Design of Hybrid-Electric Small Air Transports

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Abstract. The potential benefits of hybrid-electric or full-electric propulsion have led to the proliferation of many concepts over the past decade. The lack of conceptual design methods capable of grasping the effects of the new propulsive technologies is often due to the absence of industrial data supporting the research. In the present work, two objectives are pursued. On the one hand, the introduction of semi-empirical methods for weight estimation based on the data provided by the industrial partners of the ELICA CS2 project. On the other hand, the establishment of generative engineering as a conceptual design tool for propulsive system architecting and fault tolerance analysis. The applications of the proposed conceptual design methods deal with two different years of entrance in service.

1. The challenges of electric aircraft
The increasing perception of the environmental impact of technological progress has moved the aviation market to new demands, other than speed and payload capacity, driving factors of the past century. Direct emissions from aviation account for about 3% of the European Union’s (EU) total greenhouse gas emissions and more than 2% of global emissions [1]. The contribution of aircraft emissions to climate change has been established in literature [2], as well as the environmental cost of those pollutants. Among the others, noise can be considered the dominant part of that cost, since it is almost 75% of the total cost [3]. From this point of view, the design of new concepts integrating hybrid power sources and highly efficient propulsive system is a crucial aspect of future aviation. The rapid expansion of the sector caused by globalization, liberalization, combined with current technologies and the appearance of the low fares business models, increased the severity of aviation impact on climate change in the last decade. However, integrating aviation into discouraging policies will have negligible impacts both on future market growth and emissions, as stated in Ref. [4–6], where aviation activity growth rate has been fixed at 2.5% and the fuel efficiency improvements per year have been fixed at 1%. The growth rate proposed is conservative if compared with other studies that did not account for the status of aviation segment.

Large Air Transports are the main responsible for aviation emissions due to airlines activity, except for noise emissions [7], often related to fleets composed by old aircraft. For this reason and anticipating the renewing of the fleets, some industrial projects are pushing on the reduction of emission introducing new enabling technologies: ultra-high-by-pass ratio, electric propulsive systems, and many others. On the other hand, the interest in general aviation market has been renewed by the increment of domestic flight and, at the same time, by the possibility of a rapid entrance in service of...
new hybrid technologies [8]. At the same time, hybrid-electric propulsive systems have opened the path to the possible introduction of air transports in urban context thanks to reduced noise and pollutants. This is the market segment filled by Personal Air Vehicles and Small Air Transports (SAT). In particular, the SAT’s market segment has been investigated by ELICA (ELectric Innovative Commuter Aircraft) project to fulfill market demand of future concepts. The conceptual design chain discussed in the present work and its application have been developed in the framework of the aforementioned project.

The top-level aircraft requirements provided in the framework of the ELICA project feed the design chain discussed in previous works of the same authors [9–12]. Additional constraints to the technological level targeting years 2025 and 2035 as possible entrance in service have been fixed by Rolls-Royce driving the weight estimation loop to reliable results. The approach to the failure analysis related the estimation of one-engine inoperative (OEI) performance has been enhanced thanks to the contribution of Siemens.

The second section of this work deals with the powertrain mathematical model, before introducing the weight estimation of its components in the following one. The fourth section of the work introduces the generative engineering to support system architecting and fault tolerance analysis. The fifth section describes the results obtained designing the concept in figure 1 targeting the two different years for entrance in service. The last section concludes the work presenting the following steps of the ELICA project.

2. Powertrain modelling
In the case of the ELICA project, the serial/parallel partial hybrid electric powertrain seems to be the most promising in terms of flexibility and global efficiency for the configuration considered. This architecture, reported in figure 2, is modelled through the powertrain equations proposed in literature [11,13]. Two propulsive lines are considered. The former is directly connected to the thermal engine. The latter is composed by distributed electric propellers.
The powertrain equations necessary to describe the power distribution at each step of the design process are strongly influenced by the hybridization factors, the efficiencies, and the operating conditions. Each operating condition is characterized by the direction of the power entering in four different elements: battery, electric generator, and propulsive lines’ propellers. The feasibility of each operating condition is related to the hybridization factors and the efficiencies of each element.

