Cost-Estimating Model for Aircraft Maintenance

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2 **The present work provides a method for maintenance cost estimation for a civil aircraft. The model evaluates maintenance costs at a subsystem level in order to quantify the effective impact of each aircraft part on the total maintenance cost. An analysis at the subsystem level can offer a more precise cost estimation because the most influential parameters (that is, the cost drivers) should be different for each aircraft part. Emphasis is given on the updating of a cost-estimating model proposed in 1966 that provided equations for the maintenance cost assessment at a subsystem level using the Air Transport Association nomenclature. The reference method is enhanced with additional cost items, and the choice of cost drivers is accurately considered. The application of the developed model shows good accordance with the reference values provided by the International Air Transport Association, and results are compared with the common state-of-the-art methods.**

I. Introduction

COST estimation has been a fundamental task since the earliest phases of aircraft design. It is important to assess an order of magnitude of the whole aircraft program cost to avoid embarking on a project with unsustainable expenses. For this reason, aircraft cost analysis has received considerable attention over the past decades. This paper focuses on aircraft maintenance cost, which is part of the operating phase. The latter includes, as discussed by Roskam [1], the majority of the costs sustained during the whole aircraft's life cycle. Operating costs are generally divided into direct operating costs (DOCs) and indirect operating costs (IOCs). As stated in Raymer [2], "DOC costs concern flight operations (. . .), namely fuel, oil, crew, maintenance, depreciation and insurance." The depreciation cost refers to the "allocation of the purchase price out over a number of years, using some depreciation schedule" [2]. The DOC also includes interest cost, which derives from the need of the airlines to borrow money with a certain interest rate to finance the entire project. The IOC gathers all the rest of the operating expenses, such as "the depreciation cost of ground facilities and equipment, the sales and customer service costs, and the administrative and overhead costs" [2]. Landing fees and navigation charges could be included into IOC too. Figure 1 shows the breakdown of airline operating costs given by the International Air Transport Association (IATA) [3] for fiscal year (FY) 2013. The data refer to 55 airlines from the major regions worldwide. Percentages have been obtained by summing up the total cost contribution of each airline and then dividing by the main operating cost figures. It can be noticed that the largest portion of the airline costs is given by fuel and oil.

In the literature, several methods were proposed for the estimation of operating costs during the conceptual design phase, especially for direct operating costs. In fact, it is difficult to find equations able to estimate IOCs because these costs are strictly related to how the airline decides to run its operations. Among the state-of-the-art methods, the approach proposed by Liebeck et al. [4] for DOC assessment is noteworthy: the so-called direct operating cost plus interest (DOC + I) method. The DOC + I method represents an update of the Air Transport Association (ATA) method [5], which provides a set of empirical equations for estimating direct operating costs. The DOC + I method considers the following cost items: flight and cabin crew, maintenance, landing fees, navigation fees, fuel, depreciation, interest, and insurance. The proposed cost-estimating relationships (CERs) ~~can be easily applied since conceptual design~~ 4 ~~level~~. Another notable example of a cost-estimating method is the methodology proposed by Chen et al. [6]. This work provided equations for direct operating cost evaluation for both intra-European and Chinese markets. Other methods for aircraft operating cost 5 estimation are, for example, the Association of European Airlines method [7], published in 1989, and an economic model from NASA [8], based on operating expenses incurred in FY 1999 by 67 airlines in the United States.

A key limitation of the aforementioned state-of-the-art methodologies lies in the approach adopted for the estimation of maintenance cost, which is subdivided into direct maintenance costs (DMCs) and maintenance burden. DMCs comprise the direct cost of labor and materials required for the maintenance activity for both airframe and engine. Maintenance burden includes airline overhead, the cost of acquiring, maintaining equipment and tools, building, facilities, and other indirect costs. In summary, the available methods calculate the contribution to maintenance costs given by the airframe and engines without considering the influence of aircraft subsystems. The estimation of the maintenance cost at a subsystem level could be useful to evaluate the impact of the specific onboard systems architectures and technologies of the aircraft, thus leading to a more flexible (able to adapt to different systems' configurations) and precise (able to characterize different systems' configurations) tool. For example, unlike traditional maintenance cost-estimation methods, a methodology for maintenance cost estimation at the subsystems level would be sensitive to the adoption of innovative and more electric configurations, which could thus be evaluated from the point of view of costs, especially with respect to other reference configurations.

This issue was already dealt with in the work of Pearlman and Simpson [9], which provided CERs for maintenance costs at the subsystem level according to the ~~ATA classification~~. It is fundamental to underline that the relationships proposed in [9] are outdated because they are based on aircraft data of the 1960s. Applying these CERs, even using an appropriate escalation factor, could lead to improper results because of the aircraft technologies' improvements. These considerations have led to the development of a new maintenance cost model able to reflect costs at subsystem level on the basis of the methodology proposed in [9]. This paper is thus focused on the update of the work of Pearlman and Simpson [9]. The aim is to build new CERs for maintenance cost using current aircraft data. Moreover, a different approach than the state-of the-art methods is adopted, considering the cost of the fundamental maintenance tasks, i.e., line and base maintenance, engine overhaul, and components maintenance. This subdivision enables the evaluation of maintenance costs at the subsystem level. A higher level of detail enables a

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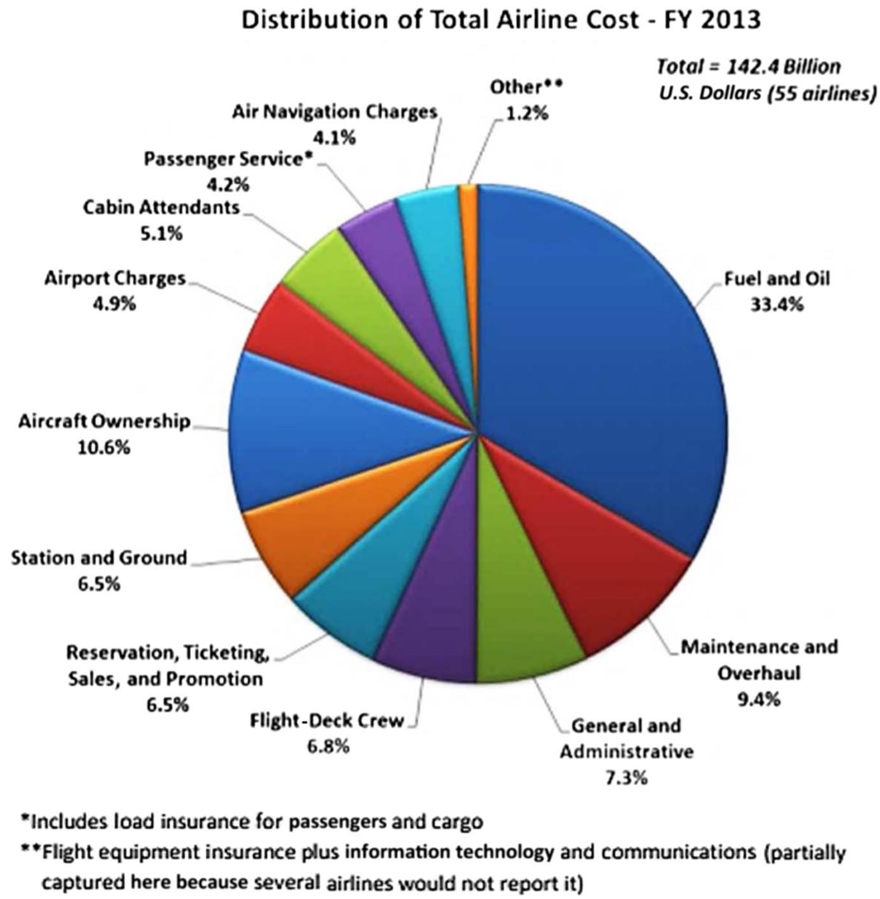

Fig. 1 Operating costs breakdown. (Source: IATA [3].)

multidisciplinary analysis focusing on part of the aircraft as well as the whole aircraft [10].

The paper is organized as follows. In Sec. II, the methodology adopted for the development of the maintenance cost model is described. New CERs at the subsystem level are created for DMCs starting from the results of [9] and using the data from [11]. For the maintenance burden, the data provided in [12] are employed. In Sec. III, the developed model is evaluated and demonstrated by means a reference aircraft (i.e., Boeing 737). Section IV gathers the conclusions of this work and remarks on future developments.

