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AN APPROACH TO PRELIMINARY SIZING OF TURBO-ELECTRIC AIRCRAFT WITH DISTRIBUTED PROPULSION

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ABSTRACT

The increased awareness towards air transport pollution has pushed for ambitious sustainability objectives to achieve within year 2050. As new technologies emerge, researchers are investigating innovative aircraft and powertrain configurations to explore potential fuel-burn savings, either retrofitting an existing aircraft or defining a new conceptual design. This work investigates the possibilities given by a turbo-electric powertrain coupled with distributed electric propulsion on a regional turboprop aircraft, presenting a method for preliminary aircraft design and exploring the results offered by a simple evaluation of the aero-propulsive interactions. With the actual technology, a potential 5% reduction in fuel consumption should be achievable on a 500 nm mission with 42 passengers. Although it is not a disruptive result, this paves the way for further investigations, indicating where improvements may be achieved.

Keywords: Aircraft Design, Aerodynamics, Hybrid-Electric Propulsion, CFD

1 INTRODUCTION

To comply with the EU Flightpath 2050 sustainability objectives for the air transport [1], which aim to a reduction of 75% CO_2, 90% NO_X and 65% of perceived noise (with respect to a year 2000 aircraft) within 2050, innovative aircraft and powerplant configurations are being investigated by the research community. A promising alternative to thermal engine propulsion is the electric propulsion. However, an all-electric regional transport or large passenger aircraft seems not feasible in the immediate future, due to the limited specific energy of the storage technology [2]. Therefore, an interest for hybrid-electric propulsion, together with distributed propulsion, has recently grown. Particular attention is posed to the distributed electric propulsion (DEP) configurations, thanks to their ability to "*distribute*" propulsors in many locations on the vehicle, not just near the power source. From the aircraft designers' point of view, DEP solutions open new degrees of freedom within aerodynamics, vehicle control, pollutants and noise emissions.

Distributed electric propulsion may help in reducing pollutants emission through favourable aero-propulsive interactions. As shown with the NASA X-57 experimental aircraft [3], DEP increases high-lift capabilities, allowing an increment of wing loading, reducing wing area, weight, and drag. For larger airplanes, a hybrid-electric powerplant, together with DEP, increases both operating empty and maximum take-off weight, which are directly proportional to aircraft purchase costs and operating costs [4]. This could be acceptable if such increases are limited and the fuel burn reduction complies with sustainability objectives. For this reason, it may be not convenient to re-engineer an aircraft to perform the same mission, as different ranges and altitudes may be exploited with the new configuration. This paper presents such example on the ATR-42 aircraft, a promising platform to exploit future benefits of such architectures, as requested by the Italian PROSIB[1] research project.

The preliminary design of a hybrid-electric aircraft has not a consolidated approach, since the only data available are on small experimental airplanes. Borer et al. [3] described the design and the performance predicted with simplified methods of the NASA X-57 SCEPTOR experimental electric aircraft, based on a Tecnam P2006T light aircraft. By substituting the wing with a smaller one sized for cruise conditions, with 12 distributed propellers for the low speed performance, they shown that a 4.8 reduction in energy consumption can be obtained at 150 kts and 8000 ft, with a gross weight slightly bigger than the stock aircraft. However, the range with the available battery technology is only 80 nm against the 670 nm achievable with fuel. Brelje and Martins [4] have shown that the design of an electric aircraft introduces new coupling between previously distinct disciplines, such as aerodynamics and propulsion, which can be effectively evaluated only with high-fidelity analyses. An investigation conducted by the Bauhaus Luftfahrt institute [5] has evaluated a potential 16% block fuel-burn reduction on a 900 nm mission for a 2035 jet aircraft with 180 pax, if 18% of the total energy comes from batteries with a specific energy of 1500 Wh/Kg. Such fuel saving is halved if the battery specific energy is 1000 Wh/Kg (nowadays is about 200 Wh/Kg).

As concern turboprop transport airplanes, recent researches have shown that, for conventional aircraft layout (i.e. tube and wing), disruptive results are obtained only if optimistic assumptions are made on the battery specific energy (>750 Wh/Kg) [6]–[8], otherwise the potential fuel saving is less than 5% [9], [10]. The benefits of DEP and tip-mounted propellers have been deeply investigated by NASA, yielding to an amplification of lift coefficient from twice to three times the flapped configuration in landing for the DEP wing [11], [12], while wingtip mounted propellers may decrease the induced drag up to 15%, depending on the wing planform and lift coefficient [13], [14].

