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Towards a methodology for new technologies assessment in aircraft operating cost

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Abstract: The need for a greener and competitive aircraft is leading to the use of new technologies. A thorough assessment of these technologies is mandatory from the initial phases of aircraft design to understand their feasibility and to select the most promising one both in terms of performances and in terms of costs. This paper proposes a methodology to assess the operating cost of innovative technologies for regional aircraft. In particular, two NASA studies have been adapted to determine the impact onto costs of MEA and AEA technologies and advanced ECS solutions for two innovative regional aircraft concepts developed during the European Clean Sky 2 research. The proposed methodology is able to assess the effect of on-board systems electrification level in terms of fuel and maintenance costs savings. The methodology, which allows to evaluate the effect of specific technological improvements onto costs, is applied exploiting the results provided by a reliable cost model and gives the opportunity to quantify operating cost savings for different regional aircraft. Applying the modified cost model to the reference aircraft under study, savings ranging from 1.6 to 3.1 % of direct operating cost are estimated for MEA and AEA technologies. Greater savings are estimated for the individual cost items involved. More specifically, a reduction of fuel cost ranging from 6 to 14.5% is envisaged as a consequence of the lower SFC associated to innovative ECS technologies.

Keywords: parametric cost estimation, operating cost, more electric aircraft, technology assessment

Acronyms

AEA	All Electric Aircraft
ASK	Available Seat Kilometer
ATA	Air Transport Association (of America)
BH	Block Hours
CER	Cost Estimating Relationship
CO2	Carbon dioxide
CS-2	Clean Sky 2
DMC	Direct Maintenance Cost
DOC	Direct Operating Cost
E-ECS	Electric Environmental Control System
ECs	Emission Certificates
ECS	Environmental Control System
EMA	Electro-Mechanical Actuator
EU	European Union
FAA	Federal Aviation Administration

FC	Flight Cycle
FCS	Flight Control System
FTFC	Far-Term Flight Controls
FTSP	Far-Term Secondary Power
FY	Fiscal Year
HC	Hydrocarbon
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IOC	Indirect Operating Cost
IRON	Innovative turbopROp configuratioN
MEA	More Electric Aircraft
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NOx	Nitrogen oxides
NTFC	Near-Term Flight Controls
NTSP	Near-Term Secondary Power
OAPR	Engine Overall Pressure Ratio
RPM	Revenue Passenger Mile
SOTA	State of the Art
TOC	Total Operating Cost
UHC	Unburned Hydrocarbons

Symbols

a	[m/s] speed of sound at cruise altitude
b	coefficient related to the range travelled at climb and descent and to the fuel used during climb
B	[-] the ratio of fuel used at climb and total fuel
$C_{A/F}$	[$] airframe cost
C_{DEP}	[$] aircraft depreciation cost
C_{E}	[$] engine cost
C_{F}	[$] fuel cost
C_{INS}	[$] insurance cost
C_{INT}	[$] interest cost
C_{noise}	[$/EPNdB] noise charge
C_{TOT}	[$] total aircraft acquisition cost
$D_{P\ A/F}$	[year] airframe depreciation period
$D_{P\ E}$	[year] engine depreciation period
DOC_{BL}	[$] baseline direct operating cost
D_{r}	Driver parameter
K_{D}	[%] Descent fuel fraction
K_{R}	[%] Reserve fuel fraction
I_{p}	[year] timeframe of insurance coverage
IR	[-] Interest rate

L_a	[EPNdB] Noise level measured at approach measuring certification point
L_{Fly}	[EPNdB] Noise level measured at fly over measuring certification point
L_{Lat}	[EPNdB] Noise level measured at lateral measuring certification point
L/D	aerodynamic efficiency at cruise
M	[M] Mach number at cruise
m'	[-] sum of payload and fuel masses divided by MTOM
m_{fCL}	[kg] mass of fuel used during climb
m_{fCR1}	[kg] fuel mass at cruise beginning
m_{fCR2}	[kg] fuel mass at end of cruise
m_{fT}	[kg] mass of block fuel per flight
m_{PL}	[kg] payload mass
MTOM	[kg] Maximum Take-Off Mass
R_T	[km] aircraft range
SFC	$[\frac{kg}{N \cdot hr}]$ Engine specific fuel consumption
T_a	[EPNdB] arrival threshold
T_d	[EPNdB] departure threshold
TP	Technology parameter
U	[h] aircraft annual utilization
V_{CR}	[m/s] cruise speed
V_{RES}	[$] aircraft residual value
$V_{SP\ A/F}$	[$] value of airframe spares
$V_{SP\ E}$	[$] value of engine spares
ΔDOC	[$] operating cost change compared to baseline direct operating cost
$\%debit$	Percentage of aircraft cost borrowed

1. Introduction

During the preliminary phases of aircraft design, it is required to select among different design alternatives considering diverse and often contrasting selection criteria. Among these, cost issues play a significant role in the definition of the most suitable and viable design option. In particular, an accurate estimation of the costs encountered during the aircraft life cycle allows the manufacturers and airlines companies to have an overview of envisaged expenses in order to invest their capitals in a safer way. A reliable cost estimation should identify the aircraft configuration which increases profitability and market competitiveness. A thorough cost analysis should also evaluate the overall resources involved in the entire product lifecycle, considering development, production, operation and disposal phases. This analysis is required in the framework of IRON (Innovative turbopROp configuratioN) research [1] in the context of Clean Sky 2 (CS-2) European research program. The goal of this public-private partnership is to develop innovative technologies able to reduce CO2 and NOx emissions, noise levels, aiming at decreasing the overall cost of regional transport aircraft.

In this context, a cost estimation model has to be developed in order to assess the impact onto costs of innovative technologies such as morphing wing, electric de-icing system, adaptive winglet, Electro-Mechanical Actuators (EMAs), hybrid Environmental Control System (ECS), innovative distribution of electric power and innovative Flight Control System (FCS). Therefore, from a technological point of view, the project deals with new subsystems architectures in line with MEA (More Electric Aircraft) and AEA (All Electric Aircraft) concepts [2]. It is well established that the exploitation of such advanced technologies provides a reduction of MTOM (Maximum Take-Off Mass) [3], [4] which is directly related to fuel savings, increased reliability, maintainability and reduced power losses. In particular, the hybrid ECS may allow a significant reduction in engine Specific Fuel Consumption (SFC) thanks to the decreased amount of bleed air extracted from the engine. Furthermore, in the field of FCS, EMAs require less maintenance effort in comparison to conventional hydraulic actuators, which need periodic checks for filter substitution and fluid level refill [5]. Eventually, MEA/AEA architectures permit to remove equipment such as hydraulic pipes and hot bleed air ducts, increasing the overall aircraft safety level [5].

