost [15]. Thus, a new way to measure the aircraft service life cost has been introduced, considering the maintenance cost as the main impact factor and basing the computation on a forecasting method. Additionally, a quantitative environmental index has been defined, linking the gasoline consumption to the transportable weight.

The remainder of the paper is organised as follows: first, a literature review on aircraft maintenance costing methods will be presented, then a new green decision support method based on the maintenance cost estimation will be introduced; finally, an application of the method and the related conclusions will be discussed.

2. Literature Review

Since some years, aircraft sustainability has become a well-known problem, but it still lacks a clear definition. As discussed in the previous section, there is a lack in the current literature of quantitative methods able to perform a realistic prediction about aircraft sustainability in the usage stage. Since the proposed method is based on the maintenance costs, the literature review will focus on aircraft maintenance and the relative costing methods proposed up to now. First, a brief overview on the aircraft maintenance process is presented, which is typically based on a cyclic maintenance policy. The process is generally composed of four stages, namely A, B, C and D. The first two types concern simple checks and several tasks that can occur for each flight, while the last two types consist of significant maintenance actions, which require specific operations on the structural parts and a complete disassembly of the aircraft. Starting from such context, a systematic literature review has been applied in order to find and study the proposed models able to estimate the aircraft maintenance costs. A research question has been previously defined:

(i) which are the international studies focused on the lifecycle cost estimation based on the aircraft maintenance costs?

In order to identify the pertinent papers, as previously briefly said, a systematic literature review was carried out; this method firstly identifies the scientific database to be used, secondly defines the search keywords and finally defines the exclusion criteria. Applying such a method, three scientific databases were used: Google Scholar (GS), Scopus (SC) and Web of Science (WoS). Moreover, three keywords groups were defined to start the computerized search:

- aircraft, aviation, airplane and aerospace;
- maintenance, condition-based maintenance (CBM), cyclic and predictive maintenance (PdM);
- costs, inspection intervals.

Later, these groups were combined by using the Boolean operators (AND, OR, etc.) and a first search returned an amount of 726 articles (477 from SC, 179 from WoS and 70 from GS). Then, five exclusion criteria for the selection of articles were defined:

- articles published before 2000;
- not English papers;
- duplicates from different databases;
- not peer-reviewed international journals;
- papers without a clear link between the groups of keywords.

Considering the first three criteria, the number was reduced to 410. Among them, just 93 papers were found to be published in peer-reviewed journals. Then, another screening consisting of reading title, abstract and keywords allowed detecting the articles that satisfy the last exclusion criteria: just 24 papers resulted in meeting all the selection criteria. Finally, a last full reading was performed in order to find the papers in line with the aim of the study. The remaining 8 peer-reviewed papers were individually examined to answer the research question.

A first analysis on the time range of the publications was carried out in order to show an increasing attention on the topic in recent years; 75% of the revised papers were published in the last three years; moreover no papers were found published before 2012 (see Figure 1).

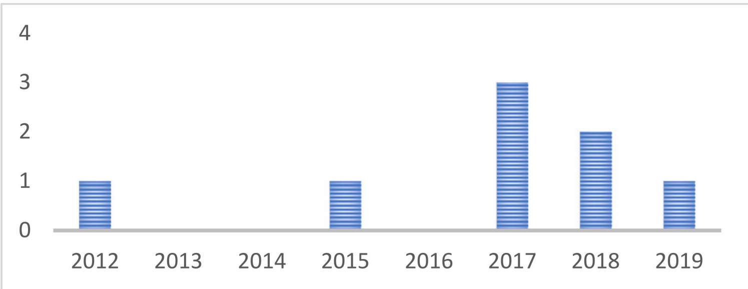

Figure 1. Number of papers per year.

Later, some drivers have been defined in order to classify the papers analysed: focus, cost analysis method, approach, and field of application and for each paper it is identified the driver covered (*). Table 1 summarizes the main results.

Table 1. Selected papers—summary of contents.

Paper	Focus		Cost Analysis Method		Approach			Field of Application	
	Costing	Inspection Cycle Time	Cost Benefit Analysis	Cost Estimation/ Optimization	Scheduled	CBM	PdM	Civil Aviation	Other
[16]	*		*	*	*			*	
[17]	*	*				*		*	
[18]	*	*		*			*	*	
[19]	*	*	*	*	*	*			*
[20]	*			*		*			*
[21]	*	*		*		*			*
[22]	*			*		*			*
[23]	*	*			*			*	

The "focus" category is split into two main goals: cost evaluation and the definition of new cyclic times for the inspection of the aircraft structure. In the same way, two different cost analysis methods were identified. Concerning the "approach" category, three options were considered: the scheduled maintenance, the condition-based maintenance (CBM) and the predictive one (PdM). Finally, the field of application category is split into civil aviation and other types of aviation systems.