The introduction of lookup tables for efficiencies and the design of an engine deck to link the two power sources are the main topics to deal with for the simulation of the flight mission. The importance of defining the fraction of thrust due to thermal power source can be considered a major issue for mission analysis. The engine deck is a data matrix providing information about the propulsive system in terms of shaft power or thrust and the fuel burnt is calculated considering the specific fuel consumption (SFC) or the thrust specific fuel consumption (TSFC) associated [14,15]. This data matrix is provided by the engine manufacturer divided in different power ratings which refer to different flight segments. In the present work, the engine deck is provided in terms of gas turbine power and fuel flow. The use of the fuel flow allows decoupling the fuel consumption from the shaft power or the thrust, which can be provided by multiple power sources in case of hybrid concepts. The input power from the engine deck and the powertrain equations are used to calculate the power managed by each element. To interrogate the engine deck, four different parameters are assigned: altitude, Mach number, throttle, and deviation from ISA temperature [16]. When approaching a conventional powerplant, three different efficiencies [14] are sufficient to describe the power distribution through the powerplant: the propulsive efficiency, \( \eta_{P_1} \), the mechanical efficiency, defined as the ratio of net mechanical power at shaft with respect to the one entering the gearbox, \( \eta_{GB} \), and the thermal efficiency, \( \eta_{GT} \), synonymous of the engine capability to convert the chemical energy inherent in the fuel to a net kinetic energy gain. However, in case of hybrid electric aircraft, to solve the system of powertrain equations a lookup table for each element of the powertrain system is necessary to provide the efficiency as a function of the entering power and RPM, where required. The only efficiency that is calculated as a dependent variable is the thermal efficiency, which is a function of fuel flow, gas turbine power, and the specific energy of the fuel itself.

An additional step for concepts boarding batteries as secondary power source is related to the dynamic discharging cycle of these elements. Powertrain equations allow calculating the required battery power, not including power losses. High voltage battery packs consist of individual modules and cells organized in series and parallel. The packaging is part of the design process that assures the required voltage and capacity, or, in other words, the required power and energy. Batteries are modelled in the present work considering electrical models from literature studies [17,18].

3. Weight estimation
The weight estimation is carried out at subsystem level to define the contribution of each element of the powertrain architecture to the total aircraft mass. Methods proposed in literature can be applied to all those components that are not modified by the electrification process. Thus, in the present work, the discussion of weight estimation is limited to those elements composing the propulsive system.

From the application of the powertrain equations at each step of the mission profile, the energetic and power requirements can be calculated. The first mass estimated is the engine dry mass, which can be related to thermal engine sizing power or maximum thrust by regression laws, as shown in literature for the case of turbofan engines [19]. In case of turboprop engines, the dry mass can be estimated considering the following equation.

\[
W_{dry\ engine} \ (kg) = 0.23 \times Power (kW) + 17.25
\]  

(1)

For turboshaft engines, data available in literature or from manufacturer have been used for the definition of the following equation linking the shaft power to the engine dry mass.

\[
W_{dry\ engine} \ (kg) = 0.18 \times Power (kW) + 35.20
\]  

(2)
The coupling of thermal engine shaft with a propeller with lower rotational speed requires the interposition of the gearbox to transmit the mechanical power. The mass of these elements strongly depends on two different parameters: the input torque and the gear ratio, that is the ratio between the input rotational speed and torque and the output values. In other words, fixed the input torque and the desired output, the mass value can be estimated by the following equation.

\[ W_{\text{Gearbox}}(kg) = a \times \text{Torque (Nm)} + b \] (3)