Considering the advantages related to the technologies addressed in CS-2 Research, the final purpose of the analysis described in this article is to provide a cost estimating methodology to evaluate the impact of innovative technologies on aircraft operating costs, which represent the highest costs incurred during aircraft life cycle. Considering the need to provide flights at competitive prices for passengers, airlines are more interested than ever in low aircraft operating costs. Therefore, the methodology here proposed can be used during aircraft design to evaluate the impact on operating costs of different design alternatives in order to select the option associated to the lowest operating costs. Taking into account the great variety of technologies analyzed in CS-2 Research, the proposed methodology shall be flexible enough to adapt to the specific characteristics of the various innovative technologies analyzed in the project.

As far as operating costs are concerned, they are usually split up into Direct Operating Costs (DOCs) and Indirect Operating Costs (IOCs). The first cost item concerns flight operations costs (more specifically fuel, oil and crew costs), maintenance, depreciation, interest and insurance costs. Landing fees, carbon dioxide, NOx, noise emissions taxes and navigation charges are usually considered into DOC. On the contrary, IOC category comprises all the rest of operating expenses, such as traffic service, sales and customer service costs, administrative and overhead costs. Hence, in a more straightforward and intuitive definition, DOCs encompass such costs directly linked to the single operating aircraft while IOCs are more connected to the specific airline which operates the aircraft and not to the aircraft itself.

In order to evaluate DOCs, different State-of-the-Art (SOTA) methodologies based on airline statistical data are available in literature. These methodologies provide Cost Estimating Relationships (CERs) consisting in mathematical functions that connect several specific parameters, the so-called cost drivers, to the operating cost. One of the most hampering aspects in the evaluation of aircraft costs lies in the selection of the most suitable estimating method depending on the case study. In particular, the selected method has to deal with the lack of data in early development phase, it has to expose cost item related to available cost data and the calculation must be as accurate as possible.

In this field, the Air Transport Association of America's (ATA) method [6] represents the first standardized approach for the estimation of the DOC of subsonic jets. Dated 1967, it provides relationships to calculate flight-related operations costs (crew, fuel, oil and insurance), maintenance costs (including both airframe and engines) and depreciation (including spares). Moreover, DOC+I (DOC plus Interest) method from Liebeck [7] is another notable approach and it represents an updated version of the ATA method. DOC+I method, through its CERs, considers: flight and cabin crew cost, airframe and engines maintenance, landing fees, depreciation, insurance and interest. Other methodologies for DOC estimation are proposed by Association of European Airlines [8], Roskam [9], Jenkinson [10], NASA (National Aeronautics and Space Administration) [11], Sforza [12], and Chen [13].

Considering IOC, only few SOTA models provide CERs able to estimate the indirect contribution to operating cost. Roskam's method [9], for example, defines IOC as a percentage of DOC, with high dependency on block distance (i.e. taxi phase plus the distance travelled by the aircraft during a generic trip) and the type of aircraft. The method does not provide a detailed cost breakdown of IOC items, which is required in the IRON project. The great criticality of this methodology lies in the ratio among IOC and DOC, which could be unknown for an innovative airplane. On the contrary, in the methodology proposed by Sforza [12], the CER for IOC evaluation can be easily exploited being function of the range and the number of passengers carried per flight but it is not completely suitable to the purpose of this work because it includes all IOC items in a single formulation. IOC is not considered in this paper since the main purpose is the assessment of new technologies which are not directly responsible for IOC change.

The major limitation of SOTA methodologies is that they are outdated. The main disadvantage of using outdated models is that they are based on cost drivers which could be unable to address the effect of specific technological improvements on costs. In this context, the application of an escalation factor based on inflation rate cannot be suitable to update the CERs results. As a consequence, an updated methodology for operating cost estimation should be developed, properly considering the influence of technological improvements on costs. This requires a modification and an improvement of existing CERs. More specifically, considering that maintenance and fuel expenses are mostly affected by the introduction of new technologies, special attention has been devoted to assess the impact of technological advancements onto these two cost items starting from the CERs available from literature. To satisfy this purpose, the following technologies (analyzed in the frame of the IRON research) have been examined:

Standard versus more-electric systems architecture, strictly related to maintenance cost;

Innovative ECS architecture and its effect on fuel cost.

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 their impact on DOC. Section 3 describes the case studies and provides the DOC evaluation for the selected baseline configuration, including the effects of technological improvements. Eventually, Section 4 draws the main conclusions of the work suggesting future developments.

2. DOC assessment and technological improvements evaluation

The DOC methodologies introduced in the previous section have been carefully compared in order to determine which of the proposed CERs provide the best results in comparison with the available reference data. Through this analysis, it has been possible to understand if a certain SOTA methodology provided results most in line with the real values. The following section reports the final selected CERs which have been included in the proposed methodology for DOC evaluation. The DOC cost items considered are the following: flight crew, insurance, depreciation, interest, fuel, maintenance, landing fees, navigation charges, noise and pollutant emission related charges.

2.1. CERs for DOC Assessment

As far as flight crew and insurance costs are concerned, in order to select the CER able to provide the most accurate values, all the available CERs for both cost items have been deeply analyzed comparing their results with the data provided in [14]. As listed in Table 1, Federal Aviation Administration (FAA) gives some guidelines on typical DOCs values for several aircraft categories (e.g. wide-body with more than 300 seats, narrow-body more than 160 seats, turboprop with more than 60 seats, and so forth).

Table 1. DOC breakdown for different aircraft categories [14].

Aircraft Category	**Fuel and Oil**	**Maint_enance**	**Crew**	**Total Variable**	**Depre_ciation**	**Rentals**	**Insur_ance**	**Other**	**Total Fixed**	**Total**
Wide-body > 300 seats	\$10,275	\$1,687	\$1,538	\$13,500	\$761	\$318	\$9	\$5	\$1,093	\$14,592
Wide-body ≤ 300 seats	\$5,719	\$1,343	\$1,174	\$8,236	\$522	\$328	\$10	\$6	\$867	\$9,103
Narrow-body > 160 seats	\$3,102	\$964	\$777	\$4,843	\$352	\$199	\$6	\$1	\$558	\$5,400
Narrow-body ≤ 160 seats	\$2,394	\$715	\$724	\$3,833	\$221	\$325	\$9	\$3	\$558	\$4,390
RJ > 60 seats	\$287	\$444	\$349	\$1,080	\$144	\$188	\$6	\$5	\$344	\$1,424
RJ ≤ 60 seats	\$145	\$468	\$379	\$993	\$59	\$179	\$6	\$3	\$248	\$1,240
Turboprop > 60 seats	NR	\$654	\$323	\$1,020	\$264	\$155	\$3	\$2	\$423	\$1,443
Turboprop 20-60 seats	\$310	\$250	\$258	\$818	\$265	\$107	\$0	\$9	\$382	\$1,200
Turboprop < 20 seats	\$1,050	\$175	\$850	\$2,075	\$0	\$479	\$241	\$167	\$888	\$2,962
All Aircraft	**\$2,322**	**\$754**	**\$688**	**\$3,764**	**\$244**	**\$270**	**\$8**	**\$4**	**\$526**	**\$4,289**

Considering also the strong influence of pilot salary onto flight crew cost, the latter has been evaluated as the product of the crew labor rate by the number of crew members. It is worth noticing that this cost could vary depending on the operating geographical area, the airline and the type of aircraft. The specific figure selected as crew labor rate for the regional aircraft case study is an estimated average obtained from reference data [14] and will be discussed in Section 3.