The objective of this work is to illustrate the effects of some powertrain parameters and the aero-propulsive interactions on the preliminary sizing of hybrid-electric transport airplane. Although the method that will be presented is feasible for any class of aircraft and powertrain (from conventional to all-electric), the authors focused on the regional air transport category, with turbo-electric powertrain (no electric energy storage system, e.g. battery, is installed).

2 METHODOLOGY

The methodology of this work follows the approach of Ref. [6], with several customizations. Once assigned the Top-Level Aircraft Requirements (TLAR), the design workflow starts with a statistical pre-design of the aircraft with conventional powertrain. This is a necessary step, since there are no consolidated methods to size a hybrid-electric aircraft from scratch. From this baseline, the sizing process, which includes the characteristics of the propulsive architecture in terms of geometry, position, hybridization parameters, and operating modes, is performed. As in the classical aircraft design workflow, aviation regulations and design requirements dictate the constraints for the choice of the sizing point, which is the combination of power loading *W/P* and wing loading *W/S* at take-off. In contrast with the classical approach, the Class-I weight estimation for the hybrid-electric configuration cannot be performed as first step, lacking statistical data on maximum take-off and operative empty weights. Even the fuel-fraction method [15] cannot be implemented. Thus, weight estimation is performed iteratively at a later step, with a mission profile analysis accounting for the energetic requirements and powertrain operating mode for each flight phase. The workflow is reported in Figure 1.

[1] Propulsione e Sistemi Ibridi per velivoli ad ala fissa e rotante.

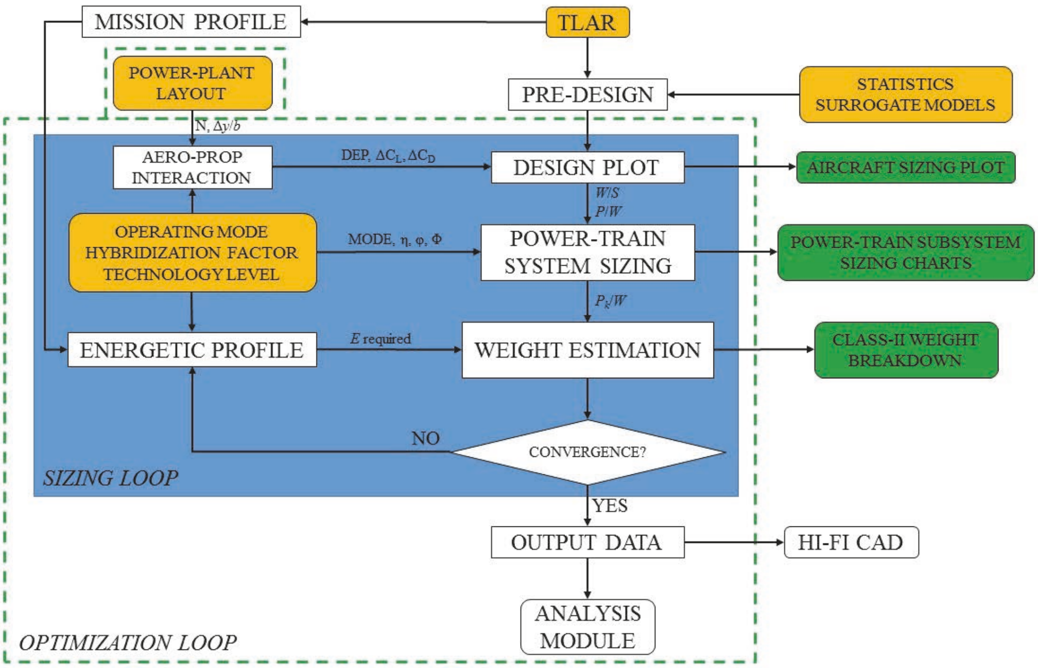
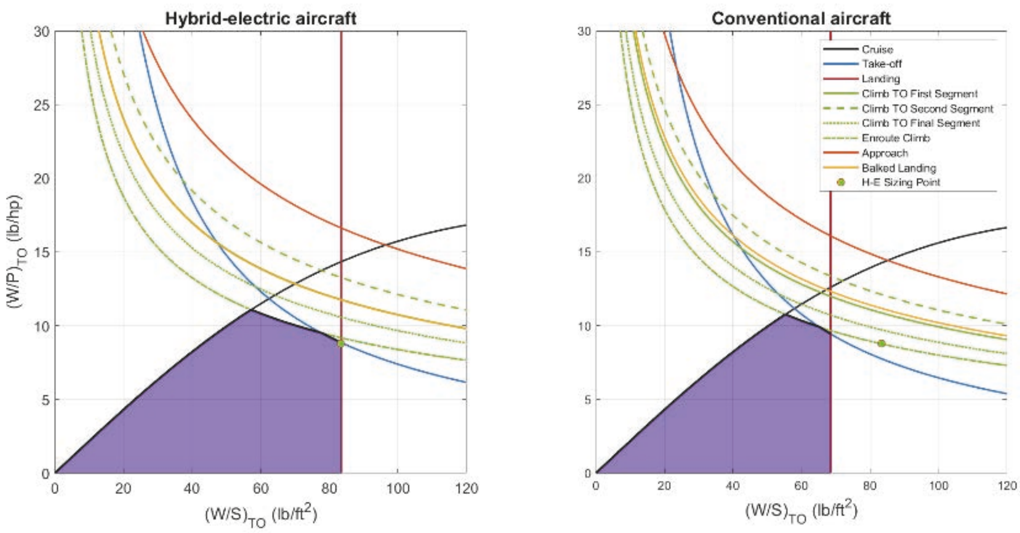