As already asserted, great attention was put on the papers that present a method to estimate the maintenance costs. A cost model was developed by Pattabhiraman et al. in order to quantify the savings, comparing different maintenance policies [19]. The total maintenance cost was computed considering the engine, the airframe and the structural maintenance costs, and estimating the number of maintenance actions. Since the number of services is unknown, two scenarios have been evaluated with optimistic and pessimistic assumptions. In 2018, Dong and Kim proposed a cost–benefit analysis in order to evaluate the performance of a structural health monitoring (SHM) system applied to the civil aviation industry [16]. The authors included in the maintenance cost estimation just the costs affected by replacing the SHM equipment, starting from the assumption that the cost analysis of an aircraft over its lifecycle is too complicated. Later, Dong et al. quantified the benefits of a condition-based maintenance based on SHM on the lifetime cost of an airplane fuselage [17]. Manufacturing costs, maintenance costs and fuel costs were considered in the analysis. Once again, the maintenance cost was simply estimated considering the cost of replacing sensors. Wang et al., 2017 determined the expected maintenance costs quantifying the future damage distribution and considering different methods for modelling the degradation process of a fuselage panel [18]; set up and repair costs were included considering both scheduled and unscheduled actions. A maintenance decision support model was developed by Lin et al. [20]; the objective was to schedule an appropriate maintenance plan for minimizing the maintenance costs. The maintenance actions were estimated starting from a reliability evaluation model and the real-time data obtained by monitoring the system. The need of real-time information excludes its application in the design phase. In 2018, Lin et al. proposed a maintenance cost optimisation model for an aircraft fleet. The aims were to simultaneously minimise the structural repair cost and the cost of wasted remaining useful life, which depends on the probability of failure [21]. Chen et al. quantified maintenance costs by means of a probabilistic simulation model [22]. They considered the cost of inspection (work force and equipment), the cost of repair (material and spare parts) and the risk due to the uncertainty linked to any special event or unexpected severe damage. A simulation case study was developed by Sun et al. in order to test the proposed maintenance cost modelling [23]. Once again, inspection and repair costs were included in the analysis and once again, several probability functions have been defined in order to quantify the unscheduled operations.

In conclusion, all the papers analysed are focused on maintenance costing methods based on a bottom-up approach that is very difficult to apply especially in the design phase, as confirmed by the literature [24,25]. The unsuitable application of bottom-up costing approach is justified by the number of details needed to build a full costing formulation. In fact, some cost contributions are easy to identify while others are difficult to estimate without a defined and detailed project. For instance, the workforce total cost computation needs to define the execution time of the work which depends on the process automation degree, the process production rate, the historic productivity for the specific parts and so on. Thus, the simple workforce cost cannot be easily computed in the design phase.

Therefore, the literature analysis has demonstrated that less attention was paid to define a specific procedure to estimate the cost of maintenance for the aircraft service life in the design phase. Thus, the first aim of this paper is to cover such a gap by defining a new method to evaluate the maintenance costs in the early stage of the design process. Starting from such result, a sustainability decision support tool has been structured, mixing both the economic (maintenance cost) and the environmental impact; the final purpose is to define a method to predict the sustainability of a specific solution in its service life.

3. Decision Support Framework for Green Design

This paper proposes a quantitative approach for assessing the lifecycle sustainability of a new design solution. The framework has been modelled considering both the economic and environmental dimensions. First, a single evaluation of each perspective will be performed, and then a final global index will be computed in order to find the greenest solution. As already explained, economic benefits will be evaluated by means of the maintenance cost, while the environmental impact will be measured with w_0, expressed as the ratio between the payload weight and the gasoline consumption. Finally, it will be possible to identify the greenest solution balancing the two factors in terms of costs and benefits, as shown in Figure 2.

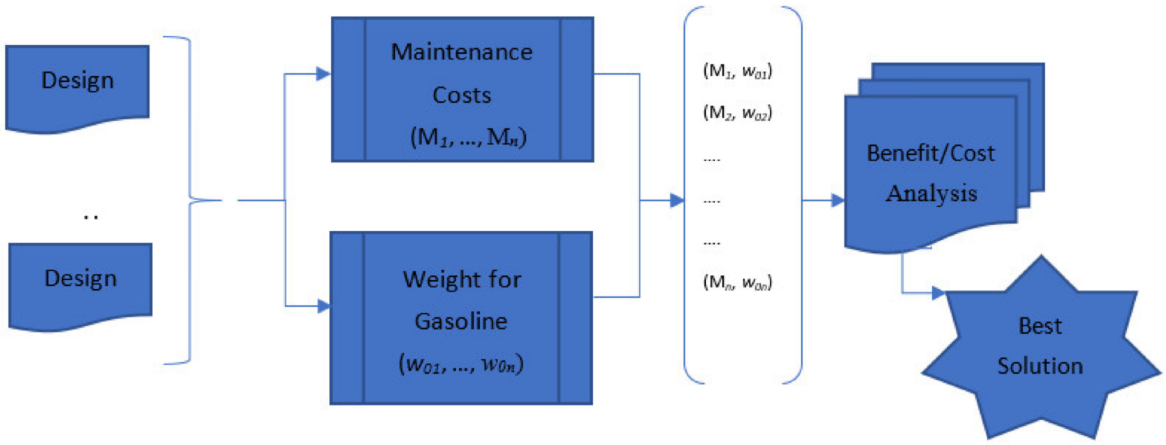

Figure 2. Framework of the sustainability decision support system.

