Conceptual Design Studies of "Boosted Turbofan" Configuration for short range

CleanSky2 LPA WP1.6.1.4 special session

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This paper describes the current activities at the German Aerospace Center (DLR) and an associated consortium related to conceptual design studies of an aircraft configuration with hybrid electric propulsion for a typical short range commercial transport mission. The work is implemented in the scope of the European Clean Sky 2 program in the project "Advanced Engine and Aircraft Configurations" (ADEC) and "Turbo electric Aircraft Design Environment" (TRADE). The configuration analyzed incorporates parallel hybrid architecture consisting of gas turbines, electric machines, and batteries that adds electric power to the fans of the engines. A conceptual aircraft sizing workflow built in the DLR's "Remote Component Environment" (RCE) incorporating tools of DLR that are based on semi-empirical and low level physics based methods. The TRADE consortium developed a simulation and optimization design platform with analysis models of higher fidelity for an aircraft with hybrid electric propulsion architecture. An implementation of the TRADE simulation and optimization design platform into the DLR's RCE workflow by replacing the DLR models was carried out. The focus of this paper is on the quantitative evaluation of the "Boosted Turbofan" configuration utilizing the resulting workflow. In order to understand the cooperation between the DLR and TRADE consortium, a brief overview of the activities is given. Then the multi-disciplinary overall aircraft sizing workflow for hybrid electric aircraft built in RCE is shown. Hereafter, the simulation and optimization models of the TRADE design platform are described. Subsequently, an overview of the aircraft configurations considered in the scope of this work is given. The design space studies of the "Boosted Turbofan" configuration are presented. Finally, the deviations of the results between the workflows with and without the TRADE modules are discussed.

I. Introduction

In this section, the background information related to the conceptual aircraft design activities regarding hybrid electric propulsion in the scope of the project "Advanced Engine and Aircraft Configurations" (ADEC) of Clean Sky 2 at the German Aerospace Center (DLR) and of the "Turbo electRic Aircraft Design Environment" (TRADE) consortium consisting of the University of Nottingham, University of Märladalen, University of Berlin and coordinator Modelon also part of Clean Sky 2 is summarized. The activities are dedicated to the challenging goals as defined in Flightpath 2050 [1] to reduce the environmental impact of transport aircraft by improving its performance.

Both the DLR and the TRADE consortium investigated the so-called "Boosted Turbofan" configuration independently. The "Boosted Turbofan" concept incorporates a parallel hybrid electric powertrain with an electric motor connected to the fan shaft and electric energy stored in batteries. The DLR developed an overall aircraft sizing workflow based on semi-empirical and low level physics based methods to evaluate hybrid electric propulsion (HEP) configurations with respect to the degree of hybridization (DOH), as described in [**15**]. In contrast, the TRADE consortium developed physics-based models of higher fidelity than the conceptual tools used in the DLR workflow for the analysis and optimization of individual systems and structural components but not carrying out the complete overall aircraft design (OAD) processes. The interest in an integration of the high-fidelity models into the overall aircraft sizing workflow led to this joint paper.

The focus of this paper is to conduct at quantitative evaluation of the "Boosted Turbofan" configuration using high-fidelity methods and the analysis of the impact of those methods on the overall aircraft design.

In the following the international research activities regarding hybrid electric aircraft concepts are presented. Furthermore, the selection process which led to the "Boosted Turbofan" configuration is outlined and the activities of DLR and TRADE are shown. In the later chapters the DLR workflow, the TRADE models, the validation platform, and the configuration investigated are described. The implementation of the TRADE design platform into DLR's workflow and the analysis of the OAD studies performed with the modified workflow will be discussed in the paper.

A. International Research Activities in the Field of Hybrid Electric Aircraft Configuration

To achieve the goals of substantial improvements in efficiency and emissions set by Flightpath 2050, one approach is to substitute fuel by other energy sources. As one of the most promising energy sources, electrical energy stored in batteries offers high potential due to high efficiency of electric machines. Furthermore, electrical powertrains enable high flexibility to the entire system as well as to the propulsion system with further improvement

of the performance. However, a full electric aircraft is not feasible in the close future due to comparably low energy and power density of batteries [2]. Investigations regarding the potential benefit of full electric aircraft configurations were carried out by NASA and Bauhaus Luftfahrt [3-10]. To avoid the severe mass impact of batteries and take advantage of the electrical powertrain hybrid electric aircraft configuration in which the fuel is partially substituted by batteries seems reasonable according to the current research [11]. The "Boosted Turbofan" configuration that is enabled by an electric powertrain is beneficial for small aircraft as well as for large aircraft, as described in [12,13,14]. Depending on the technology assumptions, degree of hybridization, mission range and payload, promising results in terms of fuel consumption compared to configurations with conventional propulsion are found.

B. Selection Process of Configurations and Activities of DLR in the Scope of Clean Sky 2, Project ADEC

The activities of DLR regarding the conceptual aircraft studies of hybrid electric configurations for short and medium rang mission started 2016 within the ADEC project which is part of the European Clean Sky 2 program. A collaborative workshop together with research entities from France (ONERA), and Netherlands (NOVAIR consortium consisting of TU Delft and NLR) was held to define a set of potentially beneficial configurations with different types of hybrid electric propulsion based on an Airbus A320. The design mission comprised 150 passengers, a range of 800 NM, and a design cruise Mach number above 0.6. The envisaged technology level was set to entry into service in 2035 (EIS2035). After the workshop, a ranking process based on quantitative and low level quantitative methods led to different configurations. The research entities selected some of these configurations for more profound analysis.