Figure 1: Hybrid-electric aircraft preliminary design workflow.

A hybrid-electric aircraft, especially a turbo-electric configuration, may benefit from distributed propulsion due to favourable aero-propulsive interaction. DEP will increase the lift coefficient C_L, moving the constraint curves at higher wing loading values, especially in take-off and landing (Figure 2), enabling the possibility to reduce the wing area and weight. Equilibrium equations from Flight Mechanics are re-written and iteratively solved to account for this possibility. The approach is to assume the same angle of attack (hence the same flight attitude) of the aircraft with conventional powertrain and convert the increment of lift coefficient C_L in an increase of wing loading W/S. To account for propeller blowing effect, the method developed by Patterson [16] has been implemented. Due to the increased wing loading, the equilibrium equation is solved again to calculate the new ΔC_L and ΔC_D. The process is executed iteratively for each constraint curve of the sizing plot until convergence to tolerance.



(a) (b)

Figure 2: Comparison between sizing plots: (a) hybrid-electric; (b) conventional powertrain.

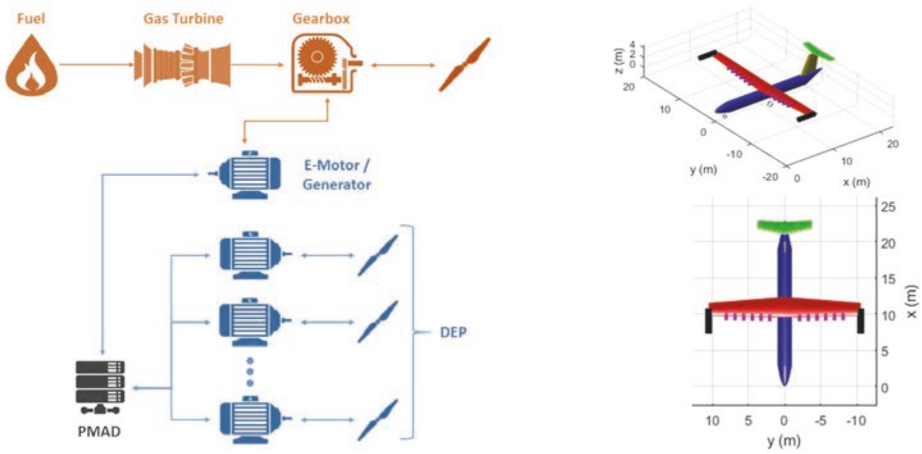


Figure 3: Turbo-electric powertrain scheme with a possible installation over a regional turboprop.

The chosen power loading $(W/P)_{TO}$ is used to solve the powertrain equations system, which states the conservation of energy between the energy sources and the propulsors, accounting for the logical connections between powertrain components and their mechanical efficiencies. Figure 3 reports a powertrain scheme for the turboelectric case. The resolution of the powertrain equations implies the assignment of an operating mode, hybridization factor, and component efficiencies for each flight phase. The operating mode states the way the energy flows from its source to the propulsors (or vice-versa). In the case of turbo-electric aircraft, a possible operating mode is well described in Figure 3, where each gas turbine drives an inverter and a primary propeller through a gearbox. The inverter provides electric power to several electric drivers, which may be directly connected to the secondary propellers distributed on the wing. A power management and distribution (PMAD) system acts as a controller. The hybridization factor states how much energy is used to power the secondary propulsors (DEP). In this work, following the approach of Ref. [6], the hybridization factor is defined as shaft power ratio, that is the ratio between the power at the shafts of the secondary propulsors (P_{S2}) and the total shaft power ($P_{S1} + P_{S2}$), according to Eq. (1).