II. Methodology

This section presents the methodology that has been developed for the estimation of the direct maintenance costs. All steps are described, including the database creation, the cost drivers identification, the CER development, and validation in order to obtain the final set of equations. The maintenance burden is also treated.

A. Direct Maintenance Cost

Figure 2 summarizes the process followed for the development of the new maintenance cost model. First, a database, which contains information about several current aircraft, is built. Three data sources have been considered within the analysis. The limited number of sources is due to the difficulty in finding reliable data to be adopted for the database. Indeed, airlines usually do not publicly release their cost data or, wherever data are available, they are not free of charge. Moreover, it has been noted that available data are often not consistent with each other, reflecting the variability of sustained

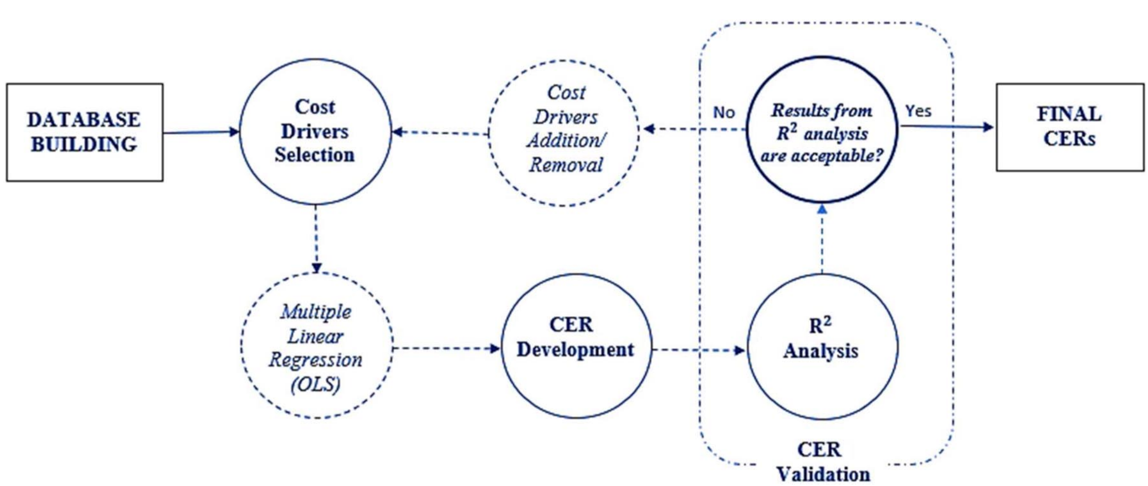

Fig. 2 Steps of maintenance cost model development.

maintenance costs between different airlines, which mostly depend on the maintenance strategies adopted at the airline level. The data sources analyzed within this research come from EUROCONTROL [13], Aviation Week [14], and the IATA [11].

The cost data from EUROCONTROL [13] include average the DOCs per block hour for several aircraft models. Maintenance costs are derived as assuming to represent 15% of total DOCs and including both the DMCs and maintenance burden. Considering that this work aims to provide separate models for the DMC and maintenance burden, in order to obtain the DMC only, a further subdivision will be required, which will add inaccuracy to the initial dataset. Therefore, the EUROCONTROL data [13] have not been included into the research. Furthermore, Aviation Week [14] reported the DOCs per block hour for a wide group of wide-body aircraft. Several data for the same aircraft model were provided for different careers, subdividing between the crew cost, fuel cost, aircraft cost, insurance, taxes, and maintenance. It is interesting to note that, once the aircraft model was fixed, the provided costs sensibly varied between careers. Therefore, although the maintenance cost was provided separately for both the DMC and maintenance burden, the variability of data for the same aircraft model made the Aviation Week dataset [14] unusable for this research. Eventually, the DMC IATA data [11] were the most suitable for this work, as they were provided for the most diffused aircraft models. Moreover, it is noteworthy that these data represent mean cost values for the major airlines from all over the world, thus excluding the possibility to have data sensible to airline-specific operation.

Establishing the data source, the reference cost datum from [11] is then subdivided between line and base maintenance, engine overhaul, and component maintenance cost. Subsequently, the cost drivers (i.e., the independent variables that influence cost) are identified using the guidelines given in [9]. For new CER development, the regression model suggested in [9] is applied. This step comprises the definition of the shape of the generic CER, the adoption of a proper regression technique, and the use of the database information for the calculation of the CER coefficients. The agreement between the developed model and the reference cost data is then analyzed using the coefficient of determination R^2 for each equation. In this way, a first validation of the CERs is provided. Indeed, if the resulting R^2 for each CER is not acceptable (i.e., it lies below an imposed threshold), a new ordinary least-squares (OLS) analysis must be performed, properly modifying the chosen cost drivers. Some cost drivers can thus be deleted or added, requiring the calculation of new CER coefficients. A new phase of CER validation then follows. Once the analysis provides acceptable R^2, the loop is closed and the final CERs are obtained. As can be noticed from Fig. 2, the flowchart depicts the described closed-loop logic, which is due to the iterative nature of cost modeling. A full description of a cost-estimating model was provided in [15].

1. Database Building

The CERs given by Pearlman and Simpson [9] were based on cost data referred to aircraft that were operating when the method had been built (i.e., the 1960s). Hence, in order to generate new CERs able to estimate more reliable costs, a new database has been built. The new database contains information for each selected aircraft model. In this paper, the database is developed using the data provided by the IATA in [11]: a report that includes the results of a preliminary analysis conducted in FY 2013 under the IATA's
6 Maintenance Cost Task Force (MCTF). The IATA's MCTF is based on data from 48 airlines from all over the world. The analyzed fleet counts 3779 aircrafts with all the world's major aircraft families involved. Table 1 shows the aircraft families studied in [11], the fleet size and the daily utilization in hours per day for each aircraft family. It can be noticed that the A320 family counts the greatest number of aircraft: that is because several models are included (A318, A319, A320, A321, and A320neo). The average daily utilization varies between 4 to 6 h per day for regionals and up until 12 h for wide-body aircraft. Table 1 also shows, for the aircraft under study, the average aircraft age and the number of flight hours (FHs) for each flight cycle (FC). The latter measures the number of flight hours between each takeoff and landing.

Table 1 Initial aircraft data

Aircraft	Fleet size	Daily utilization, h/day	FH/FC	Average age, years	DMC, $/FH
B757	180	9	2.7	19	850
B767	220	9.5	3.5	18	900
B777	450	11.7	5.1	8	1800
B737 classic	75	6.3	1.3	20.5	850
B737 NG	650	9	1.9	7.3	700
B747-400	150	10.2	5.1	16.5	1700
A320 family	890	8.4	1.8	8.2	900
A330	300	10.8	4.1	8.6	1400
A340	125	11.5	7.3	14.2	1500
E-190/195	155	6.7	1.5	4.8	700

In addition, the IATA report [11] provided reference direct maintenance cost data for the reported aircraft models. The amount of 7
direct maintenance cost, expressed in dollars per flight hour ($/FH), is reported in the last column of Table 1. It appears that the most expensive aircraft models are the B777, the B747-400, the A330, and the A340. It is important to point out that all data collected by the IATA's MTCF and gathered in Table 1 are mean values relating to all the airlines included in the survey. Moreover, these data are affected by bias because they are derived from the diagrams given in [11]. In any case, they are a good starting point for the development of maintenance cost CERs during conceptual design. The reference year for all costs presented is FY 2013. Similarly, the average aircraft age refers to FY 2013.

The direct maintenance cost for each aircraft (see Table 1) can be divided into the cost elements related to the involved maintenance activities, i.e., line, base maintenance, engine overhaul, and components maintenance. The percentage of each maintenance task was provided by the IATA [11] for FY 2013 (see Fig. 3). It can be noticed that most of the direct maintenance costs are due to engine inspection and overhaul, which are probably related to the great amount of labor required during the maintenance activity and to the engine spares cost.

From the breakdown of Fig. 3, it is now possible to subdivide into four components the total direct maintenance cost of the database (see Table 2). It is underlined that the cost percentages of Fig. 3 represent a mean value for several aircraft categories (wide-body, narrow-body, regional jet, and turboprop). In the absence of more specific data, these percentages represent a good reference point.

Concerning components'maintenance cost, a further cost breakdown is required in order to adopt the ATA classification as in [9]. The impact of the major ATA classification on the component maintenance cost is summarized in Fig. 4. It can be noticed that wheels and brakes require a great maintenance effort because they are highly consumable; as well as avionics, which include the maintenance of displays, communication equipment, navigation systems, and autopilot.