4. Maintenance Cost Estimation Method

Starting from the framework presented, the first problem concerns the computation of the maintenance cost for a specific part. In fact, the part estimation during the design stage is very difficult for two main issues: (i) the information available is not detailed, (ii) the designer is generally not skilled at costing methods. From here, the proposal to apply a well-known cost evaluation procedure, namely analogous costing method (ACM) [24,26]. This approach is generally considered rough, but it could provide interesting results if used by a designer because it is just based on shape and function similarities. Thus, the designer has to simply assign the specific part to a specific family of products. Moreover, the procedure presented in the paper allows detecting the most similar parts and calculating a maintenance cost of the part using some parameters obtained by the shape. As an introduction, some information needed to perform an ACM estimation are detailed:

- A database (DB) containing data about geometrical, mechanical and costing parameters of all the parts maintained in the past (named old parts);
- a method to select the most similar old part in terms of shape and function;
- the identification of suitable coefficients that consider the differences between the new part to design and the old part.

Moreover, the estimation procedure is divided in two main steps: (i) the similarity identification and (ii) the cost estimation. The following nomenclature will be adopted in describing the methodological steps: the "new" part is the one to design, the "old" parts are the ones contained in the database, and the "family" is the part type, i.e., a fuselage, a stringer, an aircraft, etc. In order to make the procedure consistent, new and old parts have to be designed considering the same material, the same manufacturing process and they have to belong to the same family.

Over past years, many similarity indexes have been proposed in the literature; one of the most used concerns the Euclidean distance computation considering some typical parameters ($i = 1, \ldots, n$) belonging to the elements to compare [27]:

$$d_{new-old} = \sqrt{\sum_{i=1}^{n} \left(x_{new,\,i} - x_{old,i}\right)^2} \tag{1}$$

Thus, the choice of such an approach is justified by its wide application, and the similarity between two parts has been investigated using two categories of parameters: (1) the part weight (that is generally available being one of the main design request points) and (2) the geometrical characteristics.

It is important to explain that the application of the procedure depends on the part analysed. In fact, a single element of the aircraft structure (e.g. a stringer, a frame, etc.) can be assessed using one or more geometrical variables (the length for a stringer, the curvature for a frame, etc.). An assembled element (e.g. a window, a door panel, a fuselage or a whole aircraft) needs to consider another indirect parameter to assess the similarity through Equation (1). Such a parameter must include all the characteristics of the different assembled parts. A proposal to solve the problem concerns considering the specific weight per square meter or per cubic meter; in such a case, the exposed surface changes according to the part analysed. An example is proposed considering a fuselage (Equation (2)):

$$Distance\_Parameter_{L\ 2,\ circular\ fusulage} = \frac{weight\ of\ fusulage}{\pi DL}\left[\frac{kg}{m^2}\right] \tag{2}$$

where D is the diameter of the fuselage and L is the length of the aircraft.

In such an example, the surface must be considered as the enveloping surface of the cylinder in which the cabin, the fuselage and the tail (without the wing extremities) are contained; the surface considered is highlighted in orange in Figure 3.

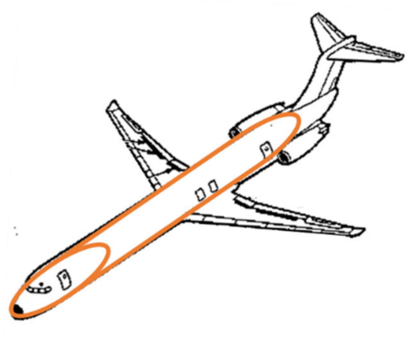

Figure 3. An example of an enveloping cylinder.

If a whole aircraft must be considered, then the surface of the wings must be included. Finally, the similarity is identified using (1). The old part, which has the smallest distance to the new part, is the most similar one.

Once the similarity calculation is concluded, the second step of the procedure can start. Starting from this point, the "old" part will identify the element found to be the most similar one. Thus, the cost estimation will be performed calculating some factors, which take into consideration the difference between the new and the old part. In general, the ACM procedure requires the application of the following equation:

$$C_{new} = C_{old} \cdot \left(F_p \cdot F_M \cdot F_C \right) \quad (3)$$

where:

- C_{new} is the cost of the new part (considering production, maintenance or any other process);
- C_{old} is the cost of the most similar old part;
- F_p is the productivity factor that considers the production or the organizational improvements adopted over the years which differ the new and old production process;
- F_M is the miniaturisation factor that considers the differences in the geometrical shape;
- F_C is the complexity factor that considers the shape complexity differences.

