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# CONCEPTUAL DESIGN STUDY OF HYBRID-ELECTRIC AIRCRAFT USING MULTIDISCIPLINARY OPTIMIZATION

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***Abstract.*** *The design of hybrid-electric aircraft has attracted the attention of worldwide researchers and engineers, following the trend for more efficient machines, which consume less fossil fuel and generate fewer pollutants. In this context, the hybridization concept brings new propulsive systems combining conventional combustion engines and batteries. This work presents the conceptual design of hybrid-electric aircraft based on historical trends tables used for initial estimate and then the application of a multidisciplinary optimization process that transforms a conventional aircraft into a hybrid-electric aircraft. The results showed that the final aircraft presents characteristics similar to its competitors in the market, corroborating its economic viability, along with low fuel consumption.*

***Keywords:*** *aircraft design, hybrid-electric aircraft, multidisciplinary optimization*

## 1. INTRODUCTION

The study of fully or partially electric aircraft has been the subject of discussion between researchers and engineers at universities and aerospace industry over the last years. The need to develop ever more efficient and greener aircraft leads to the motivation to expand technologies and to move toward previously unfeasible concepts.

Currently, most general aviation aircraft typically use internal combustion engines (ICE) as a power source. These engines burn fossil fuels with high energy densities, making this type of raw material very advantageous for aviation. However, they are highly polluting, since their burning generates the production of carbon dioxide ($CO_2$), which is the main responsible gas for global warming. The Air Transport Action Group (ATAG) points out that 2% of anthropometric carbon dioxide emissions come from aviation, and this number only tends to increase along with the number of aircraft in operation (Pornet and Isikveren, 2015). Under those circumstances, several targets to reduce these emissions have been defined by Vision 2020 and AGAPE 2020 for the next few years (Muller, 2010).

Thereby, it is meaningful to consider and rethink alternative ways of power supply. Thus, the introduction of electric propulsion systems has been a great option. First of all, batteries can be used as a power source instead of conventional fuels. Conversely, the battery uses itself brings challenges such as the weight on board and its specific energy. Moreover, engines have lower efficiency and power-to-weight ratio when compared to electric motors (Friedrich and Robertson, 2014). Hence, hybrid-electric systems are proposed to balance the advantages of both engine and motor systems, improving performance. Such systems have potential advantages including low fuel costs, lower vibrations, lower pollution, and reduced noise (Isikveren *et al.*, 2012).

After all, it is not an easy task to balance all these interests and to develop a fully or partially electric propulsion system, but it is of great importance and necessity to carry on the study and improvement of physical limitations, fulfilling the requirements and guidelines for the future. Antcliff *et al.* (2016), for instance, propose a mission analysis and sizing of advanced airframe and propulsion technologies for a small regional transport aircraft concept that delivers significant cost and performance advantages over current aircraft. Brelje and Martins (2018) survey existing tools for analyzing the mission and economic performance of aircraft with electric propulsion and describes the development of a new open-source conceptual design tool with efficient gradients.

Along those lines, this work pursues to present the conceptual design of a hybrid-electric aircraft using tables of historical trends as initial estimates and then a multidisciplinary optimization which transforms the conventional aircraft into a hybrid-electric aircraft.

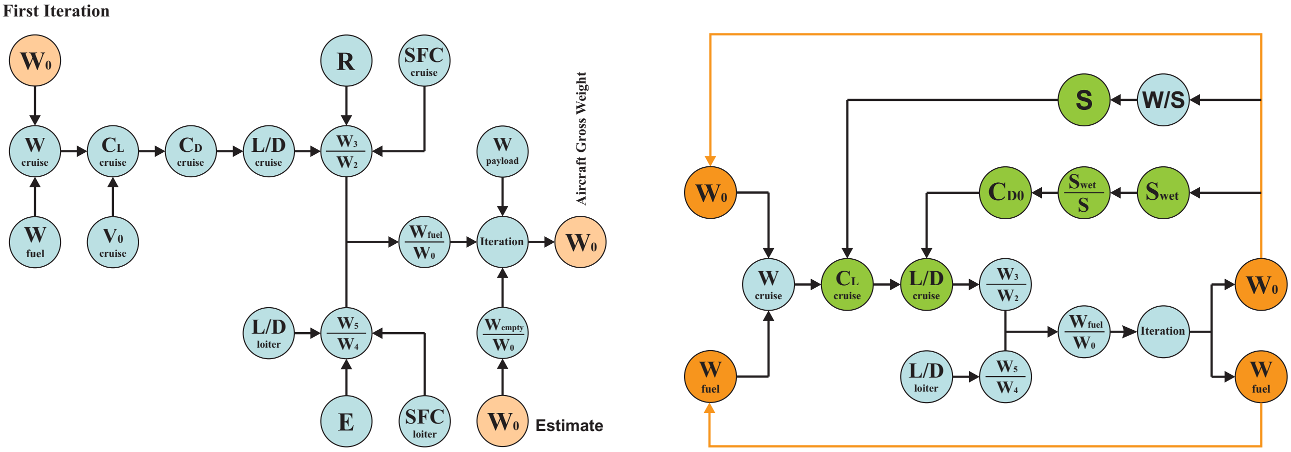
## 2. CONCEPTUAL DESIGN OF GENERAL AIRCRAFT

