PARAMETRIC APPROACH TO OPERATING COSTS ESTIMATION FOR AN INNOVATIVE REGIONAL AIRCRAFT

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Abstract

The focus of the present paper is the evaluation of the operating cost of innovative regional aircraft. The paper proposes a parametric cost model for the assessment of both Direct Operating Cost (DOC) and Indirect Operating Cost (IOC). The present work is carried out in the framework of the Clean Sky II (CS-2) *research program, in the Regional IADP IRON project, which deals with the development of an innovative regional aircraft. In particular, the methodology proposed is derived from already existing cost models and it is properly modified in order to be sensitive to innovative technologies and new subsystems configurations in compliance with the Clean Sky II requirements. Finally, the model is applied to the IRON reference aircraft to estimate the possible reduction of its operating cost due to new technologies implemented.*

1 Introduction

Cost estimation plays a fundamental role since the very beginning for the aircraft project and it is useful to choose between various designs alternatives. A complete cost analysis shall evaluate the amount of resources involved during the whole product, considering the cost of developing, producing, operating, and disposing it. This task has been accomplished also within the frame of the CS-2 Project and, in particular, in the Regional IADP IRON, carried out by Politecnico di Torino in collaboration with University of Naples Federico II. Specifically, the CS-2 Project is a European research program with the aim of developing innovative technologies able to reduce carbon dioxide (CO_2), gas emissions and noise levels produced by civil aircraft. In this context, the Regional IADP IRON aims at increasing the efficiency of regional turboprop aircraft studying both conventional and innovative configurations. Moreover, the project deals with innovative subsystems architectures like the MEA (More Electric Aircraft) and the AEA (All Electric Aircraft) concepts [1], and several breakthrough technologies such as laminar wing, morphing wing, and droop-nose technologies.

The benefits deriving form the introduction of these advanced technologies may result in MTOM (Maximum Take-Off Mass) reduction [2], [3] (which is directly linked to fuel savings), increased reliability, maintainability, flight safety and reduced power losses (e.g. reduction in Specific Fuel Consumption (SFC) due to bleed air reduction or complete removal). For example, Electro-Mechanical Actuators (EMAs) require a reduced maintenance effort with respect to conventional hydraulic actuators which, conversely, need periodic checks for filter substitution and fluid level refill [4]. Moreover, hydraulic pipes and equipment, as well as hot bleed air pipes could be completely remouved with MEA/AEA architectures increasing the aircraft safety level [5].

Taking into account the benefits associated to the technologies considered within the CS-2 Project, the final goal of the analyses performed at Politecnico di Torino is to provide a cost estimation methodology for assessing the impact of innovative technologies onto operating costs, which represent the highest costs incurred during aircraft life cycle. Furthermore, the developed model is implemented into a MATLAB® tool which is integrated by University of Naples Federico II in a Leonardo's preliminary design software to evaluate possible benefits on costs arising from different design alternatives. Within the framework of this research, this paper aims at describing the methodology developed for operating cost assessment, which is flexible and compliant with the introduction of new technologies.

As far as aircraft operating costs are concerned, they are usually subdivided into DOC and IOC. The former cost item concerns flight operations, including the costs related to fuel, oil, crew, maintenance, depreciation, interest, and insurance. Landing fees, carbon and noise taxes, and navigation charges are usually included into DOC, too. Conversely, IOC category includes all the rest of operating expenses, such as traffic service, sales and customer service costs, and administrative and overhead costs.

Several State-of-the-Art (SoA) methodologies, based on airline statistical data, are available in literature for DOC estimation. They provide specific Cost Estimating Relationships (CERs) that are function of several specific parameters, i.e. the cost drivers. In this sense, the Air Trasport Association of America (ATA) method [6] constitutes the first standardized approach for the estimation of the DOC of subsonic jets. Another remarkable approach is the DOC+I (DOC plus Interest) method from Liebeck [7], which is an updated version of the ATA method. Other examples of operating cost methodologies can be found in the AEA (Association of European Airlines) method [8], Roskam [9], Jenkinson [10], the NASA (National Aeronautics and Space Administration) Economic model [11], Sforza [12], and Chen [13]. With regard to IOC, only few SoA models provide CERs allowing the evaluation of their contribution to operating cost. In particular, the Roskam method [9] determines IOC as a percentage of DOC without providing a detailed cost breakdown of the items included into IOC. The critical issue related to this methodology is strictly connected to the ratio between IOC and DOC, which may be unknown. Conversely, the CER for IOC assessment proposed by Sforza [12] can be easily exploited, being function of the range and the number of passengers carried per flight. Taking into account that it encompasses all the IOC items in a unique formulaiton, it is not suitable whether (as in the present case) a more detailed IOC breakdown is required.

A limit of the SoA approaches introduced above lies in the fact that they are almost outdated, such as the ATA DOC method [6]. Therefore they may provide costs which do not reflect actual trends. Furthermore, considering that the current cost methodologies are function of high-level design parameters, they are unable to address the effect of specific technological improvements on costs. Consequently, each improvement shall be separately considered and its influence on costs evaluated. In account of this, the available CERs shall be properly modified and enhanced. In particular, taking into account that maintenance and fuel expenses are mostly influenced by the introduction of new technologies, special attention has been devoted to assess the effect of technological advancements onto these two cost items starting from the CERs available form literature. To fulfil this aim, the following technologies (analyzed within the frame of the Regional IADP IRON) have been analyzed:

- Standard versus more-electric systems architecture, which impacts on maintenance cost;
- Innovative ECS (Environmental Control System) architecture and its effect on fuel cost.

