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MDAO method and optimum designs of hybrid-electric civil airliners

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Abstract: Hybrid-electric civil airliners (HECAs) are considered as the forerunner of the solution of relieving aviation emissions. This paper presents a multidisciplinary design analysis and optimisation framework named GENUS, which has been extended to design HECA. GENUS is a modular, expandable, and flexible design environment, with 10 integrated modules for HECA design. Key extensions include hybrid-electric propulsion architectures (HEPAs), the corresponding powertrains and the power management strategies (PMS). In addition, a cost module and an aviation emission tracking function are developed and integrated into GENUS. GENUS is validated for investigating the design of HECAs by evaluating existing HECA concepts. Furthermore, three conventional turbofans are hybridised within GENUS to analyse the sensitivity of the performance of engines to the degree of hybridisation (DoH) of power. The effects of hybridised engines on aircraft design are evaluated based on Boeing 737, demonstrating that at least 27.18% fuel saving, 9.97% energy saving, 12.40% cost saving, and 43.56% aviation emissions migration can be achieved. Finally, the potential directions of applying GENUS to explore the design space of HECA is discussed, which is useful to maximise the benefits of HECA.

Keywords: Multidisciplinary design analysis and optimisation (MDAO), hybrid-electric civil airliner (HECA), Fuel-battery hybrid, Conceptual aircraft design

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1. Introduction

Various transport-related organisations and groups are actively investigating the possibilities of hybrid-electric aircraft (Finger et al. 2020; Friedrich and Robertson 2015a; Isikveren 2018; De Vries et al. 2019), one of the most efficient and promising solutions to counter environmental issues and to cope with the diminishing supply of non-renewable energy resources (Administration 2019; BOEING 2019; European Commission 2019; IATA 2019; ICAO 2013; Winchester et al. 2013). Hybrid-electric civil airliner (HECA) becomes a viable alternative class of aircraft that can take advantage of the synergy between different powertrains through the use of internal combustion engines (ICEs) and electric motors (EMs), allowing them to operate at their optimum conditions (Friedrich and Robertson 2015b).

Due to the obstacles in the current level of electrical technology and the well-known complexities in designing large commercial aircraft, few research groups have explored the possibilities offered by large commercial HECA, with the exception of incumbents such as Airbus and Boeing. As it is a new field for the current market, stakeholders have no experience upon which to draw and have little historical data to analyse. Therefore, many questions remain to be answered. For instance, how do we define the ‘best’ HECA? Is there any vital factor that dominates the development of HECAs? What technologies are most crucial in enabling the development of HECAs? In addition to the obvious environmental benefits, what is the long-term significance in developing HECAs compared to kerosene-powered concepts, and how do we quantify the benefits? Modelling, simulation, and optimisation are promising ways to explore the design space of new generations of aircraft. With surging requirements in research related to the design of hybrid-electric aircraft (HEA), the lack of a comprehensive integrated conceptual design tool for HECAs is becoming more serious.

This paper introduces a multi-disciplinary conceptual design tool for HECAs which has been developing to offer knowledgeable designers a platform to design HECAs according to their needs at the conceptual design stage. It is a fully coupled, multi-disciplinary, multi-variable, and multi-fidelity design environment capable of designing HEA with various mission requirements. After an introduction to the design environment, there follows the methods and validation of each module, and the integrated application. Two case studies are conducted with the aim of analysing the hybridisation of engines and aircraft, demonstrating the robustness of the design environment, and revealing the promising performance achieved through HEA. The final section presents the conclusion and future work.

2. GENUS aircraft design framework

The GENUS aircraft design environment shown in **Figure 1** is an aircraft conceptual design environment developed by researchers at Cranfield University's Aircraft Design Group, led by Smith(Smith et al. 2019). GENUS has an independent interface and provides the flexibility to embed and connect to required methods and tools in other programming languages. GENUS enables designers and users to compare various design methods by applying the environment to different aircraft concepts. It currently includes solar-powered unmanned aerial vehicles (UAVs) (Abbe 2015), the Blended wing body concept (Okonkwo 2016), hypersonic transport and space launcher vehicles (Sziroczák 2015), the supersonic business jet (Sun 2018; Sun and Smith 2019, 2020), and low observable UAVs (Sepulveda et al. 2019; Sepulveda Palacios and Smith 2019). GENUS integrates nine key disciplines: geometry, mission, propulsion specification, mass breakdown, aerodynamics, propulsion, packaging, performance, and stability. Special modules can be added for a specific analysis (**Figure 2**). The designer is allowed to execute or disable any modules as required.

3. Design analysis and optimisation methodologies

HECA design requires a higher integration of electric and fuel power systems. The modification corresponding to this specific requirement allows users to analyse and design the HECA from kerosene-powered aircraft to all-electric aircraft by adjusting the correspondent DoH. Exploring the design space on account of HEPAs, PMSs, and electrical technology levels are potential ways of discovering the potential design space of HECA.

3.1. Geometry generation

A parametric aircraft geometry can be constructed by specifying the body components and lifting surfaces. **Table 1** lists the complete geometry inputs. All the defined geometry characteristics are delivered to the embedded 3D-plotter (**Figure 3**). In addition, geometry parameters are integrated into the modules designed for mass breakdown, aerodynamics, packaging, and stability to process the complete and multi-disciplinary analysis.

3.2. Mission requirements

The mission module provides a way of collecting the necessary information for the analysis of other modules, including the conventional mission and relevant technological levels on the design of HECA. Parameters in **Table 2** define the mission. According to the analysis and prediction of electrical technologies by H. Kuhn, A. Sizmann (Kuhn and Sizmann 2012), Sarah J. Gerssen-Gondelach (Gerssen-Gondelach and Faaij 2012), Reynard (de Vries et al. 2019), László Gogolák (Gogolák et al. 2019) and JL Delhaye (Delhaye 2015), technological levels of batteries, electric machines and EMs are specified assumed in terms of the timeline from 2020 to 2050 in **Table 3**.

3.3. Propulsion system

The propulsion module includes two functional parts: the propulsion specification and propulsion integration. The baseline of the propulsion module is EngineSim, which is an open-source applet developed by NASA (NASA n.d.). For the hybrid-electric propulsion module, an electric model is added to extend the original construction and principles in EngineSim.

