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SWITCHING TO ELECTRIC PROPULSION: FLEET AND INFRASTRUCTURE SIZING

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ABSTRACT

Switching to novel aircraft power-trains featuring electric power components entails a relevant reconfiguration effort in terms of airport infrastructure. As long as batteries are used to store electric energy on board, in a future scenario where a fleet of all-electric or hybrid-electric aircraft will operate from an airfield, it will be required to recharge or swap depleted batteries in such a way to assure the same operativity level attained with conventional, fuel-burning aircraft. As nowadays batteries do not allow for a recharging time so short to be comparable with fuel refilling operations, a suitably designed mix of battery swapping and battery recharging facilities will be required on ground to grant desired operativity levels.

For the typical case of flying schools or aero clubs, where the same organisation manages both a ground infrastructure and an aircraft fleet, the sizing problem can be extended to consider simultaneously the respective costs of procurement and operation.

This paper introduces a complete analytical model to quantitatively assess the required infrastructure as well as the procurement and operative costs connected with the reconfiguration of an airfield towards an electrically powered fleet. An optimal sizing approach will be discussed, and the procedure exemplified in the realistic test case of the Aero Club Milano flying school, operating from Milan Bresso airport.

Keywords: fleet sizing, ground infrastructure sizing, electric propulsion, optimal airport reconfiguration, cost model

1 INTRODUCTION

An enabling factor for the introduction of an all-electric or hybrid-electric fleet in the air transport system is the setup of a suitable ground infrastructure. A need for an increased electric power supply has to be accounted for in the reconfiguration of an existing airports. Indeed, the price of electric energy would come to represent a more relevant cost. The energy purchase price is typically a function of time, changing greatly over a daily or weekly period - reaching up to two times and four times the minimum respectively, over these time frames [1]. A smart scheduling of the recharging activities should be pursued to reduce the energy supply cost.

Such smart recharge planning is clearly connected with the technological constraints inherent to available on-board systems and ground recharging facilities [2,3]. These can be reduced to two basic types [4], battery recharging stations (BRS) and battery swapping stations (BSS).

Battery recharging stations are conceptually similar to fuel refilling stations. A major shortcoming associated with BRS is the fact that heavier and higher-performing aircraft – e.g. today's liners – would need amounts of battery energy in the order of MWh (3.5-7 MWh for an aircraft the weight of a B737-800, depending on the mission [5]), which in turn would translate into an unacceptable recharging time, totally incompatible with the usual turnaround of a liner. The usual 90 kVA power lines and connectors currently deployed to supply aircraft systems on ground could be multiplied to increase power supply, but besides procurement cost for the hardware, this would impact on the peak power required from the grid, which is responsible for part of the energy supply cost, together with the actual energy acquired. In the Italian energy supply scenario, the cost of allowed peak power is responsible for 20% of the overall electric energy cost for a typical user [1].

An alternative to BRS are BSS, which allow recharging batteries while unplugged from the aircraft. Provided a suitable number of unplugged batteries is available, a smart scheduling of the recharge, simultaneously compatible with air operations and such to minimize power acquisition cost, can be envisaged. Clearly, a larger amount of batteries represents a higher acquisition cost and an increased logistical effort (batteries need to be transported from and to the aircraft, as well as safely stored after recharge and before being plugged in). Furthermore, similar to BRS, recharging power is limited for a single BSS, hence a higher number of simultaneous battery recharges would imply a larger number of BSS, with an ensuing higher acquisition cost.

These factors – required energy/power supply, number of BRS and BSS, and number of batteries – constitute the main output of a sizing problem where the schedule of air operations, i.e. number and time frames, is given in input. From the viewpoint of a ground operator, the reconfiguration of an airfield for operations with all-electric or hybrid-electric aircraft should imply defining these output, in order to grant minimum procurement and operative costs.