The application of the costs' subdivision of Fig. 4 to the component maintenance costs of Table 2 leads to the cost breakdown of Tables 3

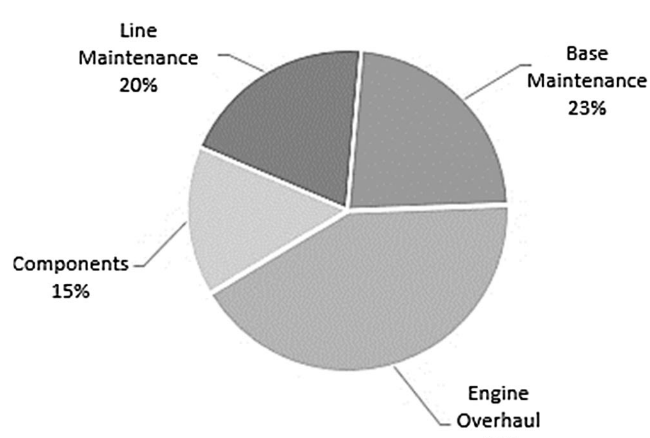

Fig. 3 DMC breakdown. (Source: IATA [11].).

Table 2 DMC subdivision

Aircraft	DMC, $/FH	Line maintenance, $/FH	Base maintenance, $/FH	Engine overhaul, $/FH	Component maintenance, $/FH
B757	850	170	127.5	357	195.5
B767	900	180	135	378	207
B777	1800	360	270	756	414
B737 classic	850	170	127.5	357	195.5
B737 NG	700	140	105	294	161
B747-400	1700	340	255	714	391
A320 family	900	180	135	378	207
A330	1400	280	210	588	322
A340	1500	300	225	630	345
E-190/195	700	140	105	294	161

8

9 and 4 for each subsystem. The ~~ATA~~ analyzed in this paper (see Fig. 4) are slightly different from those considered in [9]: the ~~APU~~, for
10 instance, was not present in the reference work, as well as the decomposition of the ~~ATA 32 in "landing gear" and "wheels and brakes."~~ The APU is here introduced by considering its high impact on costs (see Fig. 4). Furthermore, the subdivision adopted for the ATA 32 exploits the available data of Fig. 4, providing more details on the most significant component maintenance cost elements, i.e., wheels and brakes.

The selected ATAs are the most significant on the overall component maintenance cost. Moreover, the breakdown of Fig. 4 perfectly fits all aircraft categories that have been considered, and it is therefore applicable to different aircraft models.

Figure 4 shows the maintenance costs of all of the avionics. However, more details can be found in [9], where avionics was divided into the major avionic ~~ATA~~ (navigation, communications, autopilot, and instruments). In [9], it can be observed that each ATA related to avionics is influenced by different cost drivers; therefore, the derivation of a unique CER using the same cost drivers for all of
13 the avionics could lead to inaccurate results. For this reason, the percentage of maintenance component costs related to avionics (see Fig. 4) is further subdivided. The percentages of Fig. 5 are derived from the Airbus A320 data [16,17]. These percentages can be extended to any civil aircraft because the avionic system is comparable in terms of cost, in spite of different aircraft sizes and configurations, if the role and the technological age are the same. The results of the further subdivision of avionics maintenance costs with the breakdown of Fig. 5 are given in Table 5.

To be as accurate as possible in maintenance CERs generation, it is necessary to integrate the initial aircraft data of Table 1 with additional information. More data can be added by specifying, for the aircraft under study, the model considered. The specific aircraft models, if not already detailed by the IATA in [11], are chosen by analyzing the average age of the aircraft and the number of units

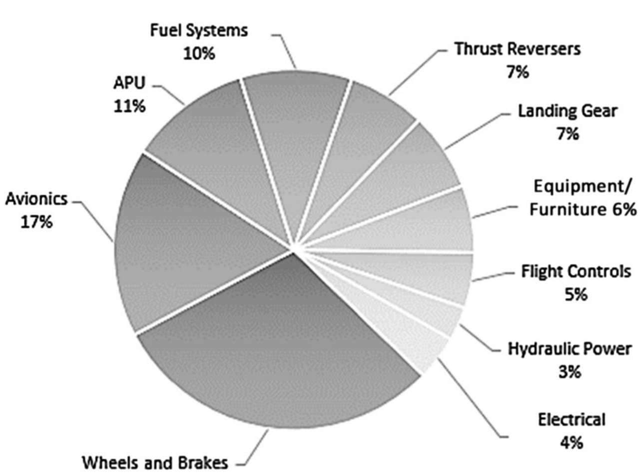

Fig. 4 Breakdown of component maintenance costs for FY 2013.
12 **(Source: ~~ICF SH&E~~.)**

produced within the same family. It is important to underline that the average aircraft ages of the database are mean values related to the fleet. The models finally adopted in this work and the engines installed are summarized in Table 6. With regard to the engines' specifications, more models for the same aircraft were usually provided. Thus, the choice fell upon the model for which data were easier to obtain because the engines had similar performance. The available engine data [18] allowed adding the engine thrust to the database.

The initial dataset of Table 1 can also be enriched with other easily traceable data such as fuselage length, aircraft cost, the age of the type of aircraft (which can be defined as "the time between the date of certification and the reporting year" [9]), the maximum takeoff weight (MTOW), and the number of engines. In Tables 7 and 8, the final aircraft data used in the analysis are gathered. The final database of this work thus consists of Tables 2–8, including both costs and aircraft data.

2. *Cost Drivers Identification*

As depicted in Fig. 2, once the database is built, the identification of cost drivers is required. It is not an easy task to find characteristics that are proven to effectively be cost drivers. The results of Pearlman and Simpson in [9] and the data from the final database (see Tables 7 and 8) can be used to solve the problem of cost ~~driver~~ identification. In Table 9, the CER coefficients found in [9] for maintenance cost estimation at the subsystem level are reported. Table 9 also shows the involved cost drivers (first row) and the considered ATA subsystems (first column). It can be noticed that the maintenance cost of each ATA component is influenced by different cost drivers, so the number of coefficients in each CER may vary (the cells with double en dashes correspond to zeros). The cost drivers introduced in [9] are 1) the fleet size; 2) the utilization in hours per year; 3) the number of landings per hour; 4) the fuselage length in feet; 5) the aircraft cost less engines in U.S. dollars; 6) the age of the type of aircraft (previously defined as reported in [9]) expressed in months; 7) the number of seats; 8) the number of years from first delivery, i.e., the number of years spent because the introduction of the first aircraft of a specific family into an airline operation; 9) the maximum takeoff gross weight in pounds; 10) the number of tires of the landing gear; 11) the time between overhauls (TBOs) of the engine in hours; 12) the fuel flow through the engines in pounds per hour; and 13) the number of engines~~, which is described as the cost driver in [9] but not directly included in the analysis.~~

The cost drivers suggested in [9] are a fundamental starting point for the development of the new maintenance cost model. Thus, the new CERs for each ATA maintain, wherever possible, the same cost drivers proposed in the reference work. These parameters usually have known values ~~because~~ the conceptual design phase and this consideration ~~are~~ of utmost importance because the final identification of the cost drivers depends highly on the data effectively available in the database.

Considering the available data, assumptions have been made to compare and, in some cases, substitute the cost drivers proposed in [9] with the aircraft characteristics gathered in the final database.