The propulsion module integrates three sub-modules: ICE module, EM module, and fan module. Based on EngineSim, four-engine types are available for ICE: turbojet, turbofan, afterburner, and ramjet. The fan is driven by uniting the power from both the ICE and the EM. The balance between the two power sources is determined by the requirement of the whole design of HECA in terms of its PMS.

GENUS implements a built-in powerplant hybridiser that transforms the conventional turbofan to an equivalent hybrid-electric engine by updating the fan diameter, bypass ratio, or EM size. This function of the hybridiser is applied to analyse and compare the engine performance across many types of powerplant such as kerosene powered powerplant, hybrid-electric powered powerplant, and electricity-powered powerplant. It allows users to compare a series of hybridised powerplants to varying degrees that meet the same design requirement by matching different EM and adjusting the bypass ratio. The analysis and comparison are further discussed in **Section 4**, taking a CFM56 turbofan engine as the baseline.

There are five types of powertrains appliable in the propulsion module (**Table 4**). Eqs (1) to (6) list all the fundamental equations to calculate the thrust for all power management strategies:

$$T_t = T_b + T_{jet} \tag{1}$$

$$T_b = \dot{m}_b \cdot \left(v_f - v_0\right) \tag{2}$$

$$\dot{m}_b = P_b \cdot \frac{Massflow}{Power} \tag{3}$$

$$P_b = P_m + P_{tur} \tag{4}$$

$$P_m = eThrottle \cdot P_{InsM} \tag{5}$$

$$P_{tur} = C_{pg} \cdot Temp_{4.5} \cdot (1 - \pi_{TL}{}^{\frac{1-\gamma}{\gamma}}) \cdot \eta_{TL} \tag{6}$$

The thrust generated by the core jet T_{jet} in Eq (1) and the ratio $\frac{Massflow}{Power}$ in Eq (3) are calculated according to the thermal cycle calculation of the conventional ICE. The bypass thrust T_b is generated by the fan and driven by the combined power Eq (2). There are two available power sources for the main shaft of the fan: the EM and the low-pressure spool of the ICE. The conventional throttle is split into two sub-throttle settings: eThrottle and fThrottle, which controls the EM and ICE usage, respectively. Eq (3) is based on the assumption that the power driving the fan is proportional to the mass flow going through the bypass.

Corresponding to each HEPA, the mathematical expression relating to thrust, power, energy consumption, and fuel consumption slightly adjusted depends on its independent situation in **Table 4**.

3.3.1. Specifications

The HEP's fundamental characteristics can be defined in two sub-systems, the ICE and the electric system (**Table 5**). From the kerosene-powered aircraft (H_P=0, H_E=0) to the universal electric aircraft (H_P=1, H_E=1), several intermediate states can be addressed by the propulsion module. Even with the same powertrain, different power management strategies can still lead to typical energy usage. The study of the SUGAR series of aircraft (Bradley et al. 2015) refers to 2 key strategies: balanced use of the EM; and force the ICE to shut down during the second half of the cruise. Based on the methods analysed for the SUGAR series aircraft, GENUS covers and extends them to 9 feasible power management strategies shown in **Table 6**. The activation ratio (Ø) indicates the degree of utilisation of energy source focused on electricity, defined in Ref. (Isikveren et al. 2014).

3.3.2. Essential performance indicators

Eqs (7) to (16) show the general performance calculations for specific hybrid-electric powerplant:

$$H_P = \frac{P_m}{P_m + P_{tur}} \tag{7}$$

$$E_t = E_f + E_e \tag{8}$$

$$E_f = F_t \cdot HV \tag{9}$$

$$E_e = P_m \cdot t \tag{10}$$

$$SFC = \frac{\dot{m}_f}{T_t} \tag{11}$$

$$SEC = \frac{E_t}{T_t \cdot t} \tag{12}$$

$$eSEC = \frac{E_e}{T_t \cdot t} \tag{13}$$

$$SPC = \frac{P_m + P_{tur}}{T_t} \tag{14}$$

$$fSPC = \frac{P_{tur}}{T_t} \tag{15}$$

$$eSPC = \frac{P_m}{T_t} \tag{16}$$

The calculation changes according to the variation of the powertrain. The EM in the model can perform three roles: passing the electric power from the battery to the combined shaft (in the general situation); passing the power from the ICE to the combined shaft (in series hybrid-electric powertrain) and charging the battery by the power from the ICE (if charging in flight).

The propulsion module plays the role of summarising and organising. It sums up the performance elements of the individual engine in a wide range of flight conditions and integrates them as the total performance of the propulsion system.

3.3.3. Validation

Due to the lack of real data relating to hybrid-electric propulsion, the validation of the updated propulsion module is carried out by comparing the data generated by GENUS to several conventional engines (Company 1975; Morris 1978; Saarlas 2007), such as JT8D (**Figure 5**a), CF6 (**Figure 5**b), and TFE731 (**Figure 5**c). In addition, the hybrid-electric propulsion module is validated by two computational hybrid-electric engines (**Figure 5**d, **Figure 5**e) named hFan+2 (1,380HP) and hFan+2 (7,150HP) (Ashcraft et al. 2011; Bradley et al. 2015; Miyairi et al. 2015; Thomas et al. 2018). hFan+2 is a gas turbine and battery-powered propulsion system and is modelled by the updated Numerical Propulsion System Simulation (NPSS) appropriate to HEA developed by Georgia Tech (Lytle 1999). The updated NPSS was validated and calibrated with the GE hFan model suggesting that the updated NPSS was appropriate for use in parametric studies related to hybrid-electric studies. To fit in the research, two hFan+2s are hybrid-electric powerplants that match two revised SUGAR Volt aircraft: 750 Balanced and 750 Core Shutdown, respectively (Bradley et al. 2015; Bradley and Droney 2011). 1380 and 7150 are the installed power of EMs embedded in the tailcone of hFan+2. 750 indicates that the assumed battery technology level is 750 Wh/kg. 'Balanced' means the EM will be used evenly through the whole mission, and core shutdown means the EM is sized to enable the core shutdown during the cruise.

The propulsion module is mainly validated from the view of thrust and SFC, two representative parameters, under various flight conditions. The comparison presents that the powerplant simulation is properly in accord with reference data. For example, the trend and area of data are consistent with the reference. In addition, when flight condition changes from take-off (0 ft, Mach 0-0.3) to cruise (45,000 ft, Mach 0.7-0.8), the mean deviation of thrust and SFC is around -10% to 10%. Meanwhile, when validating the function of the hybrid-electric propulsion module, GENUS imitates the operation of hFan+2 at each flight condition. The deviation is in the range of ±20% even the operational strategy cannot be the same as the original design. The validation of this module supports the following usage of this crucial module.