$$\varphi = \frac{P_{s2}}{P_{s1}+P_{s2}} \tag{1}$$

The efficiency η of each component is assigned a priori, assuming that each component works at the maximum efficiency most of the time. In this way, the powertrain system is linear for each flight phase, although the matrix coefficient may change among flight phases. Eq. (2) reports an example of powertrain system for the turbo-electric case

$$\begin{bmatrix} -\eta_{GT} & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\eta_{GB} & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\eta_{P1} & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -\eta_{EM1} & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\eta_{PM} & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\eta_{EM2} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\eta_{P2} & 0 & 1 \\ 0 & 0 & 0 & \varphi & 0 & 0 & (\varphi-1) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} P_f \\ P_{gt} \\ P_{gb} \\ P_{s1} \\ P_{e1} \\ P_{e2} \\ P_{s2} \\ P_{p1} \\ P_{p2} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ P_{TO} \end{bmatrix} \tag{2}$$

The energy balance gives 7 equations and 9 unknowns. Therefore, two equations are added in the last two rows to close the system. One is the definition of shaft power ratio φ, the other is simply the sum of the propulsive powers which gives the total take-off power P_{TO}.

Pax number	42		Rate of Descent	1100	feet/min
Engines number	2		Mach cruise	0.47	
Design range	840	nautical miles	Cruise altitude	17000	feet
Landing length	3600	feet	Alternate range	100	nautical miles
Take-off length	4000	feet	Alternate altitude	8000	feet
Climb Speed	170	knots	Mach alternate	0.3	
Descent Speed	220	knots	Fuel reserve	5	% block fuel
Rate of Climb	1500	feet/min	Holding	30	minutes

Table 1: ATR-42 TLAR.

Propulsors are modelled as actuator disks, which max efficiency is limited by the disk loading as stated in the momentum theory [17]: for a given thrust, as the number of distributed propellers increase, their diameter decreases, increasing disk loading and reducing the maximum theorical efficiency.
At this stage, it is known total power loading $(W/P)_{TO}$, while the total propulsive power P_{TO} will be available once the maximum take-off weight W_{TO} has been estimated. Once the powertrain equations system is solved, the specific powers W/P of each powertrain component in all flight phases are known. The most demanding values are used to size the components. By calculating fuel consumption with the energetic requirements of each mission phase, the weight estimation is iteratively performed with a Class-II method, by assuming that the statistical laws of the aircraft components' weight [18], except for the powertrain, are still valid. Fuel weight is calculated by energy requirements in the mission profile analysis. Once the loop has converged, the aircraft has been sized and data can be feed other modules to perform analyses and optimization.

3 RESULTS

The method described in Sec. 2 has been applied to a regional turboprop aircraft with the same TLAR of the ATR-42, reported in Table 1. Several DEP strategies and engines number have been investigated. DEP has been alternatively enabled in all flight phases, take-off and climb and landing, take-off and landing. The number of secondary propellers is 8, 12, 16 and 20, covering about the 60% of the wing area affected by flaps. By designers' choice, for the hybrid-electric configuration, the gas turbines and the primary propellers have been moved to the wingtips as suggested in [13], [19].
For the given mission, the best results in terms of fuel saving depend on combination of the number of distributed propellers, shaft power ratio, and enabling strategy. For the sake of brevity, only a few charts are shown in the following. Best strategy for the assigned TLAR seems to enable DEP of 20 propellers (10 electric + 1 thermal engine per wing semi-span, the highest number of propellers investigated) in take-off, climb, and landing. The trend of the weights with the shaft power ratio, indicating how much power is given to DEP, is reported in Figure 4. All the weights increase with the shaft power ratio, indicating the need of bigger electric machines as the DEP demands more power, generating a snowball effect on the weight of other components.
The curves of fuel and wing weight are not linear, whereas the curves of maximum take-off, operative empty, and powertrain weights are quite smooth. This may be due to the change in sizing plot limits with hybridization factor. As concern the fuel weight, which is the fuel burned to complete the design mission, there is an increment in fuel consumption until a 10% shaft power ratio, a minimum at 30%, a negligible variation between 35% and 65%, then a rapid increase towards the all-electric propulsion. This trend is reflected on the wing weight, which

is always heavier than the wing of the conventional configuration. At this stage, the weight of the DEP system does not alleviate the wing aerodynamic load nor the tailplanes are updated, hence results are conservative. As a figure of merit, the fuel weight savings gets an insignificant value of less than 50 lb on an 840 nm (plus reserves) mission. To grow interest in a turbo-electric regional turboprop, other features must be investigated, as will be discussed in the next section.