A different scenario is represented by airfields where a single company is simultaneously acting as ground operator and owner of a fleet. In some cases, most typically on smaller airfields serving as bases for flying schools, the operations of that fleet make for nearly the total of all air operations. For such scenario, the study of fleet switching to innovative propulsion should account for the procurement cost of novel aircraft, such to grant the same operativity level of a conventional fuel-burning fleet, yielding an extended sizing problem, where an optimal number of aircraft is obtained as an output, together with a suitably sized ground infrastructure.

The latter scenario is of great interest today, when the economic profitability of fleet switching to electric propulsion has to be assessed in detail. Lower absolute costs for both procurement and operations, as well as its limited impact on the existing air transport system, make the flying school or aero club case more likely to translate into a real field application.

In this paper, a comprehensive original method to face the problem of optimally sizing the ground infrastructure and fleet will be outlined first. An application of that method to the reconfiguration of the Milano Bresso (LIMB) airport will be presented next. This airport is operated by the company Aero Club Milano [6], which acts as airport manager, and owns an aircraft fleet, used for instructional as well as sport flights.

2 GROUND INFRASTRUCTURE AND FLEET RECONFIGURATION: ANALYTIC APPROACH

The airport infrastructure and aircraft fleet sizing introduced in Section 1 can be modelled analytically as an optimization problem. From an operator standpoint, the optimum represents a balance between the need to grant an assigned operativity level, i.e. a flight schedule, and that of minimizing procurement and operative cost.

In mathematical terms, a suitable cost function J can be built up based on cost chapters as follows:

$$J = C_E + C_P + C_{BSS} + C_{BRS} + C_B + C_{AC} \tag{1}$$

where the components C_E, C_P , C_{BSS}, C_{BRS}, C_B and C_{AC} represent the cost of the electric energy purchased from the grid, the cost of peak power, the procurement cost of the battery swapping stations and of the recharging stations, of the batteries and of the aircraft respectively. In seeking for an optimum of the cost function J, some constraints need to be considered, capable of modelling inherent technological limits, as well as mathematically formulating the physics of recharging operations. In order to correctly evaluate the constraints, the dynamics of the infrastructure are integrated over a suitable time frame of length T. The problem is allocated on a discrete time grid, where the length of each time step is τ.

The cost components and constraining equations will be described in the following subsections, highlighting their respective dependencies.

2.1 Cost components

The cost components in Eq. 1 can be expressed as follows. The cost of the energy supply C_E is bound to the energy amount $E^p(t)$ purchased from the grid over a given period, and to the monetary value per energy unit $\lambda(t)$. Due to the very low frequencies in the evolution of both functions of time (compared to a daytime scale), providing definitions in discrete time is more typical to this type of problem. Therefore it is possible to write

$$C_E = \sum_{t=0}^{T} \lambda_t E_t^p , \tag{2}$$

where the value of E_t^p represents the energy acquired between the current time t and the next one. Concerning Eq. 2, it would be easy to include a negative cost bound to putting energy into the grid. The ability to store energy in spare batteries which are not onboard may gain the ground operator the chance to resell energy to the grid, at times when its value is higher. This aspect was investigated at a theoretical level, but is not of interest for the case of smaller airports, for the absolute gain obtained selling the energy corresponding to the capacity of smaller batteries would be small, and would come at the price of a significantly increased system complexity.

Clearly, the value from Eq. 2 is a function of the time frame T considered for the analysis. That value should be taken consistently with the definitions of the other components of J, as described through the next equations.

The cost of power can be expressed as

$$C_P = (N_{BSS} P_{BSS} + N_{BRS} P_{BRS}) c_P \tfrac{N_D}{30} , \tag{3}$$

where N_{BSS}, P_{BSS}, N_{BRS} and P_{BRS} are the number and nominal power of BSS and BRS respectively. The sum between braces represents nominal peak power, i.e. the power needed in case all BSS and BRS are operating simultaneously. The c_P term represents the cost per unit peak-power per month, and the value of $\frac{N_D}{30}$ the number of days in the considered analysis (N_D) in a month. The value of N_D implicitly defines the limit for the sum in Eq. 1.