An overview of the down-selection process within the project is given in Fig. 1. The general idea is to reduce the number of configurations and to increase the level of fidelity over the curse of four phases. At DLR, the first down-selection (phase 1) was carried out by qualitative methods incorporating a Phug's matrix [16] that was filled out based on expert judgement. In this step the number of configurations was reduced from 35 to 12. The next down-selection (phase 2) was performed by low level empirical and semi-empirical methods that included first parametric studies. The number of configurations was reduced from 12 to 3. The activities at DLR related to the third phase of quantitative analyses are described in paper [15] for the AIAA conference AVIATION in 2019. During phase 3, the main target was to analyze the three most promising hybrid electric concepts – "Boosted Turbofan", "BLI-canard" and "BLI-WingFan" – utilizing an overall aircraft design workflow that consists of combined semi-empirical and low-level physics based methods. The "BLI-Canard" configuration represents a canard configuration with a boundary layer ingestion (BLI) fan at the aft position of the fuselage and mixed hybrid architecture while the "BLI-WingFan" represents a conventional configuration with BLI fan at the aft fuselage, wing tip fans for yaw control and mixed hybrid architecture, more information is given in [15]. "Boost" refers to configurations, which are mainly powered by the main engines and assisted by battery power. Therefore, the Battery power can be availed to additional fans and the main engines (also simultaneously). The "Boosted Turbofan" configuration was one of the most promising concepts related to the potential benefit in fuel consumption and a mass penalty due to the hybrid powertrain. Thus, the focus of phase 4 is to analyze the "Boosted Turbofan" configuration with models of higher fidelity.

The overall aircraft design workflow utilized in [15] is the basis for the integration of the high-fidelity models of the TRADE consortium. The workflow is set up in the DLR's "Remote Component Environment" RCE [17] and enables fast and wide design studies with low level of uncertainties for tube and wing configurations. It is used to investigate the impact of the degree of hybridization of the power distribution.

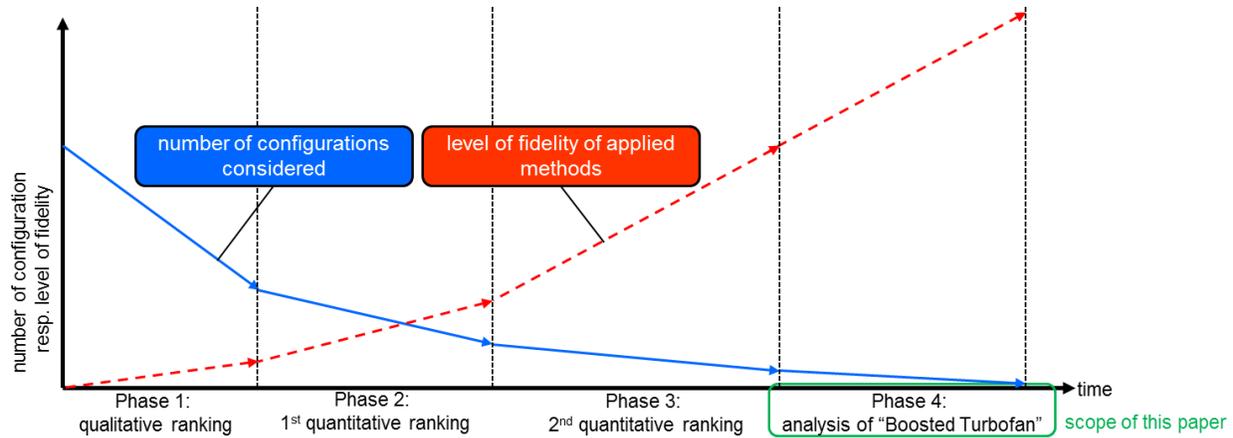A detailed description of the sizing workflow is provided in section III.

Fig. 1 Downselection process in the scope of the project ADEC at DLR

C. Hybrid Electric Aircraft Design Activities of TRADE consortium

Also within the scope of the Clean Sky 2 program, the TRADE consortium works closely with above mentioned partners. A key focus is the development of detailed physical sizing models complementing the classic OAD tools available at said partners already. The TRADE consortium consists of the University of Märladalen, the University of Nottingham, the University of Berlin and Modelon. Modelon acts as coordinator and University of Märladalen as technical architect.

In 2017, the TRADE consortium received a description of the "Boosted Turbofan" concept together with top level aircraft requirements. This was selected as the first configuration to be studied by this consortium due to limited complexity. A platform was defined in terms of requirements and technical architecture, and a prototype was implemented. This validation serves as testbed for model integration, analysis and optimization but does not replace complete OAD design processes such as available and developed in ADEC. Technical interfaces between model implementations of structural sizing, gas turbine, electrical power system, thermal management, and mission assessment were defined within the platform, and a baseline studied (EIS 2035 geared turbofan). Once all models were implemented (even the ones not used on the baseline), the "Boosted Turbofan" configuration was simulated and first analyses made. Results have been published in [18,19]. In parallel to the analysis work, improvements to the validation platform were implemented such as the use of analytic directional derivatives, model-based interface control documents and continuous integration.

In 2018, a variant of the BLI-WingFan without BLI-annular fan was selected as the second configuration for the TRADE project. The BLI-annular fan was removed within the TRADE project due to the heavy dependency on external aerodynamic effects, which are beyond the expertise of the TRADE partners. The inclusion and assessment of these effects is delivered by ADEC. This variant of the BLI-WingFan configuration ("TRADE configuration 2") is beyond the scope of this paper.

A description of the models and the validation platform is provided in section IV.

D. Overall Aircraft Design of Hybrid Electric Configuration in this paper

The "Boosted Turbofan" is analyzed in the scope of the studies presented in this paper. Furthermore, two reference configurations with conventional propulsion are included. An overview of all configurations is given in Fig. 2.