As concern the effects of hybridization factor on the wing, they are reported in Figure 5, under the assumption of constant aspect ratio. The value of 10.4, instead of the true value of about 11, comes from the statistical pre-design. Since the objective of the work is to evaluate improvements with respect to the conventional configuration, it was decided to not force the code to match the real aircraft data. As expected, the increment in shaft power ratio increases the wing loading from 75 to about 105 lb/ft^2, reduces the wing area up to 65 ft^2 (6 m^2) and the wing span up to 5 ft (1.5 m). However, the magnitude of these reductions is not enough to decrease the wing weight, which increases due to the above stated snowball effect. As stated before, wing weight alleviation due to DEP is neglected in this application.

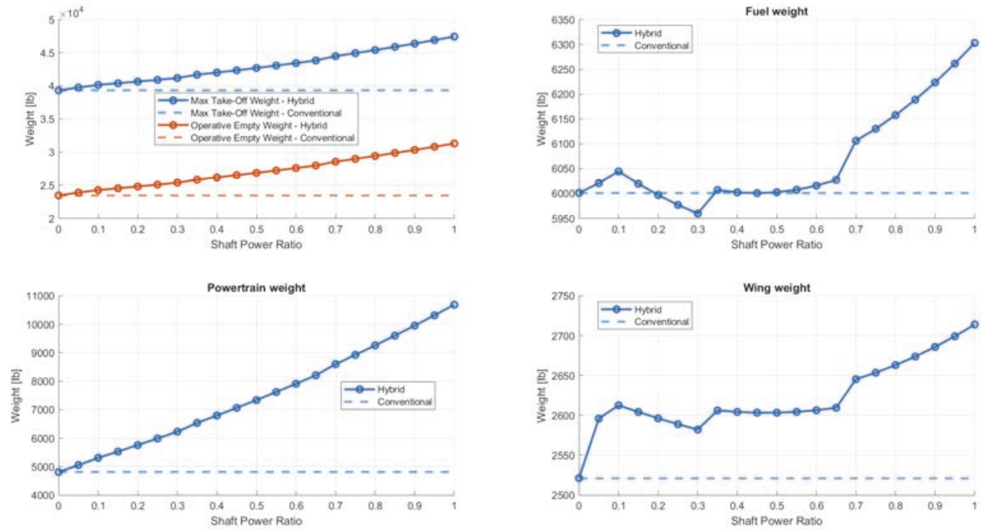


Figure 4: Weights trends with shaft power ratio for the ATR-42 design mission (840 nm), DEP with 20 propellers enabled in take-off, climb, and landing.

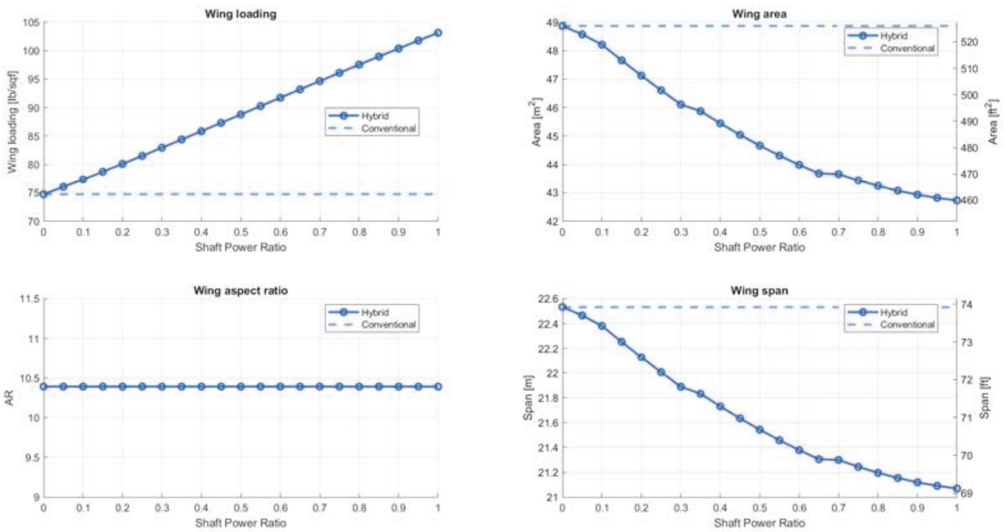


Figure 5: Effects of the hybridization factor on the wing for the ATR-42 design mission (840 nm), DEP with 20 propellers enabled in take-off, climb, and landing.