Regarding insurance cost (C_{INS}), it has been determined as follows:

$$C_{INS} = 0.0035 \frac{C_{TOT}}{I_p \cdot U} \left[\frac{\$}{BH}\right] \tag{1}$$

Where C_{TOT} is the total aircraft acquisition cost (including engines), I_p is expressed in years and it represents the timeframe of insurance coverage and U is the annual utilization in Block Hours (BH) per year. This formulation for insurance cost has been derived from the insurance cost equation available in [7]. In particular, it has been noticed that the results for insurance cost from all the analyzed SOTA models overestimated the cost data provided by FAA [14] for all aircraft categories. Conversely, thanks to a proper tuning of the coefficient in Eq. (1), it has been possible to obtain results more in line with the reference data.

Concerning aircraft depreciation cost (C_{DEP}), the following relationship suggested by the DOC+I method [7] has been used:

$$C_{DEP} = (1 - V_{RES}) \cdot \frac{C_{A/F}}{D_{P\ A/F}} + V_{SP\ A/F} \cdot \frac{C_{A/F}}{D_{P\ A/F}} + V_{SP\ E} \cdot \frac{C_E}{D_{P\ E}} \tag{2}$$

Where V_{RES} is the residual market value of the aircraft after the depreciation period, $C_{A/F}$ is aircraft cost minus engines cost and it can be found using Raymer's method [15], $D_{P\ A/F}$ is the airframe depreciation period,

$V_{SP\ A/F}$ is a factor which represents airframe spares value compared to total airframe price and $V_{SP\ E}$ is a factor which represents engine spares value compared to engine price (C_E), $D_{P\ E}$ is the engine depreciation period. For interest cost (C_{INT}) the following formulation has been selected:

$$C_{INT} = IR \cdot\ (\%debit \cdot C_{TOT}) \tag{3}$$

Where IR is the interest rate, $\%debit \cdot C_{TOT}$ is the fraction of aircraft acquisition cost paid by a bank or other financial organization. Since it is useful to obtain the cost per BH, the resulting value shall be divided by the interest period and the annual utilization (U) expressed in BH per year.

To estimate the fuel cost (C_F), Roskam's equation [9] is suggested. Maintenance cost can be estimated using the approach proposed in [16]. In particular, the method consists on the updating of a cost-estimating model proposed in 1966 that provided equations for the maintenance cost assessment. After that, the evaluation of the effect of technological improvements on maintenance costs is performed through CERs designed with NASA methodology [17]. This part of the model here described is one of the outcomes of this paper and it is deeply analyzed in the next section.

Landing fees can be obtained from Liebeck [7] and navigation charges from EUROCONTROL [18].

Since the purpose of CS-2 Program is based on aircraft environmental sustainability, the methodology here presented proposes a set of CERs able to estimate the impact of noise and emissions related charges on DOC. Actually, all the new technologies proposed in the framework of CS-2 have been conceived to reduce the polluting emissions, hence the proposed cost model has to assess the emissions charges to correctly evaluate each new technology. A suggested formula for the calculation of noise charges, proposed by the Commission of European Communities, is available in a specific directive [19]. This equation uses ICAO (International Civil Aviation Organization) certified noise levels [20] at approach (L_a), flyover (L_{Fly}) and sideline (L_{Lat}) certification points. Excluding Europe, only Japan, Korea Republic, Dominica and Iran are provided with airports actually applying noise charges. However, in the European Union (EU), where the above-mentioned directive [19] exists for noise charges calculation, there is not full alignment with this taxation methodology for all the European countries. Generally, when applied, noise charges are linearly dependent on noise level or on noise categories identified by a range of noise levels. Certain countries impose a surcharge to landing fee, this supercharge is related to aircraft noise category (based on ICAO certified noise level). Other countries apply a defined charge related to some utilization characteristics (type of aircraft, summer/winter, day/night, number of movements), in others cases the charge is directly proportional to the Maximum Take-Off Mass and at last, only in Sweden, Finland and Austria noise charges are estimated using the EU recommended [19] formulation.

Furthermore, the contribution to DOC, of charges related to nitrogen oxides (NO_x), hydrocarbons (HC) and CO2 emissions, can be assessed through the equations provided in [21]. It is important to note that some European airports (precisely in France, Germany, UK, Sweden and Switzerland), started to apply these pollutant emissions charges from 2018. These fees only concern NO_x and HC. No CO_2 emissions are taxed in Europe because, until now, airlines avoid this type of charges thanks to Emission Certificates (ECs) which allow them to emit 1 tons of CO_2 within the current year [21]. Generally, aircraft operators can cover their CO_2 emission with ECs, so that no fines have to be paid. Nevertheless, in case that ECs do not cover its overall emissions, the operator has to pay, since 2008, a tax of 100 € per ton of CO_2. In the methodology proposed, the charges for NOx and HC are calculated using [21] equations, obtained by analyzing the charges payed by the 36 most used aircraft models in the 50 busiest airports in the world in 2010. In order to have a complete overview, CO_2 emissions have also been calculated from [21], exploiting a formulation which considers that in future a percentage of CO_2 emissions will be no more covered by the ECs.

2.2. Evaluation of the technological improvement

This section analyses the effect of technological improvements on DOC. In particular, it is quantified the effect of the adoption of an innovative ECS on fuel expenses and it is assessed the effect on maintenance cost due to the introduction of innovative MEA and AEA systems architectures.

2.2.1. Effect of an innovative ECS on fuel cost

In order to assess the impact of innovative technologies on fuel expenses, it is important to determine which aircraft components have a major influence on fuel consumption. ECS represents one of the most demanding systems with regard to power required. A conventional pneumatic ECS architecture exploits compressed air extracted from the engine using an opportune engine bleed port (high or low pressure) depending on operating conditions. The bleed air is then cooled in the ECS air packs to provide the required pressurized ventilation and air conditioning to the aircraft and maintain crew's and passengers' comfort. This kind of ECS is intrinsically inefficient [2], [3], [4], and the bleed of compressed air by engine compressor increases engine SFC. To avoid this and to increase overall system efficiency, the compressed air may be produced through a dedicated electric compressor when Electric-ECS (E-ECS) technology is applied. This kind of system is already present on Boeing 787. Another envisaged ECS technology is the hybrid ECS. This technology can be considered as a compromise between a traditional pneumatic ECS and an E-ECS. Figure 1 shows a comparison between conventional and hybrid ECS architectures. It can be observed that in the hybrid ECS, the air pack is fed both by the Low-Pressure Compressor (LPC) of the engine and by the dedicated electrical compressor to supply the required pressurized air.