The conventional reference configuration represents a typical short range aircraft for entry into service in 1990. The reference configuration shows the impact of the technology assumptions of ADEC as well as of TRADE for EIS2035 considering the same design mission requirements as the conventional reference. The "Boosted Turbofan" concept incorporates a parallel hybrid powertrain and is sized for a short range mission of 2500 NM. The power provided by batteries enables to relax the off-design requirements for the gas turbines making them more efficient at cruise conditions [20].
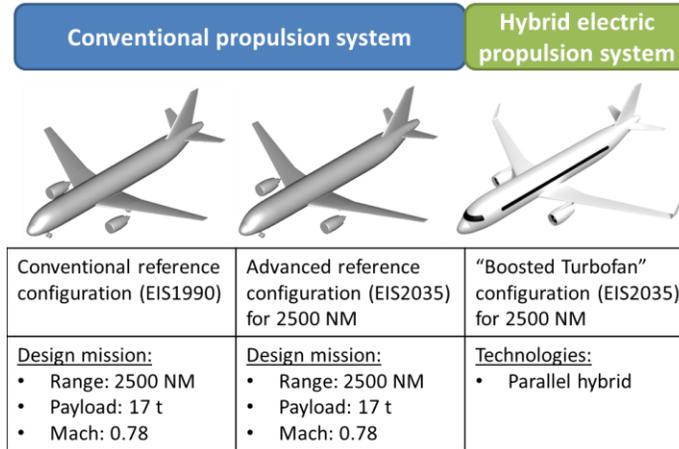
Conventional propulsion system		Hybrid electric propulsion system
Conventional reference configuration (EIS1990)	Advanced reference configuration (EIS2035) for 2500 NM	"Boosted Turbofan" configuration (EIS2035) for 2500 NM
Design mission: • Range: 2500 NM • Payload: 17 t • Mach: 0.78	Design mission: • Range: 2500 NM • Payload: 17 t • Mach: 0.78	Technologies: • Parallel hybrid

Fig. 2 Overview of aircraft configurations considered

For the aircraft design studies the following approach is used: The data of the conventional reference configuration of the paper [15] is used. This configuration is utilized to evaluate the reference configuration and to determine the impact of the assumed technologies at aircraft level without hybrid electric powertrain. It has to be mentioned that advanced airframe technologies, as e.g. hybrid laminar flow control, are not considered in these studies. Hence, this study outlines the impact of the hybrid electric powertrain and associated systems. Therefore, the reference configuration serves as a benchmark for the "Boosted Turbofan" configuration. Finally, overall aircraft design studies for the "Boosted Turbofan" configuration with respect to the degree of hybridization of the powertrain are performed. The main goal is to investigate the impact of the TRADE models of higher fidelity on OAD design studies. For clarification of the impact on ODA, results of the "Boosted Turbofan" configuration generated by the non-modified workflow are consulted. For the evaluation and comparison of the configurations, the block fuel as well as the block energy is used because it is related to emissions that are directly produced by the aircraft during a regular mission.

II.   Description of Sizing Workflow and Design Procedure

A detailed description of the OAD wokflow utilized by DLR prior to the integration of the TRADE-modules can be found in [15]. In this chapter, only a brief overview of this workflow limited to the capabilities required for the design of the conventional and "Boosted Turbofan" configurations is provided.

The OAD workflow is based on the proesses developed in the projects ATLAs [21] and FrEACs [22]and is extended for hybrid electric powertrains. It is integrated in the "Remote Component Environment" (RCE) of DLR utilizing the "Common Parametric Aircraft Configuration Schema" (CPACS) [23,24] as the data exchange format between the individual modules of the workflow.

In Fig. 3, an schematic overview of the process is given. It can be subdivided in four major parts. The first one, the "parameter study driver", is used for automated parameter variations, thus enabling automated parameter studies. I n the second part, the aircraft configuration to be analyzed is initialized. For this purpose, only empirical and semi-empirical methods are used. The third part, the "sizing loop", performs the iterative design and analysis process of the configuration until a convergence of the maximum take-off mass (MTOM) and operative empty mass (OEM) are reached. During this process, the powertrain is sized, the lift distribution is optimized, the masses and aerodynamic performance are estimated, the mission performance is calculated and the aircraft is resized according to the updated values. For the sizing loop, mainly semi-empirical and low-level physics based methods combined with surrogate models are utilized. Finally, the converged configuration is evaluated in the "post-processing" part. In the following, more details about the methods and tools are provided.
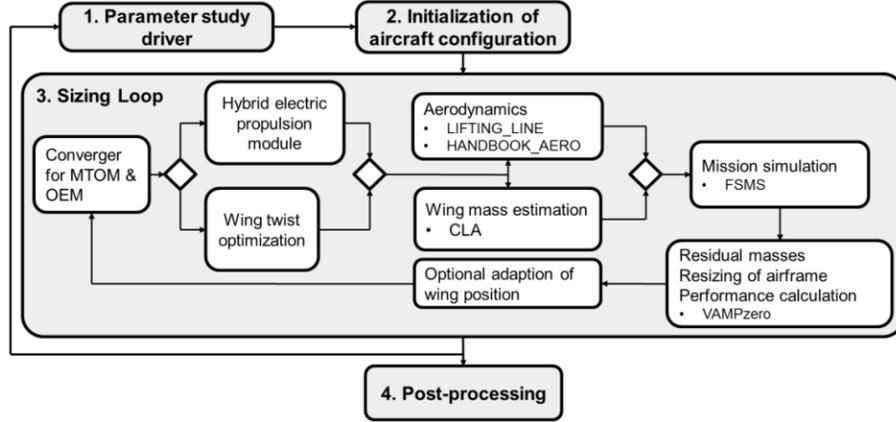
Fig. 3 Structure of workflow for sizing of hybrid electric aircraft [15]