As previously asserted, the two parts can be compared if characterised by same material, the same production technology and the same family. Thus, concerning the first factor F_p, the main difference between the old and the new part production process consists of the cycle time. Moreover, a recognised method, used to evaluate the process time variation due to the impact of the worker experience, is the one based on the learning curves; starting from such considerations, the proposed model replaces the productivity factor with the learning factor:

$$F_p = F_P^{learning} \quad (4)$$

According to [28], the most used learning function for the aerospace sector is the "Wright model"; the analytical formula is reported below:

$$y_N = C_1 \cdot N^b \qquad -1 \leq b \leq 0 \quad (5)$$

where:

- y_N is the execution time for the N-th part, produced after N-1 other parts belonging to the same family;
- C_1 is the execution time of the first part;
- N is the number of parts completed at the instant of time considered;
- b is the learning rate.

The Wright model curve is shown in Figure 4.

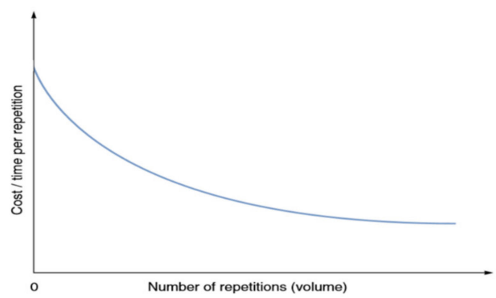

Figure 4. Learning curve trend.

The formula to compute the value of the b parameter is reported below:

$$b = \frac{log\,(1-r)}{log(2)} \tag{6}$$

Where, r is the learning rate for each doubling of operations performed. Typical values of the b parameter are presented in Table 2.

Table 2. Typical values of the b parameter.

r	*b*
5%.	−0.074
10%	−0.152
20%	−0.322
30%	−0.514
40%	−0.737

As reported in Equation (6), the b value is between −1 and 0, thus the extreme values of the time function become:

- $y_N = C_1$ if $b = 0$;
- $y_N = C_1/N$ if $b = -1$.

The b parameter is related to the estimation of the learning factor, i.e., the reduction of the execution time of one operation when the number of operations performed increases. It is important to notice that for the aerospace sector the expected time reduction is 20% for each doubling of the number of operations performed.

From the theoretical and practical point of view, the Wright model presents two limitations:

- The execution time goes to 0 for N→+∞.
- As presented by [28], the model is suitable only for manual operations, such as the maintenance operations performed in the aerospace industry.

Thus, starting from Equation (6), the execution time for a maintenance action on a new part x can be described as the execution time of an old part performed after N replications, expressed as y_X (7). The time to perform the last maintenance operation on an old similar part has to be provided by the company in order to compute C_1 (Equation (8)) and define the learning curve.

$$t_{new,X} = y_X \tag{7}$$

$$C_1 = \frac{t_{old,N}}{N^b} \tag{8}$$

where:

- $t_{new,X}$ is the execution time estimation for a maintenance service on the *x-th* new part; it is calculated starting from the N previous operations performed before it is performed;
- $t_{old,N}$ is the execution time of the last maintenance service performed on a similar old part.

Then, it is possible to apply the learning curve method through Equation (9).

$$t_{new,X} = C_1 \cdot X^b \tag{9}$$

Later, a mean value is calculated, considering k maintenance services (Equation (10)); in practice, not just one but a set of actions will be performed on the new part.

$$\overline{t_{new,X}} = \frac{\sum_{X=N+1}^{N+k} t_{new,X}^{k}}{k} \quad (10)$$

where:

- k is the number of parts belonging to the new batch to be maintained.

Finally, F_p can be calculated as the ratio between the average execution time of the new product and the production time of the old one as illustrated in Equation (11).

$$F_p = \frac{\overline{t_{new,X}}}{t_{old,N}} \quad (11)$$

As already anticipated, the second factor F_M considers the differences in the geometrical shape. Thus, for manufactured elements, F_M can be calculated as the ratio between the external surface of the new and the old parts (Equation (12)), considering such values easily available through the CAD software.

$$F_M^{manufactured\_parts} = \frac{\sum_{i=1}^{n} S_{new,\,i}}{\sum_{j=1}^{m} S_{old,\,j}} \quad (12)$$

The sum for both the division terms results from the CAD files that generally compute the external surface as the sum of multiple surfaces (*i = 1,.., n* surfaces for the new part and *j = 1,.., m* surfaces for the old part).

For assembled parts, a different way to measure such a factor was identified. In fact, the computation can be performed using (Equation (13)), where the weight w is used instead of the geometrical properties.

$$F_M^{assembled\_parts} = \frac{W_{new}}{W_{old}} \quad (13)$$

Finally, the last corrective factor F_C regards the complexity. As previously stated, the first assumption is to compare parts with the same material, production process and family. Moreover, the complexity is generally evaluated matching work-methods and technological complexity, information complexity and shape complexity [29]. Starting from the considerations above, it is possible to affirm that there are no significant difference in terms of complexity. Thus, the complexity factor can be neglected (Equation (14)).

$$F_C = 1 \quad (14)$$

Obviously, the best solution will be the one with the smallest final maintenance cost C_{new}.