The coefficients reported can be calculated as a function of the gear ratios. Results are satisfactory even when higher order terms are neglected (the third and second orders coefficients are null) and this can be of help when there is a reduced number of data available. The coefficients in the previous equation are strongly dependent on the technological levels. Thus, it could be necessary to estimate the regression laws with appropriate coefficients depending on the available data.

\[ a = -0.01 \times (\text{Gear Ratio})^2 + 0.08 \times (\text{Gear Ratio}) - 0.15 \] (4)

\[ b = -0.06 \times (\text{Gear Ratio})^2 + 1.36 \times (\text{Gear Ratio}) - 0.68 \] (5)

The equations have specific limits of validity. The gear ratios considered range from 2 to 7 and the maximum torque value admitted is 2000 Nm.

The e-motor drives aim to transform electric power in mechanical power and vice versa. The transformation has the specific objective of transforming the electric energy to move the propellers or producing electric power from the mechanical power provided by the thermal engine shaft. The mass can be estimated from the following equation.

\[ W_{\text{E-Motor}}(kg) = \alpha \times \text{RPM}^{\beta} + \gamma \] (6)

The coefficients reported in the previous equation are a function of the sizing power that can be based on statistical data available from manufacturers. For e-motor drives at state of the art, the following equations can be used.

\[ \alpha = 166 \times \text{Power (kW)} + 8469 \] (7)

\[ \beta = 8.00 \times 10^{-5} \times \text{Power (kW)} - 1.07 \] (8)

\[ \gamma = 0.06 \times \text{Power (kW)} - 3.08 \] (9)

Power electronics play a key role in power distribution and conversion, including both power management and distribution unit (PMAD) and converters/inverters. While the first is responsible for the direct control of the power distribution assuring the safety of the propulsive system and the risk management in case of failure, the seconds are responsible for switching direct current and alternating current in a power grid where units powered with direct current are connected by alternating current cabling. Mass estimation of converters, choppers, and inverters is managed with good reliability for state-of-the-art components with the following equation.

\[ W_{\text{Power Units}}(kg) = K \times \text{Power (kW)} + 1.25 \] (10)

\[ K = \frac{0.48}{\text{Voltage (V)}} \] (11)

The discussion about the power sources is here proposed for the case of e-storage unit and fuel, but it can be easily applied to the case of hydrogen fuel cells. In general, the chemical power source is always energy dependent, while the e-storage unit is sized considering the most demanding requirement between power and energy. The specific power and energy have been provided by industrial partners to assure realistic innovation trends for future products.

\[ W_{\text{fuel}}(kg) = \frac{\text{Energy}}{\text{Specific Energy}} \] (12)
\[ W_{\text{battery}}(kg) = \max \left( \frac{\text{Energy}}{\text{Specific Energy}}, \frac{\text{Power}}{\text{Specific Power}} \right) \]  

The different equations introduced in this chapter are based on components on the market or data available from literature. However, as demonstrated in the framework of the ELICA project, the coefficients can have different values depending on the entrance in service and the technological innovation foreseen for each component. For this reason, the support of components manufacturer is mandatory to have reliable results.

The last two elements discussed in this chapter are the composite propellers providing thrust. Propeller’s mass should be estimated considering both diameter and RPM. However, for the present application, considering two families of propellers, the following equations are applied.

\[ W_{\text{propeller}_1}(kg) = 40 \times D(m) \]  
\[ W_{\text{propeller}_2}(kg) = 50 \times D(m) \]

The first equation is applied in case of lower speed propellers (maximum RPM lower than 2500), while the second one is applied to propellers with high solidity working at high speed, as those used for distributed electric propulsion.

It is here explicitly noted that the statistical law proposed for weight estimation are generally valid regardless of the entrance in service. The dependence from the technological level of interest lies in the coefficients of the function used to calculate the correlation parameters (equations (4), (5), (7), (8), (9), and (11)). The functions proposed are referred to today’s technological levels.

