Investigation of the operational flexibility of a regional hybrid-electric aircraft

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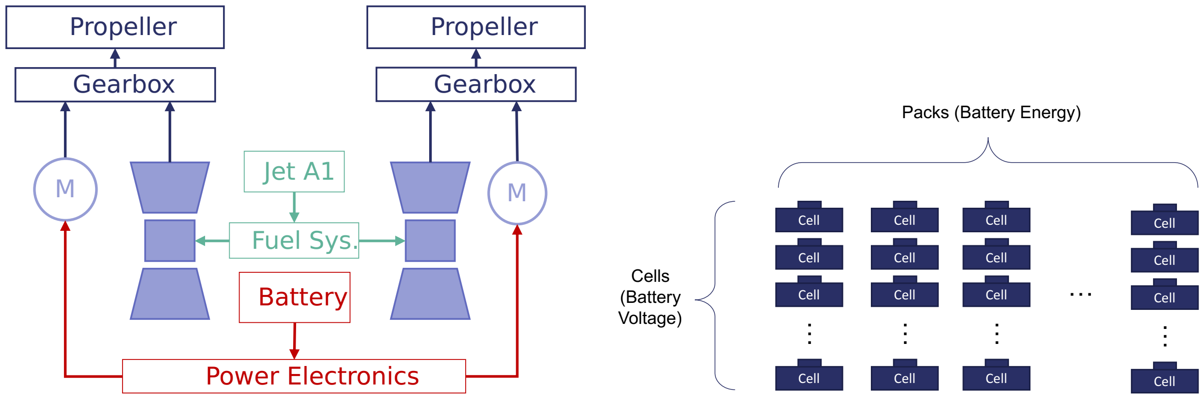
Abstract. The complexity of hybrid-electric aircraft propulsion systems is also characterized by the greater number of degrees of freedom of the energy management system, whose objective is to split the required power to fly the aircraft to the different available powertrains (i.e., gas turbines, electric motors, fuel cells, etc.). Typically, a single design mission is considered for assessing the performance of a hybrid-electric propulsion system, often with a simple constant split power between the batteries and gas turbine. A probabilistic set-based design space exploration methodology is used and allows us to study the effects of lifecycle analysis of the battery pack of a hybrid-electric 50-seater turboprop, while different mission scenarios are considered. Using this approach, it is possible to flexibly find multiple families of energy management strategies that can satisfy battery capacity requirements and the reduction of emissions simultaneously. Furthermore, the generated data can help the designers to understand the hierarchy of the requirements that drive the design of the propulsion system for a range of operating scenarios, with emphasis on the energy storage system. Hence, the airliners are offered enhanced operational flexibility of the aircraft for different and desirable mission profiles.

1. Introduction

Green and sustainable aviation has become one of the predominant research topics in the last 20 years. Aeroplanes achieving zero emissions have been set as a long term goal by stakeholders such as NASA, European Union and ICAO by the year 2050. Within the transition period, hybrid-electric propulsion is proposed as a viable solution for reducing the impact of regional aviation by the year 2030. However, these concepts pose significant challenges as they present complex systems consisting of multiple energy sources and paths, new technological challenges [1], thermal management requirements [2] and energy management strategies [3].

Previous work pertaining to the interaction between optimal energy management strategies and hybrid-electric aircraft propulsion has been published by the authors [4]. Energy management strategies were defined as continuous piecewise linear functions of degree of hybridisation (DOH) for each mission phase, where DOH is the fraction of the required power supplied by the electrical powerchain. Results indicated that piecewise functions composed of two lines were enough to capture the Pareto front, and more degrees of freedom would not yield further improvement. Furthermore, it was found that the reduction of fuel burn was sensible to DOH in the longest mission phase (cruise), while the reduction of NO_x emissions was determined mostly by the average level of hybridisation. Finally, the amount of available battery energy,