First of all, in the conceptual design of an aircraft, several trend tables were used to obtain some initial estimates. But for that, it was necessary to assign some initial configurations to the aircraft. Thus, four main configurations were assumed: twin-engine with T-tail, twin-engine with conventional tail, single-engine with T-tail, and single-engine with conventional tail. In most cases, the geometric characteristics of aircraft are represented by functions that depend directly on the aircraft category and relative weight, defined as:

$$f(a, W_0, c) = a{W_0}^c \tag{1}$$

where $f(a, W_0, c)$ represents the characteristic to be calculated (e.g., wetted area), $a$ and $c$ are constants that depend on the type of aircraft under analysis, obtained from the literature (Raymer, 1992), and $W_0$ is the gross weight estimate of the aircraft, which is iterated throughout the project.

This process of iteration and updating of the aircraft weight is performed considering the weight variation and performance during the phases of flight which the fuel consumption is higher: cruise and loiter. In Raymer (1992), the weight ratios per phase are introduced, setting a correlation between them during the aircraft mission. The simplified scheme of iteration flow is presented in Fig. 1a (first iteration) and Fig. 1b (other iterations).

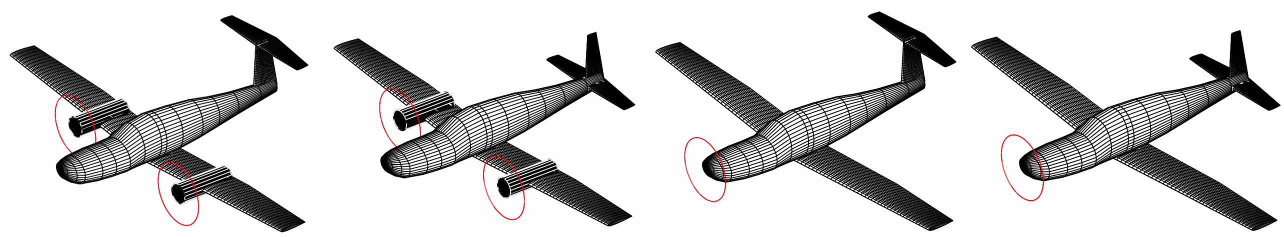



(a) (b)

Figure 1. First iteration (a) and other iterations (b) for aircraft gross weight estimation. Adapted from Venson (2013).

Moreover, the algorithm needed an engine to be considered during the performance analysis. Since the aircraft was going to be hybrid, the strategy used here was to get started choosing an electric motor instead of a conventional engine. Searching for commercial and available electric motors, the Siemens' SP260D was chosen due to its application in electric aircraft, such as the Extra 330LE, also developed by Siemens. In addition, this electric motor provides 260 kW along with a significant efficiency of 95% and it has a mass of only 50 kg.

Thus, after running the algorithm, the following aircraft configurations were obtained and are presented in Fig. 2.



(a) Twin-engine + T-tail. (b) Twin-engine + conventional tail. (c) Single-engine + T-tail. (d) Single-engine + conventional tail.

Figure 2. Sketch of the four aircraft released by the initial concept design estimate.

The results showed that single engine aircraft satisfies the specifications, either with conventional or T-tail. In both cases, the single engine provides sufficient power for the aircraft to fly and reaches the required performance. So, it was easy to choose only one engine. But for the tail, it goes beyond that.

The design of an empennage for any aircraft is extremely important since it affects the aircraft mass and center of gravity, i.e., the static and dynamic stability. Then, it is necessary to consider the effects of both empennages arrangement.

The conventional tail provides appropriate stability and control and also leads to the most lightweight construction in most cases. Moreover, for this configuration, the stabilizer trim is relatively less complex and the vertical tail is usually larger. However, engines cannot be coupled to the rear of the aircraft, which is useful for static stability. Furthermore, spin characteristics can be unfavorable in the case of conventional tail due to the blanketing of the vertical tail, in addition to the downwash of the wing being relatively large in the area of the horizontal tail.

On the other hand, the T-tail is heavier than the conventional tail because the vertical tail has to support the horizontal tail. However, the T-tail has advantages that partly compensate for this important disadvantage (weight). Because of the end-plate effect, the vertical tail can be smaller. In addition, the horizontal tail is more effective because it is positioned out of the airflow behind the wing and is subjected to less downwash. Therefore, it can be smaller. For the same reason, the horizontal tail is also subject to less tail buffeting. As the T-tail creates space at aircraft's rear, there is enough space to fix the engines, improving static stability.