Table 10 presents the assumed correspondences between the data provided by the IATA in [11] and the cost drivers introduced by Pearlman and Simpson [9]. Both references consider the fleet size in

11 **Table 3 Component maintenance cost: part 1**

	ATA 32		ATA 28	ATA 49	ATA 78
Aircraft	Wheels and brakes, $/FH	Landing gear, $/FH	Fuel system, $/FH	APU, $/FH	Thrust reversers, $/FH
B757	58.65	13.69	19.55	21.51	13.69
B767	62.10	14.49	20.70	22.77	14.49
B777	124.20	28.98	41.40	45.54	28.98
B737 classic	58.65	13.69	19.55	21.51	13.69
B737 NG	48.30	11.27	16.10	17.71	11.27
B747-400	117.30	27.37	39.10	43.01	27.37
A320 family	62.10	14.49	20.70	22.77	14.49
A330	96.60	22.54	32.20	35.42	22.54
A340	103.50	24.15	34.50	37.95	24.15
E190/195	48.30	11.27	16.10	17.71	11.27

Table 4 Component maintenance cost: part 2

	ATA 25	ATA 27	ATA 29	ATA 24	
Aircraft	Equipment/furnishing, $/FH	Flight controls, $/FH	Hydraulic power, $/FH	Electrical, $/FH	Avionics, $/FH
B757	11.73	9.78	5.87	7.82	33.24
B767	12.42	10.35	6.21	8.28	35.19
B777	24.84	20.70	12.42	16.56	70.38
B737 classic	11.73	9.78	5.87	7.82	33.23~~5~~
B737 NG	9.66	8.05	4.83	6.44	27.37
B747-400	23.46	19.55	11.73	15.64	66.47
A320 family	12.42	10.35	6.21	8.28	35.19
A330	19.32	16.10	9.66	12.88	54.74
A340	20.70	17.25	10.35	13.80	58.65
E-190/195	9.66	8.05	4.83	6.44	27.37

the analysis. The cost driver ~~utilization in hours per year~~ treated in [9] can be easily translated into ~~utilization in hours per day~~ [11]. The parameters ~~landings per hour~~ and ~~FH/FC~~ (i.e., the number of flight hours per flight cycle) are closely related to each other because they both measure the frequency of takeoffs and landings. In particular, the FH/FC combined with the utilization in hours per day gives the number of landings per day. Therefore, considering that the available
15 data are expressed in FH/FC (see Table 7), ~~it has been assumed to adopt the FH/FC~~ as a cost driver in the new cost model instead of landings per hour.

Another important assumption concerns the cost driver ~~years from first delivery~~ [9] and ~~average aircraft age in years~~ [11]. The available data from the IATA [11] do not give an exact estimation of the year of introduction of a certain aircraft type in an airline fleet (i.e., the years from first delivery) because they provide an indication of the average age of each aircraft model for the worldwide fleet considered (i.e., the average aircraft age in years). For the purposes of this analysis, the ~~parameter years from the first delivery~~ and ~~average aircraft age~~ in years are considered comparable because they both give an indication on the age of the aircraft under study. The cost drivers ~~of time between~~

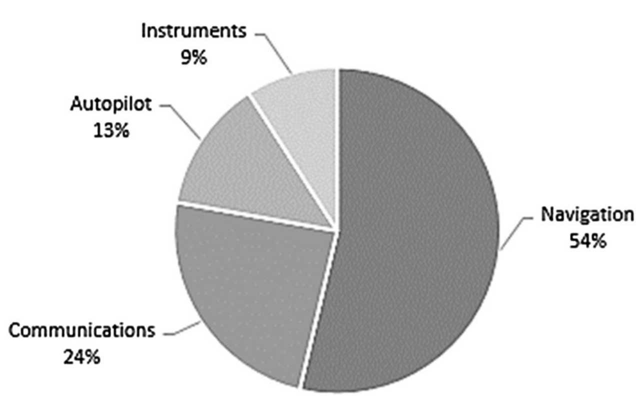

Fig. 5 Avionics maintenance cost breakdown.

~~overhauls~~ of the engine, ~~engine cost~~, and ~~fuel flow~~ mentioned in [9] cannot be included in the database; and they ~~are~~ considered as cost drivers in the present analysis due to the unavailability of data for all the aircraft models. Furthermore, due to the unavailability of engine cost in the database, it has been decided to replace the cost driver aircraft cost less engines given in [9] with the aircraft cost, which is already included in the database. To better describe the engine overhaul cost, it was decided to exploit the available data of engine thrust and number of engines as cost drivers (see Table 8). ~~The cost~~ 16
~~drivers finally adopted in this work are gathered in Table 12.~~

3. *CERs Development and Validation*

For the development of new CERs, together with appropriate database and cost drivers, it is important to define the methodology, which enables the computation of the required coefficients. In this paper, the regression model proposed in [9] is adopted. It is built on the linear relationship expressed by Eq. (1):

$$\gamma = \alpha + \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \ldots + \beta_r \cdot x_r \tag{1}$$

where 1) γ is the maintenance cost for the generic ATA component calculated on the basis of the values of the characteristics in Table 9 and expressed in ~~dollars~~ per flight hour; 2) α is a constant (see the second column of Table 9); 3) $\beta_1, \beta_2, \ldots, \beta_r$ are the regression coefficients (see Table 9, except the first and second columns); and 4) $x_1, x_2, \ldots, x_r$ are the cost drivers, which can vary, depending on the considered ATA.

The regression coefficients have been calculated by applying the ordinary least-squares regression analysis to the available data. In this paper, the same technique is adopted for the determination of the new coefficients, which update those provided in [9]. The linear relationship of Eq. (1), which is the model able to represent the available data, can be rewritten in a more general way, introducing the generic function $\phi(x)$:

$$f_r(x) = c_1\phi_1 + c_2\phi_2 + \ldots + c_{r+1}\phi_{r+1} \tag{2}$$

Table 5 Avionics maintenance cost subdivision

	ATA 22	ATA 23	ATA 31	ATA 34
Aircraft	Autopilot, $/FH	Communications, $/FH	Instruments, $/FH	Navigation, $/FH
B757	4.35	8.01	3.02	17.85
B767	4.61	8.48	3.20	18.90
B777	9.22	16.96	6.40	37.79
B737 classic	4.35	8.01	3.02	17.85
B737	3.59	6.60	2.49	14.70
B747-400	8.71	16.02	6.05	35.69
A320 family	4.61	8.48	3.20	18.90
A330	7.17	13.19	4.98	29.40
A340	7.68	14.13	5.34	31.50
E-190/195	3.59	6.60	2.49	14.70

Table 6 Detailed aircraft models and installed engines

Aircraft model	Installed engine
757-200	RB211-535E4(B)
767-300	CF6-80C2B2F
777-300ER	GE90-115B
737-300	CFM56-3B2
737-800	CFM56-7B24
747-400	CF6 80C2-B1F
A320-200	CFM56-5A1
A330-300	Trent 768
A340 -300	CFM56-5C2
E-190	GE CF34-10E

where 1) r is the number of cost drivers in a generic CER; 2) $f_r(x)$ is γ from Eq. (1); 3) $c_1\phi_1$ is α from Eq. (1); and 4) $c_2, \ldots, c_{r+1}$ are the $\beta_1, \beta_2, \ldots, \beta_r$ coefficients.

Considering the generic row i of the final database, the function $\varphi(x)$ is the value of the generic cost driver in this row (ϕ is a constant function of x). To build a CER able to fit the available data, it is important to estimate the constant α and the coefficients $\beta_1, \beta_2, \ldots, \beta_r$ for each CER. For instance, considering the line maintenance cost, the reference value γ is given by the third column of Table 2. The database contains 12 aircraft; it leads to 12 cost's observations γ_j. The generic observed value is obtained by applying Eq. (2) with the value of the cost drivers for each aircraft model. It can be shown that γ_j differs from the theoretical value by the residual U_j. The error U_j should be minimized to best fit the input data. This can be done using the values of the coefficients, which minimize the sum of the squares of U_j: hence, the term "least-squares regression analysis." In summary, the OLS allows us to determine the coefficients of Table 9 (and the updated coefficients) by finding those coefficients that minimize the relation

$$\min \sum_{i=1}^{n} (f_r(x_i) - y_i)^2 = \min \sum_{i=1}^{n} \left(\sum_{k=1}^{r} c_k \phi_k(x_i) - y_i \right)^2 \quad (3)$$

where 1) n is the total number of rows in the final database, i.e., the number of aircraft considered; and 2) y_i is the generic maintenance cost in the generic row i.

In matrix notation, it is then useful to define the following:

$$c = \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ c_{r+1} \end{pmatrix} \quad y = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} \quad A = \begin{pmatrix} \varphi_1(x_1) & \varphi_2(x_1) & \cdots & \varphi_r(x_1) \\ \varphi_1(x_2) & \varphi_2(x_2) & \cdots & \varphi_r(x_2) \\ \vdots & \vdots & \vdots & \vdots \\ \varphi_1(x_n) & \varphi_2(x_n) & \cdots & \varphi_r(x_n) \end{pmatrix}$$

where A is a $n \times r$ matrix. An example of matrix A is reported in Table 11, where the column labeled "constant" is related to the constant term α of Eq. (1), and it is always a column of ones.

