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Conceptual Design and Operating Costs Evaluation of a 19-seat All-Electric Aircraft for Regional Aviation

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This paper presents a conceptual approach for the design of an all-electric short-range aircraft for regional aviation. By using the designed aircraft and based on market and financial assumptions, the operating costs were calculated, and by means of trade analysis, an investigation of the influence of few parameters was performed. As a result, the designed aircraft reached an estimated reduction of 39% in the Direct Operating Costs (DOC) considering a frequency of 4 daily flights. Reductions in fuel costs also reached up to 80% in comparison to the current turboprop segment. Moreover, the findings indicate that the maintenance and depreciation take most of the DOC cost for most of the daily flight frequency, with the battery replacement cost increasing significantly with the increase in the daily number of flights. By a sensibility analysis was also identified that variations in the battery life cycle and aircraft purchase price cause more significant changes in the DOC than other parameters considered that could carry uncertainties.

Nomenclature

AR	=	aspect ratio
Cl_{maxto}	=	takeoff maximum lift coefficient
COC	=	cash operating costs
C_{Energy}	=	energy cost
C_{Crew}	=	crew cost
C_{main}	=	maintenance cost
C_{Depr}	=	depreciation cost
C_{Ins}	=	insurance cost
C_{Int}	=	interest cost
C_{Fee}	=	fee cost
$C_{batt\,pack}$	=	battery pack replacement cost
DOC	=	direct operating costs
E_{bat}	=	battery energy density
LFL	=	landing field length
$MTOW$	=	maximum takeoff weight
ROC_{best}	=	best rate of climb
ROD	=	rate of descent
T/W	=	thrust-weight ratio
$TOGW$	=	takeoff gross weight
V_{to}	=	takeoff velocity
V_s	=	stall velocity
W/S	=	wing loading

I. Introduction

The potential benefits of electric propulsion for aircraft recently led to an increasing interest in this topic in the academic and industry environments. The greatest motivational factor for the public interest in electrification is

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the need to reduce the environmental impact [1], once aviation contributes with 3% of greenhouse gases, and 13% of overall climate impact [2]. Besides, there is also a promising potential significant reduction in operational costs, while improving efficiency, community noise, and propulsion system reliability [3].

The demand for commercial air travel has been rising in the past years, with projections indicating a growth ratio of 4-5% globally [4]. Together, the fuel costs also have been rising in a very volatile trend. Currently, around 22% of aircraft operating cost is related to the fuel [5], with General Aviation (GA) even exceeding this percentage due to a combination of poor aerodynamics and propulsion efficiency [3]. Thus, huge efforts are being applied in research in order to reduce this volatile percentage [3]. As a result, electric-powered aircraft has been pointed out as a potential key to solve these issues [1, 4] as well as reduce the impact of aviation in the environment. Several studies relate the feasibility of the electric aircraft to its huge dependence on improvements in battery energy density. Current battery energy capacity technologies required for a fully electric aircraft are considered not sufficient to be used for a large aircraft; however, they could be viable for smaller and short-range aircraft [3]. For this reason, this kind of technology could find a niche in the growing market, once much of the increased demand for commercial aviation is for short ranges [3, 6]. Thereby, this work will focus on small and feasible electric aircraft for regional aviation.

This paper is organized as follows: the first part presents the methodology, following with the assumptions taken for the problem definition as well as for the conceptual design. The second part consists of an overview of the conceptual design process, and motivations for most of the design decision making. It also presents the major design and geometry parameters of the conceptually designed aircraft. In addition, it describes the details of the mission profile and major assumptions for the flight analysis. The third part introduces the results and the associated graphics with discussions and analysis regarding the findings. Lastly, the conclusion provides an overview of the results related to the assumptions made.

II. Methodology

In order to investigate the financial benefits and operation nuances of a reference all-electric aircraft for short-range flights, an aircraft operating costs analysis following an established methodology detailed in Section VI. The core idea is to verify if the use of an all-electric aircraft in the proposed segment would be justified from the point of view of operating costs in comparison with traditional aircraft in service currently. For this, the following objectives have been calculated, analyzed, and evaluated by means of trade studies:

1) The influence of daily flights on operating costs;
2) The impact of motor maintenance reduction on overall operating costs;
3) The impact of the range for the same baseline configuration in the operating costs;
4) The influence of major assumptions on operating costs.

The assumption for the study is the result of an author's previous study based on developed regressions for technology status, as well as a literature review. One part of the analysis consisted of investigating the daily flights and range, once they are one of the major constrained parameters affecting the aircraft operating costs, as described in the following sections. The daily flights are related to the airline's ability to operate a few or many flights daily, considering the interval between each flight boarding and disembarking and refueling (in this case, recharging). The estimation and evaluation of the time between each flight considering the battery charging is out of the scope of this study, and therefore general assumptions will be made regarding that in order to evaluate the findings. The range was investigated in such a way that was possible to analyze in which mission profile it is more economically advantageous, considering the same reference aircraft. The main motivation for this investigation is the possibility of operating as tourism and on-demand flights, as per FAA CFR Part 135 regulations, in addition to commercial scheduled flights.

The other part of the analysis was related to the influence of some uncertainties regarding the electric technology, i.e., the expected reduction in maintenance costs, the battery pack cost, and battery lifetime in flight cycles. The motor maintenance reduction is an important consideration for the cost calculations once it is stated as one of the major benefits of aircraft electrification [1, 7]. Currently, according to the author's background studies, there is no available data for the maintenance reduction gains for the utilization of electric motors. For this reason, a trade analysis to evaluate these possible gains was considered. Investigations on the battery were also considered once the battery is the main technology abrupt change in the aircraft electrification. The battery development for aircraft application is in its early stages, and thus uncertainties can be carried for cost assumptions. For this reason, the lithium-ion battery cost and life cycles were considered for analysis.