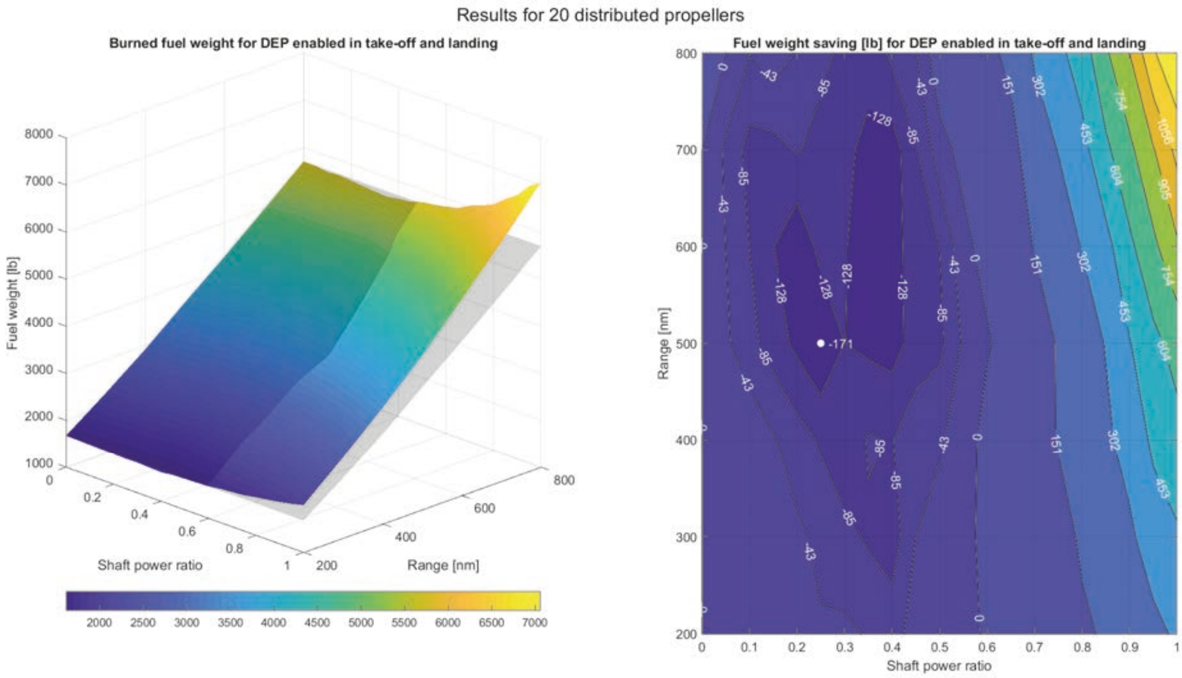


Figure 6: Design sweep for the ATR-42 turbo-electric aircraft at several ranges and shaft power ratios.

4 DISCUSSION

The results presented in Sec. 3 discourage the installation of a turbo-electric powertrain on a regional turboprop aircraft. Some calculations are conservative, and the design workflow does not include the complexity of such re-engineering, including the control logic, failure tolerance, safety issues, maintenance costs, and so on. Yet, there is way for improvement, by considering several aspects. First of all, the typical ATR mission is well below the 840 nm design mission. A design sweep including the range, varied from 200 to 800 nm, always with 100 nm alternate and reserves, has revealed that the most convenient mission has a range of 500 nm, performed with 20 distributed propellers enabled only at take-off and landing with a 25% shaft power ratio. This solution yields a fuel saving of about 170 lbs (5%) and a 2% increase in maximum take-off weight, as reported in Figure 6. The left side shows the response surface of fuel weight against range and hybridization factor. The shaded plane represents the fuel weight with the conventional powertrain. Thus, the areas of the response surface which are darker indicate that the fuel weight with turboelectric powerplant is less than the fuel weight with the conventional powerplant performing the same mission. Other results, not shown here for the sake of brevity, have shown that the strategy of take-off and climb and landing pays off only at long ranges. The take-off and landing strategy is more effective at low shaft power ratio (below 0.5) with ranges around 550 nm, with a significant increase in fuel burn at higher shaft power ratios and longer ranges. The strategy of enabling DEP in all flight phases is usually the worst, since DEP benefits are lost in cruise conditions. The right side of Figure 6 shows a contour plot of the fuel saving, indicating areas of interest and operation flexibility.