5. Final Tool for Sustainability Evaluation

As already explained, the first purpose of the paper was to identify a new procedure able to evaluate the economic performance of an aircraft during its service life. Thus, a new method to estimate the maintenance costs in the early stage of the design process has been proposed. Starting from such result, a sustainability decision support tool has been structured, balancing the economic benefits with the environmental ones; the final aim is to predict the service life sustainability of a new design solution.

Concerning the environmental assessment, a new index has been identified, starting from some considerations; first, the fuel consumption has a strong impact on the environmental performance. Moreover, in order to delete the possible bias resulting from different sizes of the aircraft, it is important to identify an indicator able to compare different aircrafts with different service loads, tank capacities and autonomy. Thus, the environmental indicator w_0 is defined as the ratio between the maximum payload weight (kg) and the mean consumption of the aircraft [l/km] during a single transport (Equation (15)).

$$w_0 = \frac{SL}{\frac{TC}{A}} = \frac{SL \cdot A}{TC} \quad \left[\frac{kg \cdot km}{lt}\right] \tag{15}$$

where:

- *SL* is the service load (SL), i.e. the payload weight for each flight (kg);
- *TC* is the maximum tank capacity linked to the consumption of gasoline for each flight (L);
- *A* is the distance (km) that the aircraft can cover with *TC*.

In such a case, the higher the value of w_0, the better the solution is.

As already asserted, the sustainability evaluation of different design solutions must consider the trade-off between the two perspectives and their different trends. In fact, the best maintenance cost is the smallest one, while w_0 has to increase to minimise its impact, as reported in Figure 5.

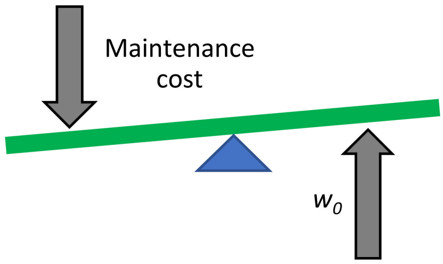

Figure 5. Maintenance cost and w_0 impact on the green design solution.

Starting from such behaviours, one a-dimensional function has been defined, in order to identify the greenest design solution. Finally, the most suitable solution will be the one with the minimum economic and environmental impact, summarised as follows (Equation (16)). Moreover, considering the normalization proposed, the better result will be the one with the smallest value, with a maximum score equal to two.

$$Greenest\ Design\ Solution = \min_{i=1,\ n}\left\{\left(\frac{C_{new,i}}{C_{new,max}} + \frac{w_{0,min}}{w_{0,i}}\right)\right\} \tag{16}$$

where:

- i is the counter of all the design solutions,
- $C_{new,i}$ is the maintenance cost of the i-th design solution;
- $C_{new,min}$ is the minimum maintenance cost among all the n design solutions;
- $w_{0,min}$ is the minimum ratio w_0 between all the n design solutions,
- $w_{0,i}$ is the ratio w_0 of the i-th design solution

6. Numerical Application to the Aerospace Industry

In order to test the feasibility of the framework proposed and to show its simple application to the aerospace industry, the presented tool was applied using a real database. The database was populated with information derived from several producers, in terms of geometrical characteristics, autonomy, tank capacity, and maintenance costs for the service life. Data were recovered using the scientific literature [23,25,30,31]. Appendix A summarizes the input data recovered and stocked before starting the analysis.

In order to validate the method proposed, three similar aircrafts were chosen to compare and identify the best green solution to design; size, autonomy and service payload have been considered in order to make a suitable choice. The three final aircrafts to evaluate are: (i) Boeing 777-300LR, (ii) Boeing 747-8I, (iii) McDonnell MD-12. In such a case, input data were recovered and stocked in a second database (Table 3).

Table 3. DB containing data on new parts.

Parameter	Boeing 777-300LR	Boeing 747-8I	McDonnell MD-12
Diameter Fuselage (m)	6.20	6.50	7.39
Height Fuselage (m)	8.70	9.84	8.51
Length (m)	63.73	76.25	63.40
Wing Width (m)	64.80	68.40	64.92
Wings Surface (m^2)	436.80	554.00	543.10
Operative Weight—OW (kg)	145,150.00	220,128.00	187,650.00
Service Load (kg)	63,957.00	76,067.00	91,160.00
Gasoline Tank Capacity—TC [lt]	181,283.00	238,610.00	195,000.00
Autonomy—A (km)	15,845.00	14,310.00	14,825.00
Aircraft maintained—N	130.00	160.00	120.00
Initial Maintenance operation time—T (h/check C)	130.00	160.00	150.00
Maintenance cost [$]	$54,600.0.00	$74,000,000.00	$66,400,000.00

Following the framework described in the previous section, the procedure starts with the maintenance cost computation; the first step concerns the similarity identification using the Euclidean distance computation. Since such a numerical example considers the whole aircraft and its total maintenance costs, the similarity index is computed using (2), and assuming that the exposed surface can be calculated as the enveloping cylinder generated by the fuselage. The three aircrafts have a weight per square meter equal to (i) 86.47 kg/m^2, (ii) 104,24 kg/m^2 and (iii) 93.10 kg/m^2, which have been computed as the sum of the wing surfaces and the envelop of the cylinder of the fuselage. Thus, calculating the distance parameter (DP) as in (2), and for each aircraft reported in Appendix A, it is possible to compute the distance between each solution and the three aircrafts examined; the best similarities are underlined and reported in Table 4. The remaining computations are presented in Appendix B.