As far as IOCs are concerned, their main cost drivers are mission parameters such as typical range and load factor (i.e. the ratio of the average payload carried to the maximum payload), hence the effect of technological improvements on IOC is negligible.

The proposed methodology for DOC assessment is summarized in Section 2. The latter includes the description of the technological improvements foreseen within this paper and the suggested methodologies for the evaluation of these technologies impact on DOC. Section 3 briefly introduces the approach for IOC evaluation. Moreover, Section 4 describes the case studies and provides the DOC evaluation for the selected baseline configuration, including the effects of technological improvements. Section 5 gathers the results IOC assessment. Section 6 describes the integration of the costs MATLAB tool whitin Leonardo software. Eventually, Section 7 draws the main conclusion of the work.

2 DOC Assessment and Technological Improvements Evaluation

The DOC methodologies mentioned above have been deeply evaluated in order to determine which of the proposed CERs provides the best results in comparison with some reference data. The following section reports the CERs included into the suggested methodology for DOC evaluation, including the following DOC items: flight crew, depreciation, insurance, interest, maintenance, landing fees and navigation charges, noise and emission related charges.

2.1 CERs for DOC Assessment

Firstly, all the available CERs for flight crew and insurance costs have been applied and the outcomes compared with the operating costs values provided by FAA (Federal Aviation Administration) [14]. In account of this, flight crew cost may be assessed as the product of the crew labor rate by the number of crew members. In addition, insurance cost may be calculated as:

$$Insurance{=}0.0035\,\frac{C_{TOT}}{Period \cdot U}\left[\frac{\$}{BH}\right] \qquad (1)$$

Where:

- C_{TOT} is the total aircraft acquisition cost (including engines);
- *Period* is expressed in years and it represents the timeframe of insurance coverage;
- *U* is the annual utilization, in Block Hours (BH) per year.

This formulation has been derived from [7] In particular, it has been noticed that the results for insurance cost from all the analyzed SoA models overestimated the cost data provided by FAA [14] for all the aircraft categories. Conversely, Eq. (1) provides results more in line with the reference data. For depreciation cost, the relationship suggested by the DOC+I method [7] can be adopted. For interest cost, the following formulation can be used:

$$Interest{=}IR \cdot (\%debit \cdot C_{TOT}) \qquad (2)$$

Where $\%debit \cdot C_{TOT}$ is a fraction of aircraft acquisition cost. In order to obtain a cost per BH, the obtained value shall be divided by the interest period and the annual utilization expressed in BH per year. For fuel cost, the Roskam [9] equation is suggested. In addition, maintenance cost can be determined using the approach proposed in [15]. Landing fees may be obtained from Liebeck [7] and navigation charges from EUROCONTROL [16]. Eventually, taking into account that the main purpose of the CS-2 Program is environmental sustainability, the methodology here presented also suggests a set of CERs to assess the impact of noise and emissions related charges on DOC. In particular, as far as noise charges are concerned, they can be determined from [17] as a function of ICAO (International Civil Aviation Organization) certified noise levels [18] at approach, flyover, and sideline Certification Points (L_a, L_{Fly}, and L_{Lat}) and of the noise threshold at the departure and arrival airports (T_d and T_a). In addition, the contribution to DOC of nitrogen oxides (NO_x) and hydrocarbons (HC) as well as CO_2 emissions, can be assessed exploiting the equations provided in [19].

2.2 Technological Improvements Evaluation

In this section, the effects of technological improvements on DOC is evaluated. In particular, two different approaches are introduced. One to quantify the effect of the adoption of an innovative ECS on fuel expenses and the second to evaluate the effect on maintenance cost due to the introduction of innovative MEA and AEA on-board systems architectures.

2.2.1 *Effect of an innovative ECS on Fuel Cost*

In order to evaluate the impact of breakthrough technologies on fuel expenses, some considerations are necessary in order to determine which aircraft components have a major influence on fuel consumption. In account of this, it is well known that the ECS constitutes one of the most demanding systems in terms of power. A conventional pneumatic ECS architecture exploits the bleed air extracted from the main engine, selecting the appropriate engine bleed port (at high or low pressure) as a function of engine operating conditions. The bleed air is then cooled in the Air Pack in order to provide the required pressurized ventilation and air conditioning to the aircraft and to maintain the passenger comfort. Conversely, the hybrid ECS technology lies in-between a traditional pneumatic and a fully electric solution. A comparison between conventional and hybrid ECS architectures is provided in Fig. 1. From Fig. 1 it can be noticed that, in the hybrid ECS, the Air Pack is fed both by the Low-Pressure Compressor (LPC) of the engine and by a dedicated electrically driven compressor which provides the required pressurized air. In an all-electric ECS architecture (E-ECS) the electrical-driven compressor constitutes the unique source of the pressurized air (there is no connection with the engine). In general, the exploitation of a pressurized air source other than the engine increases the efficiency of the ECS and results in a decrease in SFC.