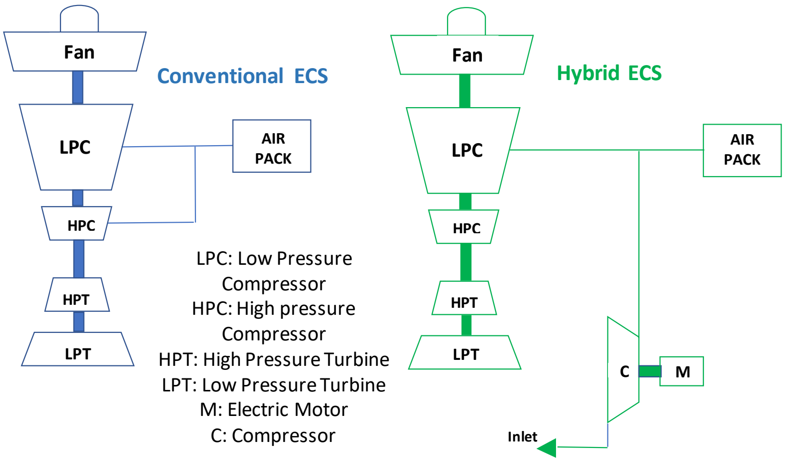


Figure 1: Conventional and Hybrid ECS architecture

To include the effect of these new type of technologies on DOC, the methodology proposed by NASA [17] is exploited. The rationale of this technique is summarized in Eq.4:

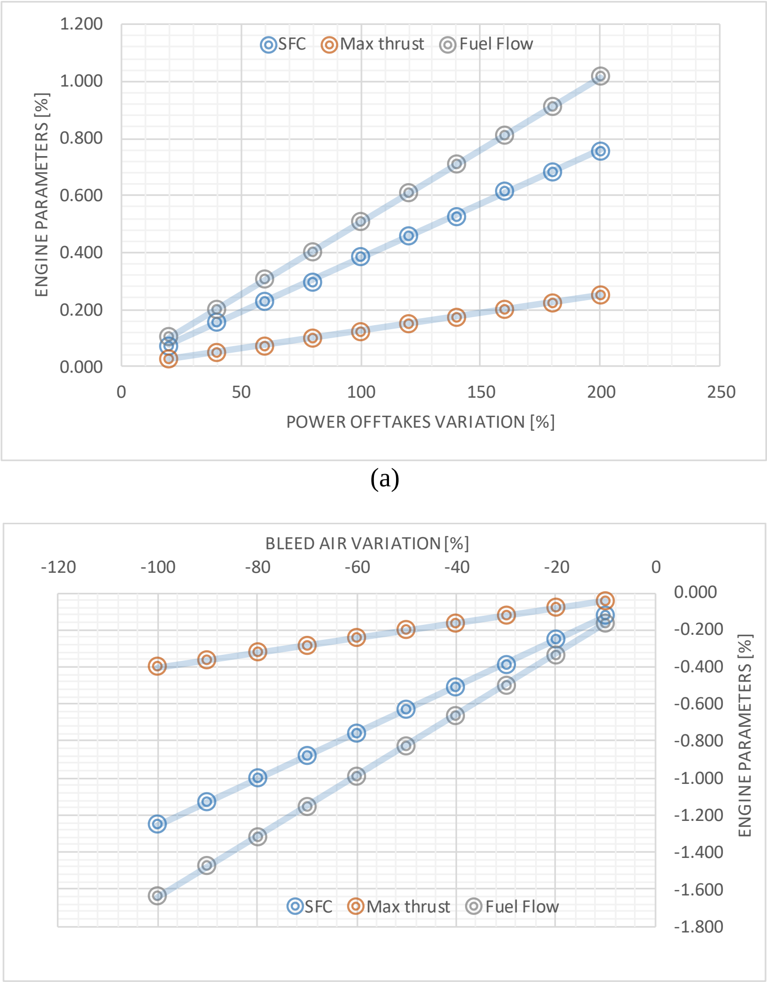
$$\Delta DOC_{ij} = DOC_{BL} \cdot \left(\frac{\frac{\Delta DOC}{DOC}}{\frac{\Delta Dr}{Dr}}\right)_i \cdot \left(\frac{\frac{\Delta Dr}{Dr}}{\frac{\Delta TP}{TP}}\right)_{ij} \cdot \left(\frac{\Delta TP}{TP}\right)_i \tag{4}$$

where from right to left:

- $\left(\frac{\Delta TP}{TP}\right)_i$ is the *technology projection* contribution, that is the foreseeable improvement in the technology parameter (*TP*). The latter is a low-level parameter such as, in the case of ECS, the percentage of bleed air;
- $\left(\frac{\frac{\Delta Dr}{Dr}}{\frac{\Delta TP}{TP}}\right)_{ij}$ is the *technology parameter partial* contribution, which represents the change of the jth driver parameter (*Dr*) due to the introduction of the innovative ith technology;
- $\left(\frac{\frac{\Delta DOC}{DOC}}{\frac{\Delta Dr}{Dr}}\right)_i$ is the *driver partial* contribution, that relates the DOC change to the variation of the jth *Dr*;
- DOC_{BL} is the value of the DOC item under study referred to a configuration selected as baseline which utilizes SOTA technologies;
- ΔDOC_{ij} is the change of a generic DOC item due to the ith innovative technology that has an effect on the jth *Dr*.

In order to exploit the NASA technique [17] to determine the impact on cost of the innovative technologies under analysis (i.e. Hybrid and E-ECS), the involved *Dr* and *TP* need to be identified. Examining the effect of the introduction of a Hybrid ECS within an aircraft, the first result is a decrease of bleed air extracted from the main engine. Secondary a simultaneous increase in mechanical power offtake required to drive the electrically driven compressor occurs.

Considering previous studies [3], [22] the impact on SFC of both bleed air and power offtakes is displayed in Figure 2. In particular, Figure 2(a) shows the relations between the mechanical power offtakes and the engine SFC, fuel flow and maximum thrust. The SFC interpolation states how an increase of power offtakes produces an inefficiency on the engine cycle and, hence, an increase in SFC. It can also be observed that if more power is extracted from the engine, a more powerful engine (with greater thrust) is required. This is due to the greater demand of fuel which increases the total fuel mass, thus increasing the total aircraft mass which in turns increases the engine thrust required. Likewise, Figure 2(b) displays the same effects and results considering the bleed air extraction from the engine compressors. It is worth to note that the same tendency occurs: the engine inefficiency increases when more power is required. MEA/AEA systems configurations usually rely on engine bleed-less architecture. Therefore, when MEA/AEA architectures are compared with the conventional ones, the bleed air can be considered totally removed (it corresponds to -100% of bleed air in Figure 2 (b)). At the same time, considering Figure 2(a) the MEA/AEA configurations correspond to the points in the graph with +200% of power offtakes. Investigating the net effect of these two contributions, the outcome is a reduction in SFC for MEA/AEA architectures. This because in E-ECS, the disadvantage of greater power offtakes is compensated and surpassed by the advantage in efficiency of a bleed-less architecture.