A. Sizing of Hybrid Electric Powertrain and Calculation of Corresponding Masses

For the "Boosted Turbofan" the HEP-module performs the sizing of the fan, the gas turbine, the battery, the electric power train components, and the cooling system according to the thrust requirements and a selected degree of hybridization (DOH). It takes into account the thrust requirements and the prescribed, power based degree of hybridization. The HEP-module provides a combined engine map that is used by the mission analysis module. It also calculates the masses and the positions of the electrical components and the battery.
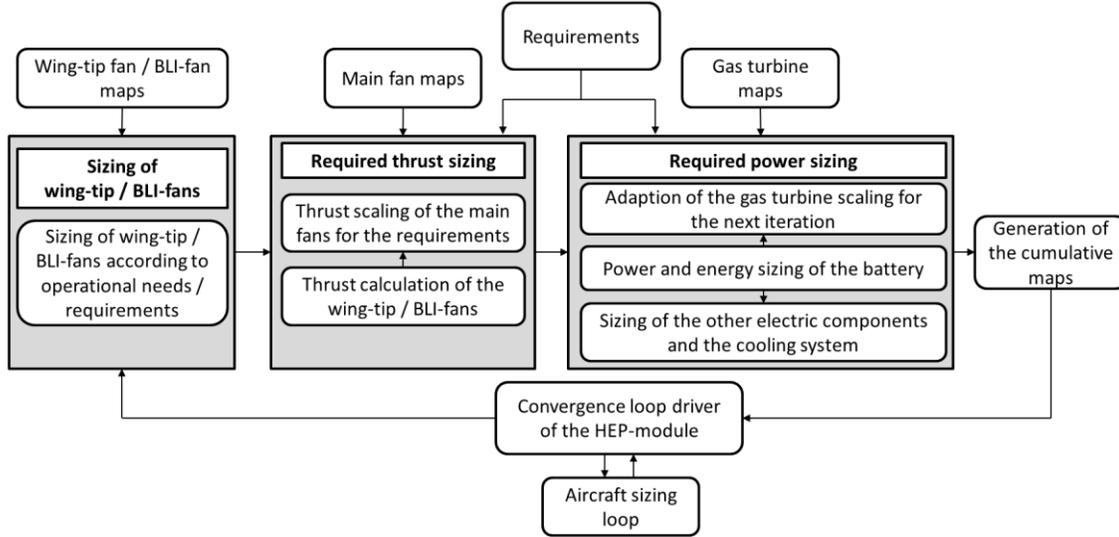

Fig. 4 Process of the "hybrid electric propulsion module" [15]

1. Description of sizing process for hybrid electric powertrain

In general, the component sizing consists of three main parts and is shown in Fig. 4. The HEP-module is developed for the sizing of series/parallel partial hybrid powertrains considering distributed propulsors and batteries. In this paper, only the aspects required for the design of the "Boosted Turbofan" configuration are presented. The main fans are sized according to the thrust requirements for take-off, second segment climb and top of climb, taking into account the residual thrust of the core engine. The battery sizing considers the power required by the propulsors and the power provided by the gas turbines. The powertrain is iteratively adapted until it meets the thrust requirements and the prescribed degree of hybridization. This power based degree of hybridization (DOH) is calculated as the maximum ratio of battery power and required total power in the critical power sizing point according to Eq. (1).

$$DOH = \left(\frac{P_{bat}}{P_{gas\ turbines} + P_{bat}} \right) \tag{1}$$

2. Thermodynamic modelling of engine components

Thermodynamically calculated maps that contain the performance parameters of the fans and the gas turbines for all relevant combinations of the altitude and the Mach number are used. During the sizing process, those maps are scaled linearly in order to meet the requirements.

3. Sizing o the system components

In Fig. 5, the parallel hybrid powertrain as it is used for the "Boosted Turbofan" configuration is shown. The powertrain consists of an electrified turbofan (ETF) that combines a classic turbofan engine with an electric machine on the low pressure shaft. A battery provides the electric power to support the gas turbine. Power electronics are used for regulating the electric machines. The layout is based on a DC distribution network. The cabling.is also considered w.r.t. mass and transmission loss. It is to be noted, that the cooling system is not shown. Nevertheless its contribution to the mass and the drag are taken into account.
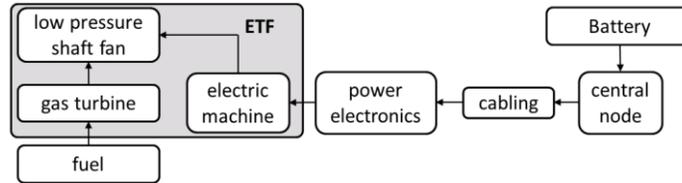

Fig. 5 General powertrain architecture

4. Battery model

The battery model estimates the technology level expected or the year 2035. The specific power and energy density are derived from [12]. In addition, a linear variation between power and energy cells as shown in Fig. 6 is introduced. This approach is based on the evaluation of published battery data and constitutes a first order approximation of a Ragone plot. For the OAD process, only the mass of the battery is considerd. The volume is thus not taken into account. The battery charge and discharge efficiency losses have been neglected.
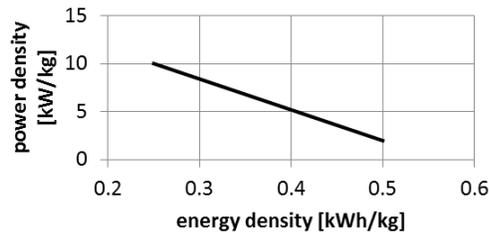

Fig. 6 Battery model

B. Disciplinary Methods in Aircraft Design Process

In this section, further disciplinary methods and tools used during the sizing loop are described. More details are provided in [15].

1. Calculation of aerodynamics

For the calculation of the aerodynamic polars that are required for the mission analysis, the DLR's vortex lattice tools "LIFTING_LINE" [53] and "HANDBOOK_AERO" are utilized. LIFTING_LINE is a vortex lattice cone and is there used to calculate the lift, the induced drag and the pitching moment of the aircraft. HANDBOOK_AERO utilizes semi-empirical methods to estimate the impact of visocus and wave drag.

2. Mass estimation for components not included in the hybrid electric powertrain

Different tools are utilized in the workflow to calculate the structural masses, the mass of the operational equipment, the furnishings, and the system masses that are not related to the hybrid electric powertrain. The wing mass is calculated by the Concept Loads Analysis (CLA) tool. It is based on reduced order models from aero-elastic analyses. Masses of the remaining components are calculated by the OAD-tool "VAMPzero" [54]. It utilizes semi-empirical methods provided by Raymer in [55] and Torenbeek in [26].