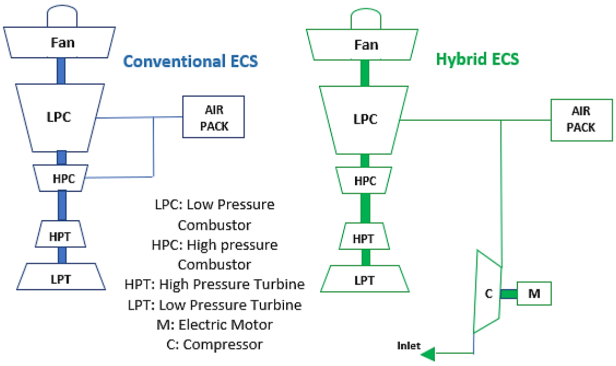


Fig. 1. Conventional and Hybrid ECS Architectures

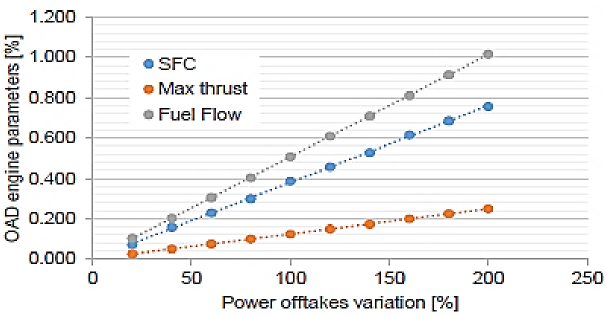
In order to include the effect of these innovative technologies on DOC, a methodology proposed by NASA [20] is exploited. The main logic flow of the approach is resumed in Fig. 2, where:

- ΔDOC_{ij} is the Delta-cost on a generic DOC item due to the ith technological improvement (*TP*) on the jth cost driver or driver parameter (*Dr*);
- DOC_{BL} is the value of the DOC item under study for a configuration selected as baseline and implementing SoA technologies;
- the *Driver Partial* relates the change in the DOC to the driver parameters;
- The *Technology Parameter Partial* relates the change in each of the driver parameters to the technology parameters;
- The *Technology Projection* is the foreseeable improvement in the technology parameters.

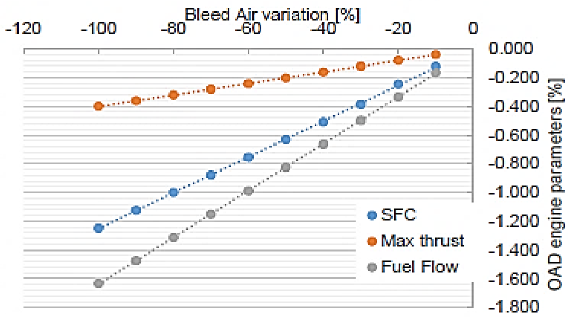
$$\Delta DOC_{ij} = DOC_{BL} \times \underbrace{\left(\frac{\Delta DOC/DOC}{\Delta Dr/Dr}\right)_i}_{\text{Driver Partial}} \times \underbrace{\left(\frac{\Delta Dr/Dr}{\Delta TP/TP}\right)_{ij}}_{\text{Technology Parameter Partial}} \times \underbrace{(\Delta TP/TP)_i}_{\text{Technology Projection}}$$

Fig. 2. NASA Methodology Logic Flow

In order to apply the NASA methodology [20] to the technologies under study (i.e. Hybrid and E-ECS), the involved cost drivers and technological parameters shall be identified. Specifically, the introduction of a Hybrid ECS within an aircraft would decrease the amount of bleed air extracted from the main engine, but it would also increase the mechanical power offtakes (required to drive the electrically-driven compressor). Based on previous studies [21], [22] the impact on SFC of both bleed air reduction and power offtakes increase is depicted in Fig. 3. In particular, Fig. 3(a) shows the relation between the increase of mechanical power offtakes from the engine and the engine SFC, fuel flow and maximum thrust. It explains how the increase of power offtakes produces an inefficiency on the engine cycle, hence an increase of SFC. The engine requires more fuel increasing the total fuel mass, hence the aircraft mass and the thrust required. Similarly, Fig. 3(b) shows the same effects and results considering the bleed air extraction from the engine compressors. Adopting a MEA/AEA systems configuration with bleedless architecture, compared to conventional aircraft the bleed air is totally removed (i.e. -100% in Fig. 3(b)) and the power offtakes increases less than 200%. It can be noticed that the net effect of these two contributions results in a decrease in SFC because the bleed air is more detrimental for engine efficiency compared to shaft power offtakes. Similar remarks apply to the E-ECS, where the bleed air elimination is accompanied to an increase in power offtakess.



(a)



(b)

Fig. 3 Relationship between bleed air percentage reduction and percentage reduction in SFC

Both these effects on SFC have been taken into account by properly applying the NASA approach [20]. For sake of clarity, the schematic representation of the methodology specifically referred to a decrease in bleed air percentage is depicted in Fig. 4. In particular:

- The ith cost driver is SFC;
- The jth technological improvement is the foreseen reduction in the bleed percentage and the related increase in power offtakess (which is a negative drawback);
- ΔDOC_{ij} is the resulting delta fuel cost;
- DOC_{BL} is the fuel cost per flight calculated for an aircraft selected as reference and implementing the SoA technologies (i.e. a conventional ECS architecture);
- The *Driver Partial* expresses the decrease in fuel cost due to a decrease in SFC;
- The *Technology Projection* is the decrease in the bleed air percentage (and the increase in power offtakess) due to the selection of an innovative ECS architecture.

$$\Delta DOC_{ij} = DOC_{BL} \times \overbrace{\left(\frac{\Delta DOC/DOC}{\Delta Dr/Dr}\right)_i}^{\text{Decrease in Fuel Cost due to SFC decrese}} \times \overbrace{\left(\frac{\Delta Dr/Dr}{\Delta TP/TP}\right)_{ij}}^{\text{Decrease in SFC due to a decrease in Bleed Air percentage}} \times \overbrace{(\Delta TP/TP)_i}^{\text{Decrease in Bleed Air percentage}}$$