As the validation shows, the propulsion module not only performs well for conventional engines but can also perform well in hybrid-electric studies. The validation proves that the propulsion module can be used for the HECA conceptual design, which will support future analysis for the HECA studies.

3.4. Mass breakdown

The mass breakdown module drives the estimated total mass into components. Also, the characteristics of each component are passed to the packaging module, processing the calculation of the CG (centre of gravity) and integrating the whole aircraft.

For a specific hybrid-electric aircraft, the module includes the prediction methods of Denis Howe (Howe n.d.), Daniel P. Raymer(Raymer 2018), and an in-house prediction method developed by Cranfield University. The propulsion mass calculation is based on the principle of EngineSim and is separated into three parts: the ICE, the fan, and the embedded EM. Additionally, the electrical accessories are taken into account in the propulsion system mass. Four classes of airliners validate the mass breakdown. The comparison in **Figure 6** shows the MTOM and the operational empty mass (OEM), the comparison shows that, the method adopt gives a slightly lower value of MTOM and OEM. From another view, the fuel mass estimated by mass estimation is more accurate. The bias from reference is mostly within the reasonable bounds (±15%), it performs better while estimating the mass of larger class of aircraft. The comparison validates the mass module for both conventional turbofan airliners and HECAs.

MTOM from GENUS is breakdown into crucial components (**Figure 7**): payload mass, propulsion mass, structural mass, system mass, operational item mass, and energy mass.

3.5. Aerodynamics analysis

The aerodynamics module plays a vital role in supporting the calculation of aerodynamics through the whole conceptual aircraft design process. It predicts and stores all relevant aerodynamic coefficients once the necessary information regarding the geometry specifications is received. Then it moves on to a surrogate module that contains the aerodynamic coefficients matrix at any flight condition, which can be extracted according to the needs of other modules. Five distinct predictive methods have been built in so far: empirical equations from textbooks (Howe n.d.; Raymer 2018), Digital Datcom (Manual 1979) from the Public Domain Aeronautical Software (PDAS) (Carmichael n.d.) in Fortran, linear potential solver PANAIR ("The PANAIR Program for Panel Aerodynamics" n.d.), Athena vortex lattice (AVL) (M.I.T. Athena n.d.), and supersonic/hypersonic arbitrary body program (SHABP) (Gentry 1973). According to various fidelity, complexity, and specific requirements, the method of implementing those calculators and the associated validation are introduced in (Sepulveda et al. 2019; Sun and Smith 2018, 2019). **Figure 8** shows a comparison of drag polars from different calculation tools in GENUS.

3.6. Packaging and CG

Packaging analysis is necessary for conceptual aircraft design because it allows designers to decide the inner layout of the aircraft and the position of each component that stems from the mass breakdown module, as it prevents interference between components. In addition, it can calculate the coordinates of the centre of gravity at different conditions.

The novelty in the proposed packaging analysis for HECA is the consideration of storing the electric energy source. The space under the cabin is reserved for cargo and batteries. During the loading and unloading of the RBUs, the CG should be determined because it is critical to the stability analysis.

3.7. Performance analysis

3.7.1. Performance specification

The performance module plays a pivotal role in GENUS as it acts as the transition phase of the conceptual aircraft design. Because this module uses all predicted and preset specifications of the hybrid-electric aircraft, such as the specified geometry, mission requirements, aerodynamic calculations, and mass status. It collects all performance information once it progresses through all of the self-defined flight segments. The sub-module 'segment module' allows variable-free detailed design by integrating the whole flight, including the start condition, end condition, PMS, and estimated endurance (**Table 7**). The performance module collects the performance and condition of the aircraft at the end of each segment (**Table 8**) and passes it into the following modules, such as stability and special modules. During the whole flight, the thrust is calculated according to the kinetic equation defined by the drag and the acceleration (Eq. (17) and Eq. (18)). Besides, a detailed flight profile example is displayed in **Figure 9**.

$$T_t = \frac{1}{2} \cdot \rho \cdot v^2 \cdot S_{gross} \cdot C_L + M \cdot a_x \tag{17}$$

$$L = M \cdot (g + a_z) \tag{18}$$

GENUS considers the power management strategies applied to each segment. The performance module collects extra performance data related to electricity consumption (bold font in **Table 8**).

3.7.2. Validation of the performance module

The validation of the performance module is carried out by comparing the outputs with the SUGAR Volt series aircraft (**Table 9**). By comparing the key performance indicators, the error between the reported data, and the data generated by GENUS is from -10.07% to 7.72%.

3.8. Stability analysis

The stability module evaluates the stability status of aircraft at various flight conditions. Longitudinal stability and lateral-directional stability characteristics in all flight conditions are generated using Digital DATCOM. For longitudinal stability analysis, the static margin in Eq (19) ought to be between 5% to 25% for airliners. The trim angle can be calculated by DATCOM's symmetric flap deflection and be constrained in the range from -25 degrees to 25 degrees. For lateral stability analysis, yawing moment and rolling moment are constrained as Eq (20) and Eq (21) show.

$$K_n = \frac{X_{np} - X_{CG}}{\bar{c}} = -\frac{C_{m_\alpha}}{C_{L_\alpha}} \tag{19}$$

$$C_{n\beta} > 0 \tag{20}$$

$$C_{l\beta} < 0 \tag{21}$$

More situations are considered in GENUS for specific HECA for stability analysis; for instance, the aircraft should be stable when loading or unloading the battery.

3.9. Special module – Cost analysis

In deciding the aircraft configuration and performance, the energy cost and operating cost of the aircraft have a significant influence.

The cost module adopts Jenkinson's method (Jenkinson et al. 1999) as the fundamental calculation to predict cost performance (**Figure 10**). For a specific HECA, the stakeholder cares more about the flight operation cost (FOC).

$$FOC = C_{batt} + C_{electricity} + C_{fuel} + C_{crew} + C_{airport} \tag{22}$$

Eq (22) shows the calculation of FOC, which consist of C_{batt} the battery cost, $C_{electricity}$ the electricity cost, C_{fuel} the fuel cost, C_{crew} the crew cost and $C_{airport}$ the airport service cost.