(a) Hybrid-Electric Propulsion Architecture (b) Battery Pack Layout

Figure 1

Table 1: Parameters of the Hybrid-Electric Aircraft

Maximum Take-Off Mass [kg]	21000	Electric Motor Efficiency	0.98
Operating Empty Mass [kg]	11550	Power Electronics Efficiency	0.985
Payload Mass [kg]	5000	Cable Distribution Efficiency	0.996
Gearbox Efficiency	0.99	Pack-to-Cell Mass Ratio	1.5
L/D (Climb)	16	Pack Energy Density [Wh/kg]	500
L/D (Cruise)	14.5	Cell Total Capacity [Ah]	7.2
Propeller Efficiency (Climb)	0.73	Cell Nominal Voltage [V]	3.7
Propeller Efficiency (Cruise)	0.86	System Nominal Voltage [V]	500

which was limited by the take-off mass, affected both the wideness of the trade-off and the overall reduction of fuel consumption and emissions over the baseline. However, the study was limited by the "rubber" battery pack model (i.e. the battery pack mass was determined by the energy density and required energy alone) and the consideration of a single design mission. The battery pack is one of the limiting technologies for hybrid-electric aircraft, which spawned multiple efforts to overcome it alongside battery health monitoring and sustainability [6]. The work presented in this paper overcomes these limitations by introducing a battery pack model based on an equivalent circuit model of the cells and two off-design missions are analysed alongside the design one.

2. Methodology

The P-DOPT (Probabilistic Design and OPTimisation) Framework [4] which has been developed in FutPrint50 is applied to identify the feasible energy management strategies in the design point and the off-design operating conditions. This framework is capable of identifying the areas of the design space, which are most likely to satisfy the set of requirements by evaluating each subspace with a probabilistic surrogate model, trained on the full model. The least feasible areas are discarded, reducing the computational cost of optimisation when searching for the best designs [5].

The aeroplane is a parallel hybrid-electric 50-passenger turboprop where the gas turbine and the electric motors provide their energy to the propeller through a gearbox, as shown in Figure 1a. Details regarding the parameters of the system are presented in Table 1.

The gas turbine is modelled as a thermodynamic equivalent of the PW127 turboprop engine using TURBOMATCH [7]. For simplicity, no thermal management system has been included in the model. The battery pack is modelled by simulating the behaviour of a cell discharging with an Equivalent Circuit Model [8] fit on experimental data. The battery pack is composed of branches of cells in series, satisfying the system nominal voltage, laid in parallel to satisfy the energy required to fly the design mission at the specified energy management strategy (Figure 1b). It is assumed that the pack is balanced, that all the cells discharge at the same rate, and no degradation effects have been included. To compare with the previous studies, the battery pack is assumed to have an energy density of 500 Wh/kg. This value is an optimistic projection. Current best values observed in aeronautic applications are around 150 Wh/kg [11]. The mission analysis code performs two types of analysis: sizing and simulation. In sizing mode, the code finds the battery pack size (number of cells in series and in parallel) which allows flying the mission at the selected energy management strategy without over-discharging the cells. In simulation mode, the battery pack size is given and the code discharges the battery pack by flying the mission with the given energy management strategy. It returns the final state of the cells and if the mission is feasible or not.

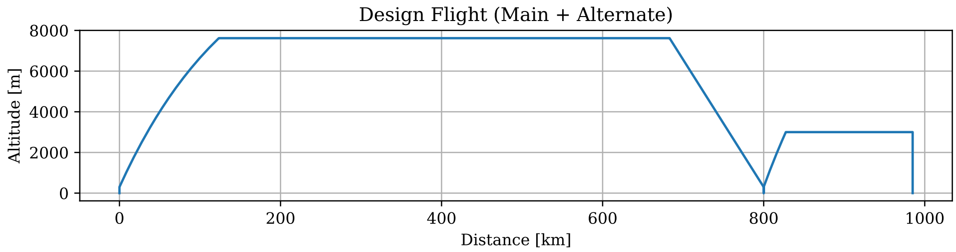
This study is carried out in two steps. First, sizing the battery pack with the design mission and then selecting the optimal one from the available results. Then, the optimisation framework is used to find the optimal energy management strategy in missions different than the sizing one. In this situation, the battery pack will operate in an off-design condition and the EMS will be tasked in recuperating as much optimal performance as possible without overdischarging the cells.