Fig. 4 Application of the NASA Methodology to innovative ECS configurations

At this point, the contributions shown in Fig. 4 shall be quantified. In particular, DOC_{BL} may be calculated exploiting the equation suggested in Section 2.1 for fuel cost assessment (DOC_f). The *Technology Projection* may be defined considering a certain variation in the percentage of bleed air and assuming a 100% of bleed for the baseline configuration. Then, the graph in Fig. 3 (at the bottom) can be exploited and the percentage variation in SFC from the baseline can be calculated. This value shall be adjusted selecting a proper power offtakes variation (at top of Fig. 3). This information constitutes two distinct *Technology Parameter Partials* (i.e. decrease in SFC due to decrease in bleed air percentage and increase in SFC due to increase in mechanical power offtakes) . Eventually, from [20] the *Driver Partial* can be expressed as:

$$\frac{\frac{\Delta DOC_f}{DOC_f}}{\frac{\Delta SFC}{SFC}} = \frac{\partial DOC_f}{\partial SFC} \cdot \frac{\Delta SFC}{SFC} \cdot \frac{SFC}{DOC_f} \tag{3}$$

Where:

$$\frac{\partial DOC_f}{\partial SFC} = \frac{\partial DOC_f}{\partial \frac{m_{fT}}{MTOM}} \cdot \frac{\partial \frac{m_{fT}}{MTOM}}{\partial SFC} \tag{4}$$

Where m_{fT} is the block fuel used per flight. It is worth noticing that, in Eq. (4) $(\partial\, m_{fT}/MTOM\,)/\partial SFC$ can be obtained from the Breguet Range Equation:

$$R_{CR} = \frac{L/D}{SFC} \cdot V_{CR} \cdot ln \frac{W_{CR1}}{W_{CR2}} \tag{5}$$

Where W_{CR1} and W_{CR2} are, respectively, the fuel weight at the beginning and at the end of cruise. For the complete description of the elements of Eq. (4), see [20].

2.2.2 Effect of MEA and AEA architectures on maintenance cost

In order to assess the benefits in terms of maintenance cost savings due to the introduction of MEA and AEA systems architectures, the final outcomes of the NASA study carried out in the '80s by Howison and Cronin [23] have been exploited. In particular, [23] analyses the effects of advanced electric/electronic technologies onto DOC introducing a reference aircraft concept and several near- and far-term configurations characterized by innovations into flight controls and, more in general, in secondary power sources (i.e. hydraulic, electrical, flight controls and air conditioning systems).
Table 1 provides the definition and the main features of the aircraft configurations treated in [23]. The innovative technologies mentioned in Table 1 are in line with the advanced technologies envisaged within the Regional IADP IRON. For the innovative configurations gathered in Table 1, [23] provides the percentage DOC savings in terms of fuel, maintenance, depreciation, and crew costs due to technological advancements. From Fig. 5 it can be noticed that great part of DOC savings are related to fuel expenses. As far as maintenance cost is concerned, NTSP and FTSP configurations are associated, respectively, to a 0.5% and 1% DOC saving. Similar DOC savings are connected to depreciation costs, whils crew costs savings are almost negligible.

Table 1 Reference Innovative configurations introduced in [16]

Configuration	Main Characteristics
Reference	• Hydraulic Flight Control System (FCS) without fly-by-wire • Pneumatic ECS
NTFC (Near-term Flight Controls)	Hydraulic FCS with fly-by-wire
FTFC (Far-term Flight Controls)	FCS with EMA and fly-by-wire
NTSP (Near-term Secondary Power)	• Hydraulic FCS with fly-by-wire; • Electric ECS
FTSP (Far-term Secondary Power)	• FCS with EMA and fly-by-wire; • E-ECS

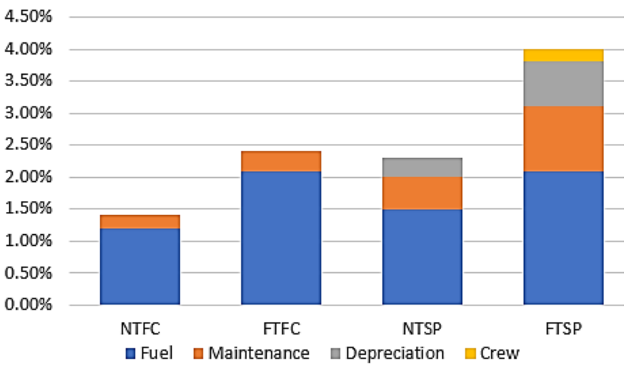


Fig. 5 DOC savings for different innovative configurations

3 IOC Assessment

As far as IOC is concerned, from a deep analysis of the available sources, it has been observed they are not able to provide an updated and sufficiently detailed methodology for IOC assessment. Therefore, in order to evaluate the impact of each cost item on IOC, a more specific set of CERs has been introduced. This new approach is based on actual career data provided by IATA [24] and ICAO [25] and exploits as cost drivers frequently used aircraft traffic parameters, such as Revenue Passenger Mile (RPM) and Available Seat Kilometer (ASK). The relationships coming from IATA (International Air Transport Association) [24] are referred to FY2012 (i.e. Fiscal Year 2012), whereas the data from ICAO [25] are for FY2017. Table 2 gathers all the relationships for IOC assessment. See Roskam [9] for a complete definition of the IOC items. In particular, from Table 2 it can be noticed that, whereas specific CERs where not available, some cost items have been expressed as a fraction of Total Operating Cost (TOC), which is given by the sum of DOC and IOC, exploiting the guidelines provided by ICAO [25].