In order to investigate the mentioned objectives, a reference aircraft is proposed and designed at a conceptual level. All decisions taken during the conceptual design took into account traditional and conventional aspects which led to a feasible aircraft in an engineering aspect. For the mission profile, a traditional takeoff-climb-cruise-descent segment with reserves was also considered. In order to support the mission determination, few performance parameters were employed, as detailed in Table 3. The operating cost calculations were employed mostly following a reliable methodology by NASA for transport aircraft. The motivation for the NASA method is due to its high application in academia as well as due to its recently formulation public availability. To that methodology, the cost of battery pack replacement by a proposed simplistic formulation was also added.

All mission analyzes performed in this work were employed using the SUAVE (Stanford University Aerospace Vehicle Environment) framework [8]. SUAVE is an open-source conceptual design environment that uses a physics-based approach instead of empirical correlations or approximations. In addition, the choice of SUAVE as a design and analysis tool was due to its extensibility for adding new features and routines while making small changes, as well as its available range of propulsion systems and analyzes capabilities. The assumptions are presented as an overview in Section III.

III. Assumptions

The market studies for the present work have been carried out by analyzing the current fleet of turboprop aircraft in service, future demands from several forecasts, and literature studies [3, 6, 9–11]. The results highlight the lack of innovation of current small turboprop and commuter for the transport segment. This indicates a current market niche in the 15-30 passenger segment for a range between 400 to 600 km for commercial and on-demand operations, which most aircraft were designed from decades ago. For on-demand flights, a short-range capability could be also interesting once around 77% of the on-Demand aviation trip demand relates to trips less than 370 km [3]. A 600 km upper limit for target range is also promising for this segment, once regional aviation represents about 40% of the commercial flights in 2015 with an average distance of 600 km in Europe [12], which the plane make ATR also highlighting that turboprop aircraft are airlines' preferred choice worldwide for distances up to 330 NM (611 km) [13].

From the point of view of regulations, an aircraft above 19 passengers as per FAA 14 CFR 121.391 Part 121, and FAA 14 CFR 135.107 Part 135 operation requirements are demanded to have one flight attendant for commercial operations and on-demand operations respectively, which can significantly increase operating costs. Therefore, a 19-passenger seat aircraft configuration was selected for this study. A traditional two-pilot configuration was also selected once the single-pilot operation is not allowed for scheduled operation and on-demand operating of ten seats or more, as per FAA 14 CFR Part 121.385 and FAA 14 CFR Part 135.99 respectively.

Due to the early stages of electric aviation and the Entry in Service (EIS) projected for the 2030s, a technology assessment over the major electric components must be done in order to evaluate the projection of the state of technology. For that, electric motors and batteries were considered. For the first one, the evaluation of current electric motors available for aircraft applications achieved a maximum power of 560kW for a single motor, and the a power density of 5.2 kW/kg for the most efficient in terms of weight and power [14, 15]. Despite this value may increase over the next years, the mentioned achieved power density was select in order to size the electric motor given the required power. For the battery, an Energy Density (E_{bat}) projection has been carried out by analyzing current status and future projections from several recent sources [1, 3, 16], so that it indicates a potential to achieve or even overcome a E_{bat} of 450 kWh/kg in 2030 for lithium-Ion batteries. The philosophy used in selecting the technology status of the battery was optimistic but maintaining the reality from the projections made by [10, 16, 17]. Thus, an E_{bat} of 450 kWh/kg was selected.

One of the major parameters that directly affect the design and must be early determined is the Takeoff Field Length (TOFL). For that, in order to explore the capabilities of the aircraft, a short field length is considered. Additionally to the utilization of bigger airports, a TOFL of 914 m capability could access around 900 and 500 airports in the United States and Europe respectively [18, 19]. Thus, the utilization of small airport fields in door-to-door operations in small cities could be vastly explored, and therefore a 800 m of TOFL was selected by considering safety margins.

Lastly, electric aircraft tends to be heavier than the conventional reciprocal configuration mainly due to the high weight of batteries. Considering the mentioned weight constraints from the certification regulations, there is a need for a lightweight structure. A full composite aircraft was not taken into account from the beginning due to the possibility of a significant increase in complexity, and compromising its feasibility considering a EIS for the 2030s. Instead, the consideration used in this project for lightweight structures derived from Nicolai ([20]) by applying components reduction factors in which about 55% of the composite utilization leads to the most cost and weight effectiveness. Together with the certification rules, the major assumptions described that will drive the project are organized as the Top

Level Requirements (TLR).

TLR	Values
PAX + Pilots	19 + 2
Payload, kg	1905
$MTOW$, kg	<8,618
TFL, m	800
Range, km	400-600

Table 1 Top Level Requirements.

IV. Aircraft Conceptual Design

The design of the reference aircraft was performed following the conceptual approach from Raymer, Gudmundsson and Roskam [21–23]. Initially, in order to estimate the Takeoff Gross Weight (TOGW), the buildup method was employed once it fastly estimates the TOGW with good accuracy [21]. Since the traditional calculations usually employ statistical data from fuel-burning engines, the battery and empty weight fractions were adjusted with data from electric aircraft designs developed in academia and industry recently. With the initial TOGW and battery fraction mass, the range was estimated using the Breguet's equation adapted for an electric flight from Raymer [21]. Initial results showed that for a TOGW of 8,300-8,600 kg, a 470-490 km of operational range with reserves can be achievable, considering a L/D of 19, W_b/W_0 of 0.39, E_{bat} of 450 kWh and 20% of battery capacity reserves.

Conjointly with the determination of the aircraft mission profile and TOGW, a constraint analysis was used in order to find the required wing area and required power for the design, meeting few performance requirements [22]. The power required and wing area are determined from the T/W and W/S ratio, respectively, with both being the most important parameters affecting the aircraft performance [21]. The required performance characteristics of interests were employed using mathematical expressions from [21, 22, 24] for each flight condition, i.e., takeoff, climb, cruise, turn, and landing. Initial analyzes demonstrated the lack of constraints for wing loading, making it difficult to choose a design point. By taking into account landing, cruise speed and Stall Velocity (V_s) constraints, a design space was found (Fig. 3), which represents a feasible region (above the takeoff curve) for the selected parameters. Once the variation of T/W is not significant inside the design space, the intermediate value of W/S was chosen. The results of design parameters from constraint analysis is summarized in Tab. 2, and it served as an input for the complete aircraft design on the next steps.