3. Mission simulation

DLR's "Fast and Simple Mission Simulation" (FSMS is used for the calculation of the mission performance. It provides the fuel consumption, the total energy demand, and the power levels required throughout the mission. The standard mission is subdivide into following segments: take-off, climb, cruise (assuming a continuous climb), descent, alternate mission, holding, and landing.

4. Calculation of remaining parameters

All the parameters that are not calculated by the aforementioned tools are estimated by the OAD-tool VAMPzero. This tool is based on semi-empirical methods and can be used as a stand-alone conceptual aircraft design code. It also can take into account higher-fidelity results from other tools as is the case in this workflow.

III. Description of TRADE Models and Validation Platform

The TRADE consortium developed a design environment which is suitable for the design of hybrid electric aircraft configurations and is capable to assess and optimize at sub-system as well as whole-aircraft level. However, the design platform was developed for a specific A320-like aircraft. As a topic manager, the DLR provided a CPACS file for a generic mid range aircraft configuration for 150 passengers with mission requirements corresponding to an A320. To capture effects of HEP on aircraft level in conceptual design stage the TRADE consortium developed physics-based models regarding the aircraft structure, gas turbine, electrical power system, thermal management and flight mission. In Fig. 7 the conceptual design platform of TRADE is shown. The advanced structural model is designed to quantify the impact of the installation of heavy equipment such as batteries or electrical machines on the sizing of the aircraft structure. Refined on-board system models are designed to capture design and performance trades in electric power systems, gas turbines, and thermal management.

These physics-based models and the design environment are described in the paper in detail. The emphasis is on the integration of the design platform into the DLR's RCE workflow and will replace the DLR's HEP module and the turbomachine performance estimates/maps as well as the mission and wing mass estimation tool of the DLR. Slightly shorter descriptions of the advanced structural model and mission model as well as of the validation platform will be given in the paper.
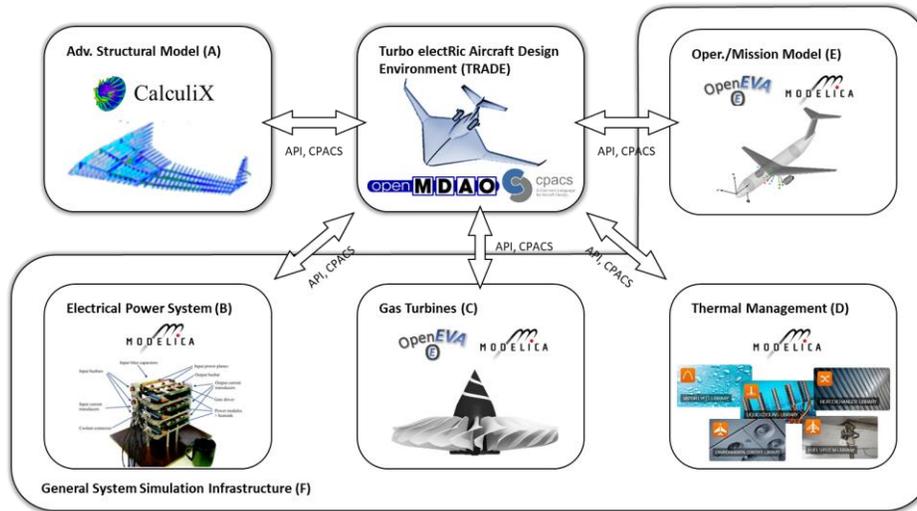

Fig. 7 TRADE conceptual design platform

A. Advanced Structural Model

Key objective of the advanced Structural Model (ASM) is to assess the structure weight impact of hybrid-electric propulsion concepts. As conventional tube-wing aircraft configurations with high aspect ratio wings (Fig. 2) are considered in this project a great portion of the weight estimation can be based on Torenbeek´s methods [26]. To cover the BTF as well as more advanced concepts (Fig. 8) the focus has to be put on wing weight estimation with special emphasis on the load relief resulting from hybrid-electric powertrain components which could be installed in and on the wing.

In 1992 Torenbeek demonstrated that a highly analytic structure beam model using aerodynamic loads based on single vortex circulation theory in span direction considering taper is accurate for slender wing weight estimation [27]. To overcome some analytic constraints of this approach and to flexibly cover load relief resulting from hybrid-electric powertrain components a numeric approach in span direction is introduced. Shear forces and bending moments are calculated at each wing rib station for each load case in order to size the load carrying wing box structure members (skin, web, ribs). Fig. 9 shows exemplary the distribution of the aerodynamic forces, the structure and fuel weight as well as the hybrid-electric powertrain component´s ("static installations") forces along the wing span located as single loads at and between ribs.
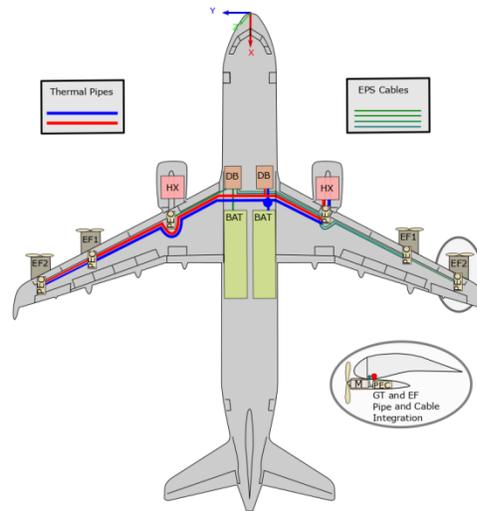
Fig. 8 Generic arrangement of possible powertrain components on a hybrid-electric aircraft
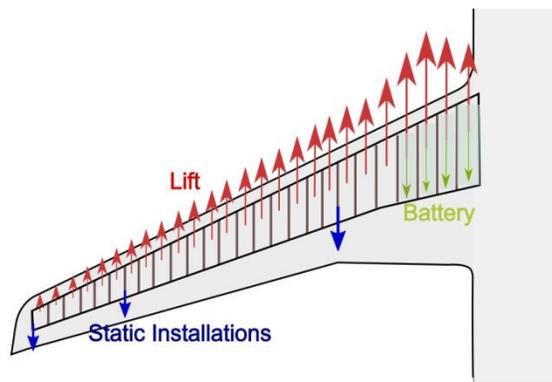