Table 2 CERs for IOC Assessment

IOC Item	CER	Source
Passenger Service	0.015 US$·RPM	[25]
Traffic Service	15 US$·Enplaned Passenger	[25]
Station and Ground	0.0092 US$·ASK	[24]
General and Administrative	0.0072 US$·ASK	[24]
Reservation and Sales	14% TOC	[25]
Advertising and Publicity	2% TOC	[25]
Aircraft Servicing	7% TOC	[25]

4 Application of the methodology

The DOC methodology presented within this paper has been applied to the following case studies related to the CS-2 Project:

- A conventional civil regional aircraft with a 90-seat configuration characterized by high wing and wing-mounted engines, i.e. ATR90 (Fig. 6);
- A MEA concept with a conventional configuration, i.e. CS-2 Conventional aircraft (Fig. 6);
- An AEA concept with innovative configuration (e.g. low wing and engines mounted in the fuselage aft section), i.e. CS-2 Innovative (Fig. 7).

Subsequently, the two approaches for the evaluation technological advances effect on DOC (referred to fuel and maintenance costs) are applied for the innovative concepts. Eventually, IOCs are calculated.

Fig. 6 Aircraft with Conventional Configuration (ATR or CS-2 Conventional)

Fig. 7 Aircraft with Innovative Configuration [26]

4.1 Conventional Civil Regional Aircraft

The baseline vehicle for DOC assessment has been conceived as a stretched version of the ATR72-500 turboprop. It is equipped with 2 PW150A engines. Moreover, the ATR90 is marked by a conventional on-board systems architecture including a pneumatic ECS, a hydraulic FCS (no fly-by-wire) and landing gear, a conventional EPGDS (Electrical Power Generation and Distribution System) where engines are the main source of secondary power.

4.1.1 Inputs for DOC Assessment

In order to assess the DOC of the baseline vehicle, the DOC methodology described in Section 2.1 has been applied. In particular, a value of 212 US$/BH (FY2018) for flight crew labor rate has been assumed, deduced from MIT data [27]. Specifically, the data referred to FY2016 have been considered and a mean value has been found and scaled to FY2018. Subsequently, the obtained mean value (referred to narrow body and widebody aircraft) has been reduced of 50% taking into account the flight crew costs for turboprops provided by FAA [14]. In addition, Table 3 shows the main inputs for depreciation, insurance, and interest costs evaluation. As far as depreciation cost is concerned, the inputs suggested by Liebeck [7] have been adopted. Furthermore, a fuel price of 2 $/gal coming from IATA has been used [28]. As far as maintenance cost is concerned, the inputs required by the methodology proposed in [15] are gathered in Table 4.

Table 3 Inputs for Depreciation, Insurance, and Interest Costs

Cost Driver	Value	Unit
Period (Depreciation and Interest)	25	years
Annual Utilization	2200	BH/year
Interest Period	10	years
Interest Rate	5	%
%debit	85	%

Table 4 Inputs for Maintenance Cost

Cost Driver	Value	Unit
Fleet Size	39	
Daily Utilization	4.72	hours
Flight Hours/Flight Cycle (FH/FC)	0.87	hours
Fuselage Length	28.8	m
Age of Type of Aircraft	23	years
Aircraft Age	18	years
Number of Tires	6	
Thrust per Engine	18000	N

Eventually, concerning navigation charges and landing fees, all the main inputs are provided in Table 5. In particular, the unit rate of charge value for navigation charges evaluation is referred to Italy [29]. Moreover, the values of C_{noise}, T_a, and T_d for noise charges have been obtained from [30] and are specifically referred to Swedavia Airport (Sweden).

In addition, the values of NO_x and UHC emissions for the PW150A engine have been deduced from Fig. 8 considering that the PW150A engine has 63% margin to CAEP6 for NO_x, i.e. 21.2 g/kN emissions, and 39% margin to CAEP6 for UHC, i.e. 5.6 g/kN emissions.

Table 5 Inputs for Navigation Charges and Landing Fees

Cost Driver	Value	Unit
Unit Rate of Charge	80.07	
C_{noise}	3.58	$/EPNdB
L_a	93.1	EPNdB
L_{fly}	78.3	EPNdB
L_{side}	84	EPNdB
T_a	89	EPNdB
T_d	82	EPNdB
$p_{CO2,free,p}$	43	%
$c_{t,CO2,m}$	18	US$

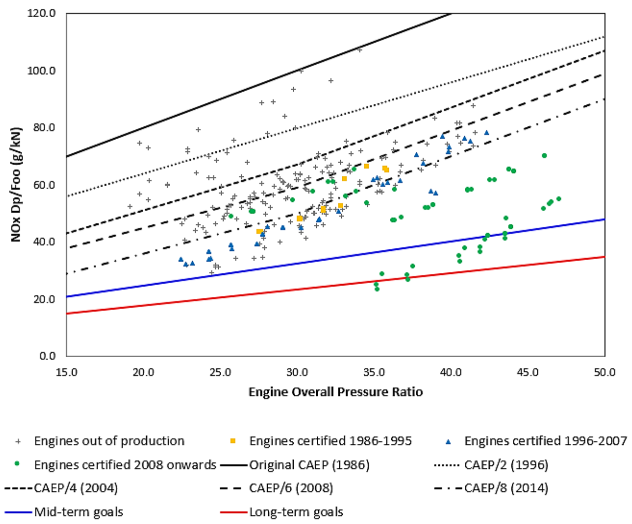


Fig. 8 Continuous improvement over time for engine NOX emissions performance [31]

4.1.2 DOC Results

The overall DOC per BH for the ATR90 vehicle is 3726.40 US$/BH in FY2018. From Fig. 9, which shows the final DOC breakdown, it can be noticed that for a conventional turboprop configuration great part of DOC is constituted by maintenance cost (considering Direct Maintenance Cost (DMC) and maintenance burden) which is strictly related to the high utilization in terms of BHs per year of this aircraft category. The relatively low fraction referred to fuel expenses is connected to the application at low ranges (i.e. 200 NM) which implies a reduced amount of block fuel.