The cost module also provides individually evaluation. The indirect operating costs (IOC) of HECA is estimated between 15% and 50% of the total operational cost. It is not insignificant, but it is hard to quantify the exact cost because it requires new maintenance facilities and the introduction of new skills for advances in technology (Jenkinson et al. 1999).

For kerosene-powered aircraft, the specific air range (SAR) [m/kg] is a vehicular efficiency to evaluate the distance the aircraft can fly per unit of kerosene. For (hybrid-)electric-powered aircraft, Arne Seitz et al. (Seitz et al. 2012) proposed the energy specific air range (ESAR) [m/Joule] in Eq (23), which is an equivalent indicator to show how far the aircraft can fly per unit of energy. The cost specific air range (COSAR), a cost index, was proposed by C.Pornet (Pornet et al. 2014a) in 2014 to enable various HECA to be considered. COSAR is defined as the distance a HECA can fly per unit of energy cost, and it is defined in Eq (24):

$$ESAR = \frac{V \cdot L/D}{SPC \cdot W} \tag{23}$$

$$COSAR = \frac{V \cdot L/D}{(\sum_i SPC_i \cdot c_i) \cdot W} \tag{24}$$

Where V represents the flight velocity [m/s], W is the weight of the aircraft [N], L/D is the lift to drag ratio, SPC is the specific power consumption in [W/N], and c is the specific cost of the energy. For a specific HECA, the ESAR and the COSAR can also be written as:

$$ESAR = \frac{V \cdot L/D}{(SPC_{fuel} + SPC_{electricity}) \cdot W} \tag{25}$$

$$COSAR = \frac{V \cdot L/D}{(SPC_{fuel} \cdot c_{fuel} + SPC_{electricity} \cdot c_{electricity}) \cdot W} \tag{26}$$

Where SPC_{fuel} is the specific power consumption from the ICE, $SPC_{electricity}$ is the specific power consumption from the EM [W/N], c_{fuel} is the specific cost of kerosene [£/kWh], and $c_{electricity}$ is the specific cost of electricity [£/kWh]. GENUS offers several choices about units of money and energy so that users can analyse the cost performance without the inhibits among different currencies. A set of cost is displayed below in **Table 10**.

3.10. Optimisation

There are three optimisation algorithms built into GENUS: the genetic, gradient, and hybrid optimisers; the hybrid optimiser runs through the genetic and gradient optimisers sequentially.

In order to ensure that the solutions are independent of the initial setting of the design variables, to avoid the possible deviation led by different starting points, to balance between the accuracy of the resolution and endurance of the optimisation, the full factorial design of experiments (DOE) is implemented on top of algorithms. After determining the variables and their ranges in the optimisation, the DOE function will choose the starting point of each variable evenly according to their correspondent range settings. For instance, if the number of factors equals one, the starting point will only be pre-set from the input panel. The number of the starting point is introduced as:

$$N_{StartPoint} = {N_{factor}}^{N_{Variable}} \tag{27}$$

Where, $N_{StartPoint}$ is the number of the complete set of the starting point of the optimisation, N_{factor} is the number of shares defining the number of starting points for each variable, $N_{Variable}$ is the number of variables.

While collecting all solutions of optimisations within the specific starting point, the DOE function will choose the best solution based on the objective of the optimisation.

Such a flexible optimiser allows knowledgeable users to free up any variables, restrict any constraints, and choose their preferred algorithm to look for solutions on their way of exploring the aircraft design space.

3.11. Integrated validation

Aircraft design is a complex systematical subject. GENUS, as an integrated conceptual aircraft design environment, involves nine key modules and the optimiser introduced in the content above. This part displays a series of HECA designs and comparisons with C. Pornet's research (Pornet et al. 2014b).

Table 11 collects all the preconditions from C. Pornet's research and the correspondent setting in GENUS. Based on the same basic presetting, a series of HECA designs is generated by GENUS with the optimisation settings shown in **Table 12**. Eq (28) to (31) display the calculation of errors in **Table 12**.

$$MTOM\_error = \frac{CalMTOM - EstMTOM}{EstMTOM} \tag{28}$$

$$FuelMass\_\ error = CalFuel - EstMTOM \cdot FF \tag{29}$$

$$BattMass\_error = EstMTOM \cdot BF - CalBatt \tag{30}$$

$$Motor\_error = \frac{SizedPower - EstPower}{EstPower} \tag{31}$$

The relative changes in MTOM, block fuel, and ESAR evaluated against the advanced kerosene-powered aircraft are illustrated versus design range with three battery technology levels in **Figure 11**.

Follow the precondition listed above, a group of HECAs are designed by GENUS to compare the conceptual design of HECAs with three technology assumptions, and with the range target from 800 nm to 2,400 nm. **Figure 11** compares the block fuel, MTOM, ESAR among all the design cases. Also, the trendlines generated by the comparison match C. Pornet's research even with the different design methods. It is notable that in the comparison of block fuel, the relative change generated by GENUS has a similar pattern and trend to the reference-data but is higher than the reference. The possible reasons are listed below:

- GENUS design the HECA with DOD assumed as 0.8, whereas the reference DOD is not given (likely to be 1.0).
- The calculated BPR of GENUS optimum cases are all smaller than the BPR from the reference, which is 16.2.
- The advanced technology mentioned in the reference is not clear copied in GENUS cases. GENUS matches the performance of propulsion by adjusting the efficiencies of each component of the powerplant.
- The L/D of GENUS cases are smaller than C.Pornet's because of the different aerodynamics coefficients prediction methods. (e.g. L/D estimated by DATCOM is smaller than that estimated by PANAIR)

According to the analysis, by changing the DOD from 0.8 to 1, block fuel's relative change moves downward in **Figure 12**, which displays the sensitivity of the DOD visually.