Table 4. Euclidean distance between different design solutions.

Aircraft	DP	Boeing 777-300LR	Boeing 747-8I	McDonnell MD-12
Airbus A380	166.95	29.71	1.79	20.27
Boeing 777F	136.50	0.73	28.66	10.17
Boeing 747-8F	147.90	10.67	17.25	1.23

The following step regards the cost estimation, starting from the computation of the three corrective factors described in the previous section. Thus, the productivity factor is calculated for each design solution.

$$F_{p,1} = \frac{T \cdot (N+1)^{-0.322}}{T \cdot (N)^{-0.322}} = \frac{24.0216}{24.0431} = 0.99911 \quad (17)$$

$$F_{p,2} = \frac{T \cdot (N+1)^{-0.322}}{T \cdot (N)^{-0.322}} = \frac{42.2916}{42.5621} = 0.99364 \quad (18)$$

$$F_{p,3} = \frac{T \cdot (N+1)^{-0.322}}{T \cdot (N)^{-0.322}} = \frac{40.5599}{40.6684} = 0.99733 \quad (19)$$

Then, the miniaturization factor computation is shown below.

$$F_{M,1} = \frac{OW_{new}}{OW_{old}} = \frac{145150}{144379} = 1.0054 \tag{20}$$

$$F_{M,2} = \frac{OW_{new}}{OW_{old}} = \frac{220128}{277000} = 0.79469 \tag{21}$$

$$F_{M,3} = \frac{OW_{new}}{OW_{old}} = \frac{187650}{197131} = 0.95191 \tag{22}$$

Finally, the final maintenance cost is estimated using Equation (3), together with the absolute error derived from the procedure tested.

$$C_{new,1} = 50500000\ \$ \cdot 0.99911 \cdot 1.0054 \cdot 1 = 50724348\ \$ \tag{23}$$

$$C_{new,2} = 86000000\ \$ \cdot 0.99364 \cdot 0.79469 \cdot 1 = 67908590\ \$ \tag{24}$$

$$C_{new,3} = 72300000\ \$ \cdot 0.99733 \cdot 0.95191 \cdot 1 = 68639073\ \$ \tag{25}$$

In fact, the absolute error can be calculated starting from the real cost of maintenance obtained in practice and the amount reported in Table 3. Table 5 summarises the results obtained for each solution.

Table 5. Absolute error of the maintenance cost estimation procedure.

Aircraft	Error
Boeing 777-300LR	+7%
Boeing 747-8I	+8%
McDonnell MD-12	−3%
Mean error	6%

Once the maintenance costs are calculated, the environmental indicator w_0 is calculated for each design solution using (15); the resulting values are reported in Table 6.

Table 6. w_0 for the three design solutions.

Aircraft	w_0 (kgkm/lt)
Boeing 777-300LR	5590.15
Boeing 747-8I	4561.92
McDonnell MD-12	6930.50

Finally, Equation (16) is applied and the final index is derived (Table 7).

Table 7. Green Evaluation for the three design solution.

Aircraft	w_0 (kgkm/lt)	Maintenance Cost ($)	Green Index
Boeing 777-300LR	5590.15	507,243.48	1,555,065
Boeing 747-8I	4561.92	679,085.90	1,989,358
McDonnell MD-12	**6930.50**	686,390.73	1,658,238

Table 7 and Figure 6 show that the greenest solution is the first one (Boeing 777-300LR), i.e the one with the minimum green index value. This result was achieved using a quantitative approach based on both the environmental and economic dimensions. Splitting the two contributors, the first design solution provides the best economic benefit. Alternatively, the third aircraft results have the worst economic performance but the best green solution; nonetheless, comparing the first and last solutions, the McDonnell MD-12 is characterized by a worse performance in terms of km travelled with one liter of gasoline.