In addition, from Fig. 9 it can be observed that noise and emission related charges constitute a negligible part of DOC. In particular, concerning noise charges, from Fig. 8 it can be noticed that the Engine Overall Pressure Ratio (OAPR) strongly influences NO_x emissions and, as a consequence, cost. In the present case, the PW150A engine is characterized by an OAPR of 18 and, therefore, the related NO_x emissions are low.

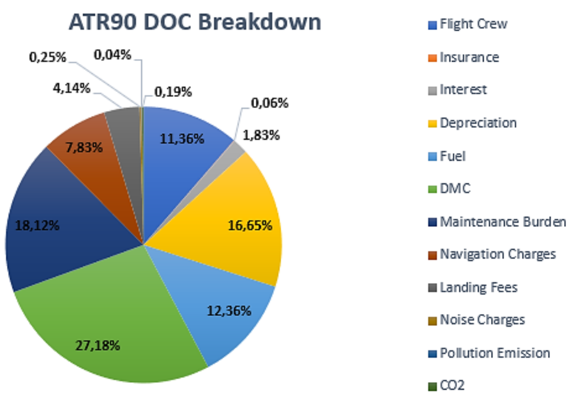


Fig. 9 DOC Breakdown for ATR90

Similar remarks apply to UHC emissions, which have been estimated starting from Fig. 8 too. The DOC results obtained in Fig. 9 have been compared with available DOC data other than the FAA data [14] used to choose between the available SoA CERs. In particular, data from Aviation Week [32] referred to ATR72 turboprop aircraft for FY2010 have been exploited. The proposed DOC methodology has been applied in order to verify whether the selected CERs correctly reproduce available costs from [32]. Fig. 10 shows both the available cost data (in US$/BH) for ATR72-500 and the calculated costs referred to FY2010.

It can be noticed that, as far as flight crew cost, aircraft cost (i.e. depreciation and interest), insurance, DMC, and fuel and oil expenses are concerned, the calculated costs are quite in line with available data. Concerning insurance cost, in order to align results, Eq. (1) has been applied considering insurance on an annual basis and not on the overall service life (i.e. *Period* has been assumed equal to 1 year).

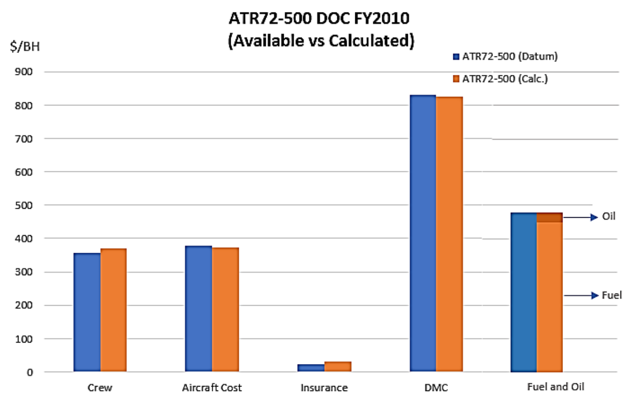


Fig. 10 DOC Evaluation for ATR72-500 aircraft

Moreover, the available fuel and oil cost has been verified assuming a fuel cost of 2.26 US$/gal for FY2010 and a fuel consumption of 201 gal/hour (i.e. block fuel), resulting in a fuel cost of 454.64 US$/BH. Subtracting the calculated fuel cost to the reference datum for fuel and oil costs (i.e. 479 $/BH), a cost of 24.36 $/BH for lubricant oil has been obtained. This value, representing almost 5% of fuel and oil expenses, is in line with Roskam [9] assumptions. Analyzing maintenance burden (not included into Fig. 10), it has been noticed that the guidelines reported in [15] (in which maintenance burden represents 40% of maintenance cost) lead to an overestimation of this cost item. Indeed, from the Aviation Week data [32], maintenance burden constitutes almost 19% of maintenance cost. It may suggest that maintenance burden depends on the aircraft category.

Once the methodology was validated, the costs calculated for ATR90 (see the breakdown of Fig. 9) and the available ATR72 costs have been compared (scaling ATR72 costs to FY2018). Results are shown in Fig. 11. It is underlined that, taking into account the outcomes of Fig. 10, some DOC items for ATR90 have been slightly modified in order to provide a more precise comparison. From the results of Fig. 11, the following remarks can be made.

- *Flight Crew Cost*: the results for ATR90 are in line ATR72 costs taking into account that they are both 2-crew aircraft.
- *Fuel Cost:* for fuel costs calculation it has been assumed a similar range (i.e. 200 NM for ATR90 and 192 NM as reported in [32]). Moreover, for ATR72 costs have been scaled

to FY2018 considering a fuel price of 2 US$/gal (as for ATR90).

- *Aircraft Costs:* the significant difference between ATR72 and ATR90 costs for this item are due to the higher acquisition cost of the ATR90 aircraft which, in turn, is strictly connected to the greater Operating Empty Weight.
- *Insurance:* for a better comparison of results, ATR90 insurance cost has been re-calculated exploiting the same assumptions on *Period* as for ATR72. As expected, the greater amount of insurance cost for ATR90 is due to its greater acquisition cost.