Fig. 9 Forces (view turned by 90 degrees) to be considered for shear force and bending moment calculation

For the weight estimation of secondary wing structure, leading and trailing edge devices the original approach by Torenbeek [27] is used. The weight of the fuselage is based on Torenbeek´s methods [26]. The weight of vertical tail plane and horizontal tail plane are calculated using normalized specific surface weights [26]. The required surface of the horizontal and vertical tail plane are based on simplified calculations for stability and controllability provided by the so called necessary "horizontal tail plane volume" and "vertical tail plane volume". For the latter one engine inoperative occurrence is considered. For future configurations – so beyond BTF – as shown in Fig. 8 this criteria has to be sharpened as electric power cross-feeding from the side of the operative gasturbine to electric propulsors on the other wing side may reduce the necessary size of the vertical tail plane to counteract reduced the yawing moment.

All necessary outer aircraft geometry data used in the module for the weight estimation are derived from the CPACS input file. Additional data e.g. for leading and trailing edge devices, their positions in span direction and in wing depth direction as well as rib distances, etc. are based on own statistic data of existing aircraft similar to the BTF configuration considered. For the wing aerodynamic profile a constant relative thickness in span direction is assumed. The structure materials provided in the CPACS file are conventional aluminum alloys which allow to use the methods presented above. This structure module also provides aircraft geometric data to other modules, especially to the Operative and Mission Module.

9

B. Electrical Power System

The Electrical Power System (EPS) includes three sub-models: the Electrical Machine (EM) model, the Power Electronics Converter (PEC) model and the Battery model. In the next three paragraphs the aforementioned models will be briefly described.

Electrical machine modelling

The machine topology selected within the project framework is a Permanent Magnet Synchronous Machine (PMSM). Indeed, the PMSM is well known for its greater power density (kW/kg) and efficiency compared to alternative topologies. Therefore, it is considered a good candidate for aerospace applications [56]. In order to further increase the machine power density and performance a Halbach magnetized surface PM array is installed on the rotor allowing to adopt a hollow rotor structure hence lighter compared to conventional rotors. Furthermore, the Halbach PM array leads to a less distorted sinusoidal air-gap flux density which reduces both torque ripple and iron losses for the machine [57].

The University of Nottingham recently developed an in-house design tool for EM modelling and designing [56]. The tool exploits a Genetic Algorithm (GA) to generate an optimized machine design once the specifications are provided. A multi-domain calculator which considers electromagnetic, thermal and mechanical performance, is included in the design tool in order to fully evaluate the machine designs. Both active and inactive machine mass are calculated in the tool since the latter can be as high as 34% of the total machine mass [58]. Hence, it has a remarkable influence in the total mass.

The EM model relies on in-built lookup tables, therefore a finite power range had to be considered. Indeed, in the case study examined the EM rated power spans from 200 to 2000 kW. The lower limit is defined as the minimum electrical power required by the on-board auxiliary systems while the upper limit is set in order to limit the maximum current flowing in the EM having fixed the voltage level of the electrical network and the machine insulation. Ten different EM designs are computed with the design tool considering a per-unit length. The required power can then be obtained by adjusting the machine length; as the power is proportional to the length [59]. Finally, the EM model provides the performance and loss calculation for six key operating points during the mission.

Power Electronic Converter modelling

For the "Boosted Turbofan" configuration, the power electronic converter (PEC) is required for converting DC power from the battery to the AC power for the electrical machine. The PEC allows the control of the frequency and voltage applied to the electrical machine [59] [60]. For HEP applications, high power density, high efficiency and high operating temperatures are desirable features for the PEC, which must also be suitable for high power applications. Emerging Wide Band Gap (WBG) semiconductor devices such as silicon carbide devices as compared to conventional Metal-Oxide Semiconductor Field Effect Transistors (MOSFET) and Insulated Gate Bipolar Transistors (IGBT) offer better switching and thermal capabilities, however they are not quite suited for high power applications [61]. The PEC model in this work is based on parameters for IGBT technology, but allows for future technologies.

A key requirement of the PEC modelling within this project is its interface with the other multidisciplinary subsystem models within the aircraft. The modelling methodology of the PEC is first established around the input and output parameter requirements of the PEC model with respect to the aircraft subsystem models. Further, a modular approach is adopted for the PEC design to enable multi-level configurations, allow for easier maintenance and redundancy as well as easier replacement of the modules by those with different or future technology specifications [61]. The PEC model is designed around 200 kW and 500 kW modules, each having its own sets of specifications that include specific power density (kW/kg), power density (kW/m3), maximum operating temperature, and efficiency. The thermal management of the PEC is modelled based on standard liquid cooled cold plates connected in parallel. The cooling system for the PEC is designed around the nominal flow rate, mass, volume and nominal thermal resistance of a standard cold plate and is a function of the mass flow rate given by the onboard thermal system model and the maximum power losses of the PEC modules.