The minimization problem becomes the following:

$$\min \sum_{i=1}^{n} \left(\sum_{k=1}^{r} c_k \phi_k(x_i) - y_i \right)^2 = \min \|Ac - y\|_2^2 \quad (4)$$

where $\|Ac - y\|_2$ is the Euclidean norm of the vector $Ac - y$. The term $\|Ac - y\|_2^2$ is a function for which the absolute minimum

Table 7 Final aircraft data: part 1

Aircraft	Fleet size	Daily utilization, h/day	FH/FC	Fuselage length, ft	Aircraft cost, $\$\times 10^6$	Age of type of aircraft, months
757-200	180	9	2.7	155.25	84.17	360
767-300	220	9.5	3.5	180.3	185.80	300
777-300ER	450	11.7	5.1	242.4	320.20	108
737-300	75	6.3	1.3	109.7	65.02	348
737-800	650	9	1.9	124.93	94.36	216
747-400	150	10.2	5.1	231.8	292.13	288
A320-200	890	8.4	1.8	123.26	95.12	300
A330-300	300	10.8	4.1	208.11	248.87	240
A340 -300	125	11.5	7.3	208.11	243.58	240
E-190	155	6.7	1.5	118.90	46.20	96

Table 8 Final aircraft data: part 2

Aircraft	Seats	Average aircraft age, years	MTOW, lb $\times 10^3$	Number of tires	Number of engines	Thrust, lbf
757-200	200	19	255	10	2	43,100
767-300	261	18	413	10	2	52,700
777-300ER	370	8	775	14	2	115,300
737-300	149	20.5	139.48	6	2	22,000
737-800	180	7.3	174.17	6	2	22,700
747-400	524	16.5	910	18	4	58,090
A320-200	150	8.2	162.04	6	2	25,000
A330-300	277	8.6	507	10	2	67,500
A340-300	277	14.2	606	12	4	56,000
E-190	114	4.8	105.36	6	2	18,500

14 **Table 9 Maintenance cost regression coefficients at subsystem level[a]**

ATA	Constant	Fleet size	Utilization, h/year	Landings per hour	Fuselage length, ft	Aircraft cost (less engines), $ ×10⁶	Aircraft age, months	Number of seats	Years from first delivery	MTOW, [lb] × 10³	Number of tires	Engine TBOs	Engine cost $ ×10⁶	Fuel flow, lb/h
21	12.8057	0.2323	−0.0034	2.2102	— —	— —	−0.0218	0.0480	— —	— —	— —	— —	— —	— —
22	3.8946	— —	— —	−9.9766	— —	−0.8373	0.017	— —	1.1637	— —	— —	— —	— —	— —
23	10.4762	0.0136	0.0002	−2.8274	— —	— —	0.0893	−0.111	— —	— —	— —	— —	— —	— —
24	11.3600	— —	−0.0007	— —	— —	1.0948	— —	−0.0757	— —	— —	— —	— —	— —	— —
25	1.0194	— —	−0.0019	−1.4317	— —	— —	— —	0.1014	— —	— —	— —	— —	— —	— —
26	1.5094	— —	— —	— —	— —	— —	— —	−0.0102	— —	— —	— —	— —	— —	— —
27	−6.9100	— —	−0.0070	9.5600	— —	0.8789	0.0319	0.0133	— —	— —	— —	— —	— —	— —
28	−6.5823	— —	−0.0010	— —	— —	— —	−0.0106	0.0462	1.7955	−0.0067	— —	— —	— —	— —
29	12.6430	— —	— —	~~4.0279~~	— —	— —	−0.0363	−0.9582	— —	— —	— —	— —	— —	— —
30	2.8879	— —	−0.0005	— —	−0.0147	−0.5990	0.0336	— —	0.5880	— —	— —	— —	— —	— —
31	−0.6533	0.0490	0.0004	−0.7322	— —	— —	0.0134	−0.0126	— —	— —	— —	— —	— —	— —
32	−12.2165		−0.0041	21.5193	— —	0.4131	0.1431	— —	— —	— —	2.1463	— —	— —	— —
33	~~−23717~~	0.0550	0.0002	−0.7673	— —	— —	— —	— —	0.4511	— —	— —	— —	— —	— —
34	24.4086	−0.0529	— —	−20.4812	— —	0.4842	0.4842	0.0496	−0.1242	— —	— —	— —	— —	— —
35	3.1205	— —	— —	−4.5941	— —	— —	0.0166	−0.0209	0.3612	— —	— —	— —	— —	— —
36	−10.0549	— —	−0.0007	— —	0.0848	— —	0.0271	— —	— —	— —	— —	— —	— —	— —
38	2.2865	— —	0.0006	14.6253	— —	1.7464	— —	−0.0297	−3.5606	— —	— —	— —	— —	— —
51–57	15.1442	— —	— —	— —	— —	−2.2131	— —	— —	— —	— —	— —	— —	— —	— —
71–80	−37.6278	— —	0.0182	— —	— —	— —	1.7295	— —	— —	— —	— —	0.0156	0.0115	−0.009
RCM	189.0560	−2.8534	−0.0111	— —	— —	— —	— —	— —	−16.8581	— —	— —	— —	— —	— —

[a]Source: Pearlman and Simpson [9].

Table 10 Available data from IATA and cost drivers from Pearlman and Simpson [9]

Pearlman and Simpson [9]	IATA [11]
Fleet size	
Utilization in hours per year	Utilization in hours per day
Landings per hour	FH/FC
Years from first delivery	Average aircraft age in years

Table 11 Example of matrix A

Aircraft	Constant	Daily utilization, h/day	FH/FC	Aircraft cost, $ $\times 10^6$
757-200	1	9	2.7	84.17
767-300	1	9.5	3.5	185.80
777-300ER	1	11.7	5.1	320.20
737-300	1	6.3	1.3	65.02
737-800	1	9	1.9	94.36
747-400	1	10.2	5.1	292.13
A320-200	1	8.4	1.8	95.12
A330-300	1	10.8	4.1	248.87
A340 -300	1	11.5	7.3	243.58
E-190	1	6.7	1.5	46.20

corresponds to the zeros of $\nabla \|Ac - y\|_2^2$ (∇ is the gradient). Hence, the linear regression coefficients can be found by resolving the following:

$$\nabla \|Ac - y\|_2^2 = 0 \tag{5}$$

Equation (5) can then be rewritten as follows:

$$A^T Ac - A^T y = 0 \tag{6}$$

where A^T is the transposed matrix of A. Finally, the solution of the linear system of equations is required:

$$A^T Ac - A^T y \tag{7}$$

where c contains the sought coefficients. Finally, Eq. (7) enables us to update the coefficients of Table 9 using the information provided by the final database of Tables 2–8.

18 The OLS analysis is not the unique method to perform linear regression analysis, but it is the most diffused and ~~reveals easy to apply.~~ Limitations of the OLS methodology lie in the presence of outliers (i.e., data points that are inconsistent with the rest of data [19]), which could be related to lacking or inaccurate data. As suggested in [19], in order to perform a more robust analysis, alternative linear regression techniques such as S or M estimates could be exploited. A detailed explanation of these approaches can be found in [20,21]. Alternatively, to avoid OLS limitations, a nonlinear model could be considered, which could be able to capture nonlinear interactions between the cost drivers and data. A nonlinear analysis can be performed, thanks to iterative methods such as Newton–Raphson and Gauss–Newton approaches, as suggested in [22]. This option has not been examined in this work, considering that iterative routines have optimal properties in large data samples, but could lead to erroneous results in small datasets. In the present case, the database includes a small amount of initial cost data; hence, the exploitation of an iterative method could lead to good results within the data range but could reproduce incorrect trends out of that range. For this reason, in this work, a linear model has been chosen to represent the available cost data.

At this point, it is possible to gather all available information for the development of the new CERs, which is the last step depicted in Fig. 2. This process is first carried out using the cost drivers suggested in Table 9 for each ATA within the limits of the available data and the assumed matches with the IATA information. The generic CER is then analyzed through the coefficient of determination. R^2 statistically measures how well the regression equation approximates the given data points. If $R^2 = 1$, the model perfectly fits the data; a null R^2 indicates a bad match of the regression line with the data. The choice of the R^2 threshold (below which the resulting regression model is not acceptable) is not unique, and it strongly depends on several factors such as data availability (and accuracy) and the design phase. The availability of small datasets could result in poor data correlations that should be evaluated, case to case, in order to establish if the provided results could be assumed as very initial cost estimates. Furthermore, an advanced design phase could offer large datasets, which could increase the expected methodology accuracy. From these considerations, it emerges that the suitable R^2 threshold should be selected by taking into account the peculiarities of the case under study.