(a)

(b)

Figure 2: Consequences on SFC, Max Thrust and Fuel Flow for different type of ECS architectures [3].

Starting from these considerations, the effects of different ECS architectures on SFC have been considered by opportunely applying the NASA approach [17]. In particular, the terms of equation n.4 can be reviewed as follows:

- The *TP* is the quantity of bleed air provided by the aircraft engine;
- $\frac{\Delta TP}{TP}$, i.e. the *technology projection* contribution is the reduction in bleed air (which, on the contrary, corresponds to a necessary increase in mechanical power offtake [3]);
- The D_r is the engine SFC on which the *TP* operates;
- $\left(\frac{\frac{\Delta Dr}{Dr}}{\frac{\Delta TP}{TP}}\right)_1$ the *technology parameter partial* n.1 represents the decrease in SFC due to a decrease in bleed air;
- $\left(\frac{\frac{\Delta Dr}{Dr}}{\frac{\Delta TP}{TP}}\right)_2$ the *technology parameter partial* n.2 represents the increase in SFC due to an increase in mechanical power offtake;

- $\frac{\frac{\Delta DOC}{DOC}}{\frac{\Delta Dr}{Dr}}$ the *driver partial* contribution represents the decrease in C_F due to engine SFC decrease;
- ΔDOC_{ij} is the change in DOC due to C_F reduction;
- DOC_{BL} is the DOC with a C_F calculated for an aircraft selected as reference and implementing the SOTA technologies (i.e. conventional ECS architecture).

Therefore, the next step is to quantify the contributions of equation n.4. In particular, C_F for DOC_{BL} can be calculated utilizing the equation proposed in Section 2.1. The *technology projection* can be determined considering a certain variation in the percentage of bleed air and assuming a 100% of bleed for the baseline configuration. After that, through the graph in Figure 2 (b) the percentage variation in SFC compared to the baseline can be estimated. However, an adjustment is necessary to consider the variation in SFC due to the power offtakes (reported in Figure 2 (a)) as well. The aggregate information is constituted by two distinct *technology parameter partials* (i.e. the decrease of SFC due to the decrease in bleed air percentage and the increase in SFC due to the increment in mechanical power offtakes).
More specifically, from [20] the *D_r* can be expressed as:

$$\frac{\frac{\Delta C_f}{C_f}}{\frac{\Delta SFC}{SFC}} = \frac{\partial C_f}{\partial SFC} \cdot \frac{SFC}{C_f} \tag{5}$$

Where:

$$\frac{\partial C_f}{\partial SFC} = \frac{\partial C_f}{\partial \frac{m_{fT}}{MTOM}} \cdot \frac{\partial \frac{m_{fT}}{MTOM}}{\partial SFC} \tag{6}$$

Where m_{fT} is the block fuel used per flight. It is worth noting that, in Eq. (6) $(\partial\, m_{fT}/MTOM\ )/\partial SFC$ can be obtained from the Breguet range equation:

$$R_{CR} = \frac{L/D}{SFC} \cdot V_{CR} \cdot ln \frac{m_{fCR1}}{m_{fCR2}} \tag{7}$$

Where m_{fCR1} and m_{fCR2} are, respectively, the fuel mass at the beginning and at the end of cruise. V_{CR} is the cruise speed. For the complete description of the elements of equation n.7, see [20].

2.2.1. Effect of MEA and AEA architectures on maintenance cost

In order to determine the maintenance benefits (in terms of cost savings) related to the introduction of MEA and AEA system architectures, the final result of NASA study performed by Howison and Cronin [23] is exploited. Specifically, the analysis of NASA's research is focused on the effects of advanced electric/electronic technologies onto DOC. Particularly, it introduces a reference aircraft concept and several near/far -term configurations (characterized by innovations into flight controls and air conditioning system). Table 2 lists the definitions and the main features of the aircraft configuration discussed in [23]. Looking at the innovative technologies mentioned in Table 2 it is possible to note that these are in line with the advanced technologies envisaged within the IRON project. For the innovative configurations in 2, the NASA report [23] provides the percentage of DOC savings in terms of fuel, maintenance, depreciation, and crew costs linked to technological advancements in the afore-mentioned subsystems. From Figure 3 it can be observed that great part of DOC savings is related to fuel expenses. However, also the maintenance cost is investigated and the NTSP (Near-term Flight Controls) and FTSP (Far-term Flight Controls) configurations are associated to a 0.5% and 1% DOC saving respectively. Similar DOC savings are linked to depreciation costs, while crew costs savings are almost negligible.

Table 2. Reference Innovative configurations introduced in [23].

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

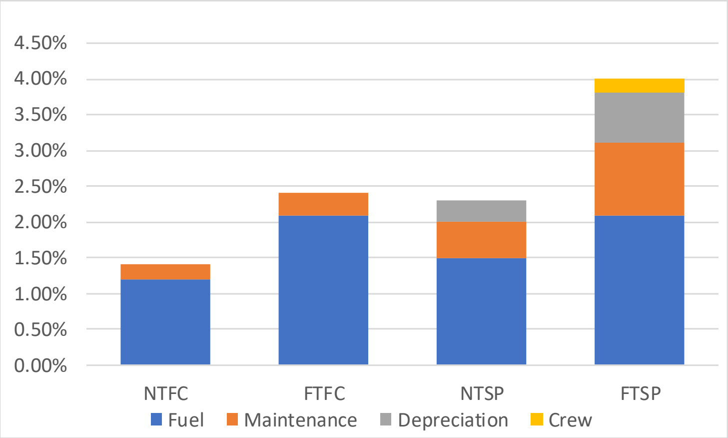


Figure 3: DOC savings for different innovative configurations.

3. Application of the methodology

The DOC methodology proposed in Section 2 has been applied to CS-2 IRON Project reference aircraft which consists in:

- a conventional civil regional aircraft with a 90-seat configuration characterized by high wing and wing-mounted engines, i.e. a hypothetical ATR90 (Figure 4);
- a MEA concept with a conventional configuration, i.e. CS-2 conventional aircraft (in this case it is possible to take as reference Figure 4 as well) with more electric on-board systems;
- an AEA concept with innovative configuration. This regional aircraft named CS-2 Innovative (Figure 5) has low wing configuration, engines mounted in the fuselage aft section and all electric on-board systems.

Since MEA and AEA configurations represent innovative concepts, the techniques presented in Section 2 allowing to evaluate the effects on DOC (in particular, fuel and maintenance costs) of technological advances have been applied.

Figure 4: Aircraft with Conventional Configuration (ATR90 and CS-2 Conventional).

Figure 5: Aircraft with Innovative Configuration [26].