It may be argued that the achieved results are not enough to raise an interest in a turbo-electric powertrain for such aircraft category. The attention may be moved to the phenomena involved in the aero-propulsive interactions. The increase in lift coefficient, which is limited to a value of about 1.0, is obtained with the method of Ref. [16]. This method is based on a surrogated model developed from the results of 2D CFD RANS analyses on a symmetric airfoil in clean configuration. It is the author's opinion that higher values may be obtained if the typical airfoil in clean and flapped configurations is investigated with high fidelity methods, developing a surrogate model closer to the aircraft category of interest. Such approach has been successfully applied in the design, analysis, and optimization of conventional and innovative turbopropeller aircraft [20]–[29] and implemented in local and collaborative design chains [30]–[34]. Finally, Ref. [16] investigated variations in disk diameter, longitudinal position, and thrust. At time of writing, the authors are also investigating the effect of the disk vertical position, that may be favourable if more than half of the disk blows below the airfoil, improving the aerodynamic performance with flaps deployed.

5 CONCLUDING REMARKS

At this time, the DEP turboelectric aircraft configuration is not enough promising compared to the needed technological steps to reach a flying product. However, some advantages have been highlighted changing the design mission to attain a fuel reduction of about 5%. The key factors of the success of DEP aircraft are: (*i*) the demonstration of higher aerodynamic improvements, leading to larger wing area reduction respect to what predicted with simplified methodologies; (*ii*) the improvements in multidisciplinary approaches among aerodynamics, propulsion, flight control systems, emissions and costs in the preliminary aircraft design; (*iii*) the improvements of enabling technologies (i.e. electric machines, energy storage systems); (*iv*) the increasing awareness towards noise and gaseous emissions.

6 ACKNOWLEDGMENTS AND REFERENCES

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REFERENCES

[1] European Commission, “Flightpath 2050,” 2011.

[2] *Commercial Aircraft Propulsion and Energy Systems Research*. Washington, DC: The National Academies Press, 2016.

[3] N. K. Borer *et al.*, “Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator,” in *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016.

[4] B. J. Brelje and J. R. R. A. Martins, “Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches,” *Prog. Aerosp. Sci.*, vol. 104, no. September, pp. 1–19, 2019.

[5] C. Pornet *et al.*, “Methodology for Sizing and Performance Assessment of Hybrid Energy Aircraft,” *J. Aircr.*, vol. 52, no. 1, pp. 341–352, 2014.

[6] R. de Vries, M. T. Brown, and R. Vos, “A Preliminary Sizing Method for Hybrid-Electric Aircraft Including Aero-Propulsive Interaction Effects,” in *2018 Aviation Technology, Integration, and Operations Conference*, 2018, no. June.

[7] M. Voskuijl, J. van Bogaert, and A. G. Rao, “Analysis and design of hybrid electric regional turboprop aircraft,” *CEAS Aeronaut. J.*, vol. 9, no. 1, pp. 15–25, Mar. 2018.

[8] K. R. Antcliff, M. D. Guynn, T. V. Marien, D. P. Wells, S. J. Schneider, and M. T. Tong, “Mission Analysis and Aircraft Sizing of a Hybrid-Electric Regional Aircraft,” Jan. 2016.

[9] J. Zamboni, R. Vos, M. Emeneth, and A. Schneegans, “A Method for the Conceptual Design of Hybrid Electric Aircraft,” *AIAA Scitech 2019 Forum*, 2019.

[10] M. Strack, G. Pinho Chiozzotto, M. Iwanizki, M. Plohr, and M. Kuhn, “Conceptual Design Assessment of Advanced Hybrid Electric Turboprop Aircraft Configurations,” in *17th AIAA Aviation Technology, Integration, and Operations Conference*, 2017.

[11] K. A. Deere, S. Viken, M. Carter, J. K. Viken, M. Wiese, and N. Farr, “Computational Analysis of Powered Lift Augmentation for the LEAPTech Distributed Electric Propulsion Wing,” 2017.

[12] K. A. Deere, S. Viken, M. Carter, J. K. Viken, J. M. Derlaga, and A. M. Stoll, “Comparison of High-Fidelity Computational Tools for Wing Design of a Distributed Electric Propulsion Aircraft,” 2017.

[13] P. Della Vecchia, D. Malgieri, F. Nicolosi, and A. De Marco, “Numerical analysis of propeller effects on wing aerodynamic: tip mounted and distributed propulsion,” *Transp. Res. Procedia*, vol. 29, pp. 106–115, Jan. 2018.

[14] T. Sinnige, N. van Arnhem, T. C. A. Stokkermans, G. Eitelberg, and L. L. M. Veldhuis, “Wingtip-

Mounted Propellers: Aerodynamic Analysis of Interaction Effects and Comparison with Conventional Layout," *J. Aircr.*, pp. 1–18, Nov. 2018.

[15] J. Roskam, *Airplane Design Part VI: Preliminary Calculation of Aerodynamic, Thrust and Power Characteristics*. Lawrence, KS: DAR Corporation, 2012.