Hence, since the aircraft is going to have a lightweight engine at the nose, considering the information above and aiming an easier structural analysis, the conventional empennage was chosen for this aircraft design.

Thus, at this point, an overall configuration for the aircraft had been defined. However, it was necessary to improve and refine the aircraft adjusting equations and algorithms for it to become a hybrid-electric one. In other words, the performance equations had to be solved, what would imply in new results and configurations. But, first of all, the propulsion system architecture had to be determined.

## 3. HYBRID-ELECTRIC AIRCRAFT DESIGN

A hybrid aircraft has a combination of two or more sources capable of generating power into a single power system. The commonly used term “hybrid-electric” describes a system that utilizes one or more heat engines together with one or more electric-motors in a specific configuration.

When designing a hybrid-electric propulsion system, there are many distinct possible architectures. The series and parallel hybrid architectures are the most commonly used. But, to choose which one of them is the best for a certain project, it depends on the applications and limitations of the project that they are being designed for.

Series architecture involves an internal combustion engine (ICE), a generator, a battery pack, an inverter, a controller and electric motors, as shown in the simplified diagram in Fig. 3. The ICE is used to drive a generator, which in the sequence provides power to the controller. This controller also receives power from an inverter, which drains power from a battery pack. Thus, the controller combines both powers from the ICE and the battery pack and finally provides power to the electric motors.

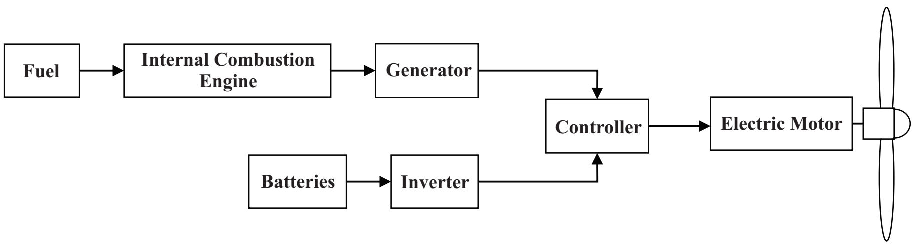



Figure 3. Series architecture diagram.

The main benefit of a series architecture is that the ICE driving the generator can be designed to operate at a consistent and optimum engine speed because the ICE is not directly mechanically linked to the propellant of the aircraft. Also, the arrangement can be installed in different positions on the aircraft layout system. A drawback to a series architecture is that the electric motor must be sized based on the capability to provide the maximum power output the aircraft requires. If so designed, the aircraft can operate fully electric using the battery pack, turning the ICE off, operating at its maximum efficiency point, leading to improved fuel efficiency and lower carbon emissions compared to other configurations.

On the other hand, the parallel architecture comprises a turboshaft engine, a battery pack, an inverter, and an electric motor, as shown in the simplified diagram in Fig. 4. Fuel is used to power a turboshaft engine and batteries are used to power an electric motor. Both turboshaft engine and electric motor power the drive train coupled to the propellers.

Good performance is possible, in this case, because the power is generated with both engines. Different control strategies are used in a preferred approach. If the power required by the transmission is higher than the output power of the turboshaft engine, the electric motor is turned on so that both engines can supply power to the transmission. If the power required by the transmission is less than the output power of the ICE, the remaining power is used to charge the battery pack. Moreover, mechanical and electric power could be decoupled, and the system has a high operating flexibility enabling three modes of operation: purely combustion; purely electric and hybrid.

Pornet and Isikveren (2015) argue that the parallel architecture as the most appropriate arrangement for large aircraft due to the lower weight associated since the batteries only feed an electric generator, which helps the main shaft of a

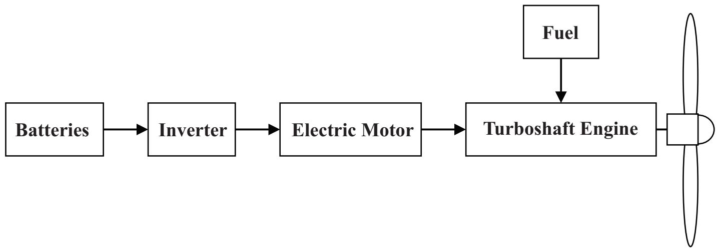



Figure 4. Parallel architecture diagram.

turbojet engine, for example. However, the aircraft designed here is small, carrying four passengers, which makes the architecture simpler. Therefore, the series-architecture was chosen for the aircraft, since the engine is already an electric-motor, requiring only electric power to move it. Figure 5 depicts the propulsion system architecture proposed.