3. Test Cases

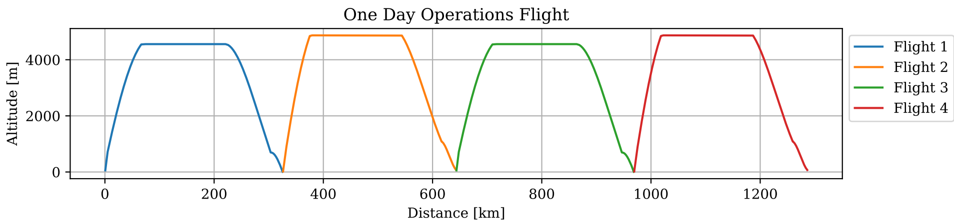
This study includes three different missions: a design mission to size the battery pack and two operating missions for exploring feasible energy management strategies under off-design conditions. Figure 2a presents the flight profile of the design mission, which has been obtained from FutPrint50 published work [9]. For the scope of battery pack sizing, only the main portion is hybridised with electrical power. The mission presented in Fig. 2b is modelled after a one-day operation of an ATR-42 between Aberdeen and Sumburgh by Loganair in Scotland. Two sets of return trips are carried out, one in the morning and one in the afternoon. It is assumed the battery pack is fully charged at the beginning of the day and recharged only at the end. Refuelling is allowed on the basis that the aircraft is stopped for a minimum 30-minute turnaround. Finally, the mission presented in Fig. 2c is modelled after a commuter flight with multiple stops in Portugal, between the cities of Bragança and Portimão, by the airline Sevenair. Also, in this case, it is assumed the battery pack is fully charged at the beginning of the day and recharged only at the end. However, no refuelling is permitted during stops as these are short layovers for embarking or disembarking passengers only.

The energy management strategy is defined as a linear function of the degree of hybridisation, the percentage of how much of the power provided to the propeller comes from the electrical source, for each mission phase (climb and cruise). This function is fully defined with two points, as shown in Figure 3. In the case of multiple flights in the same mission, the same EMS is used for all the flights.

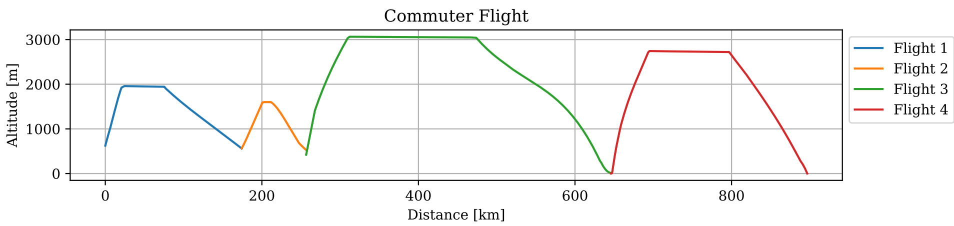
The overall optimisation problem is shown in Equation 1. The framework is tasked to find the energy management strategies that produce the least fuel consumption and NO_x emissions given the constraints on Take-Off Mass (TOM) and Depth of Discharge (DOD) of the battery pack. The selected probability for the exploration phase is 0.5, while the input parameters were discretised with 6 levels total producing 1296 different subspaces.



(a) Design Mission



(b) One-Day Operations Mission



(c) Commuter Flight Mission

Figure 2: Missions considered for this study.