4. Hybridisation of conventional turbofans

The main incentive in hybridising the turbofan is to shrink the core engine while embedding the EM. The hybridised engine is expected to satisfy the mission of the original engine through an increase in the size of EMs. **Figure 13** to **Figure 15** shows the performance of powerplants at full throttle and static sea level (SSL). It displays a series of powerplants with the growing size of EMs. The prototypes of the three series are CFM56, CF6, and TFE731. As the EM size grows, the electrical power will take a greater fraction of the power load of the whole powerplant, while the core engine will shrink to its lower boundary. All graphs can be expressed into two phases by the change of static sea-level thrust 'SSL T':

- Phase 1: In the top graph of each of the three sets in **Figure 13** to **Figure 15**, all the hybridised thrust (SSL_T) of three hybridised powerplants remain stable at the platform determined by their prototypes, indicating that the growing EM fills the thrust gap as the core engine shrinks. The proportion of the power supply is presented by specific kerosene power consumption (SSL_fSPC) and specific electrical power consumption (SSL_eSPC) bars in the top graph, which has a similar trend to the energy consumption (i.e. specific kerosene energy consumption 'SSL_fSEC' and specific electrical energy consumption 'SSL_eSEC') in the bottom graph. What is noticeable here is the total specific power consumption (SSL_SPC), and total specific energy consumption (SSL_SEC) decrease despite the constant thrust. This is because the energy utilisation efficiency of EMs is higher than that of inner combustors (i.e. same thrust can be generated by a smaller EM than an inner combustor). Therefore, from the view of improving power and energy efficiency, it is better to use an EM size at the end of phase 1.
- Phase 2: SSL_T dips and then returns to the level of the prototype's SSL_T. The hybridisation process is achieved replacing part of core engine with EM, reflected by enlarging the BPR with fixed fan diameter. As the EM grows from 0MW to 7.8MW in **Figure 13**a, BPR gradually reaches its upper boundary, which means the core engine shrink to its physical limitation and cannot shrink any more. It is a limitation of this propulsion architecture (EM embedded at the tail cone of a turbofan), the core engine must be able to work individually, so the ram drag is supposed to smaller than the gross thrust (Eq.(32) and Eq. (33)) If enforced the BPR increasing, it is unable to offer any power/thrust. Then the hybridised powerplant transforms into a universal electric powerplant, but the EM is not large enough to fill the gap left by the core engine yet, because the power of the core engine has dropped sharply. The EM growth continues until the universal hybridised power can support the requirement thrust that equals that of the prototypes.

$$NetT = GrossT - DRam \tag{32}$$

$$DRam = Dram + u0 \cdot \frac{BPR}{g0} \tag{33}$$

For all the engines hybridised in **Figure 13** to **Figure 15**, the process of electrifying turbofans is similar, and all need to go through two phases. The differences are the corresponding critical EM size and the change in timing from a conventional internal combustor engine into an all-electric engine.

5. The hybridisation of conventional airliners

5.1. Optimisation for HECA design

As electrical technology improves, HECA offers more possibilities and flexibility. The kerosene-powered 2,000 km B737 is the baseline. It is hybridised with two assumed technology levels (Tech-2050 and Tech- 2035) listed in **Table 13**. Both optimum aircraft follow the detailed flight segments listed in **Table 14**.

5.2. Analysis and evaluation

In contrast to the kerosene powered B737 (BOEING 2013), there are six distinct characteristics of the hybridised B737:

- Hybridised B737 case shows the potential benefits of hybrid-electric airliners using advanced technology in fuel-saving (39.17% and 27.18%), energy-saving (22.03% and 9.97%) in **Figure 16**, and cost-saving (19.62% and 12.40%) in **Figure 16** and **Figure 17**.
- Higher technology level brings much more potential for saving fuel, energy and cost;
- Higher technology level brings a deeper degree of hybridisation when loading the same EM and PMS (i.e. energy hybridisation in **Figure 16**).
- The hybridisation results in the mass penalty to the airliners design, which is inevitable due to the lower specific energy of the battery. The higher the level of technology being used, the less mass penalty the aircraft receives (**Figure 18**).
- **Figure 19** and **Figure 20** compare the key parameters of two hybridised powerplants at some representative conditions, that construct the performance matrix of powerplant and also enable the data usage of following modules and convenient comparing and checking the powerplant design. Besides, they show that with the same technology level, a higher power hybridisation degree can be achieved for the powerplant at a higher altitude.
- **Table 15** reveals the potential contribution of electrifying the airliners to environment protection. It helps reduce the amount of CO_2 generation with two technology levels (Tech-2050 and Tech-2035) by 49.57% and 43.56% separately, which mitigates the greenhouse effect, especially the near field emission.

6. Conclusion

This paper introduces GENUS, which is a robust conceptual design environment for HECA design. Considering that aircraft design is a complex process, GENUS integrates nine basic disciplines and allows users to import other modules as required, ensuring the comprehensiveness of the design environment. Designers are allowed to determine and control the variation of variables associated with geometry, mass breakdown, propulsion specification, performance setting, etc. It is also flexible to activate or disable any modules to be involved in the optimisations. Each module contains at least one fidelity method being appropriate to various classes of aircraft. In addition, three options in optimising algorithms are available in GENUS for different optimising problems. GENUS has been applied to design and evaluate existing HECA concepts, demonstrating the HECA-related new features which are listed as follows.

- Consider the allocation of electrical energy, including its placement, the resulted mass gain and its effects on the stability of the aircraft under different combinations of payload, fuel and battery
- Extend the propulsion system to cover various HEPAs and the corresponding powertrains, enabling GENUS to operate detailed power management strategies to control and to trade off the selection between fuel and electric power
- Set new performance indicators to comprehensively evaluate HEP and HEA
- Add the cost module to evaluate and compare the cost of all design options
- Add the aviation emission monitoring function throughout the whole flight.

This paper also presents the application of GENUS to hybridise three conventional turbofans (i.e. CFM56, CF6, and TFE731) and to analyse the effects of engine hybridisation on B737 design with two levels of technology, i.e. YEIS 2035 and 2050. It reveals the advantages of GENUS in effectively carrying out HECA design, from which the benefits achieved by HECA have been highlighted and are summarised as follows:

- Hybridisation enables the powerplant to be more power-efficient and energy-efficient. Increasing the installed power of motors, which is used to hybridise the aircraft, could improve the power and energy efficiencies of the hybrid-electric powerplant.
- The hybridised B737 concept shows that HECA promotes cost-saving by 12.40-19.62%, kerosene saving by 27.18 -39.17% and energy saving by 9.97-22.03 % when the applied technology changes from YEIS 2035 to 2050. Additionally, the total emissions of the aircraft are mitigated by 43.56% and 49.57% in YEIS 2035 and 2050 respectively, especially at the near-field emission (i.e. by 38.42% and 46.05%

respectively). It implies the function of analysing the design and potential of HECAs.