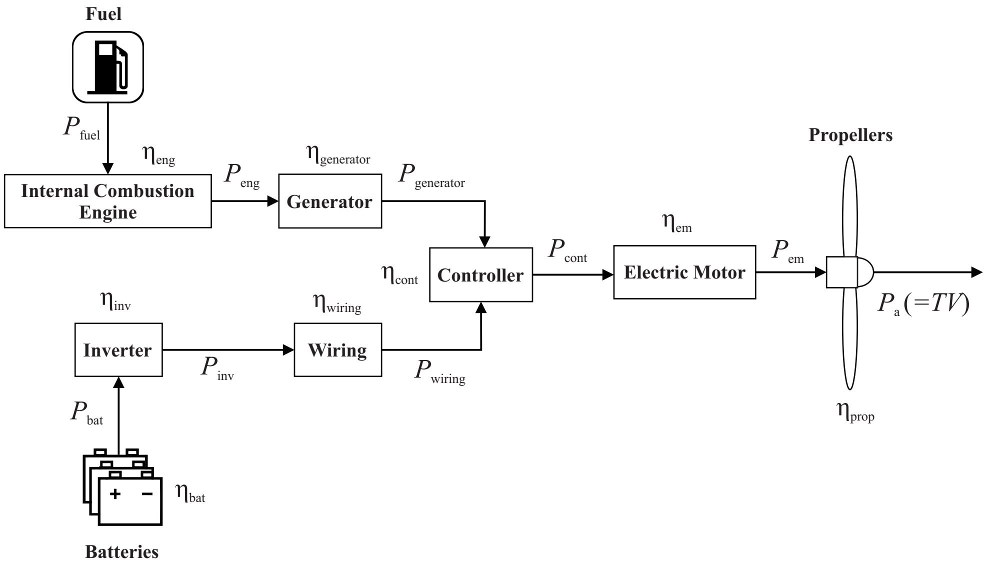



Figure 5. Series propulsive system architecture of hybrid-electric aircraft.

In the analysis of the participation of each of the energy sources (energy internal combustion (ICE) and batteries), it was considered that ICE would be maintained at its optimum rotation speed and would provide a "constant" power during takeoff, climb and cruise phases. In this way, as the aircraft requires more power than ICE provides, the batteries would be responsible for supplying the remainder of the electrical power, ensuring the operation of the electric motor, which is located on the nose of the aircraft. In the loiter and landing phases, the ICE would no longer be used. Thus, the motor is fully powered by the batteries.

Now it is necessary to come up with the new performance analysis. First, the classic Bréguet's range is formulated for a conventional fuel-powered aircraft at zero wind conditions, and thrust vector parallel to the airspeed vector, which defines the following:

$$R = \int_{W_{\text{final}}}^{W_{\text{start}}} \frac{V}{c_T} \frac{C_L}{C_D} \frac{1}{W} dW \tag{2}$$

where $c_T$ means the specific fuel consumption.

The solution to the integral depends on the flying strategy used (e.g., gradual climb at a constant airspeed and angle of attack) and the models used to represent the propulsion system and the aerodynamic characteristics. Solutions to the most common flying strategies can be found in many standard textbooks on aircraft performance (Eshelby, 2000). But, fundamentally, these solutions use the idea that weight changes gradually throughout the flight. Therefore, the range equation cannot be applied to the hybrid aircraft to be designed here, which uses an electric system (batteries) as an energy supply.

Thus, Voskuijl *et al.* (2018) present a new formulation for the range equation relating the energy stored to the consumption of a hybrid aircraft with parallel architecture. Since the architecture of both aircraft under analysis here is going to be in series, the formulation is reevaluated for the scheme available in Fig. 5, which results in the following equation:

$$R = \frac{\eta_{\text{cont}}\eta_{\text{em}}\eta_{\text{prop}}}{g\left(\frac{c_p}{\eta_{\text{generator}}}\frac{H_{\text{fuel}}}{g}(1-S)+\frac{S}{\eta_{\text{inv}}\eta_{\text{wiring}}}\right)}\frac{C_L}{C_D}\frac{H_{\text{battery}}H_{\text{fuel}}}{\psi H_{\text{fuel}}+(1-\psi)H_{\text{battery}}}\cdot \ln\left(\frac{\frac{(\psi H_{\text{fuel}}+(1-\psi)H_{\text{battery}})}{H_{\text{battery}}H_{\text{fuel}}}gE_{\text{start}}+W_{\text{empty}}+W_{\text{payload}}}{W_{\text{empty}}+W_{\text{payload}}}\right) \quad (3)$$

where $\eta$ are the components' efficiencies, $g$ the gravitational acceleration, $c_p$ the power-specific fuel consumption, $H$ the specific energy density for battery and fuel, $E$ the initial energy accumulated in the aircraft as fuel and battery, and $W$ the weight breakdown of the aircraft. The variables $S$ and $\psi$ are degrees-of-hybridization in terms of power and energy, which represent battery's contribution as an aircraft's supplier. They are defined as $S = P_{\text{electric}}/P_{\text{total}}$ and $\psi = E_{\text{electric}}/E_{\text{total}}$.