4. Fault tolerance analysis

This section is dedicated to the fault tolerance analysis of the propulsive system, intended as the verification of the safety conditions and performance in the event of one failure. When designing a new aircraft, the designer must ensure its controllability in the most critical of probable situations, excluding only events whose estimated frequency is sufficiently lower than the operational life. A driving factor could be the thrust provided by each propeller or the power management architecture making some propellers more reliable than others or even the positions of the propellers themselves with respect to the center of gravity, which is crucial when dimensioning the vertical tailplane.

Classically, One Engine Inoperative (OEI) condition stands for the loss of one of the engines and therefore, for twin-engine aircraft, half of the available thrust. A conventional aircraft must guarantee compliance with the constraints imposed by regulation even in the worst-case scenario, corresponding to the loss of the critical engine. The latter is identified as the engine responsible for the greatest yaw moment, for example by virtue of its greater distance from the center of gravity of the aircraft or asymmetry in thrust. Also, tailplane sizing is primarily driven by this yaw moment. The same definition of OEI condition for hybrid-electric aircraft must be generalized including other units. Depending on the mechanical or electrical interconnections between the components, the degree of hybridization, and the type of power sources, the failure of an element can have different consequences in terms of residual power and yaw moment. Depending on the case, the analyst may be interested in using two different criteria for determining the critical scenario: the minimum (residual) thrust criterion and the maximum yaw moment criterion.

The relation between system architecting for hybrid-electric aircraft and their intended fail-safe behaviour brings an interesting potential to combine the activities of designing and failure/fault tolerance analysis. At early stages of the design process, the foresight of the designer is limited by many aspects. Firstly, the objective of meeting new market demands improving an original baseline. Secondly, the necessity of approaching a multidisciplinary design from different perspectives, typically involving informal or semi-formal representations or drawings of the concept. Finally, the inclusion of multiple tools created for the specific type of architecture, which could be a limiting factor in case of wide design spaces. In the context of conceptual design, generative engineering is the
most suited approach \[20\]. With generative engineering, a new method to support the creative task of finding and selecting the right architecture solutions for systems becomes available.

This work will highlight the main steps for the creation and selection of a failsafe architecture, in the context of hybrid-electric propulsion system design, through the application of generative engineering by Siemens. The first and mandatory step is the identification of the components and the number of each of them. The components chosen are characterized by a certain number of inputs, outputs, and input/output ports. The links are constrained by the nature of the ports that can be electrical or mechanical. Moreover, each component can be linked to one or more elements in inputs and/or in outputs. Assuming a certain set of additional constraints on the number of elements, that for the present case are related to the number of propellers, thermal engines, and gearboxes, the generative engineering evaluates all the physically feasible solutions, determining the number of generators, e-motor drives, and battery packs.

At the end of the creative task, the failures of interest are selected. In the present context, several failures associated to each element of the propulsive system are considered as plausible critical condition. The resulting architectures are evaluated considering three objective functions. The minimum mass, the minimum thrust loss, and the minimum residual yaw moment.

5. Application
The application proposed in the present work deals with two hybrid-electric concepts regarding as many target years of entrance in service, that are 2025 and 2035. For sake of completeness, a conventional concept related to nowadays technological level of maturity will be compared to the other two hybrid concepts. The main objective of the application is highlighting the potential fuel saving percentage related to the electrification and re-engining of a flying platform. The aircraft is powered by two main inboard propellers and eight high-lift propellers, for the case of the two hybrid concepts, specifically designed to benefit of the aero-propulsive interactions. Thanks to the increment of the maximum lift coefficient allowed by distributed electric propellers, the necessary wing area is reduced in case of hybrid concepts of about 20%.

| Geometry      | Conventional (y. 2020) | Hybrid-Electric (y. 2025) | Hybrid-Electric (y. 2035) |
|---------------|------------------------|---------------------------|---------------------------|
| Wing area (m²)| 42.43                  | 33.94                     | 33.94                     |
| Wing span (m) | 22.58                  | 22.58                     | 22.58                     |
| Wing AR       | 12.02                  | 15.02                     | 15.02                     |