3.1. Conventional regional aircraft

The baseline vehicle selected for DOC assessment, named ATR90, can be considered a stretched version of the ATR72-500 turboprop. The aircraft installs two wing-mounted engines similar to PW150A. The on-board systems architecture can be deemed conventional. It is composed of a pneumatic ECS, hydraulically driven FCS and landing gear without the use of fly-by-wire technology. The EPGDS (Electrical Power Generation and Distribution Systems) is assumed conventional and the engines represent the main source of secondary power.

3.1.1. Inputs for DOC assessment

In order to evaluate the DOC of the baseline vehicle, it is adopted the DOC assessment methodology reported in Section 2.1. The cost of the crew is obtained by multiplying the number of crew members by the value of 212 US$/BH (FY2018) which is the average crew labor rate deduced from MIT (Massachusetts Institute of Technology) data [27]. In particular, the data in [27] are referred to FY2016 but a mean value has been extracted and scaled to 2019. The resulting mean value (referred to narrow body and widebody aircraft) has been reduced by 50% considering flight crew costs for turboprops provided by FAA [14]. Furthermore, Table 3 displays the main inputs for C_{INS} , C_{DEP} and C_{INT} evaluation. C_{INS} is calculated through Eq. (1) defined in Section 2.1. Regarding C_{DEP}, it is calculated adopting the inputs suggested by Liebeck [7]. C_{INT} is calculated using equation n.3. Moreover, in order to obtain the fuel cost through Roskam [9] equation, a fuel price of 2 $/gal coming from IATA has been chosen [28]. As far as maintenance cost is concerned, the inputs required by the methodology proposed in [16] are reported in Table 4.

Table 3. Inputs for Insurance, Depreciation and Interest costs.

Cost Driver	**Value**	**Unit**
Period (Interest and Depreciation)	25	years

Annual Utilization	2200	BH/year
Insurance 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

Regarding landing fees and navigation charges, all the main inputs are reported in Table 5. The unit rate of charge for navigation charges calculation is referred to Italy [29] due to the specific request of IRON project. Nevertheless, the values of C_{noise}, T_a and T_d for noise charges have been obtained from [30] that represent a good example of implementation of the formula proposed in Recommendation ECAC/24-1 of Commission of European Communities.

In addition, in order to consider pollutant gas emissions, the values of NO_X and HC emissions for the PW150A engine have been derived from Figure 6 considering that PW150A engine has 63% margin to CAEP6 for NO_X, i.e. 21.2 g/kN emission, and 39% margin to CAEP6 for HC, 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$

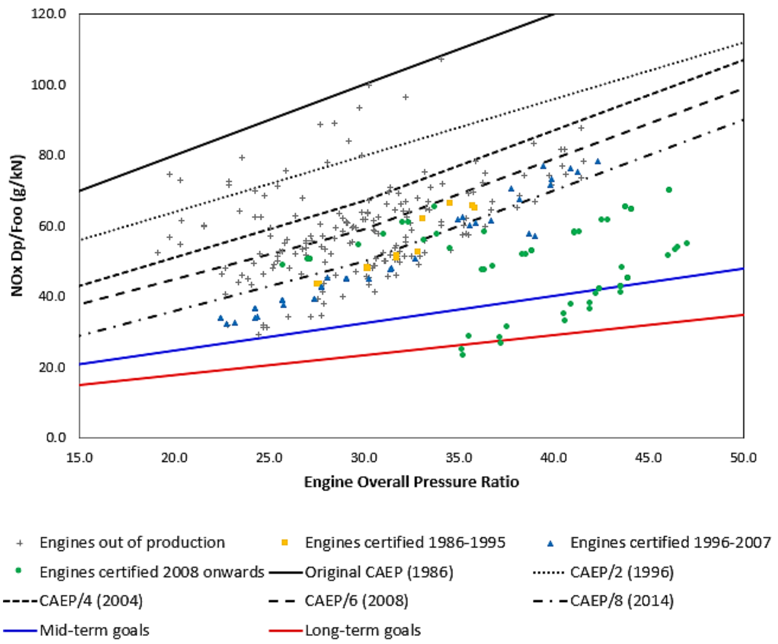


Figure 6: Continuous improvement over time for engine NO$_X$ emissions performance [31].

3.1.2. DOC results

The total DOC - calculated per BH - for the ATR90 baseline vehicle is 2808 US$/BH considered in FY2019. Figure 7 displays the final DOC breakdown. The greater part of DOC is constituted by maintenance cost (considering Direct Maintenance Cost - DMC and maintenance burden). This could be due to the relatively high complexity (presence of gearbox and propeller) of turboprop engine that required additional maintenance tasks compared to turbofan. Moreover, turboprop engines are usually more efficient (i.e. lower SFC) compared to turbofan engines and this leads to a relatively low fuel expense. Furthermore, Figure 7 proves that noise and emission related charges constitute a negligible part of DOC at the moment. Particularly, regarding emission charges, from Figure 6 it is possible to observe that the Engine Overall Pressure Ratio (OAPR) deeply influences NO$_X$ emissions and, as consequence, operating cost. The baseline ATR90 vehicle is supposed to have two PW150A engines, which are characterized by an OAPR of 18. From the trend of Figure 6, considering engines certified after 2008, it is clear that they produce lower NO$_X$ emissions.

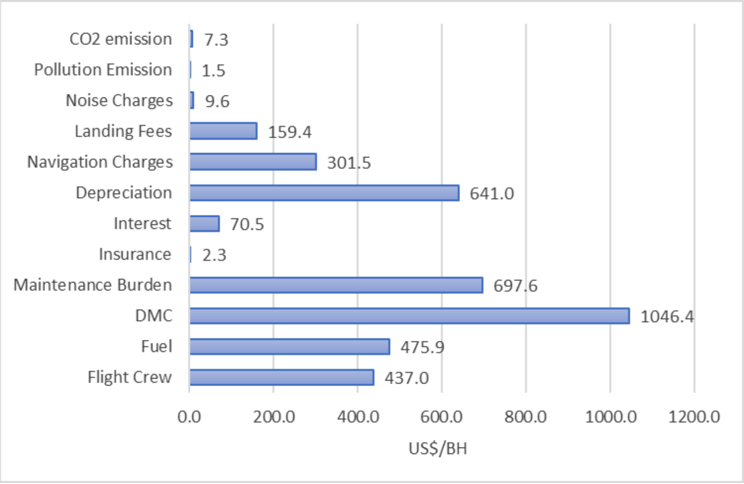


Figure 7: Complete DOC Breakdown for ATR90 baseline aircraft

Regarding UHC (unburned hydrocarbons) emissions, it is possible to adopt similar considerations as for NO_X. Indeed, this type of emissions have been evaluated starting from Figure 6 as well.