## 4. DESIGN ASSUMPTIONS

### 4.1 Typical Aircraft Mission Profile

Based on historical data and FAR – Part 23, some mission characteristics were chosen and are presented in Tab. 1. The flight level FL120 was chosen to avoid any pressurization issues since the regulation 14 CFR 91 requires supplemental oxygen system for aircraft flying over FL120. The cruise speed for this project was chosen to be 185 knots, since similar aircraft, such as the Diamond DA42, usually fly around this velocity during cruise. Also, a rate of climb of 1500 fpm and a rate of descent of 900 fpm were assumed from the competitors' trends. The range of the aircraft was fixed at 1860 km and the endurance in cruise is obtained dividing these ranges by the respective cruise speed. Additionally, the total endurance is an estimation of the time to reach the mission requirements (climb and cruise), the assumptions (descent) and the FAR Sec. 125 regulations (taxi, take-off, approach, loiter and landing). Thus, evaluating the time spent during all phases of flight, reaching the parameters in Tab. 1, the typical flight mission regarding altitude and flight time is showed in Fig. 6. Percentage values mean the portion each flight phase represents in the total mission.

Table 1. Mission characteristics.

| Parameter | Value |
|---|---|
| Service ceiling [ft] | 12000 |
| Cruise speed [knots] | 185 |
| Rate of climb [ft/min] | 1500 |
| Rate of descent [ft/min] | 900 |
| Range in cruise [km] | 1860 |
| Endurance in cruise [hr] | 5.43 |
| Total endurance [hr] | 7.22 |

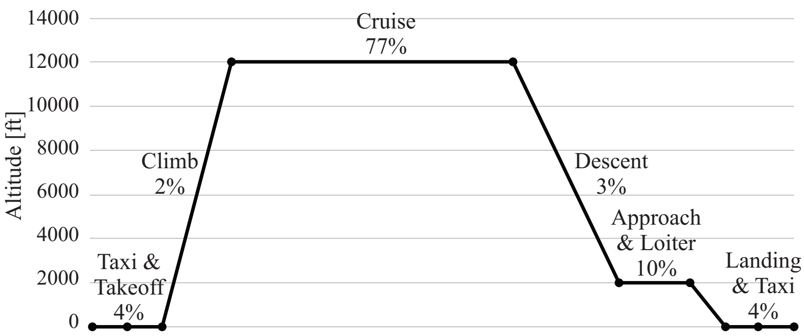



Figure 6. Aircraft typical flight mission.

### 4.2 Battery Design

The choice of batteries to be used in the aircraft hybrid system was based on the estimates proposed by Hepperle (2012) for the technology available in 2025, which are shown in Tab. 2. The theoretical specific energy values are not truly feasible in actual applications. The amount of energy that the batteries are able to provide is much less than the expected. In other words, there is an efficiency associated with these chemical reactions involved. Thus, when choosing a battery system, it is very important to consider these effects.

Table 2. Specific energy density of current and future chemical battery systems. Adapted from Hepperle (2012).

| System | Theoretical specific energy density | Actual battery energy density expected in 2025 |
|---|---|---|
| Li-Ion | 390 Wh/kg | 250 Wh/kg |
| Zn-$O_2$ | 1090 Wh/kg | 400-500 Wh/kg |
| Li-S | 2570 Wh/kg | 500-1250 Wh/kg |
| Li-$O_2$ | 3500 Wh/kg | 800-1750 Wh/kg |

Later, it was performed an assessment of the feasibility of using such batteries in both aircraft in the future. According to Bruce *et al.* (2012), studies with Li-S and Li-$O_2$ batteries are in full development and implementation. However, the reliability and safety of these types of batteries are still unknown, which makes them unviable for aerospace applications.

On the other hand, Zn-$O_2$ batteries have been developed since the 1960s and already have medical and telecommunication applications. In addition, companies such as Teck Cominco Metals and Tesla Motors hold patents for the application of this type of battery in the automotive industry. Thus, due to its energy density (higher than for Li-Ion), the maturity of their behavior and safety, which is crucial for aerospace applications, the type of battery chosen for both aircraft was the Zn-$O_2$. Using a more conservative approach, the energy density that will be considered for this battery will be 400 Wh/kg.

### 4.3 Internal Combustion Engine (ICE)

To choose an internal combustion engine (ICE) that better fits the aircraft, it was compared the viability of two turbo-engines. The first one is a 4-cylinder engine with rated power below the power required for cruising (145 kW) and climb (215 kW), while the second one is a 6-cylinder engine with a power output greater than those required in both cruise and climb conditions. Table 3 shows the main characteristics of each ICE.