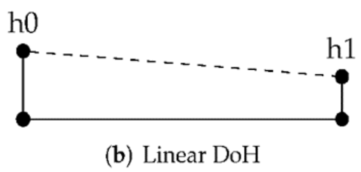


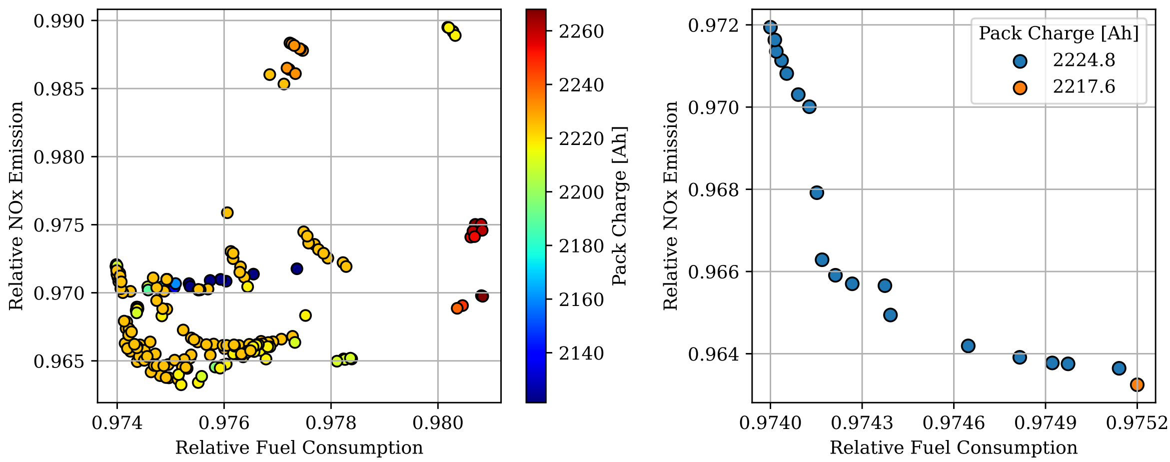
Figure 3: Definition of the Energy Management Strategy function

$$\begin{aligned} &\text{given} && X = \{DOH0_{cl},\ DOH1_{cl},\ DOH0_{cr},\ DOH1_{cr}\} \\ &\underset{X}{\text{minimise}} && M_{fuel},\ M_{NO_x} = f(X) \\ &\text{subject to} && TOM \leq 20100\,kg \\ & && DOD \leq 0.8 \end{aligned} \tag{1}$$

4. Results

4.1. Design Point

Figure 4 presents the full results of the sizing analysis. The framework identified several sub-Pareto fronts, with close values of battery pack charge. Interestingly, the points defining the global Pareto front (Fig. 4b) share the same battery pack capacity, that is they have the same battery pack size. The selected layout is 309 packs composed of 136 cells each, yielding 500 V voltage and 2225 Ah capacity at the battery pack level.



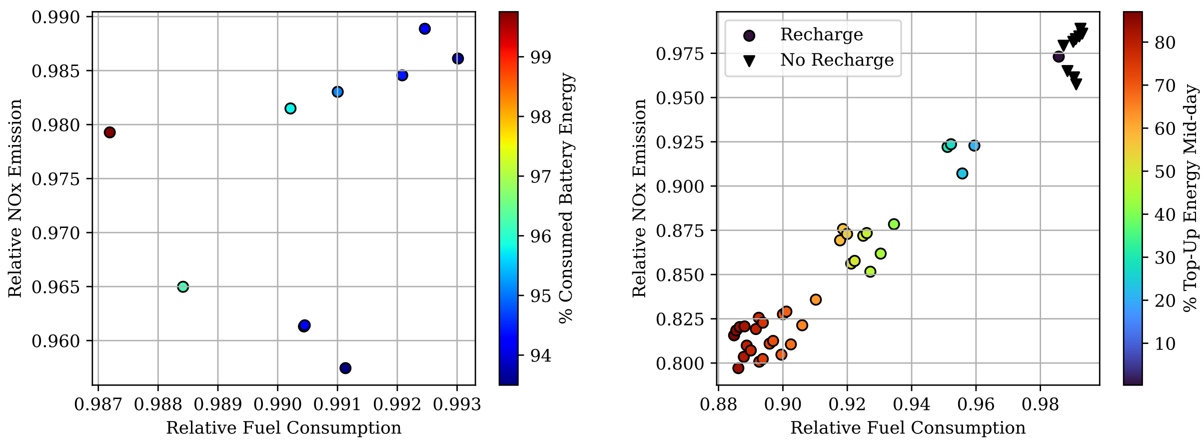
(a) Design condition solutions.