On account of this, considering the small data sample available for the present study, the choice of a narrow threshold (i.e., R^2 very close to one) could negatively affect the effective applicability of the resulting method. Therefore, lacking other indications, it has been ~~assumed that~~ the value suggested by the International Society of Parametric Analysts [23], which indicates that a good fit is provided by $R^2 \geq 0.7$. If the R^2 obtained from OLS lies below the imposed threshold, other cost drivers are added to increase R^2. Additional cost drivers are considered one by one, thus obtaining more accurate CERs, even though a larger number of inputs is required. Remembering that specific data are seldom available during the initial phases of a project, all CERs are stored so that the user can choose which CER to adopt based on the available data and on the required accuracy. The described approach has been applied for the development of the CERs related to line and base maintenance, engine overhaul, and all the ATA components.

First, the CERs for the line and base maintenance cost assessment have been built. It is underlined that [9] did not provide a clear distinction between the two cost items, introducing a general maintenance component called routine checks and miscellaneous (RCM) (see also Table 9). The latter "includes general aircraft handling, the smaller preflight, layover and turnaround checks carried out by line maintenance personnel, as well as the routine checks up to and including aircraft overhaul" [9]. Therefore, RCM can be ascribed to both line and base maintenance activities.

Table 12 Coefficient of determination for each maintenance cost element 17

Maintenance element	R^2
Line maintenance	0.706
	0.747
	0.937
	0.935
Base maintenance	0.706
	0.747
	0.937
	0.935
Engine overhaul	0.928
Autopilot	0.916
Communications	0.867
Electrical	0.932
Equipment/furnishings	0.840
	0.897
Flight controls	0.937
Fuel system	0.823
	0.827
Hydraulic power	0.856
Instruments	0.867
Wheels and brakes	0.936
Landing gear	0.936
Navigation	0.917
APU	0.659
	0.746
	0.736
Thrust reversers	0.928

Table 13 Updated CER coefficients

	Constant	Fleet size	Utilization, hours/day	FH/FC, h	Fuselage length, ft	Aircraft cost, $ $\times 10^6$	Age of type of aircraft, months	Number of seats	Average age, years	MTOW, [lb] $\times 10^{-3}$	Number of tires	Number of Engines	Thrust, lbf
Line maintenance	−38.8410	−0.0960	34.7140	——	——	——	——	——	−2.0868	——	——	——	——
	59.3590	−0.0154	9.9939	28.325	——	——	——	——	−1.4008	——	——	——	——
	190.4000	0.0269	−17.7630	13.338	——	0.8728	——	——	0.1384	——	——	——	——
	193.1600	0.0107	−18.6940	14.537	——	0.8842	0.1193	——	−1.9720	——	——	——	——
Base maintenance	−29.1310	−0.0720	26.0350	——	——	——	——	——	−1.5651	——	——	——	——
	44.5190	−0.0116	7.4954	21.244	——	——	——	——	−1.0506	——	——	——	——
	142.8000	0.0202	−13.3220	10.004	——	0.6546	——	——	0.1038	——	——	——	——
	144.8700	0.0080	−14.0200	10.903	——	0.6632	0.0894	——	−1.4790	——	——	——	——
Engine overhaul	135.1600	——	−19.7540	——	——	——	−0.0189	——	——	——	——	110.72	0.0055
Autopilot	2.7564	——	——	0.1178	——	0.0175	−0.0007	——	−0.0065	——	——	——	——
Communications	5.1822	0.0013	−0.1459	1.020	——	——	−0.0060	0.0177	——	——	——	——	——
Electrical	7.0216	——	−0.3866	——	——	0.0423	——	0.0003	——	——	——	——	——
Equipment/furnishings	5.6303	——	−0.0389	1.363	——	——	——	0.0232	——	——	——	——	——
	2.2867	——	−0.7416	0.665	0.0983	——	——	0.0051	——	——	——	——	——
Flight controls	9.7101	——	−0.7535	0.499	——	0.0503	0.0017	−0.0004	——	——	——	——	——
Fuel system	6.1745	——	1.4496	——	——	——	−0.0230	0.0481	0.0333	0	——	——	——
	4.8767	——	1.5254	——	——	——	−0.0189	0.0484	−0.0111	——	——	——	——
Hydraulic power	3.4695	——	——	0.638	——	——	−0.0042	0.0127	——	——	——	——	——
Instruments	1.9568	0.0005	−0.0551	0.385	——	——	−0.0022	0.0067	——	——	——	——	——
Wheels and brakes	53.1630	——	−3.8567	2.668	——	0.2730	0.0034	——	——	——	0.5725	——	——
Landing gear	12.4050	——	−0.8999	0.622	——	0.0637	0.0008	——	——	——	0.1336	——	——
Navigation	11.4910	−0.0039	——	0.484	——	0.0630	0.0097	0.0108	−0.2987	——	——	——	——
APU	−3.5330	——	3.9745	——	——	——	−0.0183	——	——	——	——	——	——
	7.9736	——	1.1987	3.541	——	——	−0.0103	——	——	——	——	——	——
	8.0316	——	0.7763	3.984	——	——	——	——	——	——	——	——	——
Thrust reversers	5.1810	——	−0.7572	——	——	——	−0.0007	——	——	——	——	4.2443	0.0002

Table 14 Final CERs

	Constant	Fleet size	Utilization, h/day	FH/FC, h	Fuselage length, ft	Aircraft cost, $ $\times 10^6$	Age of type of aircraft, months	Number of seats	Average age, years	Number of tires	Number of engines	Thrust, lbf
Line maintenance	-38.8410	-0.0960	~~−38.8410~~	~~−0.0960~~	~~34.7140~~	——	——	——	~~——~~	——	~~−2.0868~~	——
——	——											
	59.3590	−0.0154	9.9939	28.325	——	——	——	——	−1.4008	——	——	——
	190.4000	0.0269	−17.7630	~~13338~~	——	0.8728	——	——	0.1384	——	——	——
	193.1600	0.0107	−18.6940	14.537	——	0.8842	0.1193	——	−1.9720	——	——	——
Base Maintenance	-29.1310	-0.0720	~~−29.1310~~	~~−0.0720~~	~~26.0350~~	——	——	——	~~——~~	——	~~−1.5651~~	——
——	——											
	44.5190	−0.0116	7.4954	21.244	——	——	——	——	−1.0506	——	——	——
	142.8000	0.0202	−13.3220	10.004	——	0.6546	——	——	0.1038	——	——	——
	144.8700	0.0080	−14.0200	10.903	——	0.6632	0.0894	——	−1.4790	——	——	——
Engine overhaul	135.1600	——	−19.7540	——	——	——	−0.0189	——	——	——	110.72	0.0055
Autopilot	2.7564	——	——	0.1178	——	0.0175	−0.0007	——	−0.0065	——	——	——
Communications	5.1822	0.0013	−0.1459	1.020	——	——	−0.0060	0.0177	——	——	——	——
Electrical	7.0216	——	~~−03866~~	——	——	0.0423	——	0.0003	——	——	——	——
Equipment/ furnishings	5.6303	——	−0.0389	1.363	——	——	——	0.0232	——	——	——	——
	2.2867	——	−0.7416	0.665	0.0983	——	——	0.0051	——	——	——	——
Flight controls	9.7101	——	−0.7535	0.499	——	0.0503	0.0017	-0.0004	~~−0.0004~~	——	——	——
——												
Fuel system	6.1745	——	1.4496	——	——	——	−0.0230	0.0481	0.0333	——	——	——
	4.8767	——	1.5254	——	——	——	−0.0189	0.0484	−0.0111	——	——	——
Hydraulic power	3.4695	——	——	0.638	——	——	−0.0042	0.0127	——	——	——	——
Instruments	1.9568	0.0005	−0.0551	0.385	——	——	−0.0022	0.0067	——	——	——	——
Wheels and brakes	53.1630	——	−3.8567	~~2.663~~	——	0.2730	0.0034	——	——	0.5725	——	——
Landing gear	12.4050	——	−0.8999	0.622	——	0.0637	0.0008	——	——	0.1336	——	——
Navigation	11.4910	−0.0039	——	0.484	——	0.0630	0.0097	0.0108	−0.2987	——	——	——
APU	−3.5330	——	3.9745	——	——	——	−0.0183	——	——	——	——	——
	8.0316	——	0.7763	3.984	——	——		——	——	——	——	——
Thrust reversers	5.1810	——	−0.7572	——	——	——	−0.0007	——	——	——	4.2443	0,0002

On account of this, the cost drivers for the RCM shown in Table 9 (i.e., fleet size, utilization, and years from first delivery), if necessary, have been turned into the available cost drivers of Table 10 (i.e., ~~utilization in hours per day~~ and ~~average aircraft age in years~~). The latter have then been exploited for line and base maintenance ~~CER~~ development. The R^2 resulting from this analysis is 0.706 (see Table 12), which is very close to the imposed R^2 threshold of 0.7. To improve R^2 for both cost items, other drivers with a direct influence on the cost of line and base maintenance activities have been added, one by one, from the database. As can be noted from Table 12, the further inclusion of cost drivers (i.e., FH/FC, aircraft cost, and age of type of aircraft) progressively increases the final R^2 up to 0.935. Table 13 shows the coefficients obtained by the OLS analysis for all the cost items.