Description	Values
T/W	0.27
W/S, lb/ft^2	48
Cl_{maxto}	2.0
V_S, ft/s	140
Wing area, ft^2	376.2
Wingspan, m	22
Power, kW	1365

Table 2 Design parameters from constraint analysis.

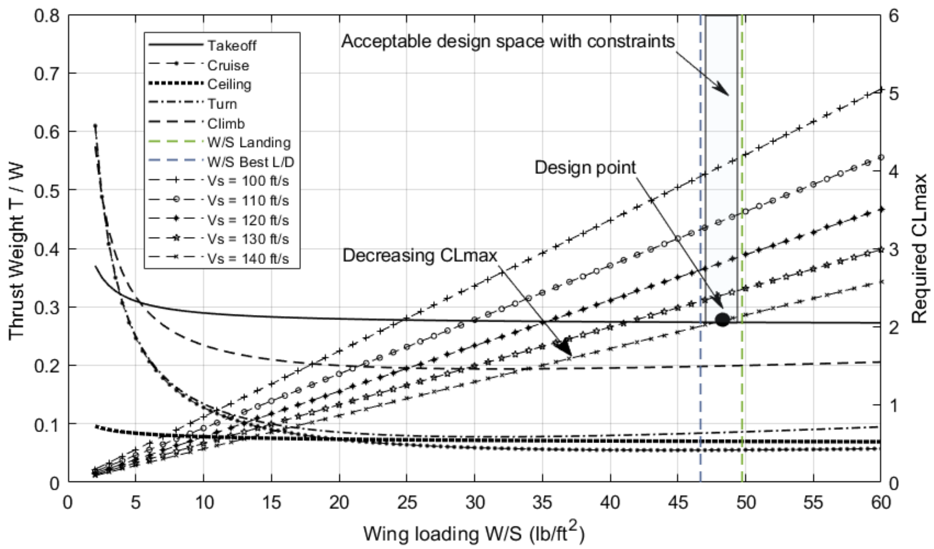


Fig. 1 Constraint analysis with stall speed variation.

The selected wingspan for the constraint analysis was fixed based on modern traditional and electric aircraft designs, as well as for meeting the cruise L/D required for the range of interest according to the analytical method proposed by Raymer for an estimate of the L/D. The Cl_{maxto} was based on the estimated gains according to Raymer for a single-slotted flap and its value, conjointly with the wing area. Its value is a result from a V_S of 140 ft/s (153 km/h) and $T/W = 0.27$. Lastly, from the constraint analysis presented in Fig. 1, the required power for takeoff is 1365 kW.

The decision of the main wing configuration consisted of analyzing low and high wing positions. The high wing configuration demonstrated the best approach regarding its flexibility, mainly for the utilization of 4 motors as well as for the uncertainties of the required propeller diameter and its distance from the ground.

The tail and fuselage sizing was based on traditional aircraft design. The fuselage design can be seen in Fig. 2, and major parameter considered for the fuselage design was the number passengers as well as the cabin dimensions. All cabin design parameters such as height, seat pitch and width, and the aisle dimensions were based on commuter segment standards from [22, 25, 26] and a 1-1 seat abreast arrangement was selected. Even without the consideration of a pressurized cabin, a conventional tube with a circular cross-section was selected for the fuselage due to its best cabin arrangement for a 19-seat configuration among other cross-sections, according to the author's studies. Without the need for luggage space for short-range commuter flights, the space underfloor was properly allocated for battery and systems. The major parameters for the designed fuselage are a diameter of 1.8m, a total length of 14.95m, and a 1.44m of height from the floor.

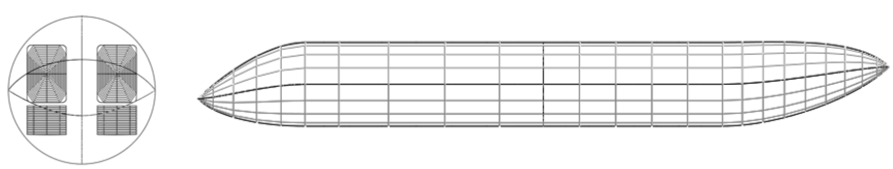


Fig. 2 OpenVSP model of the fuselage design.

Given the fuselage length, the horizontal and vertical stabilizers were designed following the sizing process from Raymer as well as using reference data for commuter aircraft from Roskam. The key decision for the selection of the tail configuration was the location of the horizontal tail with respect to the wing in order to prevent the loss of control in stall characteristics, as means of the estimated method proposed by Raymer. Thus, as can be seen in Fig. 4 the complete aircraft, for the proposed high-wing, a conventional low-horizontal tail configuration attached to the rear cone was selected to prevent the wing wake.

Considering the mission defined in Section V, the reference aircraft weight breakdown was performed using SUAVE's standard component weight calculations (by methodologies from [27, 28]) as well as from assumptions from Section III. As expected in electric aircraft concepts, the battery represents a great part of the TOGW being around 55% of the empty weight and 26% of overall weight, as can be seen in Fig. 3. For all cost analysis performed and described in Section VII, the same aircraft weight breakdown was used.

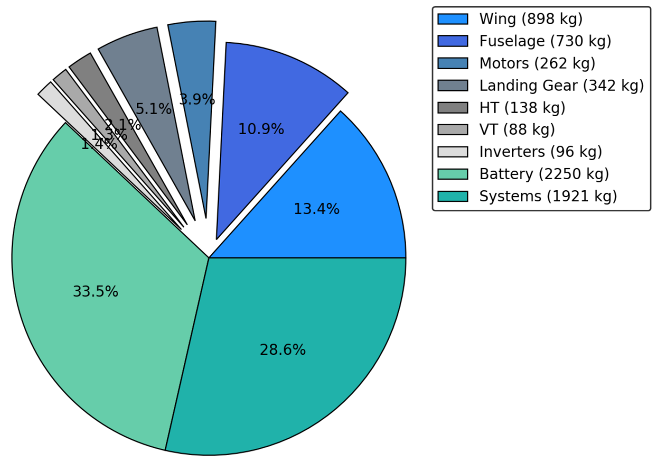


Fig. 3 Weight breakdown for the reference aircraft.