The component C_{BSS} represents the procurement cost of the BSS, and can be written as

$$C_{BSS} = N_{BSS} c_{BSS} \tfrac{N_D}{T_{BSS}} , \tag{4}$$

where c_{BSS} is the acquisition cost per unit of the BSS, and T_{BSS} the expected lifespan of the device. Therefore, $\frac{N_D}{T_{BSS}}$ represents the relative extension of the analysis, measured in days, over the expected lifespan of the device. The cost of the unit BSS can be defined based on a technological regression, as a function of P_{BSS}.

In a similar fashion, the cost model for BRS can be written as

$$C_{BRS} = N_{BRS} c_{BRS} \frac{N_D}{T_{BRS}} \,. \tag{5}$$

The cost model for batteries yields

$$C_B = N_B w_B, \tag{6}$$

where w_B is the cost per battery. It should be noted that, at a theoretical level, considering a sufficiently long time frame for the computation of cost, driving the number of total batteries to a minimum would not imply a lower overall battery cost, but only a lower initial procurement cost. A lower number of batteries would imply each of them should sustain more charge and discharge cycles. This in turn would decrease their life more rapidly, implying more batteries would be needed on the long run, with an ensuing higher overall cost. On the other hand, a higher number of spare batteries would entail a higher initial procurement cost, and their efficient use would be associated in turn to a higher number of BSS. In this sense, the C_B term makes sense only on a time frame sufficiently limited with respect to the battery lifespan.
Finally, the aircraft procurement cost C_{AC} can be arranged similarly to Eq. 4 and 5, proportional to the number of aircraft N_{AC} needed for operativity, yielding

$$C_{AC} = N_{AC} c_{AC} \frac{N_D}{T_{AC}} \,, \tag{7}$$

where c_{AC} is the aircraft procurement cost per unit, and T_{AC} the expected lifespan of the aircraft.

2.2 Constraints

The parameters influencing the components of the cost function need to satisfy an array of constraints, which reflect both technological limits and models of the recharging processes.
The state of charge $SoC_{i,t}$ of the i-th battery at time index t should be between a minimum SoC^{min} and a maximum SoC^{max}, as required by technological limits. This is expressed by Eq. 8,

$$SoC^{min} < SoC_{i,t} < SoC^{max}. \tag{8}$$

Battery charging can be carried out through a BSS or BRS. Battery charging (positive) rate $P_{bat_{i,t}}$ cannot exceed a technological limit expressed by a nominal P_{bat}^{max}. This yields

$$\begin{gathered} 0 < P_{bat_{i,t}}^{BSS} < P_{bat}^{BSS,max} \zeta_{i,t} \phi_{i,t} \\ 0 < P_{bat_{i,t}}^{BRS} < P_{bat}^{BRS,max} \xi_{i,t} \psi_{i,t} \,. \\ \phi_{i,t} + \psi_{i,t} \leq 1 \end{gathered} \tag{9}$$

At any time, a battery can be recharged only if it is linked to a BSS or BRS, and this is returned by the binary variables $\zeta_{i,t}$ and $\xi_{i,t}$ in Eq. 9, which will be 1 if the battery is linked to a BSS or BRS device respectively, and null otherwise. Two separate constraining equations are written, in case the battery is linked to either a BSS or BRS. Two further binary variables $\phi_{i,t}$ and $\psi_{i,t}$ are added to exclude simultaneous recharging of the same battery from a BSS and a BRS – their sum is constrained under 1.
A further constraining equation is represented by the energy balance for the i-th battery, yielding

$$SoC_{i,t} = \left(P^{BSS}_{bat_{i,t}} + P^{BRS}_{bat_{i,t}}\right)\tau\eta_c + SoC_{i,t-1}, \tag{10}$$

where η_c is the efficiency of the recharging process. The initial value of the state of charge $SoC_{i,0}$ needs to be assigned. The energy amount acquired from the grid and corresponding to the recharge power, is

$$E^p_t = \tau \sum\nolimits_i \left(P^{BSS}_{bat_{i,t}} + P^{BRS}_{bat_{i,t}}\right), \tag{11}$$

where the sum has to be carried out on the number of active charging devices (BSS and BRS). More binary variables and corresponding constraints are deployed at an implementation level, to grant consistency when reducing all constraining equations to a linear form.