This evaluation also implies the potential application of GENUS to HECA design due to its robustness and flexibility in investigating the effects of different factors (e.g. DoH, BPR, etc.) on the performance of HECA. Firstly, the design space of HECA can be effectively explored using GENUS to determine whether aircraft hybridisation can bring benefits in SFC, SEC, and SPC. Secondly, a feasible design space can be potentially obtained to maximise the benefits of aircraft hybridisation by analysing the sensitivity of the performance of HECA to relevant design parameters, based on existing technologies. Finally, feasible design space of HECA can be expected to be obtained by carrying out a comprehensive sensitivity analysis by changing the composition of the propulsion system. In a similar way, the impact of technological improvements (e.g. the specific energy of batteries, the specific power of electrical machines, etc.) on the performance of HECA can also be evaluated using GENUS, which can inform decisions relating to research and development investment in various research domains.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions.

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Table List

Table 1 Parametric Geometry in GENUS

Geometry Class	Geometry Component	Parameters
Body Component	Fuselage	XYZ apex; the number of sections; cross-section shape; section dimensions; section apex; and master component
	Nacelle	
Lift Surface	Wing	XYZ apex; the number of sections; each section is defined by Aerofoil, Span, Root chord, Tip chord, Root incidence, Twist, Sweep, Dihedral
	Canard	
	Vertical tail	
	Horizontal tail	

Table 2 Parametric Mission in GENUS

Mission Information	Parameters
Mission	Estimated maximum takeoff mass (MTOM)
	Target range
	Payload: number of passengers and crew
	Manoeuvre load factor
	Airport condition: Takeoff altitude, takeoff distance, landing distance
	Cruise condition: cruise Mach number, cruise altitude,
Technological status	Technology year that represents the total technology level
	Battery technology: Specific energy, specific power, energy density, Depth of discharge (DOD)(Norris 2002), mass gain rate
	Electrical accessory technology: specific power of inverter, Solid-state power controller (SSPC), and thermal management system
	Cable density

Table 3 Specification of estimated technologies

Parameter class	Technology indicator	Value		
	Year of entry into service (YEIS)	2035	2040	2050
Battery	Max charging cycles of the battery	1,750	2,000	5,000
	Specific energy of battery [kJ/kg]	3,240	3,780	4,860
	Energy density of battery [kJ/m^3]	864,000	913,000	1,100,000
Electrical accessories	Specific power of EM [kW/kg]	6.5	15	20
	Specific power of inverter [W/kg]	17,800	23,300	34,000
	Specific power of SSPC [kW/kg]	17,800	23,300	34,000
	Specific power of thermal controller [kW/kg]	17,800	23,300	34,000
	Cable density [kg/m]	9.2	9.6	10

Table 4 Powertrains

Battery-kerosene hybrid-electric powertrain	**Figure 4**(a)	$T_t = T_b + T_{jet}$ (34) $P_b = P_m + P_{tur}$ (35) $E_t = E_e + E_f$ (36) $F_t = F_{TtoP}$ (37)
Kerosene-powered powertrain	**Figure 4**(b)	$T_t = T_{jet}$ (38) $P_b = P_{tur}$ (39)

		$E_t = E_f$ (40) $F_t = F_{TtoP}$ (41)
Battery-powered powertrain	**Figure 4**(c)	$T_t = T_b$ (42) $P_b = P_m$ (43) $E_t = E_e$ (44) $F_t = 0$ (45)
Kerosene powered series hybrid-electric powertrain	**Figure 4**(d)	$T_t = T_b + T_{jet}$ (46) $P_b = P_m = P_{tur}$ (47) $E_t = E_f$ (48) $F_t = F_{TtoM}$ (49)
Kerosene-powered and charge in the air powertrain	**Figure 4**(e)	$T_t = T_b + T_{jet}$ (50) $P_b = P_{tur} - P_c$ (51) $E_t = E_e + E_f$ (52) $F_t = F_{TtoP} + F_{TtoM}$ (53)

Table 5 Powerplant module parameters

Propulsion Specification Class	Parameters
The scale of the propulsion system	Type of powerplant and the number of each powerplant type, maximum Mach number, maximum altitude, preset of the total engine
Design point	Mach number; altitude; fThrottle; eThrottle; afterburner condition
ICE definition	Fan diameter; bypass ratio; fan pressure ratio; compressor pressure ratio; nozzle to core area ratio; the material of each component; efficiency of each component
Electrical part	Estimated installed power of the EM, electricity transfer efficiency

Calculator	Hybrid electric or not; update bypass ratio or fan diameter

Table 6 Summary of power management strategies

Power manage strategy	Activation ratio	Powertrain	Instruction
Green	$\emptyset = 1$	Battery-powered powertrain	Universal electric strategy, battery-powered, is usually used during taxing, cruise, etc.
Kerosene-powered	$\emptyset = 0$	Kerosene-powered powertrain	Kerosene powered
ICE preferred	$0 < \emptyset < 1$	Battery-kerosene hybrid-electric powertrain	The engine system preferentially chooses the ICE to generate the power to meet the requirement and uses electrical power to fill the gap.
EM preferred	$0 < \emptyset < 1$	Battery-kerosene hybrid-electric powertrain	The engine system preferentially chooses the EM to generate the power to meet the requirement and uses ICE to fill the gap.
Fixed throttle	$0 < \emptyset < 1$	Battery-kerosene hybrid-electric powertrain	The engine only works at fixed turbine throttle and electrical throttle, mainly being applied during takeoff, climb, etc.
Fixed the ICE throttle	$0 < \emptyset < 1$	Battery-kerosene hybrid-electric powertrain	The ICE only works at fixed turbine throttle, while the EM fills the gap. It allows the ICE to keep working in the most efficient condition to improve fuel efficiency.
Fixed electrical throttle	$0 < \emptyset < 1$	Battery-kerosene hybrid-electric powertrain	The EM works at the fixed electrical throttle while the ICE fills the gap. It

			allows the EM or battery to keep working in the most efficient condition.
Charge in the air	$\emptyset = 0$	Kerosene-powered and charge in the air powertrain	In the charge mode, the ICE always works at the large (full) throttle, as it must charge the battery while meeting the current power requirement of flying.
Series hybrid	$\emptyset = 0$	Kerosene powered series-electric powertrain	It disabled the battery pack and spool that connect the ICE and the fan to analyse and evaluate various HEPAs.