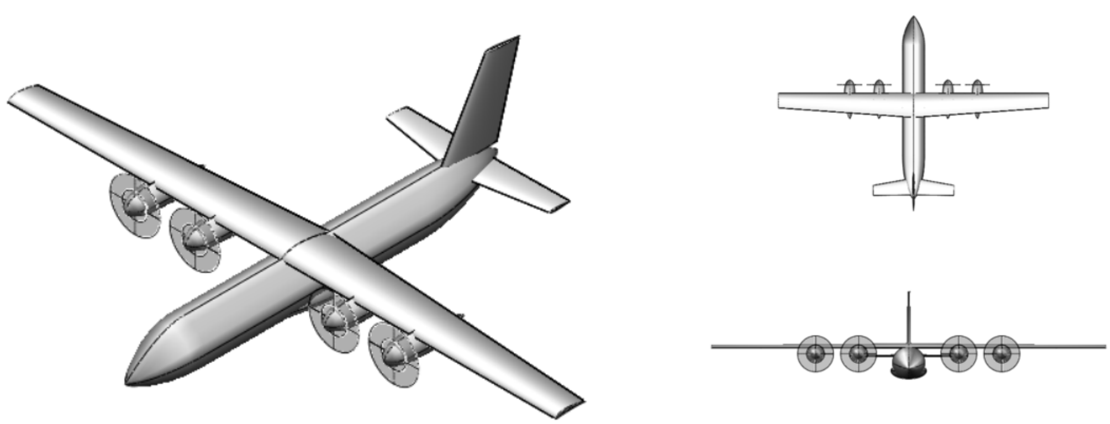


Fig. 4 OpenVSP model of the complete aircraft designed.

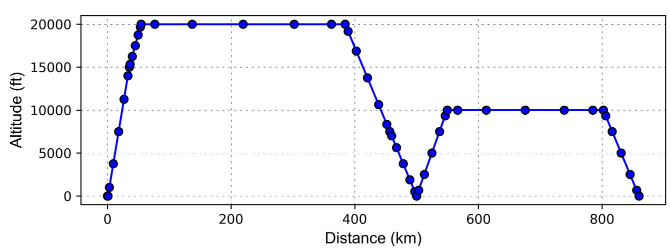
V. Mission definition

The proposed mission consists of a traditional commercial transport mission profile, with the operational and reserves segment. The takeoff segment consists of the TFL defined previously (Section III) and it is performed at sea-level altitude with a Takeoff Velocity (V_{TO}) related to the Stall Velocity (V_s) according to [24]. The climb is performed at the Best Rate of Climb (ROC_{best}) and airspeed for ROC_{best} adjusted for each altitude. The cruise segment is performed at the Velocity for Maximum Lift to Drag ratio ($V_{maxL/D}$), in which the aircraft achieves its best range capabilities. The last segment, descent, is performed following a similar turboprop Rate of Descent (ROD).

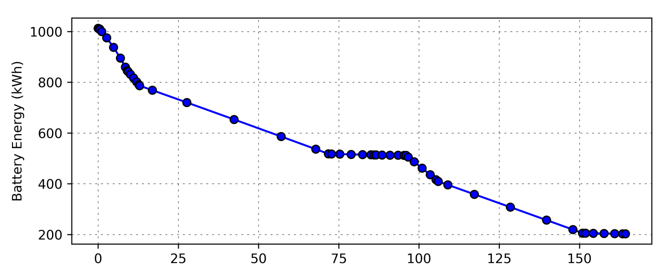
Segment	**Description**
Takeoff	TFL = 800m, ISA+15°C sea-level, V_{TO} = 1.2V_s
Climb	ROC_{best} 1750 - 1300 ft/min, V$_{climb}$ = $244 - 297 km/h$
Cruise	25000 ft, at $V_{maxL/D}$ = 336 km/h, M = 0.31
Descent	Rate of Descent = 880 ft/min,
Reserves	
Climb reserve	ROC_{best} 1000 ft/min
Alternate + loiter	50 km alternate, plus 45 min loiter at 10000 ft
Descent	Rate of Descent = 750 ft/min

Table 3 Segments description for mission profile.

The reserves segment was employed according to ICAO regulations (Annex 6, Part I, 4.3.6 "Fuel Requirements"), which requires 45 minutes of loiter and the required alternate airport distance. Once for the fuel determination for an alternated airport the specific route must be specified, 10% of the overall operational range was considered for the present study. All mission segments can be seen in Fig. 5a as well as the mission details of parameters in Table 4. As part of the mission assumptions, it was considered an operational battery discharge limited in 85% of total stored energy in order to preserve the battery life, as recommended by [29, 30]. The battery discharge profile can be seen in Fig. 5b, with the operational range consuming 1112 kg of 2250 kg in total, as shown in Table 4. Once SUAVE's routine analysis considers all flight physics involved, such as aerodynamics and performance, it was possible to refine the range estimated from Breguet's equation in Section IV. Thus, the operational range could increase to 500 km, and it was used as the reference mission shown in the first part of Fig. 5a and described in Tab. 4.



(a) Mission profile



(b) Battery energy consumption

Fig. 5 Flight segments and battery consumption for the proposed mission profile from SUAVE.

In order to avoid overestimating the cost calculations, only the operational range of 500 km was considered for analysis. Thus, the operational mission time (referred in this study as block time) consists of the operational flight time with the addition of the ground time (as per Eq. 5), totalizing 1.73 h.

Description	**Value**
TOGW, kg	8560
Total range, km	909.7
Total time, hr	3.02
Total battery weight, kg	2250
Total battery energy, kWh	1012
Remain capacity	15%

Table 4 Complete mission parameters.