(b) Global Pareto front of the Design condition.

Figure 4

4.2. One-Day Operations

Figure 5a presents the points capable of carrying out the mission with the energy available in the battery pack. Few are able to carry out this mission, given that the combined length of the 4 flights is longer than the design mission. The improvement over the baseline is also quite limited, with 3% on NO_x emissions and 1.5% for fuel consumption.



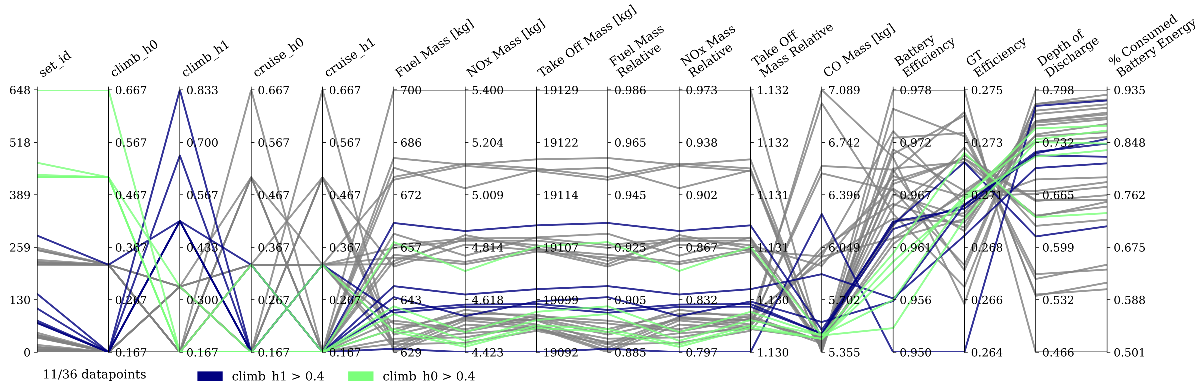
(a) Design points meeting the One-Day Operations mission.

(b) Design points with partial recharge after two flights.

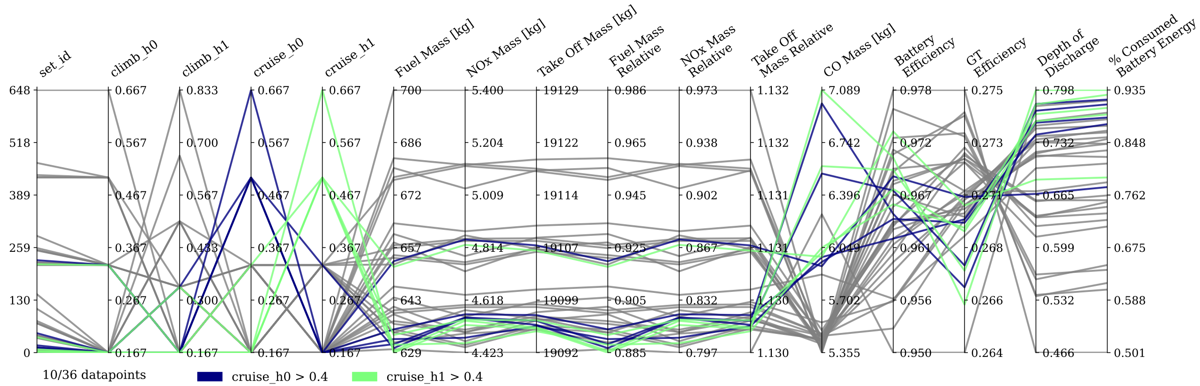
Figure 5

Introducing a partial recharge after the morning operations (the first two flights) reveals interesting results. The amount of energy recharged is what is required to complete the remaining two flights with a fully discharged battery at the end of the day. Figure 5b presents this scenario and compares it with the original case. Every identified operating condition performs better in terms of emissions than the original scenario: for instance, restoring 40% of the total battery energy allows to reduce the fuel consumption and the NO_x emissions by 6% and 12% respectively. However, increasing the amount of current through the battery pack and charging-discharging from a state of partial charge to high or low states of charge might increase the battery aging pack [10]. Further studies should be carried out where battery degradation effects are taken into consideration when searching for optimal energy management strategies and aircraft operating conditions. Especially, impact of higher currents and depth of discharge limits should be investigated in regards to their impact on aging.