2.3 Optimization structure and implementation aspects

The optimization of the cost function in Eq. 1 is carried out based on a desired operativity data. The flight schedule is assigned over a considered time frame, yielding a number of aircraft that need to be airborne at any collocation point. The number of aircraft, batteries and recharging devices is then steered by the optimizer to yield the minimum cost as defined by Eq. 1.

Retrieving the expression of J from Eq. 1, it can be now computed as a function of the optimization variables of E^p_t, N_{BSS}, N_{BRS}, N_{BSS}, N_B and N_{AC}. Other quantities appearing in Eq. 2 to 7, namely λ_t, P_{BSS}, P_{BRS}, c_P, c_{BSS}, T_{BSS}, c_{BRS}, T_{BRS}, c_{BSS}, w_B, c_{AC} and T_{AC} can be considered as assigned technological parameters. Further optimization parameters include the binary variables appearing in the constraining Eq. 9, and those required to express all constraints through linear equations. The resulting optimization problem is based on a mix of discrete and non-discrete variables, and can be faced via dedicated MIP (mixed-integer programming) solvers.

An analysis on suitably simplified case studies has been carried out to check the problem is well posed and validate results, as well as testing the performance of different commercial MIP solvers. The selected solution algorithm is GUROBI, which implements a MILP (mixed-integer linear programming) approach, fully compatible with a linear formulation of the optimal problem.

3 INFRASTRUCTURE AND FLEET RECONFIGURATION AT MILAN BRESSO

The procedure introduced in Section 2 can be applied to the analysis of the reconfiguration of the airport base and fleet of Aero Club Milano (ACM), which operates from Milan Bresso (LIMB).

The Milan Bresso airfield features a single 1,080 x 30 m asphalt runway, which does not pose limits to terminal operations by any aircraft in the single-engine propeller-driven weight category. The current fleet of the ACM is composed of 21 aircraft, of which 20 are single-engine propeller-driven. In the current analysis, it has been hypothesized to switch from the current aircraft models, mainly Cessna C172 and Piper PA-28, to a homogeneous fleet of Pipistrel Panthera Hybrid [7], which is in an advanced design stage, under the auspices of project MAHEPA [8]. The basic features of the battery of this aircraft are reported in Table 1.

In order to analytically set up the sizing problem, the recharge power values P_{BSS}, P_{BRS} of the ground recharging devices have been defined at the nominal recharge power of the aircraft, i.e. 60 kW. Similarly, the maximum SoC^{max}, the recharge efficiency η_c and the unit cost w_B have been defined based on the data in Table 1.

Parameter	**Value**
Nominal capacity	13.8 kWh
Usable capacity	11-12 kWh
Life @ 75% DOD	800 cycles
Charging efficiency	93%
Charging power	60 kW

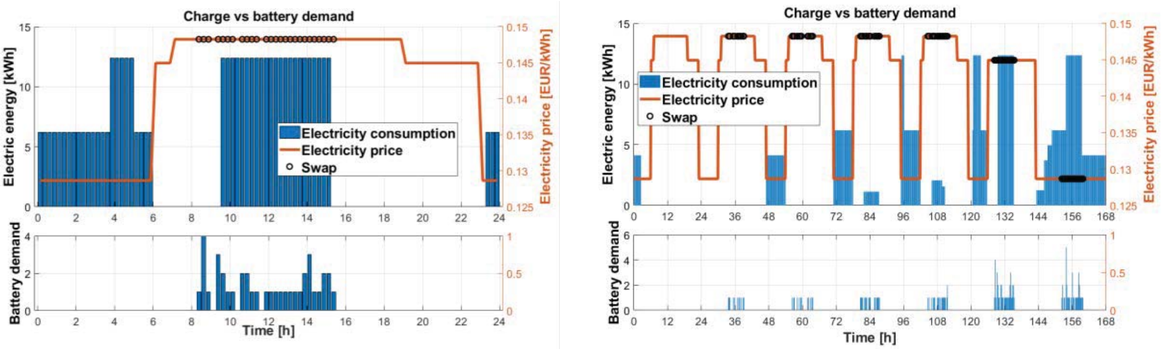
Table 1: Basic data of Pipistrel Panthera Hybrid battery.