VI. Operating Costs

The Operating Costs calculation was made mostly based on the methodology proposed for NASA from McDonnell Douglas [31], and on minor supporting calculations from Raymer, Gudmundsson ,and Roskam. The evaluations were carried out through Direct Operating Cost (DOC), which combines "cash costs" and "ownership" costs, and Cash Operating Cost (COC), which consider only the "cash costs". For the cash costs components, the cost of energy, crew, maintenance, fees (only landing fee) , and battery pack were considered; and for the ownership costs ones, the cost of depreciation, insurance, and interest. Then, the DOC total cost is organized as the sum of all components, as shown in Eq. 1, with the COC total cost represented in Eq. 2.

$$DOC = C_{Energy} + C_{Crew} + C_{main} + C_{Depr} + C_{Ins} + C_{Int} + C_{Fees} + C_{batt\,pack} \tag{1}$$

$$COC = C_{Energy} + C_{Crew} + C_{main} + C_{Fees} + C_{batt\,pack} \tag{2}$$

The NASA method, commonly referred to as "DOC+1" method in some references, has its formulation based on ’90s turbine-powered transport aircraft. Once the present study consists of evaluating the commuter and turboprop segment, a verification regarding the maintenance costs was carried out in order to evaluate the applicability of the model. By analyzing the maintenance cost per block hour from similar turboprop, and by using mission and financial assumptions from Tab. 5, the calculated \$338 per block hour of maintenance is aligned with the estimated \$360 [32–34] for the segment. Thus, there was no need to apply correction factors.

The aircraft purchase price related to depreciation cost was also another component that could carry uncertainties regarding its formulation. A price-per-pound base in order to estimate the aircraft purchase price is commonly used. However, commercial transport aircraft are not sold on a price-per-weight basis; instead, its selling price represents a market-based price [31]. For this, a regression was proposed to relate the aircraft purchase price and its number of passengers. Considering only turboprop aircraft data ([9, 35, 36]) with the adjusted purchase price to the year of 2020, the regression from Fig. 6 shows a good relationship between both parameters. Thus, by using the data from the relationship, a regression (Eq. 6) was performed in order to estimate and apply the aircraft price for cost calculations. For the aircraft designed, it was employed a 10% increase factor in the estimated purchase prince in order to account for the possibility of an increase in the initial price due to the introduction of a clean-sheet design in the market in comparison to the current in service aircraft.

$$C_{aircf} = 407408PAX - 2967.4 \tag{3}$$

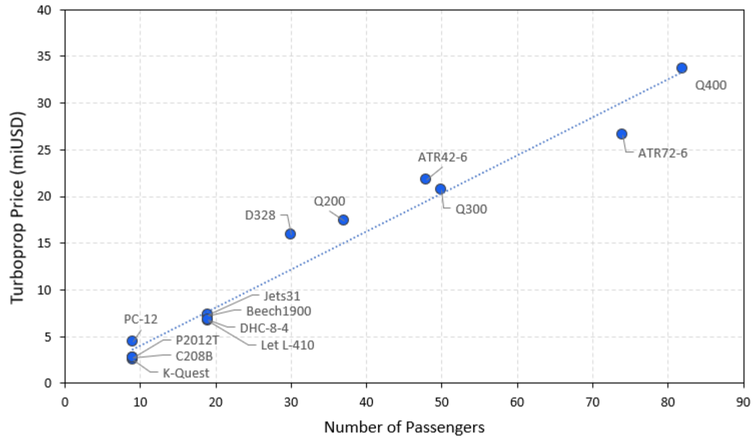


Fig. 6 Turboprop purchase price adjusted for 2020.

One of the main concerns regarding emerging electric aircraft is the need for battery replacement after the battery reaches its useful life. Respecting that, the battery replacement cost was considered for the cost calculations. The unique independent component from the mentioned methods, the battery cost replacement was modeled considering its total price amortized in each flight cycle as presented in Eq. 4. The basis for this calculation is a consideration of a standard 2000 flight cycles needed for lithium-ion battery pack replacement, according to [37, 38]. Lastly, all calculations were performed by means of block time, i.e., the flight time plus time spent on the ground, following the formulation (Eq. 5) proposed by Roskam.

$$C_{batt\,pack} = \frac{E_{bc} E_{price}}{B_{cycles}} \frac{M_{cycles}}{B_{cycles}} \tag{4}$$

$$t_{block} = t_{mission} + 0.51(10^{-6}) W_{to} + 0.125 \tag{5}$$

The financial assumptions considered for the cost calculations are summarized in Tab. 5, and all monetary values were converted for 2020 values considering the Customer Price Index (CPI). For the reference operation assumptions, the major parameter considered is the number of daily flights. For that, based on average US turboprop regional daily hour operation of 7h from [32], and the block time from Tab. 5, it was considered 4 flights per day as a reference for the analyzes and comparisons, also called as "reference mission" in the next sections.

Financial assumptions	Values	Refs.
Pilot salary, $/hourly	56	[39, 40]
Maintenance labor, $/hourly	45	[23, 41]
Depreciation period, years	10	[21]
Airframe residual value, %	10	[21]
Battery, $/kWh	300	[7, 42]
Electric motor, $/kW	50	[7, 43]
Energy cost, $/kWh	0.11	[44]

Reference operation	Values
Range, km	500
Flight time, h	1.6
Block time, h	1.73
Daily flights	4
Yearly flights	1460
Yearly block time, h	2526

Table 5 Financial and operation assumptions.

VII. Results and analysis

Results are divided into two subsections. The first one contains analysis of the overall operating costs findings regarding a few metrics for the reference mission. It also presents an analysis focusing on fuel and energy costs. The other subsection shows some plots for the trade analysis performed for major parameters affecting the operating costs. Lastly, a sensibility analysis regarding the major cost and non-cost assumptions was employed in order to verify each influence as a percentage of DOC change.

A. Operating costs analysis and comparison with competitors

Considering only the energy cost instead of fuel costs and the battery replacement cost as the differences from traditional aircraft operating costs, the calculated DOC costs and its components related to the present study are summarized in Tab. 6. The results for DOC per block hour considering 4 daily flights represents a significant reduction of 39%, considering an average of $1753 DOC per block hour for current in service 19-seat turboprop segment given available data from [32, 33]. The reduction could be a result of the combination of a drastic reduction in fuel costs as well as the age of the designs. In addition, the cost for an engine overhauling after a specific number of flight cycles for turboprop aircraft is also a high costly component that increases the traditional aircraft DOC in contrast to electric aircraft. Then, with DOC being all costs related to the aircraft flying operations, a significant DOC reduction as found could increase the operation profitability of the airline as well as allow airlines with a reduced budget to operate the aircraft.