Table 3. Main characteristics of Austro AE330 and Lycoming IO-580 engines.

| Characteristic | Austro AE330 | Lycoming IO-580 |
|---|---|---|
| Number of Cylinders | 4 | 6 |
| Rated Power [kW] | 134 | 220 |
| Mass [kg] | 186 | 201 |
| Dimensions [m] | 0.74 x 0.85 x 0.57 | 0.99 x 0.87 x 0.53 |
| Fuel Consumption [kg/hr] | 31.20 | 47.68 |

The degree of hybridization was considered so that the ICE used its maximum capacity during taxi & take-off, climb and cruise phases. For the remaining phases, aiming to reduce noise during the approach, loiter, and landing, the ICE would stay in idle, and all the power required for that phase would be supplied by the batteries.

Table 4 shows the comparison of the 4-cylinder engine with the proposed hybridization, and Tab. 5 shows a 6-cylinder engine with a higher power than required and without hybridization. Analyzing costs, the 4-cylinder engine has an estimated cost of US$ 106.64 in fuel and US$ 25.84 for the total recharge of the batteries, resulting in a total cost of US$ 132.48 per flight, while the 6-cylinder engine has a total cost of US$ 185.42 per flight. Therefore, there is a saving of US$ 52.94 per flight when using the Austro AE330 engine. In addition, the 4-cylinder engine is 38 kg lighter and has a 27% lower volume than the 6-cylinder engine, which justifies its application in conjunction with the hybridization of the aircraft.

Table 4. 4-cylinder engine with proposed hybridization.

| Phase of Flight | S | Time [hr] | Battery Weight [kg] | Fuel Weight [kg] |
|---|---|---|---|---|
| Take-off + Climb | 0.4126 | 0.13 | 31.37 | 4.16 |
| Cruise | 0.1092 | 5.52 | 226.62 | 172.41 |
| Loiter | 1.0000 | 0.50 | 46.83 | 0.00 |
| Descent + Landing | 1.0000 | 0.22 | 20.81 | 0.00 |
| TOTAL | - | 6.37 | 325.63 | 176.57 |

Table 5. 6-cylinder with higher power required and without hybridization.

| Phase of Flight | S | Time [hr] | Battery Weight [kg] | Fuel Weight [kg] |
|---|---|---|---|---|
| Take-off + Climb | 0.0000 | 0.13 | 0.00 | 6.32 |
| Cruise | 0.0000 | 5.52 | 0.00 | 266.48 |
| Loiter | 0.0000 | 0.50 | 0.00 | 23.68 |
| Descent + Landing | 0.0000 | 0.22 | 0.00 | 10.52 |
| TOTAL | - | 6.37 | 0.00 | 307.01 |

## 5. MULTIDISCIPLINARY OPTIMIZATION FOR HYBRID-ELECTRIC AIRCRAFT

After formulating the new range equation for hybrid-electric aircraft, an optimization algorithm was implemented to find the best aircraft configuration.

The type of optimization implemented was based on the differential evolution algorithm proposed by Storn and Price (1997). In this method, 300 generations were created, where each generation contained 10 members per population. However, because of the several iteration variables, the genetic algorithm requires too much processing, which generates a huge computational cost, spending many hours to reach the final result. In this case, for example, it took an average of 15 hours to end the optimization, which justifies the low value of 10 members per population.

The input variables for the objective function were generated based on the values of geometry, weight, and performance from the results presented in Section 4. Table 6 shows the maximum and minimum values used in each optimization variable. Thus, the genetic algorithm used these inputs to find the best configuration option for the aircraft to achieve a lower gross weight as an optimization variable.

Table 6. Maximum and minimum values for each optimization variable.

| Optimization Variable | Max | Min |
|---|---|---|
| Takeoff Engine Power [kW] | 200 | 260 |
| Climb Engine Power [kW] | 200 | 260 |
| Wing position along the aircraft's longitudinal axis [m] | 3.238 | 5.397 |
| Wingspan [m] | 8.033 | 13.388 |
| Wing root-chord [m] | 1.313 | 2.188 |
| Wing taper ratio | 0.525 | 0.875 |
| Wing swept angle [°] | 0.000 | 10.000 |
| Wing breaking-point [m] | 1.339 | 2.231 |
| Wing dihedral [°] | 0.000 | 5.000 |
| Wing incidence angle [°] | 0.000 | 3.000 |
| Wing twist [°] | 0.000 | 3.000 |
| Wing profile | 1.000 | 5.000 |
| Horizontal tail span [m] | 1.134 | 1.890 |
| Horizontal tail taper ratio | 0.525 | 0.875 |
| Horizontal tail root-chord [m] | 0.794 | 1.324 |
| Horizontal tail swept angle [°] | 0.000 | 5.000 |
| Horizontal tail profile | 1.000 | 3.000 |
| Vertical tail span [m] | 1.126 | 1.876 |
| Vertical tail taper ratio | 0.525 | 0.875 |
| Vertical tail root-chord [m] | 0.883 | 1.472 |
| Vertical tail swept angle [°] | 0.000 | 5.000 |
| Vertical tail profile | 1.000 | 2.000 |
| Fuel Weight [kg] | 54.348 | 380.437 |

Different airfoil profiles were used for the objective function to be used in the wings and empennage. All of them were also optimization variables:

(i) Wing: NACA 23010, NACA 23012, NACA 23015, NACA 23016 and NACA 63415;
(ii) Horizontal Tail: NACA 0012, NACA 0009 and NACA 2412;
(iii) Vertical Tail: NACA 0012 and NACA 0009.