Similar remarks apply to the construction of the CERs for the APU that, as already mentioned, was not treated in [9]. Thus, no cost drivers are already available in the literature and some tests have been performed to define the more suitable cost drivers. ~~Table 12~~ shows the three CERs obtained for the APU maintenance cost characterized by higher R^2. The first and the third CERs are influenced by three cost drivers. From the results of ~~Table 13,~~ it appears that these CERs introduce acceptable results in terms of R^2, remembering the imposed threshold [23]. The second CER is the function of four cost drivers, and it presents a R^2 very similar to the one of the third CER. Considering this, it has been decided to delete the second CER because it was judged of little use to store two CERs with the same accuracy (and one CER requiring more inputs than the other).

Moreover, from the coefficients of Table 13, the first CER for the fuel system shows that there is no correlation between the cost driver weight and the maintenance cost associated to this subsystem. Moreover, the related R^2 of Table 12 rises when the examined cost driver is removed in the second CER.

Applying these considerations, the final set of regression coefficients for the maintenance cost model are listed in Table 14. It is important to underline that each CER of Table 14 provides a cost for FY 2013, which is the reference year for the costs provided by the IATA in [11]. To obtain a cost estimation for the year 2017, the result of each CER should be multiplied by a cost escalation factor (CEF) [1] of 1.05.

B. Maintenance Burden

The cost of the maintenance burden is usually expressed as a percentage of the direct maintenance cost (this assumption is adopted in the state-of-art methods considered), and it is difficult to find or to build a CER with well-defined cost drivers as for direct maintenance cost. This is primarily due to the lack of available data; then, it is strictly related to the heterogeneous nature of this cost element, which makes it difficult to find cost drivers. In [12], the breakdown of the total maintenance cost, which is given by the sum of the direct maintenance cost and the maintenance burden, is reported. The breakdown given in Fig. 6 represents typical values for a civil aircraft, and it is not related to a specific year.

From Fig. 6, it can be noted that the direct maintenance cost represents 60% of the total maintenance cost. The DMC is given by the sum of all costs calculated using the CERs of Table 14. Once the DMC is known, the total maintenance cost $C_{\mathrm{tot,MAINT}}$ is given by the following proportion:

$$C_{\mathrm{tot,MAINT}} = \frac{\mathrm{DMC}}{0.6} \tag{8}$$

The maintenance burden can now be calculated by remembering that, by assumption, it is 40% of the total maintenance cost.

III. Results

The developed maintenance cost model is validated using a test case. The reference cost data provided by the IATA and included in the final database of Tables 2–8 are exploited. The test case is the

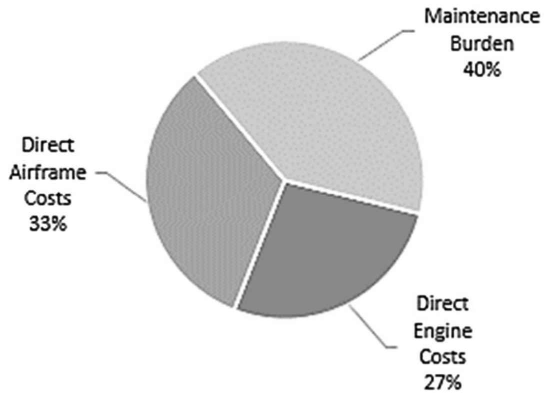

Fig. 6 Total maintenance cost breakdown (Source: [12].).

B737-700, which is a model of the 737 ~~next generation~~ (NG) family, and it has slightly different characteristics as compared to the B737-~~600~~ treated in the database. For the assessment of maintenance costs at the subsystem level, the CERs developed in this study and reported in Table 14 are used. As far as the values of the cost drivers for the selected aircraft are concerned, it is possible to reuse the data of the final database for the B737 NG, except for the aircraft cost, the age of the type of aircraft, the average aircraft age, the fuselage length, and the number of seats, which vary between the models of the
19 B737 NG family. These cost drivers and their specific values for the B737-700 are gathered in Table 15 ~~[24]~~.

The results of the application of the CERs of Table 14 are shown in Table 16. All costs are related to FY 2017. Where multiple CERs for the same cost element are available, all formulas are applied. From

20 **Table 15 Specific cost drivers for B737-700**

Cost driver	Value
Aircraft cost	80 ~~mio,~~ U.S. $ ~~[24]~~
Age of type of aircraft	15 years
Aircraft age	7.3 years
Fuselage length	110.4 ft
Number of seats	128

Table 16 Maintenance costs at subsystem level for B737-700

Maintenance cost element	$/flight hour
Line maintenance (CER 1)	267.46
Line maintenance (CER 2)	202.06
Line maintenance (CER 3)	134.29
Line maintenance (CER 4)	137.42
Base maintenance (CER 1)	200.59
Base maintenance (CER 2)	151.55
Base maintenance (CER 3)	100.72
Base maintenance (CER 4)	103.07
Engine overhaul	303.22
Autopilot	4.42
Communications	7.40
Electrical power	7.31
Instruments	2.81
Wheels and brakes	51.92
Landing gear	12.12
Navigation	19.17
Equipment/furnishings (CER 1)	11.39
Equipment/furnishings (CER 2)	8.80
APU (CER 1)	30.42
APU (CER 2)	23.74
Flight controls	8.58
Fuel system	22.39
Thrust reversers	11.39
Hydraulic power	5.84

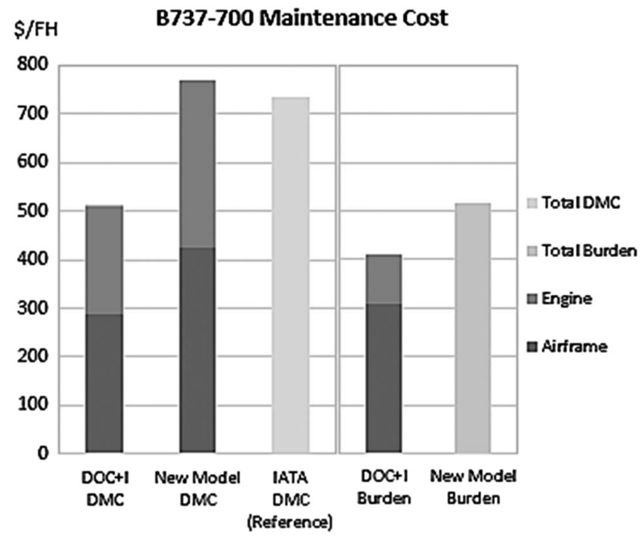

Fig. 7 Comparison of results of B737-700 maintenance cost between DOC + I method, new model, and IATA reference data.

Table 16, it can be noticed that, as the R^2 rises (see Table 12), the cost converges to a definite value. The resulting costs for each subsystem (Table 16) and for the total DMC (the latter is shown in Fig. 7 as new model DMC) are consistent with the reference costs of the database for the B737 NG family. Thanks to the information given by Fig. 6, ~~from~~ 21
~~the total amount of DMC is then extracted the direct maintenance cost related to both engine and airframe separately.~~ Both contributions are depicted in Fig. 7, which also includes the maintenance burden obtained with Eq. (8) (see the ~~new model burden~~ column).