Metric	Total	Energy	Crew	Maint.	Deprec.	Ins.	Inter.	Fees	Bat. pack
$DOC/Mission	1852	59.5	193.7	584.9	501.8	20.4	339.6	41.5	110.9
$DOC/Block hour	1071	34.4	112	338	290.1	11.79	196.3	24	64
$DOC/km	3.7	0.12	0.39	1.17	1	0.04	0.68	0.08	0.22
$DOC/seat-mile	0.21	0.007	0.002	0.066	0.057	0.002	0.038	0.005	0.012

Table 6 DOC metrics for reference aircraft and mission.

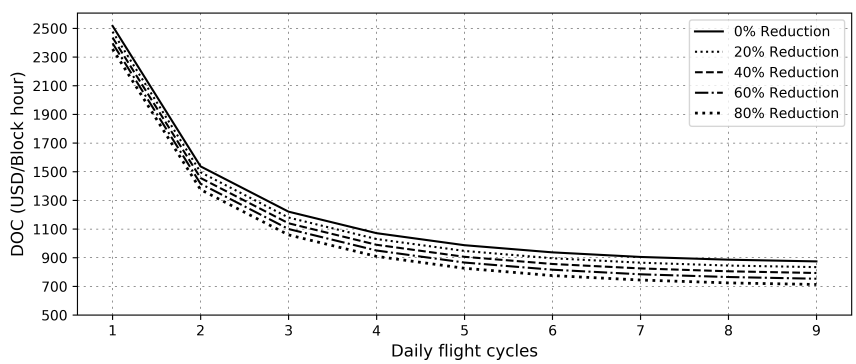
For energy costs, a comparison between conventional-fueled turboprop and the designed electric aircraft is presented. As can be seen in Tab. 7 for the reference mission, the reductions in fuel costs could achieve over 88% for the upper segment, and an average of 81% of similar aircraft size and segment. This reduction in fuel costs is substantial considering an average DOC of $1753 for the 19-seat turboprop segment. The reduction is also aligned to [3], in which the electric aircraft could reduce the energy costs by 10 times. Together with the emergence of new electric aircraft designs, the electrification by re-engining current aircraft in service is also another potential and cheaper option from the point of view of fuel costs.

Metric	Ref. aircraft	30-seat	19-seat	9 to 12-seat
Fuel cost, $/Bock hour	34.4	287	180	126
Mission fuel cost, USD	59.5	496	311	218
Difference from ref. aircraft	-	-88%	-81%	-73%

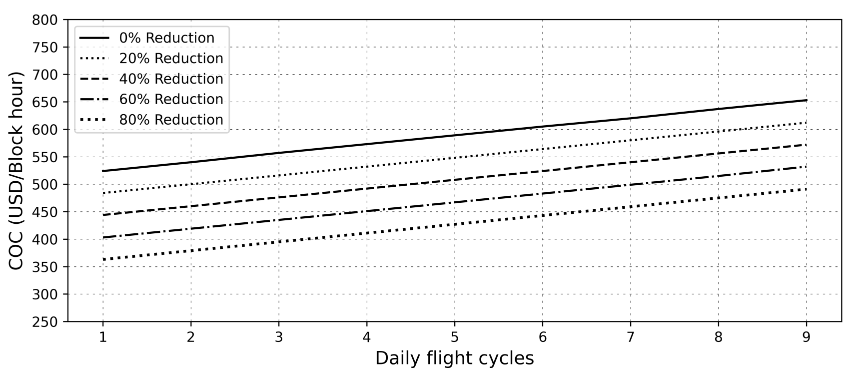
Table 7 Fuel and energy cost considering the reference mission and available data.

B. Trade studies

The maintenance reduction gains, one of the main acclaimed benefits for electrification, was investigated by applying reductions factors in the DOC components of motor maintenance labor and material cost. As can be seen in Fig. 7a, a 20% reduction in motor maintenance cost leads to an average of 4% in total DOC. This DOC reduction was also enhanced by the increase of daily flights. Even so, the consideration of a potential reduction for motor maintenance cost needs to be carefully employed as pointed in [7], once in the electric aircraft concepts the maintenance costs for landing gear due to higher TOGW can increase as well as the battery replacement maintenance cost can emerge, surpassing the reductions proportioned from motor maintenance costs. Furthermore, considering 4 daily flights, the maintenance cost related to the motors is about $202 (or 60% of total maintenance costs). Thus, the application of a reduction factor of 50% (as per Fig. 7a) resulted in a 10% DOC reduction. Once the number of motors is a direct variable affecting the motor maintenance cost calculation according to the employed method, a motor maintenance reduction factor of 50% would produce a similar DOC reduction to the utilization of two motors instead of four in the designed aircraft. Therefore, considering the designed aircraft at the mentioned daily utilization can be suggested that the choice between two or four motors would result in a considerable DOC per block hour change from the point of view of motor maintenance costs. Even though the fuel cost represents a much larger reduction, this result may also help the decisions for the selection of the number of motors in the early stages of aircraft conceptual design.



(a) Direct Operating Costs (DOC)



(b) Cash Operating Costs (COC)

Fig. 7 Operating costs with motor maintenance reduction factors.

Even applying a different formulation of DOC's capital costs, it can always carry uncertainties regarding the aircraft price. And for this reason, COC is also considered in operating costs evaluations. For this, as shown in Fig. 7b, even with increasing daily utilization, there is the same linear increase in COC for each maintenance reduction factor. This COC increase is strictly due to the battery pack replacement cost, which increases its proportion with high daily utilization, as can be seen in Fig. 8. This result is not only interesting from COC reduction, but it also indicates that a reduction in aircraft purchase price would enhance the maintenance reduction gains. Lastly, the evaluation of COC also indicated that the battery replacement cost is the only factor negatively affecting COC and it is an important variable to consider for the design and the operation.