The unit cost of the recharging devices c_{BSS} and c_{BRS} has been fixed at 39.8 k€, based on a technological-statistical regression, for the considered recharge power of 60 kW [9].

3.1 Simplified sizing problem

The sizing problem has been carried out at first for a simplified scenario, where only BSS are considered as recharging devices. This yields a simplification in the formulation of the cost function and constraints. The traffic data in input has been taken from the actual operations of the ACM on a given Saturday in October 2017. This month is associated to the most intense flying activity, due to the good weather and shrinking daylight time. It has been selected based on a worst-case, conservative approach for the sizing.

The sizing analysis has been carried out first considering a time frame of a single day, and next on the corresponding week. The considered discretization time τ is 15 minutes. The top plots of Figure 1 display the results in terms of electric energy need over time, compared to the supply cost of energy in Italy, based on historical data (orange line). The results for the one-day and one-week cases are shown on the left and right plots respectively.



(a) (b)

Figure 1: Energy expenditure and recharging schedule at Milan Bresso, BSS only. (a): busiest day; (b) busiest week

On the bottom plots, the battery requirement bound to the assumed schedule of operations is reported. It is possible to note how the optimal recharge strategy takes advantage of the low energy price during night hours to recharge a first set of batteries. The remaining recharge operations are carried out on condition, soon after the beginning of flight operations during daylight hours. This is more advantageous than having a larger number of batteries, charged ahead of their respective time of use. After use, batteries are not charged until a lower power procurement price is reached, i.e. after daylight hours.

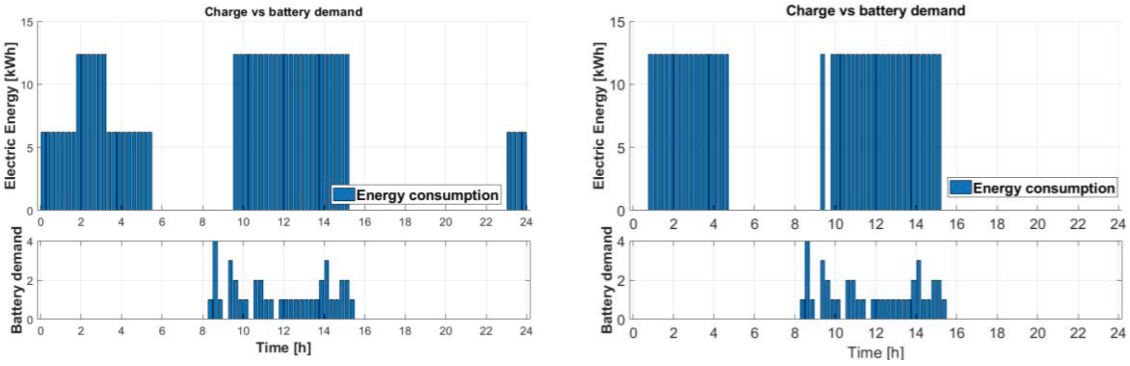
Table 2 compares the results of the sizing for the one-day and one-week cases. As expected, the number of batteries and BSS is the same, as Saturday corresponds to the most demanding day of the week. The number of aircraft needed to cover the operative requirements is lower than the current fleet of ACM. This is due to the fact that the scenario investigated here does not account for redundancy, which would be required in real-world operations to mitigate the effect of prolonged unavailability of some aircraft resulting from maintenance and faults, nor it considers that some aircraft with specific instrumentation configuration are indeed required for specific missions, like IFR training, but are generally far less used than others in the current ACM fleet.