The total costs of the engine, the airframe maintenance, and the maintenance burden of Fig. 7 are then compared with the results given by the application of the state-of-the-art methods. The method proposed 22
by Chen et al. [6] ~~results difficult to employ~~ due to the required cost drivers. This is the case of the aircraft cost, which is expressed in Deutsche Marks (DMs). This currency has been obsolete since 1999, so it is difficult to convert costs given in U.S. dollars to DMs for years after 1999. These considerations and the fact that the equations given in [6] are quite complex have not allowed the correct application of the method in this final part of the study. NASA's economic model [8], which provides maintenance costs at the airline level on a yearly basis, seems to also not be suitable for a comparison. For the purposes of this work, a more detailed analysis considering the specific aircraft model is required. The evaluation of annual costs for the entire airline, in fact, makes it difficult to determine the cost of the single aircraft, considering that the total fleet can be made by different aircraft models. The results of this method were, in summary, too generic.

Thus, the comparison with the results of the state-of-the-art methods is limited to the application of the DOC + I method [4], which is easier to apply. The required inputs for the DOC + I method are summarized in Table 17.

The contribution to maintenance costs given by the engine and airframe is calculated, analyzing the labor and material costs associated for both elements. The main cost driver for the airframe maintenance

Table 17 DOC + I method inputs 23

Input	Value
Operating empty weight	37.65 ~~tons~~ 83,000 lb
Engine model	CFM56-5A1
Engine dry weight	5,126 lb
Airframe weight	72,568 lb
Flight hours per trip	1.9 h
Sea-Level static thrust per engine	9.08 lbf 20,600 tons
Number of engines	2

[b] http://www.boeing.com/company/about-bca/ [retrieved 19 Dec. 2017]

cost is airframe weight, which is calculated by subtracting the dry weight of both engines from the operating empty weight. For the engine and
24 airframe maintenance, a required input is the labor rate expressed in ~~$/MMH~~. In the DOC + I method, a value of 25 $/MMH is suggested for the year 1993. In this paper, in order to scale this datum to FY 2017, a CEF of 1.69 is used and a labor rate of 40.3 $/MMH is obtained. This CEF is also adopted to scale to FY 2017 the equations related to maintenance material cost, which was related to 1993.This datum cannot be fully verified due to the lack of precise data on the labor rate; it is, in fact, a difficult parameter to estimate and could significantly vary, for example, in relation to the experience of the maintenance personnel and the specific tasks performed. The maintenance costs given by the DOC + I method for the B737-700 are included in Fig. 7 (see ~~DOC + I DMC~~ and ~~DOC + I burden~~). Costs from the DOC + I method are given "per trip"; thus, to make a comparison with the already calculated costs of Fig. 7, they have been divided by the average number of flight hours per flight. The costs per flight hour provided by the IATA [11] are taken as reference. The comparison of the results given by the new method with the results of the DOC + I method (Fig. 7) shows that the
25 DOC + I method underestimates the direct maintenance costs for both the engine and airframe. ~~A good accordance of results is found for the maintenance burden.~~ The discrepancy in DMCs is probably related to the estimation of the labor rate, for which the value is not completely confirmed.

IV. Conclusions

In conclusion, this paper deals with the development of a new model for the estimation of aircraft maintenance costs at the subsystem level in comparison with most of state-of-the-art models where the cost items are given at the aircraft level. The results show that the maintenance effort estimated by the new CERs is in line with the reference values.

It is important to note that the aircraft considered in the database constitute the most popular models available on the market nowadays. For this reason, the developed model can be considered exhaustive for a great part of the expected cases. Furthermore, some difficulties have been encountered during the application of state-of-the-art methods in terms of the availability of the required cost drivers. On the contrary, the new cost model is straightforward and the cost drivers included in the new CERs (and thus the required inputs) are intuitive and easy to find.

Further developments of the model will deal with the introduction of more specific cost drivers so that the costs related to new technologies can be evaluated.

26 References

[1] Roskam, J., *Airplane Design, Part VIII*, 1990.
[2] Raymer, D., *Aircraft Design: A Conceptual Approach*, 2012.
[3] "Airline Cost Management Group (ACMG) Report FY 2013, Enhanced Version," International Air Transport Association, Montreal, Sept. 2014, http://www.iata.org/whatwedo/workgroups/Documents/ACMG/ACMG-report-FY13-public.pdf [retrieved June 2017].
[4] Liebeck, R. H., Andrastek, D. A., Chau, J., Girvin, R., Lyon, R., Rawdon, B. K., Scott, P. W., and Wright, R. A., "Advanced Subsonic Airplane Design and Economic Studies," NASA CR-195443, 1995.
[5] "Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport," Air Transport Association, 1967.
[6] Chen, G., Yingming, H., Nüβer, H., and Wilken, D., "A Method of Evaluating Civil Aircraft Market Adequacy," 1997.
[7] "Short-Medium Range Aircraft – AEA Requirements," Association of European Airlines, Brussels, 1989.
[8] Harris, F. D., "An Economic Model of U.S. Airline Operating Expenses," NASA/ CR–2005-213476, 2005.
[9] Pearlman, C., and Simpson, R. W., "Maintenance Cost Studies of Present Aircraft Subsystems," 1966.
[10] Fioriti, M., Boggero, L., Corpino, S., Isyanov, A., Mirzoyan, A., Lombardi, R., and D'Ippolito, R., "Automated Selection of the Optimal On-Board Systems Architecture Within MDO Collaborative Environment," *18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, AIAA Paper 2017-3150, June 2017.
[11] "FY2013 Maintenance Cost Preliminary Analysis," [online presentation], International Air Transport Association, Montreal, Sept. 2014, http://www.iata.org/whatwedo/workgroups/Documents/MCC-2014-ATH/D1/1000-1030-fy13-mtce-cost-analysis-IATA.pdf [retrieved Feb. 2017]. 27
[12] Dixon, M., *The Maintenance Costs of Aging Aircraft: Insights from Commercial Aviation*, RAND Corp., Santa Monica, CA, 2006.
[13] "Innovative Cooperative Actions of Research and Development in EUROCONTROL Programme CARE INO III - Dynamic Cost Indexing," Transport Studies Group, Univ. of Westminster, London, 2008.
[14] "Industry Data, Aircraft Operating Costs," Aviation Week, 2014.
[15] *GAO Cost Estimating and Assessment Guide*, U.S. Government Accountability Office Rept. GAO-09-3SP, 2009.
[16] Fioriti, M., and Chiesa, S., *Innovative Solutions for Light, Very Light, and Unmanned Aircraft Preliminary Design and Life Cycle Cost Estimation*, LAP Lambert Academic, Saarbrücken, Germany, 2011. 28
[17] Fioriti, M., Pavan, G., Corpino, S., and Fusaro, R., "Impacts of a Prognostics and Health Management System on Aircraft Fleet Operating Cost during Conceptual Design Phase by Using Parametric Estimation," *5th CEAS Air and Space Conference*, Delft, The Netherlands, Sept. 2015. 29
[18] "Outlook/Specifications: Gas Turbine Engines," *Aviation Week and Space Technology*, Jan. 2005, pp. 122–134.
[19] Alma, Ö. G., "Comparison of Robust Regression Methods in Linear Regression," *International Journal of Contemporary Mathematical Sciences*, Vol. 6, No. 9, 2001, pp. 409–421. doi:10.12988/ijcms
[20] Huber, P., "Robust Estimation of a Location Parameter," *Annals of Mathematical Statistics*, Vol. 35, No. 1, 1964, pp. 73–101. doi:10.1214/aoms/1177703732
[21] Rousseeuw, P., and Yohai, V., "Robust Regression by Means of S-Estimators," *Robust and Nonlinear Time Series Analysis*, edited by, edited by J. Franke, W. Härdle, and D. Martin, Springer-Verlag, New York, 1984, pp. 256–272. doi:10.1007/978-1-4615-7821-5_15
[22] Gujarati, D., *Basic Econometrics*, 4th ed., McGraw–HiII/lrwin, New York, 2003.
[23] *Parametric Estimating Handbook*, 4th ed., International Society of Parametric Analysts, Vienna, VA, April 2008. 30
~~[24] http://www.boeing.com/company/about-bca/, Boeing Commercial Airplanes Group, [retrieved Feb. 2017].~~ 31
~~[25] "Airbus Aircraft 2017 Average List Prices," Airbus, http://www.airbus.com/content/dam/corporate-topics/publications/backgrounders/Airbus_commercial_aircraft_price_list_Jan17.pdf [retrieved Feb. 2017].~~ 32

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