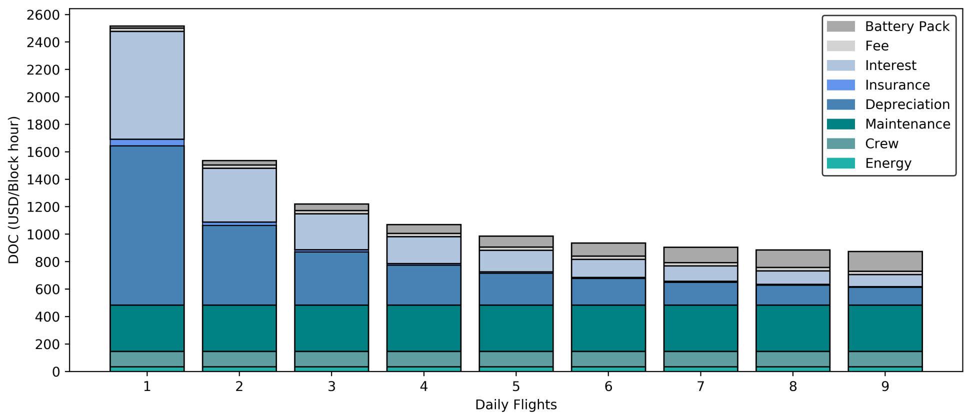


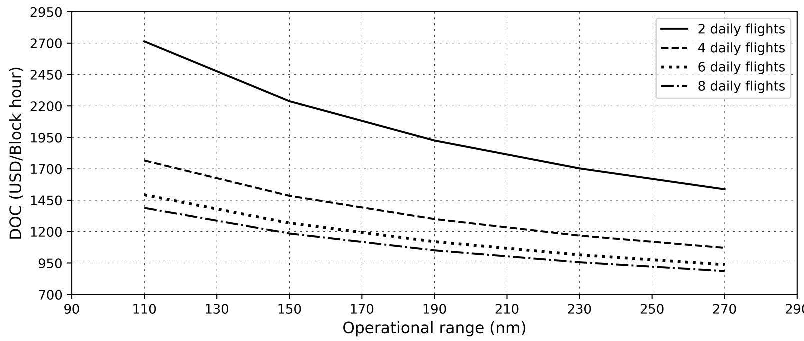
Fig. 8 Daily flights influence on DOC breakdown.

Figure 8 presents the DOC breakdown for each flight cycle. From 1 to 3 daily flights, the DOC decreases significantly, mainly due to the direct influence of daily flights on ownership costs. Thus, interest and depreciation costs tend to decrease with high daily utilization. Even though there is a significant reduction in ownership costs, Fig. 8 can explain the DOC amortization for high daily utilization due to the increase in COC, as shown in Fig. 7b. The DOC related to battery pack replacement becomes even more proportionally significant than energy, crew, and interest above utilization of 6 flights daily. With batteries having a high life cycle capability, the COC increase can be softened, and consequently, the DOC can be reduced at a higher intensity, and then it may be an important variable when deciding among other electric aircraft. A four daily frequency would result in a DOC reduction of thirty-nine percent, with the potential to increase even more with higher daily utilization. However, even considering an optimistic battery charging time of one and a half hours, a daily frequency above six flights could not be possible, and therefore the optimization of DOC can be highly constrained from three to six daily flights.

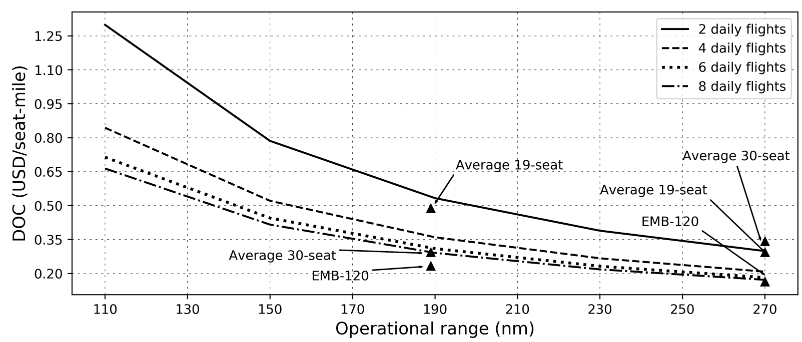
As can be seen in Fig. 9a, the reduction of the operational range has a negative influence on DOC, with this influence intensifying at low daily utilization. Consequently, operating the aircraft at low daily frequencies can negatively outweigh the gains compared to aircraft in the same segment. Considering the average DOC of $1753 for 19-seat segment, the designed electric aircraft would have DOC gains per block hour at most part of the operational range at an utilization at least 4 daily flights. The high DOC per block hour can also make financially unviable tourism and on-demand operations for operational ranges above 500 km, in which in general is operated at low daily frequencies.

Moreover, an analysis considering the DOC over the seat-mile metric was performed. The DOC per seat-mile is a widely used metric to compare the efficiency of airlines, and it is calculated by dividing the DOC per hour by the number of seat times the miles flown. In general, the lower the DOC per seat-mile, the more profitable and efficient the operation. It can be seen from Fig. 9 that for lower ranges, the DOC per seat-mile increases significantly. Following the same conclusion of the DOC analysis, operation up to two daily flights would not be advantageous in comparison to the 19-seat segment, as also for the 30-seat segment. Compared to other aircraft data from [32, 33], the aircraft designed has a better DOC per seat-mile than its segment and above, but worst than the Embraer 120. Considering a mission of 350 km (190 nm), the cost efficiency decreases significantly, mainly due to the 37% lower seat capacity than the 30-seat segment. On the other hand, a 19-seat electric aircraft start to be more efficient for operations with a daily frequency of four or more flights. It could also compete with the 30-seat segment with a daily frequency of six flights. Another conclusion from this analysis is the decrease in efficiency for reduced travel distances. This could be explained to the fact that even demanding lower energy for shorter distances, the weight and pack cost of the battery will not change. And this also may indicate that all-electric aircraft operating efficiency would be linked to the battery capacity.

Additionally to the DOC analysis, a sensibility analysis was performed in order to evaluate the influence on DOC of major assumptions that could carry the greatest uncertainties in relation to the others considered. Thereby, the energy price, aircraft price, battery pack cost, and battery life cycles were considered for analysis at a frequency of four daily



(a) DOC per block hour.