In order to choose the best solution among the available SOTA CERs, DOC outcomes obtained in Figure 7 have been compared with available DOC data from literature. More precisely, data from Aviation Week [32] concerning ATR72 turboprop aircraft for FY2010 have been used. Thus, the suggested DOC methodology has been employed to verify whether the selected CERs accurately reproduce available costs contained in [32]. Table 6 reports both the available cost data (in US$/BH) for ATR72-500 and the calculated costs referred to FY2010. It is possible to notice that, as far as flight crew cost, aircraft cost (i.e. depreciation and interest), C_{INS}, DMC, fuel and oil expenses are concerned, the calculated costs are almost in line with available data except for C_{INS} (21.2% of estimating error). C_{INS} has been estimated using equation n.1 which represent the model that is more in line with real cost data. In this case, to make the comparison worth, C_{INS} calculation has been considered on annual basis (i.e. I_p has been supposed equal to 1 year). Despite the notable estimating error, in absolute terms, C_{INS} represents a negligible cost item compared with the other DOC items.

Table 6. DOC Evaluation for ATR72-500 aircraft as reference. Calculated costs are compared with actual cost (FY2010) showing the estimating error.

DOC main items	**Actual data US$/BH FY2010**	**Estimated cost US$/BH FY2010**	**Estimating error %**
Crew	356	356	0
Fuel and oil	479	455	5.3
Aircraft Cost	379	374	1.4
Insurance	24	30	21.2
Direct maintenance	830	800	3.7

Furthermore, fuel & oil cost data available in [32] have been verified assuming a fuel cost of 2.26 US$/gal for FY2010 and a fuel consumption of 201 gal/hour (i.e. block fuel), corresponding to a fuel cost of 454.64 US$/BH. Then, by subtracting the calculated fuel cost to the reference datum for fuel and oil costs reported in [32] (i.e. 479 US$/BH), it has been possible to obtain a cost of 24.36 US$/BH for lubricant oil. It can be noticed that this value corresponds to almost 5% of fuel and oil expenses and this percentage is in line with Roskam [9] assumptions. From Aviation Week data [32], maintenance burden represents nearly 19% of maintenance cost. After having validated the methodology, the costs calculated for the baseline vehicle ATR90 (available in the breakdown of Figure 7) have been compared with ATR72 costs (scaling ATR72 costs to FY2019). The results are listed in Table 7. It is important to point out that:

- $Flight\ Crew\ Cost$: the outcomes for ATR90 are in line with ATR72 costs supposing that both operate with two pilots at the same labor rate.
- $Fuel\ Cost$: for fuel cost estimation it has been assumed a similar range (i.e. 200 NM for ATR90 and 192 NM for ATR72 according to [32]). Furthermore, ATR72 costs have been reported in FY2018 taking into account a fuel price of 2 US$/gal (that is the same used for ATR90).
- $Aircraft\ Costs$: the substantial difference between ATR72 and ATR90 costs derives from the greater operating empty mass for ATR90 aircraft which leads to a higher acquisition cost.

- $Insurance$: in order to better compare the results among ATR90 and ATR72, ATR90 insurance has been re-calculated considering the same assumptions on period (1 year) exploited for ATR72. As expected, ATR90 presents a greater amount of insurance cost due to greater acquisition cost.
- $Direct\ Maintenance\ Cost$: ATR90 is linked to a greater DMC due to its greater dimensions.
- $Maintenance\ Burden$: due to overestimation in the proposed methodology, it has been necessary to adjust the maintenance burden assuming it around 19% of maintenance cost (exploiting [32]).

Table 7. DOC Comparison for ATR72-500 and ATR90 (FY2019)

DOC main items	**ATR72-500 US$/BH FY2019**	**ATR90 US$/BH FY2019**
Crew	421	437
Fuel and oil	435	476
Aircraft Cost	448	711
Insurance	28	58
Direct maintenance	981	1046

3.2. Innovative regional aircraft

As previously reported, two innovative concepts (i.e. the CS-2 Conventional and the CS-2 Innovative) have been analyzed with the aim to estimate the effect of specific technological advancements on DOC.

3.2.1. Effect of an innovative ECS on fuel cost

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

$$\frac{\frac{\Delta C_F}{C_F}}{\frac{\Delta SFC}{SFC}} = \frac{m' \cdot A' \cdot e^{A' \cdot SFC}\left(D\frac{m_{Ft}}{MTOM} - 1\right)SFC}{\frac{m_{Ft}}{MTOM}\frac{m_{PL}}{MTOM} \cdot \left(B - De^{A' \cdot SFC}\right)} \qquad (8)$$

Where:

$$m' = \left(\frac{m_{Ft}}{MTOM} + \frac{m_{PL}}{MTOM}\right) \qquad (9)$$

m_{PL} is the payload mass. Moreover, in equation 10:

$$A^{\prime} = \frac{R_T}{0.225 \cdot a \cdot L/D \cdot M}(1 - bB) \qquad (10)$$

Where:

- R_T is the range (including climb, cruise, and descent);
- a is the speed of sound at cruise altitude;
- 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 ATR90, see [20] for further details);
- B is the ratio of fuel used at climb (m_{fCL}) to m_{fT}.

Moreover:

$$D = 1 - (K_D + K_R) \tag{11}$$

Where K_D is the descent fuel fraction and K_R the reserve fuel fraction. Using as inputs the ATR90 data, through equation n.8 a $Driver\ Partial$ equal to 0.26 is obtained. After that, the $Technology\ Projection$ and the related $Technology\ Parameter\ Partial$ shall be defined. Table 8 displays the values supposed for $\frac{\Delta TP}{TP}$ for bleed and power offtakes contributions for the two CS-2 concepts. From Figure 3 it is possible to extract the related values for $\frac{\Delta Dr/_{Dr}}{\Delta TP/_{TP}}$. The savings in terms of fuel cost are available in Table 8 for both the advanced concepts.

Table 8. Fuel cost savings changing ECS technology.

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

3.2.2. Effect of MEA and AEA architectures on maintenance cost

In order to exploit the results of the NASA study [23] presented in Section 2.2.2 and evaluate the effect of advanced subsystems architectures on DOC, the characteristics of CS-2 conventional and innovative aircraft described in Section 3.2 have been compared with the main features of the near- and far- term configurations introduced in [23]. The latter are reported in Table 2. In particular, Table 9 displays the consistency between NASA aircraft configurations analyzed in [23] and the IRON case studies. It can be noticed that both reference vehicles (NASA and IRON) have similar features in terms of flight controls and ECS. Similar remarks can be done for CS-2 innovative concept and FTSP configuration. On the contrary, it is not possible to compare the CS-2 conventional turboprop with any introduced NASA configuration because an aircraft characterized by hybrid ECS is not analyzed in [23].

Table 9. Comparison of NASA and IRON configurations.