The PEC model measures the power requirements of the electrical machine during the six flight stages, the mass flow rate, input pressure and temperature from the thermal system of the aircraft and then computes the required number and type of PEC modules as well as cold plates based on the aforementioned inputs and the specifications of the selected PEC modules. After accounting for power losses that are generated based on the efficiency characteristics of the PEC modules, the PEC model outputs its own power requirements for the six flight stages to the battery model, and the output temperature and pressure to the onboard thermal system model. Of note is that the maximum operating temperature of the PEC modules, used as design constraints, influence the size of the PEC cooling system and in turn the size of the onboard thermal system model. The mass and volume of the PEC, including the PEC modules, cooling system in addition to the controller and control cables, is generated as an output to the structural model of the aircraft.
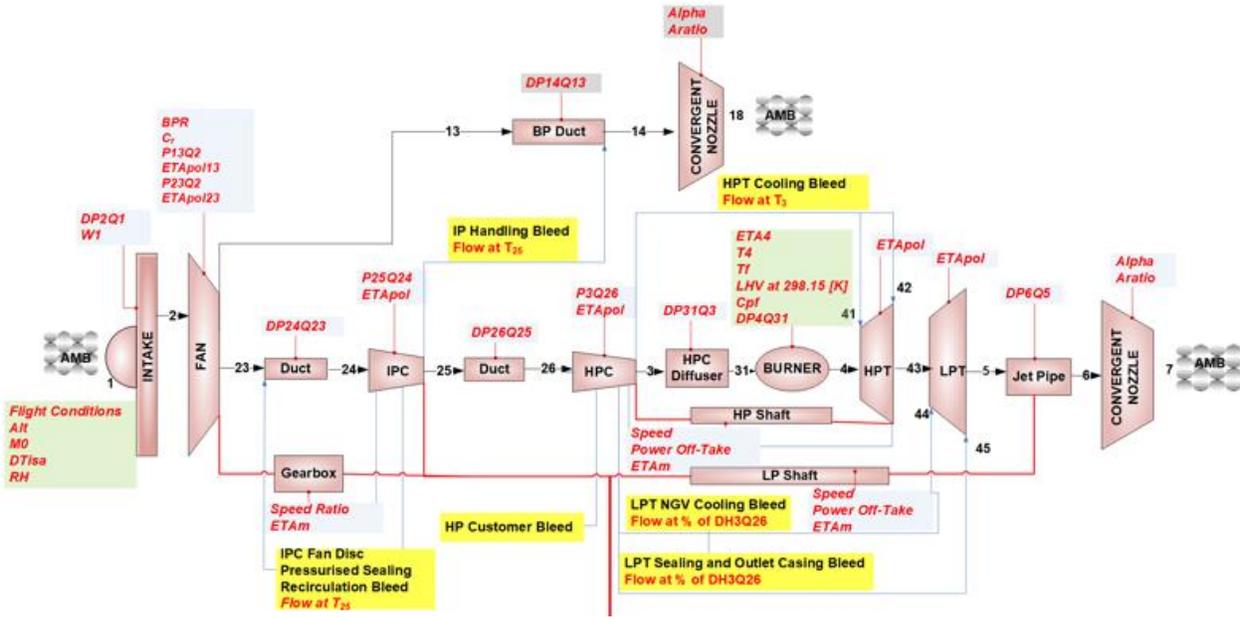
Battery modelling

Battery technology is a key driver for the advancement of hybrid electric aircraft. The technology and performance of the battery are highly dependent on the material used [62]. Each technology has its advantages and may be more suitable for one application rather than another. Lithium ion batteries, with their relatively high specific energy density, power density, life cycle and reliability, are a good candidate for HEP aircraft and have been used for the battery modelling in this work [63]. The thermal management of the battery is another key aspect to consider during design, as batteries perform optimally within a narrow temperature range which may vary between 25°C and 40°C [64]. Batteries can be air cooled or liquid cooled. The battery model in this work considers liquid cooling based on standard cold plate technology. Depending on the flight scenarios considered during design assessments, the battery may need to have high energy density and/or high power density. The battery modelling approach allows for both high energy and high power demands.

The battery is modelled in three main parts. The first level, namely the 'battery module' component, determines the power and energy ratings of the battery modules from the power requirements of the PEC model, the flight durations from the mission model over the six flight stages and accounts for the minimum and reserve state of charge of the battery. It computes and generates the mass, volume and power losses of the battery modules by employing datasheet based power density, energy density and efficiency characteristics of a Lithium ion battery. The 'cooling model' component of the battery receives the power losses during various flight stages from the battery module component and the mass flow rate from the onboard thermal system model, which it uses to size the thermal subsystem of the battery. The temperature range within which the battery has to be operated in is used as a constraint variable and plays a key role in the sizing of the battery cooling system and also the onboard thermal system. The size of the battery, which includes the battery modules and its cooling system with consideration to the required controller, are produced as an output to the structural model of the aircraft. The output temperature and pressure generated by the battery model are passed on to the onboard thermal system model.

C. Gas Turbine

The key capability of the gas turbine model is to perform gas turbine design for the selected configurations in TRADE platform. This includes the gas turbine performance prediction, sizing and weight estimation. For performance prediction, a multidisciplinary simulation tool for energy system, in particularly for aircraft propulsion system, EVA (EnVironment Assessment) [29- 31] is utilized. This tool has previously been developed/applied in future aero engine conceptual design within E.U. funded projects (VITAL, NEWAC, DREAM, TRADE). As illustrated in Fig. 10, it covers a wide range of disciplines, including engine performance and mechanical design, aircraft design and performance, emissions, noise prediction and environmental impact, as well as production, maintenance and direct operating costs. For the current TRADE framework, only the engine performance and aircraft performance modules are integrated. Representative work performed includes geared turbofan and open rotor [32], intercooled and intercooled recuperated turbofan [33- 36] and emissions analysis [37].