Figure 6 presents the full dataset of Fig. 5b with selections highlighting input values defining the energy management strategies. Particularly, Fig. 6a indicates that strategies with a linearly decreasing DOH for climb have lower emissions than those with linearly increasing DOH. These results contrast with a previous find by the authors [4], most likely because the battery pack modelling of that study did not capture the cell behaviour during discharge. One outlier is present and is due to the design space framework: the set boundary consisted of a low "climb h0" range with a high "climb h1" range and the optimiser pushed at the limits of the boundary.



(a)



(b)

Figure 6: Topology of the Energy Management Strategies.

4.3. Commuter Flight

Figure 7 presents the operating points satisfying the commuter flight mission. For this operating condition, the aircraft produces fewer emissions than the baseline when at least 55% of the battery available energy is used. To operate the return flight with the same energy management strategy, a partial recharge is required, as discussed in the previous case in 4.2. Furthermore, when comparing the results of the two scenarios (Fig. 5b and Fig. 7) both present a bigger improvement in the reduction of NO_x emissions compared to the other objective. This result is a consequence of the type of flights analysed: the predominant phase of commuter flights is climb which affects the NO_x emissions the most since the gas turbine operates at a higher power setting [4].

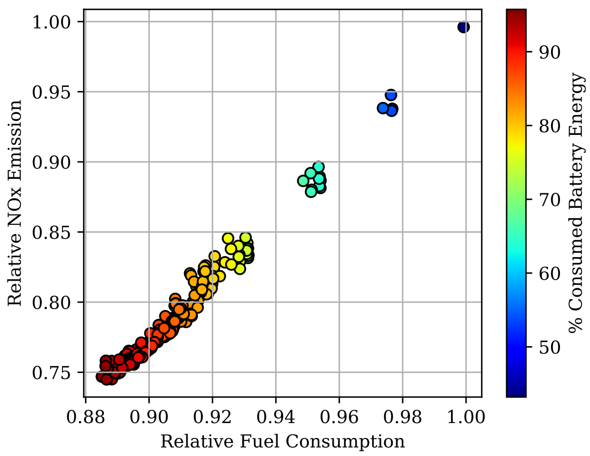


Figure 7: Design points meeting the Commuter Flight mission.

5. Conclusions

A study of energy management strategies of missions with different operating conditions has been presented. A battery pack model based on an equivalent circuit model was introduced and sized according to a design mission. With the battery configuration frozen, two scenarios of operations have been analysed: a single day of regional airline operations consisting of 4 flights and a commuter flight composed of several stops. From the analysis of the One-Day operations mission, it was evident that allowing for partial recharge significantly improves the reduction of emissions. For instance, NO_x emissions improved from 3% to 12% reduction with a partial recharge of the battery by 40%. However, the lifespan of the battery might be affected, as the current and depth of discharge might increase battery aging. Furthermore, the improved battery model suggested different energy management strategies in the climb phase than previously identified. Indeed for this type of short haul-flights, the climb phase plays the biggest role in the emissions and therefore should be prioritised when allocating the available battery energy. Future work should include the increasing of the number of degrees of freedom by setting a specific energy management strategy for each flight, rather than using a common one. Then, as it was learned from this analysis, battery degradation should be captured and included in the figures of merit alongside emissions. Finally, a comprehensive study taking into consideration emissions, aircraft availability and costs, both from direct operations and maintenance, would provide more insight into this trade-off between short-term performance and battery life.

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