Aircraft Configuration	**Main Systems Characteristics**
NASA Reference ATR90 (IRON)	Hydraulic FCS without fly-by-wire Pneumatic ECS
CS-2 Conventional (IRON)	EMA and fly-by-wire Hybrid ECS
FTSP (NASA) CS-2 Innovative (IRON)	EMA and fly-by-wire E-ECS

At this stage, it is possible to compare the NASA and IRON CS-2 configurations in order to evaluate the savings in terms of maintenance costs introduced in Section 2.2.2. Specifically, considering the similarities between the CS-2 innovative and the FTSP aircraft, it is assumed that the use of EMAs and E-ECS would determine a 1% decrease in DOC due to a maintenance cost decrease (see FTSP column of Figure 3). Moreover, considering a hybrid ECS (operating with EMA and fly-by-wire) in the CS-2 Conventional configuration, it has been supposed that a smaller decrease in maintenance cost would happen. Particularly, a 0.7% of reduction in DOC has been hypothesized (from NTSP column of Figure 3). These assumptions have been applied to ATR90 DOC results, considering the same DOC items reported in [23]. It is highlighted that, as far as insurance cost is concerned, the value for ATR90 is the same as in Table 7. Final results are displayed in Figure 8, which provides the DOC savings (related to a decrease in maintenance cost) increasing the electrification level of the aircraft. For sake of clarity, it is observed that, originally, the CS-2 Innovative concept was a 130-seat aircraft (not 90-seats as ATR90 and CS-2 Conventional). Hence, in order to successfully estimate the DOC saving due to electrification only, the CS-2 Innovative aircraft has been treated as a 90-seat too.

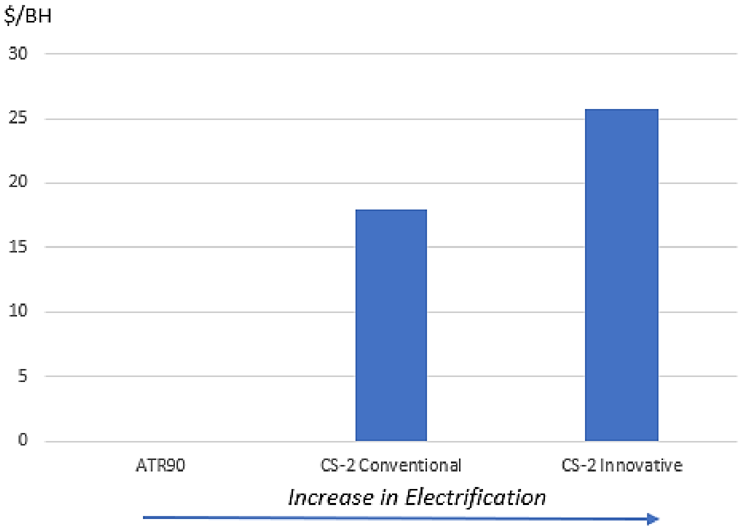


Figure 8. DOC saving due to an increase in electrification degree. Effect of systems electrification on maintenance cost.

3.2.3. Final assessment of new technologies included in CS-2 aircraft

Gathering the cost saving both in maintenance and in fuel cost, the final assessment of the new technologies included in CS-2 aircraft is achieved. As listed in Table 10 and 11 the systems electrification entails a sensible effect mainly on fuel cost and secondly on maintenance cost. The fuel cost is reduced by 6.1% and 14.5% respectively for CS-2 Conventional aircraft and CS-2 Innovative aircraft. The cost savings in terms of maintenance are smaller but not negligible as DMC is the most important DOC item in absolute terms (see Figure 9).

Table 10. Main DOC items for CS-2 aircraft compared to ATR90 (absolute terms)

DOC main items	**ATR90 US$/BH FY2019**	**CS-2 Conventional US$/BH FY2019**	**CS-2 Innovative US$/BH FY2019**
Crew	437	437	437
Fuel and oil	476	450	418
Aircraft Cost	711	711	711
Insurance	58	58	58
Direct maintenance	1046	1028	1020
Total	**2727**	**2683**	**2644**

Table 11. Main DOC items for CS-2 aircraft compared to ATR90 (relative terms)

DOC main items	CS-2 Conventional %	CS-2 Innovative %
Crew	0	0
Fuel and oil	6.1	14.5
Aircraft Cost	0	0
Insurance	0	0
Direct maintenance	1.8	2.5
Total	**1.6**	**3.1**

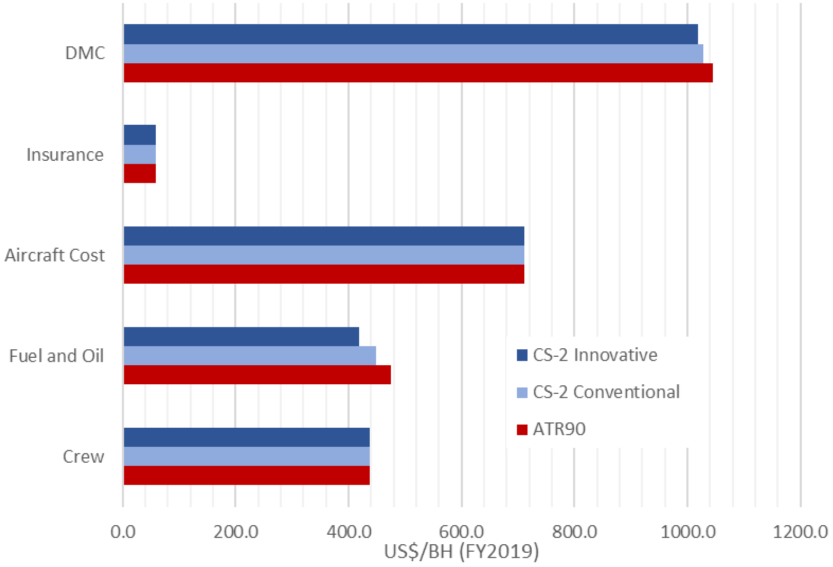


Figure 9. Comparison of main DOC cost items for ATR90 and CS-2 aircraft

4. Conclusions

This paper provides a methodology to evaluate the MEA and AEA technologies in terms of aircraft operating costs savings. In particular, the effect of an innovative ECS on fuel cost is assessed since the ECS plays a significant role in fuel savings. Contextually, the effect of electrified ECS and FCS is assessed in terms of maintenance cost as well. The feasibility of the methodology is proved by applying it to two innovative aircraft - proposed in the framework of IRON research – with two different systems electrification levels. However, the methodology could be applied to other aircraft categories. The results show a notable reduction of fuel cost ranging from 6 to 14.5%. Smaller savings are noticed on maintenance cost (from 1.8 to 2.5%) that, in absolute terms, are still notable due to the great importance of maintenance cost compared to the other DOC items.

The proposed methodology is limited to MEA and AEA technologies that represent the innovation on the systems branch. The methodology should be extended to other branches such as aerodynamics, structure design and propulsion. This ambitious perspective requires a proper definition of the main cost drivers and technology parameters involved (and the mathematical relationship between the two) for each branch but would allow to evaluate the overall impact on operating cost of the main new technologies domains proposed in the aeronautic context. Moreover, an extension to other costs of product lifecycle is to be expected. The capability to evaluate the effect on development and production costs is important to better assess the feasibility of new technologies even if the operating costs represent the greater part of aircraft life cycle cost.

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