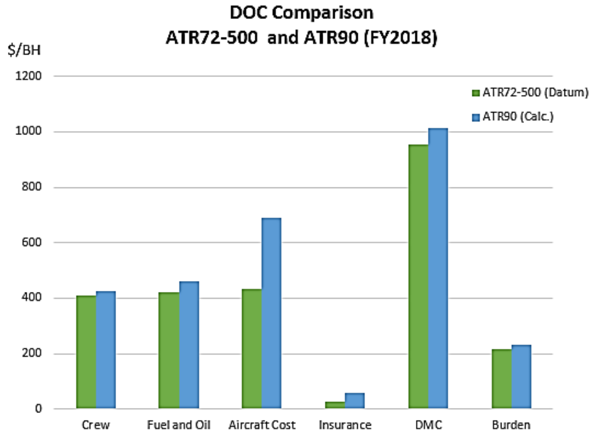


Fig. 11 DOC Comparison for ATR72-500 and ATR90 (FY2018)

- *Direct Maintenance:* as projected, DMC for ATR90 is greater due to its greater dimensions and engine power.
- *Maintenance Burden:* as for insurance cost, the maintenance burden for ATR90 has been re-calculated assuming that it constitutes almost 19% of maintenance cost.

4.2 Innovative Civil Regional Aircraft

As already introduced, two innovative concepts have been considered, i.e. the CS-2 Conventional and the CS-2 Innovative, in order to evaluate the effect of specific technological advancements on DOC. The CS-2 Conventional is characterized by an electrically actuated FCS with EMA and a hybrid ECS. The CS-2 Innovative has the same FCS as the CS-2 Conventional but it is provided with an electric ECS.

4.2.1 *Effect of an innovative ECS on Fuel Cost*

In order to assess the effect of the introduction of an innovative ECS configuration on fuel cost, the following equation from the NASA methodology [20] has been exploited:

$$\frac{\frac{\Delta DOC_f}{DOC_f}}{\frac{\Delta SFC}{SFC}} = \frac{m' \cdot A' \cdot e^{A' \cdot SFC}\left(D\,\frac{m_{Ft}}{MTOM} - 1\right) SFC}{\frac{m_{Ft}}{MTOM}\frac{m_{PL}}{MTOM} \cdot (B - De^{A' \cdot SFC})} \qquad (6)$$

Where:

$$m' = \left(\frac{m_{Ft}}{MTOM} + \frac{m_{PL}}{MTOM}\right) \qquad (7)$$

m_{PL} is the payload mass and SFC is expressed in $\frac{kg}{N \cdot hr}$. Moreover in Eq. (8):

$$A' = \frac{R_T}{0.162 \cdot a \cdot L/D \cdot M}(1 - bB) \qquad (8)$$

Where:

- R_T is the range (including climb, cruise, and descent);
- a is the speed of sound at cruise altitude expressed in miles per hour;
- *L/D* is the aerodynamic efficiency at cruise;
- *M* is the cruise Mach;
- *b* is a coefficient related to the range travelled at climb and descent and to the fuel used during climb (9.2 for ATR, see [20] for further details);
- *B* is the ratio of fuel used at climb ($m_{f,CL}$) to m_{fT}.

In addition, in Eq. (9):

$$D = 1 - (K_D + K_R) \qquad (9)$$

Where K_D is the descent fuel fraction and K_R is the reserve fuel fraction. The application of Eq. (6) using the ATR90 inputs provides a *Driver Partial* equal to 0.26. In order to determine the fuel cost saving (i.e. ΔDOC_F) the *Technology Projection* and the related *Technology Parameter Partial* shall be defined. Table 6 shows the values assumed for $\frac{\Delta TP}{TP}$ for bleed and power offtakes contributions for the two CS-2 concepts. The related values of $\frac{\Delta Dr/Dr}{\Delta TP/TP}$ can be found in Fig. 3. The final savings in fuel cost for both concepts are also shown in Table 6.

Table 6 Fuel Cost Savings

	CS-2 Conventional		CS-2 Innovative	
	$\frac{\Delta TP}{TP}$	ΔDOC_F, US$/BH	$\frac{\Delta TP}{TP}$	ΔDOC_F, US$/BH
Bleed	-50%	-31.20	-100%	-135.21
Power Offtakes	+50%	5.20	+150%	78.00
TOTAL	-	-26.00	-	-57.20

4.2.2 Effect of MEA and AEA architectures on maintenance cost

In order to apply the outcomes of the NASA study [23] introduced in Section 2.2.2 and to assess the impact of innovative subsystems architectures on DOC, the features of the CS2 aircraft described in Section 4.2 shall be compared with the main characteristics of the near- and far- term configurations studied in [23] and gathered in Table 1. Table 7 shows a comparison of the aircraft configurations in [23] and the IRON case studies. In particular, it can be noticed that both reference vehicles have similar characteristics in terms of flight controls and ECS. Similar remarks are valid for the CS-2 Innovative concept and the FTSP configuration. Different is the case of the CS-2 Conventional turboprop, which is not directly comparable to any introduced NASA configuration, being characterized by a hybrid ECS (which is not treated by NASA [23]).