The propulsive architecture has been divided in two different subsystems powering the propulsive lines on each semispan, as shown in figure 2. To be compliant with regulation constraints, the aircraft’s minimum control speed should not exceed by more than 20% the take-off stall speed. Considering the take-off configuration, the calibrated airspeed is 51.52 m/s. However, the value that should be considered is the one accounting for the increment of lift coefficient allowed by distributed propulsion (43.70 m/s). Based on the latter, the maximum value of minimum control speed is 52.43 m/s. The key elements for the enhancement of the propulsive architecture are the duplication of the battery packs and the link between the two subsystems, which allows the redistribution of the electric power between the propulsive units. The redistribution of the power supplied, with the objective of reducing the thrust loss and the yawing moment generated by asymmetric thrust and drag, is one of the benefits related to hybrid-electric powertrain. In fact, the minimum control speed measured at the failure of the thermal engine, that is the most critical condition, is 77.20 m/s, which can be reduced to 47.20 m/s by redistributing the propulsive power to reduce the residual yaw moment.

The mass breakdown of the aircraft is detailed in the following table.
Table 2. Mass breakdown for the three concepts considered.

| Mass (kg)                  | Conventional (y. 2020) | Hybrid-Electric (y. 2025) | Hybrid-Electric (y. 2035) |
|----------------------------|------------------------|---------------------------|---------------------------|
| Maximum Take-Off Weight    | 7988.5                 | 8612.0                    | 8486.3                    |
| Operative Empty Weight     | 5055.1                 | 6225.2                    | 6105.2                    |
| Payload                    | 1766.7                 | 1766.7                    | 1766.7                    |
| Powertrain                 | 1117.8                 | 2586.3                    | 2461.1                    |
| Structure                  | 2411.5                 | 2606.6                    | 2606.6                    |
| Fuel                       | 1166.7                 | 620.0                     | 614.1                     |

Flight mission results are reported considering the fuel saving percentage as the main objective to discern the competitiveness of one aircraft from another. Two different mission profile are compared: the first one is the design mission of about 500 nmi, the second one is the typical mission of about 200 nmi. With the aim of reducing the fuel consumption during long flight phases, as cruise, the battery has been designed to provide higher quantity of energy to the detriment of the maximum power supplied.

Table 3. Performance of the three concepts considered.

| Performance                  | Conventional (y. 2020) | Hybrid-Electric (y. 2025) | Hybrid-Electric (y. 2035) |
|------------------------------|------------------------|---------------------------|---------------------------|
| Design mission fuel (kg)     | 1111                   | 590 (-47%)                | 585 (-47%)                |
| Design mission block fuel (kg)| 803                    | 427 (-47%)                | 423 (-47%)                |
| Typical mission fuel (kg)    | 642                    | 322 (-50%)                | 312 (-51%)                |
| Typical mission block fuel (kg)| 334                   | 159 (-52%)                | 151 (-55%)                |

6. Conclusions
The 19 pax aircraft designed in the framework of the ELICA project are in line with regulation constraints on commuter aircraft. For the present case, the considerations are solely related to the fuel consumption as driving factor to assess the competitiveness of the configuration chosen.

The electrification and re-engining of the aircraft allow a fuel saving percentage of about 52% on the block fuel of the typical mission with the technological level foreseen for year 2025. On the other hand, the technological level considered for the year 2035 would allow a fuel saving percentage of about 55%. The encouraging results are in line with Clean Sky 2 objectives, even if the benefits are far from market expectations. In fact, limiting the assessment of the configuration competitiveness to the fuel saving percentage presented would not motivate the high investment that a revolutionary design chain requires. Thus, for the future steps of the project, the enhancement of performance and the use of fuel cells designed in substitution of the thermal engine are the two main objectives.

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