Parameter	**One-day sizing**	**One-week sizing**
Number of batteries (N_B)	16	16
Number of chargers (N_{BSS})	1	1
Number of aircraft (N_{AC})	10	10
Recharged batteries	39	136
Overall energy requirement [kWh]	410	1,430
Peak power [kW]	60	60
Power losses [MJ]	103	361

Table 2: Results of sizing, comparison.

3.2 Complete sizing problem

In a more complete scenario, both BSS and BRS are considered. For the case of Milan Bresso, no substantial difference in the output of the design procedure has been highlighted. The recharge time by a BRS is compatible with the 15 minutes average turnaround time for ACM operations, thus the adoption of a BRS or BSS bears a similar impact on operativity. Figure 2 highlights the similarity of the sizing solutions in the respective cases, with both BRS and BSS (left) and with BRS only (right). Both compare well with Figure 1(a), where only BSS are considered.



(a) (b)

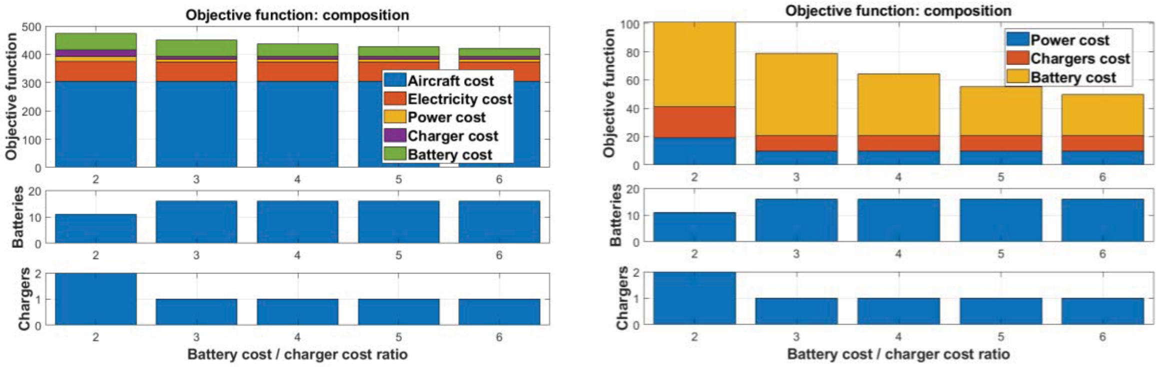
Figure 2: Comparison of sizing solutions. (a) BSS only; (b) BSS and BRS

The breakdown of optimal cost corresponding to a sizing solution where both BRS and BSS are considered is shown in Figure 3. The right plot presents the cost components due to power, as well as procurement of recharging devices and batteries, magnified with respect to the left plot. The latter is dominated by aircraft and energy procurement cost. The columns refer to sizing solutions with different battery unit cost parameter w_B.

As previously reported, a change in this quantity has an indirect effect also on the number of charging devices. From the lower plots in Figure 3, moving leftwards column by column, it is possible to check that under a certain w_B the solution changes to a higher number of rechargers, which increase greatly the recharging ability of the ground infrastructure, and consequently yield a lower number of required batteries.

4 CONCLUDING REMARKS

A method to resize an existing airport based on the adoption of a hybrid-electric fleet has been introduced. The method minimizes the procurement cost for aircraft and battery recharging devices, as well as the running cost of energy. This result is obtained without altering the capacity of an existing conventional fleet. An application of the methodology to the case of the fleet of Aero Club Milano has been presented, highlighting its effectiveness.



(a) (b)

Figure 3: Breakdown of cost for different values of w_B. (a) General view; (b) detail of smaller cost components

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