Table 7 Comparison of NASA and IRON configurations

Configuration	Main Characteristics
NASA Reference ATR90 (IRON)	• Hydraulic FCS without fly-by-wire • Pneumatic ECS
FTSP (NASA) CS-2 Innov. (IRON)	• EMA and fly-by-wire; • E-ECS
CS-2 Conv. (IRON)	• EMA and fly-by-wire; • Hybrid ECS

At this point, the comparison of the NASA and IRON CS-2 configurations allows exploiting the maintenance costs savings introduced in Section 2.2.2. In particular, considering the similarities between the baseline concepts and between the CS-2 innovative aircraft and the FTSP configurations, it is assumed that the introduction of EMA and E-ECS would determine a 1% decrease in DOC due to (direct) maintenance cost decrease. Furthermore, considering the presence of the hybrid ECS (in conjunction with EMA and fly-by-wire), it has been assumed that a smaller decrease in maintenance cost would occur in the CS-2 Conventional configuration. In particular, a 0.7% decrease in DOC has been hypothesized. These assumptions have been applied to the ATR90 DOC results, considering the same DOC items treated in [23]. It is underlined that, as far as insurance cost is concerned, the value used for ATR90 is the same shown in Fig. 11. Results are shown in Fig. 12, which provides the DOC saving (due a decrease in maintenance cost) as a result of an increase in the degree of electrification of the aircraft. For sake of clarity, it is specified that, originally, the CS-2 Innovative concept is a 130-seat aircraft (not 90-seat as ATR90 and CS-2 Conventional). In account of this, in order to effectively evaluate the DOC saving due to electrification only, it has been assumed that the CS-2 Innovative aircraft is 90-seat too.

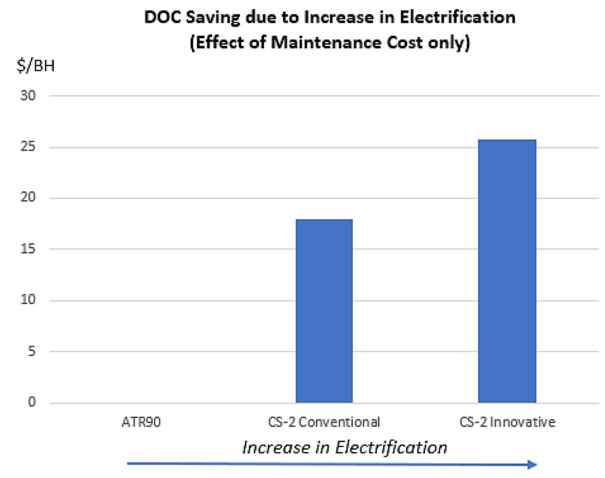


Fig. 12 DOC saving to an increase in electrification degree (Effect of maintenance cost)

5 IOC Results

Fig. 13 shows the breakdown deriving from IOC assessment exploiting the methodology described in Section 3. In particular, a range of 200 NM and a load factor of 85% have been assumed. The overall IOC amounts to 3076.17 US$/BH.

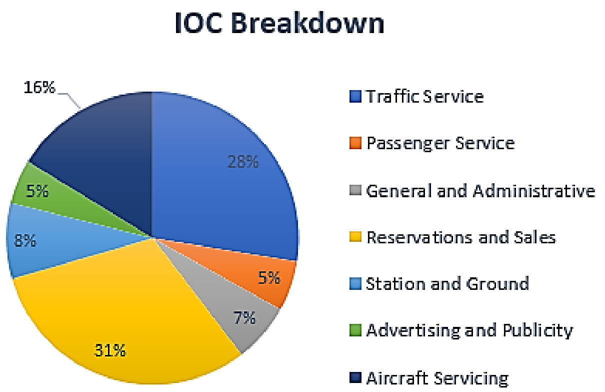


Fig. 13 IOC Breakdown

6 Tools Integration

The IRON Clean Sky II project expects the integration of the Leonardo preliminary design software, GRASM, and Costs tool, LICYA, which performes DOC estimations, developed by the authors (Politecnico di Torino). A part of integration procedure is an interface that has been implemented in Matlab® R2017a environment and compiled in order to be executed as stand-alone application.

As it is possible to see from Fig. 14, the interface performs three different tasks.

- Read the output file of GRASM.
- Write data in "LCC_estimation.xlsx".
- Initialize mass breakdown values as a percentage of MTOM.

As regards the first point, GRASM provides some relevant data such as OEW and fuel mass, range and emissions for LTO cycle. These data are written in different sheets of LICYA input file: "MassBreakdown" and "Operating". Concerning the "MassBreakdown" sheet, the interface defines also a first-attempt values of each item. The MTOM percentage for each item has been estimated as suggested in [10] and [33]. These values can be changed by user before the launch of LICYA.exe since the Excel® input file is not protected. Due to GRASM does not provide the value of MTOM, the column of the weights for each item is filled once the MTOM is specified.

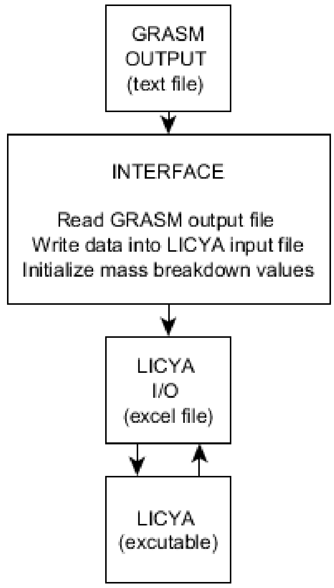


Fig. 14 Procedure for the GRASM-LICYA integration.

7 Conclusions

This paper provided a deep analysis on aircraft operating cost, focusing both on the definition of a proper methodology for operating cost assessment and on the evaluation of the effect of specific technological improvements on DOC. In conclusion, it has been observed that the introduction of innovative ECS technologies (i.e. hybrid and all-electric) significantly influence fuel expenses. Similarly, an increase in the degree of electrification of subsystems (in particular of ECS and flight controls) has a considerable impact on maintenance cost. As a result, a remarkable DOC saving in both cases is envisaged.

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