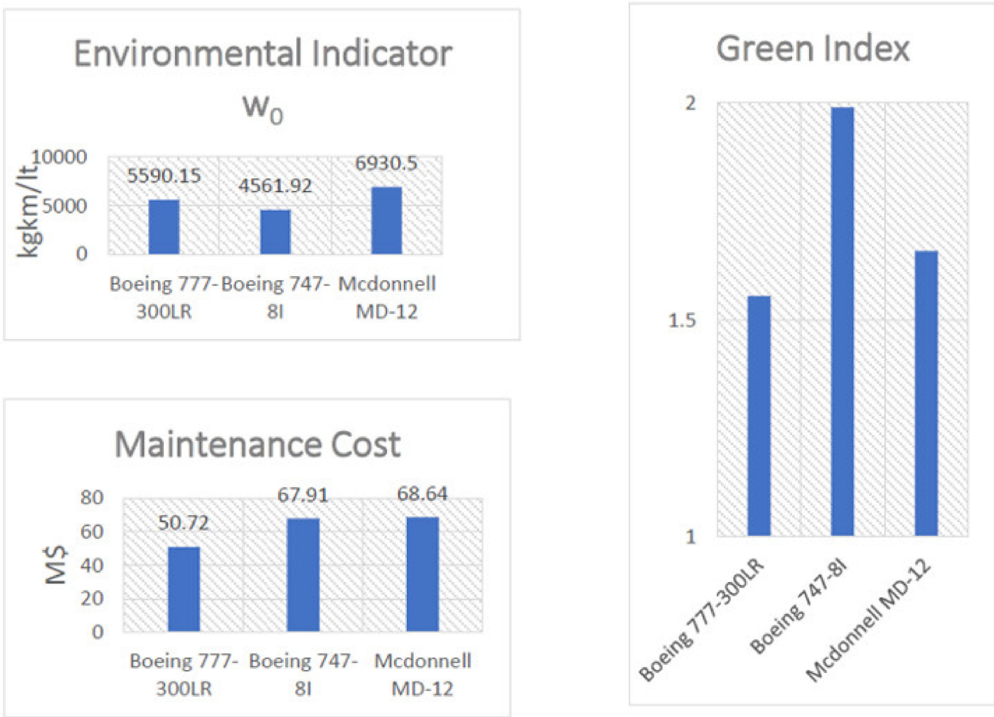

Figure 6. Results of the green assessment of the design for three different solutions.

The final consideration is on the validation of the procedure proposed. A comparison with the results of other models is not possible because of the absence of different approaches to compare. In any case, the environmental index takes into consideration the fuel consumption, recognized by the sector as the most important factor impacting environmental sustainability. Concerning the economic indicator, the average error (6%) shows an acceptable approximation. Therefore, the whole method can be considered as a suitable approach to assess the green level of a solution in the design stage.

7. Final Remarks and Conclusions

The paper intends to face an open issue on aircraft sustainability, i.e. the possibility for a designer to identify the greenest solution among different alternatives. As clearly discussed in the first paragraphs, there is a significant lack in the international literature of quantitative approaches, able to evaluate the economic and environmental sustainability of different design solutions. Thus, this paper tries to cover such a gap by defining a new green assessment procedure that is easier to implement in the first stage of the design process, which suffers by a great lack of information.

Based on this assumption, a new assessment framework was proposed, which simply needs very little information in order to calculate the environmental impact of the designed solution. Moreover, a new method is defined to estimate the maintenance costs starting from very simple data on the geometry and the weight of the aircraft. In this way, the designer can combine and balance two main aspects, which influence the sustainability of the aircraft service life. The method has also demonstrated to be applicable and easy to implement.

Since the model has been developed to be applied in the preliminary phase of the design process, the main limitation is related to possible variances that could result during the next design steps. Thus, the numerical values could change when the designer will have available more detailed information. In any case, the procedure was validated and it shows a good approximation and robustness, thus the indicators should maintain the same priority. Finally, future researches could improve the model, also considering the impact of new sensor technologies on aircraft maintenance costs.

Lastly, it is worth underlining that this study has some limitations on the procedure implemented, which could be improved using different types of multi-criteria decision making methods such as the fuzzy-AHP [32], the AHP-TOPSIS [33] or other optimization approaches with several criteria to assess [34]. Thus, future works could be planned to compare the proposed methodology with different approaches used in other fields, as previously reported.

Finally, another possible future research could explore the possibility to enlarge the type and the nature of the factors for the sustainability assessment; this possibility could lead the model to also consider the social dimension.

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Appendix A

Table A1. DB containing data on old parts (part 1).

Aircraft	Diameter Fuselage (m)	Height Fuselage (m)	Length (m)	Wing Width (m)	Wings Surface (m^2)	Operative Weight—OW (kg)
Airbus A380	7.14	10.84	72.57	79.75	845.00	277,000.00
Airbus A300B2	5.64	7.71	53.61	44.83	260.00	85,910.00
Airbus A300B4	5.64	7.71	53.61	44.83	260.00	88,505.00
Airbus A300-600	5.64	7.63	53.85	44.84	260.00	87,500.00
Airbus A300-600F	5.64	7.63	54.08	44.84	260.00	81,707.00
Airbus A350-900	5.96	8.60	66.80	64.75	442.00	142,400.00
Airbus A380-1000	5.96	8.60	73.79	64.75	464.30	155,000.00
Airbus A318-100	4.14	5.93	31.45	34.10	122.40	39,500.00
Airbus A319-100	4.14	5.97	33.84	34.10	124.00	40,800.00
Airbus A320-200	4.14	5.97	37.57	34.10	124.00	42,600.00
Airbus A321-200	4.14	5.97	44.51	34.10	128.00	48,500.00
Boeing 777-200	6.20	8.68	63.73	60.93	427.80	135,550.00
Boeing 777-200ER	6.20	8.68	63.73	60.93	427.80	138,100.00
Boeing 777-300	6.20	8.68	73.86	60.93	427.80	160,530.00
Boeing 777-300ER	6.20	8.78	73.86	64.80	436.80	167,829.00
Boeing 777F	6.20	8.78	63.73	64.80	436.80	144,379.00
Boeing 747-8F	6.50	9.84	76.25	68.40	554.00	197,131.00
Boeing 787-8	5.77	8.03	56.72	60.12	377.00	119,950.00
Boeing 787-9	5.77	7.42	62.81	60.12	377.00	128,850.00
McDonnell MD-11	6.00	8.69	61.20	51.97	338.90	128,808.00
McDonnell MD-11ER	6.00	8.69	61.20	51.97	338.90	132,049.00
McDonnell MD-11CF	6.00	8.69	61.20	51.97	338.90	130,768.00