[16] M. D. Patterson, "Conceptual Design of High-Lift Propeller Systems for Small Electric Aircraft," Georgia Institute of Technology, 2016.

[17] G. J. J. Ruijgrok, *Elements of airplane performance*. Delft University Press, 1990.

[18] E. Torenbeek, *Synthesis of subsonic airplane design: an introduction to the preliminary design, of subsonic general aviation and transport aircraft, with emphasis on layout, aerodynamic design, propulsion, and performance*. Delft: Delft University Press, 1982.

[19] T. C. A. Stokkermans, N. van Arnhem, T. Sinnige, and L. L. M. Veldhuis, "Validation and Comparison of RANS Propeller Modeling Methods for Tip-Mounted Applications," *AIAA J.*, vol. 57, no. 2, pp. 566–580, Feb. 2019.

[20] F. Nicolosi, P. Della Vecchia, and D. Ciliberti, "An investigation on vertical tailplane contribution to aircraft sideforce," *Aerosp. Sci. Technol.*, vol. 28, no. 1, pp. 401–416, 2013.

[21] F. Nicolosi, P. Della Vecchia, and D. Ciliberti, "Aerodynamic Interference Issues in Aircraft Directional Control," *J. Aerosp. Eng.*, vol. 28, no. 1, p. 04014048, Jan. 2015.

[22] P. Della Vecchia, F. Nicolosi, and D. Ciliberti, "Aircraft directional stability prediction method by CFD," in *33rd AIAA Applied Aerodynamics Conference*, 2015, vol. 2015-Janua, no. June.

[23] F. Nicolosi, P. Della Vecchia, D. Ciliberti, and V. Cusati, "Fuselage aerodynamic prediction methods," *Aerosp. Sci. Technol.*, vol. 55, pp. 332–343, 2016.

[24] F. Nicolosi, P. Della Vecchia, D. Ciliberti, and V. Cusati, "Development of new preliminary design methodologies for regional turboprop aircraft by CFD analyses," in *29th Congress of the International Council of the Aeronautical Sciences*, 2014.

[25] D. Ciliberti, F. Nicolosi, and P. Della Vecchia, "A new approach in aircraft vertical tailplane design," in *22th AIDAA Conference*, 2013.

[26] P. Della Vecchia and F. Nicolosi, "Aerodynamic guidelines in the design and optimization of new regional turboprop aircraft," *Aerosp. Sci. Technol.*, vol. 38, pp. 88–104, 2014.

[27] D. Ciliberti, P. Della Vecchia, F. Nicolosi, and A. De Marco, "Aircraft directional stability and vertical tail design: A review of semi-empirical methods," *Prog. Aerosp. Sci.*, vol. 95, pp. 140–172, Nov. 2017.

[28] F. Nicolosi, S. Corcione, P. Della Vecchia, V. Trifari, and A. De Marco, "Design and aerodynamic analysis of a regional turboprop innovative configuration," in *6th CEAS Conference*, 2017, no. 893, pp. 1–16.

[29] F. Nicolosi, S. Corcione, V. Trifari, P. Della Vecchia, and A. De Marco, "Design Guidelines for High Capacity Innovative Regional Turboprop Aircraft," in *AIAA Scitech 2019 Forum*, 2019.

[30] F. Nicolosi, A. De Marco, L. Attanasio, and P. Della Vecchia, "Development of a Java-Based Framework for Aircraft Preliminary Design and Optimization," *J. Aerosp. Inf. Syst.*, vol. 13, no. 6, pp. 234–242, Jun. 2016.

[31] V. Trifari, M. Ruocco, V. Cusati, F. Nicolosi, and A. De Marco, "Java framework for parametric aircraft design – ground performance," *Aircr. Eng. Aerosp. Technol.*, vol. 89, no. 4, pp. 599–608, Jul. 2017.

[32] A. De Marco, V. Cusati, V. Trifari, M. Ruocco, and P. Della Vecchia, "A Java Toolchain of Programs for Aircraft Design," in *Aerospace Europe 6th CEAS Conference*, 2017.

[33] P. S. Prakasha *et al.*, "Multidisciplinary Design Analysis of BWB Aircraft Through Collaborative Design Approach : AGILE EU Project," in *31th Congress of the International Council of the Aeronautical Sciences, ICAS 2018*, 2018.

[34] P. S. Prakasha *et al.*, "Model Based Collaborative Design & Optimization of Blended Wing Body Aircraft Configuration : AGILE EU Project," in *2018 Aviation Technology, Integration, and Operations Conference*, 2018.