(b) DOC per available seat mile.

Fig. 9 Operating costs versus range.

flights. As can be seen in Fig. 10, the energy price, and battery pack cost has a minor influence on DOC. For the first one, this influence can be explained by the lower percentage of energy cost on DOC for electric aircraft, showing a very positive scenario in comparison to combustion-engined aircraft which is highly negatively affected by the fuel price volatility. For the second one, even though the battery pack cost is significantly higher than the assumed cost of the electric motors, it represents less than four percent of the total aircraft price. Once it is amortized in each flight, it would not be a major issue from the point of view of operating costs for electric aircraft in this segment.

The considered parameter with the highest influence on DOC was the battery life cycle, and its negative behavior by decreasing its value is linked to the hyperbolic nature of the formulation proposed (Eq. 4). From the reference considered of 2000 cycles before changing the battery, a reduction of 50% in this value would elevate the DOC by 20%, which could reduce by half the gains promoted by electric aircraft. Increasing the battery life above 2000 cycles would produce minor gains, and a reduction to 1500 cycles would not significantly raise the DOC. In this way, battery life between 1500 to 2000 cycles would allow maintaining the DOC gains promoted from the electric aircraft in this segment. Once the aircraft price is linked to three of the DOC components, it also has a significant influence on DOC. However, even though decreasing the aircraft price has a considerable positive influence on DOC, large discounts on purchase price may not be financially possible and therefore the DOC benefits may be limited to small changes. As a result, optimizing the design for a reduced industrial cost which significantly affects the aircraft price, and a detailed selection of the battery options regarding its life cycle could significantly impact the operating costs positively.

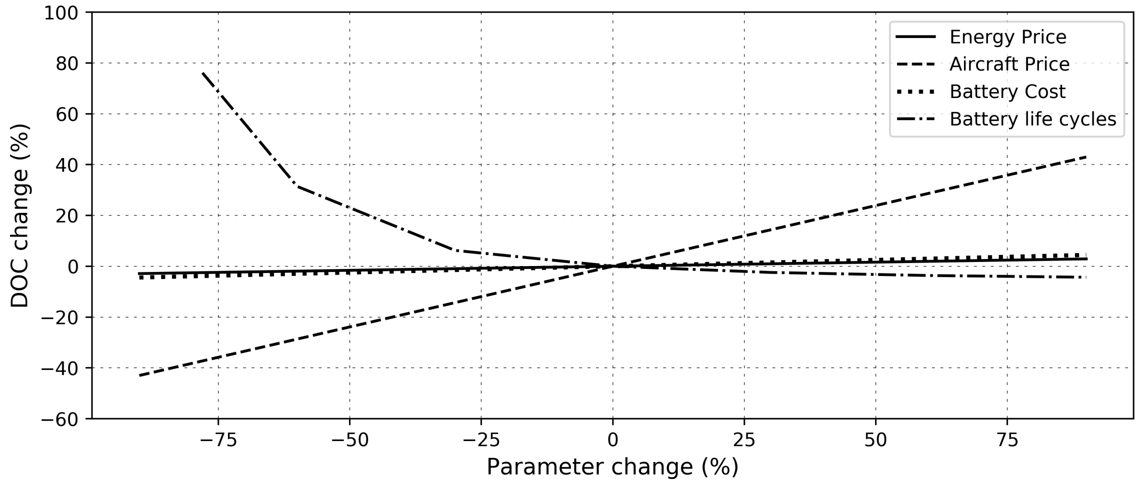


Fig. 10 DOC sensibility analysis.

VIII. Conclusion

The all-electric aircraft was designed meeting all the TRL as well as following the applicable operation regulations. As expected, the battery weight occupied a great part of the TOGW, confirming the characteristic of electric aircraft concepts having a greater weight overall weight in comparison to traditional combustion-engine aircraft.

An adaptation of the operating costs method was necessary in order to account for the energy cost and battery replacement pack. For the first one, the energy consumed during the mission was extracted from SUAVE analysis and outputs. For the second, a simplified model was employed based on an estimated lithium-Ion battery pack life cycle from references. The cost and mission assumptions were taken by references and reasonable estimates.

The analysis of the results confirmed the operating benefits considered as first assumptions, and therefore an 80% reduction in fuel cost was achieved and 39% for total DOC considering the mission profile and the number of flights utilized. If accounting for the potential reduction in the motor maintenance cost, there is a potential to reduce by half the DOC in comparison to the hourly DOC of the current aircraft segment. Considering the designed aircraft, the choice between two or four motors also leads to a 10% change in the DOC per block hour, making it a key decision during the early stages of electric aircraft development.

For low daily flight frequencies, the ownership costs dominate the DOC per block hour, and its proportion becomes less significant above four daily flights. Moreover, the analyzes also indicated that the parameters related to the battery are one of the major driving factors affecting the operating costs, and therefore should be carefully investigated when considering all-electric concepts. Thus, the use of battery pack replacement cost demonstrated a great importance when analyzing all-electric operating costs. The results indicated that from the point of view of operating costs, an all-electric aircraft could be justifiable, and could offer a very interesting approach in order to reduce aviation environmental impact as well as significantly reducing the airline operating cost for the segment under 20 passengers.

IX. Future Works

This section, will be presented a few further studies that could be performed in the future as a continuation of present work. Even showing good agreement with references, mainly for the maintenance costs, the formulation of the DOC method employed is based on turbofan-engined narrow-body aircraft from decades ago, and therefore a method for calculating DOC for small to medium turboprop should be investigated in the future. Since an electric motor requires different standards for maintenance, a new approach for modeling electric motors maintenance cost in order to substitute traditional combustion-engined databases is also a future objective of study for the continuing of present work. In order to find the bests capabilities of electric aircraft as well as understand the major driving project variables and its differences from traditional combustion-engined designs, an optimization work could be considered. Lastly, considering the clean-sheet design aspect as well as the new technology transition for all-electric aircraft from combustion-engined designs, an industrial cost evaluation should be also considered in addition to the operating costs for better evaluate the potential benefits of aircraft electrification.

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