Table A2. DB containing data on old parts (part 2).

Aircraft	Service Load (kg)—SL	Gasoline Tank Capacity—TC (lt)	Autonomy—A (km)	Aircraft Maintained—N	Initial Maintenance Operation Time—T (h/Check C]	Maintenance Cost
Airbus A380	84,000.00	323,546.00	14,800.00	50.00	150.00	$86,000,000.00
Airbus A300B2	37,980.00	44,000.00	6300.00	650.00	120.00	$48,762,000.00
Airbus A300B4	45,000.00	44,000.00	6670.00	640.00	115.00	$49,050,000.00
Airbus A300-600	41,500.00	68,160.00	7500.00	600.00	135.00	$47,000,000.00
Airbus A300-600F	54,600.00	68,160.00	7500.00	600.00	125.00	$46,890,000.00
Airbus A350-900	53,300.00	138,000.00	15,000.00	250.00	150.00	$78,804,000.00
Airbus A380-1000	68,000.00	156,000.00	16,100.00	40.00	160.00	$83,000,000.00
Airbus A318-100	15,000.00	23,859.00	5750.00	420.00	95.00	$23,200,000.00
Airbus A319-100	17,700.00	23,859.00	6950.00	450.00	100.00	$24,150,000.00
Airbus A320-200	19,900.00	23,859.00	6200.00	460.00	100.00	$26,843,000.00
Airbus A321-200	25,300.00	23,700.00	5950.00	400.00	100.00	$29,456,000.00
Boeing 777-200	54,920.00	117,300.00	9705.00	520.00	140.00	$50,500,000.00
Boeing 777-200ER	60,000.00	117,300.00	13,085.00	560.00	145.00	$54,000,000.00
Boeing 777-300	64,000.00	169,210.00	11,170.00	540.00	150.00	$53,200,000.00
Boeing 777-300ER	69,853.00	181,283.00	13,650.00	400.00	156.00	$56,800,000.00
Boeing 777F	103,737.00	181,283.00	9205.00	360.00	160.00	$50,500,000.00
Boeing 747-8F	132,360.00	226,118.00	7630.00	120.00	190.00	$72,300,000.00
Boeing 787-8	43,318.00	126,206.00	13,620.00	190.00	140.00	$65,200,000.00
Boeing 787-9	52,587.00	126,429.00	14,140.00	250.00	145.00	$67,300,000.00
McDonnell MD-11	52,362.00	146,173.00	11,500.00	150.00	120.00	$75,890,000.00
McDonnell MD-11ER	49,391.00	157,529.00	13,410.00	100.00	120.00	$74,569,000.00
McDonnell MD-11CF	73,942.00	146,173.00	14,908.00	100.00	120.00	$72,000,000.00

Appendix B

Table A3. Euclidean distance between different design solutions.

Aircraft	DP	Boeing 777-300LR	Boeing 747-8I	McDonnell MD-12
Airbus A300B2	116.86	20.37	48.30	29.81
Airbus A300B4	120.39	16.84	44.77	26.28
Airbus A300-600	118.68	18.55	46.48	27.99
Airbus A300-600F	110.52	26.71	54.64	36.16
Airbus A350-900	133.38	3.85	31.78	13.30
Airbus A380-1000	134.15	3.08	31.00	12.52
Airbus A318-100	120.79	16.44	44.36	25.88
Airbus A319-100	118.55	18.68	46.61	28.12
Airbus A320-200	115.63	21.60	49.53	31.05
Airbus A321-200	116.15	21.08	49.01	30.53
Boeing 777-200	129.25	7.98	35.90	17.42
Boeing 777-200ER	131.68	5.54	33.47	14.99
Boeing 777-300	139.91	2.68	25.25	6.77
Boeing 777-300ER	145.13	7.90	20.03	1.55
Boeing 787-8	134.58	2.65	30.58	12.10
Boeing 787-9	136.13	1.10	29.03	10.54
McDonnell MD-11	140.63	3.40	24.53	6.04
McDonnell MD-11ER	144.17	6.94	20.99	2.51
McDonnell MD-11CF	142.77	5.54	22.39	3.90

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