Table 7 Setting of each flight segment

Segment	General parameters
Taxi	Taxi speed, taxi time, flap condition, power management strategy.s
Take-off	Start speed, end speed, start altitude, end altitude, high lift device condition, power management strategy, charge condition, afterburner condition, etc.
Climb	
Cruise	
Descend	
Landing	

Table 8 Phased performance at the end of each segment

Class of performance	Parameters
Mass	Fuel consumption, **mass gain of battery**, the total mass of aircraft, CO_2
Propulsion	Thrust, SFC, SEC, SPC, fSPC, eSPC, eSEC, power hybridisation
Aerodynamics	Drag, lift to drag ratio, angle of attack
Flight condition	**Energy hybridisation**, Mach number, altitude, duration, range, total energy consumption, **electricity consumption, state of charging (SOC)**

Table 9 Validation of performance module

Reference aircraft	Index	Reference	GENUS	Error
Balanced SUGAR Volt (1380 HP)	Boeing equivalent thrust (BET) [N]	85,405.82	86,049.46	0.75%
	Range [m]	1,666,800	1,647,614	-1.15%
	Block fuel [kg]	2,641.85	2,803.45	6.12%
	Block energy [J]	1.30E+11	1.40E+11	7.69%
	Fuel fraction [%]	87.80%	86%	-2.05%
Balanced SUGAR Volt (1750 HP)	BET [N]	80,067.96	80,466.29	0.50%
	Range [m]	1,666,800	1,644,548	-1.34%
	Block fuel [kg]	2553.83	2,661.65	4.22%
	Block energy [J]	1.27E+11	1.31E+11	3.15%
	Fuel fraction [%]	86.60%	88%	1.62%
Core shutdown SUGAR Volt (7150 HP)	BET [N]	92,078.15	92,587.34	0.55%
	Range [m]	1,666,800	1,655,032.38	-0.71%
	Block fuel [kg]	2,322.62	2,359.57	1.59%
	Block energy [J]	1.49E+11	1.64E+11	10.07%
	Fuel fraction [%]	67.30%	62.10%	-7.73%

Table 10 An example of cost setting

Name	Value	Comment
Execute	True	
Currency	$	The currency can be chosen among $, £, ¥, €, ￥, etc. The corresponding cost will be converted according to the currency.
Produced Year	2035	It will change according to the technology choice in the mission setting.

Flying Hour [Hr/Year]	5,000	
Max Charge times	1,750	
Battery Cost [$/kg]	44	The price of material can be manual editing in the GUI, which will affect the final cost estimating.
Fuel Price [$/Gallon]	6	
Electricity Price [$/kWh]	0.03	

Table 11 List of preconditions

Class	Item	Referenced research	GENUS
Mission	Wing loading	$645\text{kg}/m^2$	
	PAX	180	
	Cruise condition	ISA+10°C, FL350, M0.76	
	Design range	800-2,400nm	
	Baggage volume	0.22 m^3 per PAX	
	Reserve fuel	EU-OPS(European Commission 2008)	ICAO Annex 6 (ICAO 2010)
Aerodynamics	L/D	18.04-18.91	13.5-17.0
Propulsion	Simulating tool	GasTurb11(Kurzke 2010)	EngineSim(NASA n.d.)
	Technology	YEIS 2035	Advanced
	BPR	16.2	Calculated
	Core engine	Unaffected by electrical power	
	Pressure ratio	OPR 65	FPR 1.65 CPR 37.576
	Design condition	ISA, FL350, m0.78	
	Design SFC	13.24g/kN/s	13.3g/kN/s

	Design thrust	15-35 kN	
	EM size	5,400-9,100 kW	Calculated
Battery	Specific energy	750, 1,000, 1,500 Wh/kg	
	Energy density	1,500 kWh/m^3	
EM	Specific power	20kW/kg	
PMS	EM usage	Used during cruise only	
	Power hybridisation during the cruise	50%	
	Way of hybridising	One engine is in battery-powered mode during the cruise, and the other is in kerosene-powered mode.	Both engines work in the hybrid-electric mode during the cruise: use EM first and inner combustor as a substitute.

Table 12 Settings for optimisation in GENUS

Module	Objective	Variable	Constraint	
Geometry	-	Wingspan	Wing loading error	= 0
	-	Wing Chord		
Mass	Minimum MTOM	MTOM	MTOM error	< 5%
	-	Fuel fraction	Fuel mass error	< 0
	-	Battery fraction	Battery mass error	< 0
Propulsion	-	EM installed power	EM power error	< 3%
	-	BPR	Takeoff distance	< 3,000 m
	-	-	Landing distance	< 3,000 m
	-	-	Takeoff speed (35ft)	> $1.2V_S$
	-	-	Second climb	> 2.4%

		gradient	
-	-	Missed approach climb gradient	> 2.1%
-	-	Cruise thrust	> Cruise drag

Table 13 Technology assumed for case studies

Parameter class	Technology indicator	Assumed value	
		Tech-2050	Tech-2035
Battery	Max charging cycles of the battery	5,000	1,750
	Specific energy of battery [kJ/kg]	5,400	3,240
	Energy density of battery [kJ/m^3]	5,400,000	864,000
Electrical accessories	Specific power of EM [kW/kg]	20	6.5
	Specific power of inverter [W/kg]	37,500	17,800
	Specific power of SSPC [kW/kg]	37,500	17,800
	Specific power of thermal controller [kW/kg]	37,500	17,800
	Cable density [kg/m]	10	9.2
Others	Electrical efficiency	0.99	0.93
	YEIS	2050	2035

Table 14 Performance and PMS settings for optimisation

Segment	Height [m]	Aim Mach	Operate Mode
Taxi	0	0.029	Fuel-powered
Takeoff	0	0.180	Full throttle
Climb to 35ft	0-11	0.180	
Climb to 400ft	11-124	0.369	
Landing gear	124	0.385	

retraction			
Climb to cruise	124-11,000	0.785	Fuel-powered Max continuous thrust
Cruise	11,000	0.785	Hybrid-electric $\phi = 0.5$
Descend	11,000-610	0.389	Fuel-powered
Approach	610-15	0.350	
Flare	15-0	0.316	
Landing	0	0	Fuel-powered Full throttle

Table 15 Comparison of CO_2 emission [kg]