For the trimming, aerodynamics, and dynamic stability analyses, it was necessary to use a program to aid in the process. For this genetic algorithm, the chosen program was the AVL (Athena Vortex Lattice). AVL is a program developed at MIT for the aerodynamic and flight-dynamic analysis of rigid aircraft of arbitrary configuration.

Therefore, the AVL provides aerodynamics and stability results in the genetic algorithm. In addition, it is possible to calculate the performance characteristics using the hybridization ratios. So, it compares these values to the specified criteria shown in Tab. 7.

During the optimization, if the aircraft does not meet all the criteria presented, a penalty is added to an optimization variable. Thus, these aircraft with penalties are discarded over time by the objective function.

In the optimization process, multi-disciplinary boxes are used to integrate areas of structure, stability, center of gravity, aerodynamics, flight mechanics, performance and costs, as shown in Fig. 7. The input variables in each box are described

Table 7. Specified criteria for genetic algorithm.

| Domain | Parameters | Min | Max |
|---|---|---|---|
| Geometrical | $AR_W$ | - | 13 |
| | $AR_{HT}$ | - | 7.5 |
| | $AR_{VT}$ | 1.5 | 5.5 |
| Performance | Takeoff Length [m] | - | 457.20 |
| | Landing Length [m] | - | 457.20 |
| | Rate of Climb [ft/min] | - | 1500 |
| | Angle of Climb [°] | 5 | 30 |
| | Range [km] | 1852 | - |
| | $E_{\max}$ | 10 | 20 |
| Stability | $c_{m\alpha}$ | - | -0.40 |
| | Empty Static Margin | 10 | 40 |
| | MTOW Static Margin | 10 | 40 |
| | Trimmed Angle of Attack [°] | 0 | 5 |
| | Elevator Deflection [°] | -10 | 10 |
| | $c_{n\beta}$ | 0.05 | - |
| | $c_{l\beta}$ | - | -0.04 |

in Tab. 6. Thus, for all geometric and weight changes made, each of the boxes generates penalties in order to eliminate an aircraft that does not meet the design requirements, remaining only the best results.

## 6. RESULTS AND DISCUSSION

Having the optimization done, a tridimensional model of the studied hybrid-electric aircraft was generated, as shown in Fig. 8. The design requirements defined in the multidisciplinary optimization were related to the category of four passengers aircraft based in the global market.

Searching for other aircraft of the same category, it was found models such as the Cessna TTx, Cirrus SR22, and Diamond DA42. The aircraft obtained exhibited performance characteristics similar to its competitors in the same category, justifying its economic viability. Nevertheless, it has a very relevant feature: its fuel economy, provided by the hybrid-electric propulsive system. A comparison with its main competitors is presented in Tab. 8.

Table 8. Main characteristics of the studied aircraft and its competitors.

| Characteristics | Studied Aircraft | Diamond DA42 | Cirrus SR22 | Cessna TTx |
|---|---|---|---|---|
| Wingspan [m] | 13.38 | 13 | 11 | 11 |
| Fuselage length [m] | 8.12 | 8.56 | 8.28 | 7.68 |
| Height [m] | 2.96 | 2.49 | 2.72 | 2.74 |
| Range [km] | 1875 | 1693 | 1289 | 2352 |
| Endurance [hr] | 7.22 | 8.8 | 4.5 | 5.25 |
| Cruise speed [km/h] | 343 | 326 | 226 | 435 |
| Take-off field [m] | 442 | 776 | 600 | 390 |
| Landing field [m] | 442 | 620 | 620 | 805 |
| MTOW [kg] | 1855 | 1999 | 1111 | 1633 |
| Passengers + Crew | 4 | 4 | 4 | 4 |
| Fuel [kg] | 176 | 231 | 220 | 280 |
| Service ceiling [m] | 3660 | 5500 | 4100 | 7620 |
| Climb Rate [ft/s] | 1559 | 1337 | 720 | 1400 |

Therefore, the aircraft developed in this work meet the mission requirements and also is competitive in the aviation market. Since it presents good general and performance characteristics, its main differential certainly would be lower fuel consumption because of the hybrid-electric system onboard, attracting new customers. The aircraft presents a longer nose compared to the other aircraft because all the propulsive system, which includes batteries, inverter, ICE, generator, controller and electric motor were assumed to be placed at the front of the aircraft.