Item	Tech-2050	Tech-2035	B737 in GENUS
Taxi [kg]	0	0	1.15
Takeoff [kg]	1.24	1.48	2.15
Climb to 35ft [kg]	0.22	0.25	0.39
Climb to 400ft [kg]	1.58	1.77	2.84
Landing Gear Retraction [kg]	0.67	0.74	0.28
Climb to Cruise [kg]	10.90	12.20	21.94
Cruise	6,508.75	7,284.40	12,903.66
Descend	10.08	11.10	24.88
Approach	2.17	2.58	2.62
Flare	0.02	0.019	0.06
Landing	0.30	0.34	0.61
Total	6,535.92	7,314.88	12,960.55

Near Field Pollution	4.03	4.60	7.47
Near Field Emission Reduction	-46.05%	-38.42%	-
Total Emission Reduction	-49.57%	-43.56%	-

Figure List

Notation

Acronyms

AVL	Athena vortex lattice
BET	Boeing equivalent thrust [N]
BattMass_error	The mass error of battery consumption that is constrained in optimisation
BF	Battery mass fraction
BRP	Bypass ratio
CalBatt	Calculated battery consumption [kg]
CalFuel	Calculated fuel consumption [kg]
CalMTOM	Calculated MTOM [kg]
CG	Centre of gravity
COSAR	Cost specific air range [m/£]
DOC	Direct operating costs [£]
DOD	Depth of discharge [%]
DoH	Degree of hybridisation
DOE	Design of experiments
EM	Electric motor
EIS	Entry into service
ESAR	Energy specific air range [m/Joule]
EstPower	Estimated installed power of the EM [W]
EstMTOM	Estimated MTOM [kg]
Esec	Electrical specific energy consumption [Joule/N/s]
Espc	Electrical specific power consumption [Watt/N]
FF	Fuel mass fraction

FL	Flight level [hundreds of feet]
FOC	Flight operation cost [£]
FuelMass_error	The mass error of fuel consumption that is constrained in optimisation
Fspc	Fuel specific power consumption [m/Watt]
HEA	Hybrid-electric aircraft
HECA	Hybrid-electric civil airliner
HEP	Hybrid Electric Propulsion
HEPA	hybrid-electric propulsion architecture
HV	Heat value [Joule/kg]
ICE	inner combustion engine
IOC	Indirect operating cost [£]
ISA	International standard atmosphere
Motor_error	The error of the installed power of the motor that is constrained in optimisation
MTOM	Maximum takeoff mass [kg]
MTOM_error	The mass error of the MTOM that is constrained in optimisation
OEM	Operational empty mass [kg]
PAX	Passenger
PMS	Power management strategy
RBU	Replaceable battery unit
SAR	Specific air range [m/kg]
SEC	Specific energy consumption [Joule/N/s]
SFC	Specific fuel consumption [kg/N/s]
SHABP	Supersonic/hypersonic arbitrary body program
SizedPower	Calculated power of the sized motor [W]

SOC	State of charging [%]
SPC	Specific power consumption [Watt/N]
SSL	Static sea level
SSPC	Solid-state power controller
Tech-2050	The technology level YEIS 2050
Tech-2035	The technology level YEIS 2035
UAVs	Unmanned aerial vehicles
YEIS	Year of entry into service

Symbols

α_x	The horizontal component of the acceleration $[m/s^2]$
α_z	The vertical component of the acceleration $[m/s^2]$
$\bar{c}$	Mean aerodynamic chord [m]
$C_{airport}$	Airport service fee [£]
C_{batt}	Battery cost [£]
C_{crew}	Crew cost [£]
$C_{electricity}$	Electricity cost [£]
C_{fuel}	Fuel cost [£]
$c_{l\beta}$	rolling moment
C_{m_α}	Moment coefficient curve slope
C_L	Lift coefficient
C_{L_α}	Lift coefficient curve slope
$c_{n\beta}$	yawing moment
C_p	Specific heat constants of air

C_{pg}	Specific heat constants of gas
$DRam$	Ram drag [N]
E_e	Total electricity consumption [Joule]
E_f	Total kerosene energy consumption [Joule]
E_t	Total energy consumption [Joule]
$eThrottle$	Throttle used to control the EM
$fThrottle$	Throttle used to control the ICE
F_t	Total fuel consumption [kg]
F_{TtoM}	Fuel used to charge the battery [kg]
F_{TtoP}	Fuel used to drive the fan [kg]
g	Acceleration of gravity $[m/s^2]$
$GrossT$	Gross thrust [N]
H_P	DoH of power [%]
H_E	DoH of energy [%]
K_n	Stick fixed static margin
L/D	Lift to drag ratio
L	Lift [N]
M	Aircraft Mass [kg]
$\dot{m}_b$	Air mass flow goes through the bypass [kg/s]
$\dot{m}_f$	Fuel mass flow goes through the ICE [kg/s]
$NetT$	Net thrust [N]
$N_{StartPoint}$	The number of the complete set of the starting point of the optimisation
N_{factor}	The number of factors that defines how many starting points of each variable

$N_{Variable}$	The number of variables
P_b	Total power pass to the fan [Watt]
P_c	Power transferred from the ICE to charge the battery [Watt]
P_{InsM}	Installed power of the equipped EM [Watt]
P_m	Power transferred from the motor to the main shaft [Watt]
P_{tur}	Power transferred from the ICE to the main shaft [Watt]
S_{gross}	Gross wing area $[m^2]$
t	Endurance [s]
T_b	Bypass thrust generated by the fan [N]
$Temp_2$	The temperature at the inlet of the powerplant [K]
$Temp_{4.5}$	Temperature before the low-pressure turbine [K]
$Temp_{t4}$	Highest temperature the turbine material can tolerate [K]
T_{jet}	The jet thrust generated by the ICE [N]
T_t	Total thrust of the propulsion system [N]
v	flight speed [m/s]
v_0	Airspeed at the inlet [m/s]
v_f	Airspeed at the fan outlet [m/s]
V_S	Stall speed [m/s]
W	The gross weight of the aircraft [N]
X_{CG}	Coordinate value of CG point on the longitude axis of the fuselage [m]
X_{np}	Coordinate value of the neutral point on the longitude axis of the fuselage [m]
ø	Activation ratio
ρ	Air density $[kg/m^3]$

η_{TL}	Work efficiency of the low-pressure turbine
π_{TL}	The pressure ratio of the low-pressure turbine
$\boldsymbol{\gamma}$	The ratio of specific heat

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