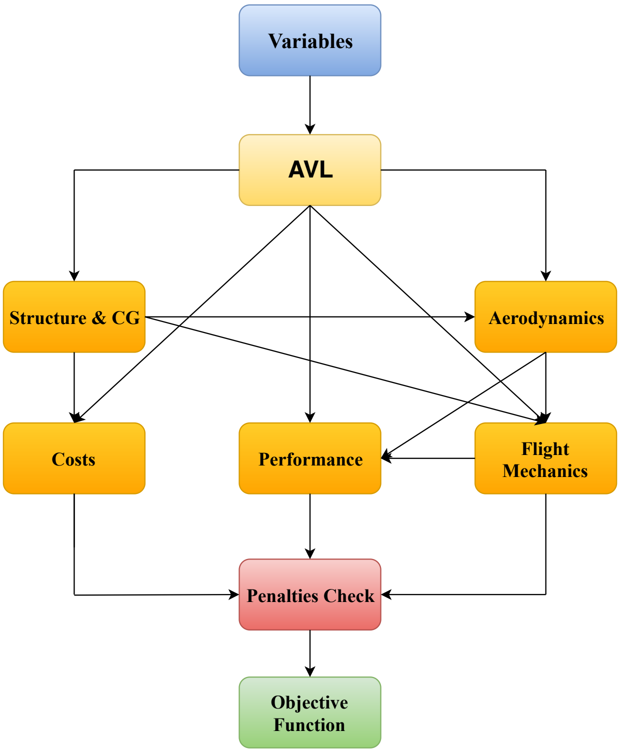



Figure 7. Multidisciplinary optimization flowchart.

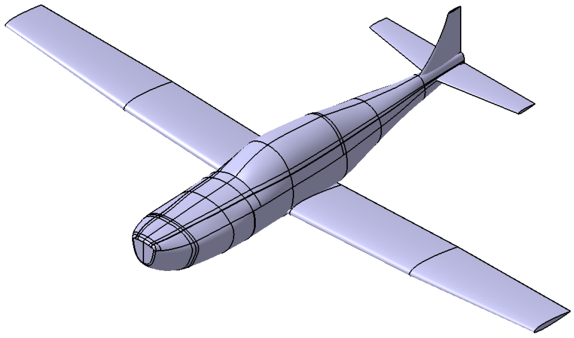


Figure 8. Tridimensional illustration of the hybrid-electric aircraft obtained by multidisciplinary optimization.

## 7. CONCLUSION

This work is based on the development of a hybrid-electric aircraft of four passengers. The requirements for the project were proposed using historical data from competitors with similar characteristics.

The design methodology presented by Raymer (1992) and Venson (2013) allowed to create an initial aircraft estimate using several historical data. At this stage, four main different configurations of aircraft were considered: twin-engine with T-tail, twin-engine with conventional tail, single-engine with T-tail, and single-engine with conventional tail. The configuration that most met the required specifications was the single-engine with conventional tail.

Two architectures of hybridization were presented: the architecture in series and in parallel. It was considered the complexity, efficiency, and weight of the configurations for the project, what led to the architecture in series to be chosen for the propulsive system since it is simpler and is easier to implement in small aircraft. Thus, it was developed a new formulation of equations for range from the analysis of the energy stored variation during the flight time.

To complete the conceptual project, some additional characteristics were proposed to reach the requirements. The typical mission of both aircraft was created historical trends and aeronautical regulations. Next, a study was performed to choose the best battery system, which would make up the hybrid system of the aircraft, where it was evaluated the feasibility of different batteries components and their applicability. Thus, the Zn-$O_2$ battery was chosen due to its energy density (higher than for Li-Ion), the maturity of behavior and safety, which is crucial for aerospace applications.

The selection of the ideal ICE was also evaluated comparing the utilization of the hybridization in turbo-engines of different rated powers. It was verified that the use of an ICE of lower-rated power, associated to a hybrid-electric system, would be more efficient and economical when compared to an engine with higher rated power used by the competitors, justifying the hybrid architecture chosen for these aircraft.

Having the initial dimensions in hands and the assumptions fixed for both aircraft, a genetic algorithm was created using the methodology of Differential Evolution presented by Storn and Price (1997). Thus, many variables of optimization were selected to evaluate the best aircraft configuration that would meet all the project criteria, where the objective function was the maximum reduction of the aircraft weight. To do so, the software AVL was used as a tool to analyze the characteristics of different configurations proposed by the algorithm e generate optimum aircraft.

After all, the “icing on the cake” of this study is the electric-hybrid propulsive system. No doubt this is going to be the future. The companies and the industry seek for these more efficient and sustainable technologies, which would allow reduction of fuel consumption, reduction of noise during landing, improvement of cruise performance, and aid in the reduction of greenhouse gas emissions. However, there are many issues involving these new approaches, since more electric systems imply the need to generate more power, distribute power to more places, and deal with more waste heat than ever before. Therefore, the development of new architectures and devices will be essential.

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