Fig. 10   Gas turbine performance prediction tool - EVA [29]

Fig. 11   Performance model schematic of a geared turbofan

The basic gas turbine architecture selected in TRADE is a two-and-half shafts geared turbofan. Performance model schematic for this engine is shown in Fig. 11. Hot-day (ISA+10) top of climb is used as the aerodynamic design point of the gas turbine, while key off-design points, such as hot-day (ISA+15) take-off, cruise, descent, ICAO LTO cycle points are included in the modelling. Engine performance table for a predefined mission is also created for every gas turbine design. Separate characteristics are used for the fan core and fan bypass, as well as the compressors and turbines. Generic matching procedure reported in [38] is adopted for off-design matching. Variations of the caloric properties in the ideal gas assumption are included in the model, including the effects of temperature, fuel air ratio and water to air ratio etc. Pressure losses in various components, including the intake, ducts and nozzles, are defined as a fraction of the components' inlet total pressure and can be modified for a specific design. A fixed mechanical efficiency is assumed for all the engine shafts, while the power off-take can be extracted from any of these shafts. For the boosted geared turbofan concept studied in TRADE, the electrical power input from the electrical power system is added to the low pressure shaft of the main engine. Substantial effects in the gas turbine off-design performance of varying power input boosting the low pressure shaft has been studied using the TRADE platform [39]. Handling bleeds for compressors are inputs for all operating points, as it could be critical for most operations with high power boosting. Bidirectional power transmission between the gas turbine and the electrical power system is implemented for an improved design platform suited for a second aircraft concept with wing tip fans in TRADE, for which the extracted power can be utilized for driving the wing tip mounted ducted fans or charging the battery. Cooling flows for both turbines are given as inputs while the average external surface blade metal temperature is computed using a simplified approach presented in [40]. Nozzle variability is included in the improved design platform to enhance the operability of the electric driven ducted fans with a wider range of power input. A study of the variable geometry for low pressure ratio fans using the same simulation tool can be found in [41]. Typical gas turbine design parameters, such as bypass ratio, pressure ratios and turbine inlet temperature, as well as the components technology level assumptions are given as explicit inputs to the model. A number of key performance parameters, such specific thrust, specific fuel consumption, turbine metal temperatures and jet velocity ratio are direct outputs for optimization. In addition, a limit of the ground clearance, which is the distance from the lowest point of the engine to the ground, is considered as a constraint. The engine size effect in the high pressure combustor (HPC) efficiency for high overall pressure ratio (OPR) and high specific thrust conditions is implemented in the model for configuration 2 using the correlation presented in [33]. For the "Boosted Turbofan" configuration, mainly the power transmitted between the gas turbine and the motor and their speed connection, are exchanged through interfaces between the gas turbine and the motor. A gearbox with associated losses can be defined if a speed ratio is needed to maximize the motor efficiency. The electric fans considered in the second configuration introduced more design variables to the model, i.e. fan pressure ratio, power ratio between the power supplied from the battery and the main engine, and rotational speed etc.

For the first configuration, the gas turbine sizing and weight estimation is largely built on empirical correlations and methods presented in [42- 45], as well as the calibration of public domain information available for the existing geared engine [46]. Calculations of the major engine core components, the fan, compressors, turbines, ducts, burner, shafts, mixer, and nozzles, are replaced by a weight estimation tool developed by Modelon within the Jet Propulsion Library (JPL) at the later stage of TRADE, based on Weight Analysis of Turbine Engines (WATE) developed by NASA [47]. In the end, the performance prediction tool and the weight estimation tool, are wired through Modelica and packed into one Functional Mock-up unit (FMU) using Dymola.

D. Thermal Management System

The thermal management system (TMS) is necessary to pull away the heat generated due to the in-efficiencies in the components of the hybrid-electric propulsion system. The TMS benefits in regulating the operating temperature in the electrical components for achieving a better performance. Electrical motor, inverter, battery, gearbox, secondary gearbox and bearings are the six heat load sources, being considered to be cooled in this configuration. A re-circulating serial loop liquid coolant system is designed for transporting the heat from the sources those are connected through pipe lines. Jet oil is considered as the coolant for the configuration. The Interfaces between the heat sources are established with the coolant state and the mass flow rate. A centralized liquid-to-air heat exchanger is used as the primary means for rejecting the heat to the by pass air in the gas turbine. Other components of the TMS are: the coolant reservoir and the pump. The components are built as physical models in Modelon Liquid Cooling Library and Heat Exchanger Library.using the Modelica language. A micro-channel based tube and fin cross flow arrangement (mixed-air, unmixed-liquid) multiple pass heat exchanger design is considered. The heat transfer analysis is made with prediction of the thermal resistance and the effectiveness is calculated based on the ε-NTU approach. In the pipe line model, heat transfer to the environment is neglected and the pressure loss is computed from a given constant diameter and variable length. The length is a direct result from the heat load positioning with an optional constant length multiplier.

The thermal management system is designed with an objective of minimizing the weight of the thermal system, which includes weight of the heat exchanger, pipe lines, coolant reservoir and the liquid. Two of the dimensions in the heat exchanger are considered as the design variable for the optimization envelope, while the third dimension is kept constant. The by-pass air states and coolant maximum temperature are considered as the boundary condition for the heat exchanger design. The pressure drop correlations are used in order to compute the pressure drop in the coolant, based on which the required pump head is computed. The coolant flow rate as in controller set point is another design variable for the system, affected from the heat load and the desired operating temperature in the electrical components. Under the scenario, maximum operating temperature in the electrical components is set up as constraints in order to regulate the coolant flow in the system. The instrument package from Modelica is used to establish the design variables, in-equality constraints and the objective for the optimization platform.

E. Operational and Mission Model

The mission model in the TRADE platform is essentially the aircraft performance module inside EVA. Specific revisions are made to fit the model into the hybrid aircraft design environment. As the final carrier of all the sub-systems designs, the key capability of the mission model is to define the flight profile trajectory for the selected hybrid aircraft configuration. With the engine performance data generated from the gas turbine model and the aircraft weight information produced by all the other sub-systems, the mission model could predict the block fuel for the designed aircraft with a given set of payload-range requirements. Fuel burned is calculated for the entire flight mission including reserves as illustrated in Figure 4. Since the aircraft aerodynamics is out of the TRADE scope, the aerodynamic performance data of an A320 type aircraft is used. The aircraft aerodynamics are modeled according to [48, 49], and aircraft performance modelling is based on [48, 50]. The aircraft drag polar is predicted at component level from the aircraft components geometry. High lift device settings are activated for the take-off and approach phases. Take-off field length calculation is performed for all engines operating and one engine inoperative conditions up to 1500 feet. A step-up cruise procedure is used to select the optimum cruise altitude for the pre-defined mission with fixed cruise Mach number.
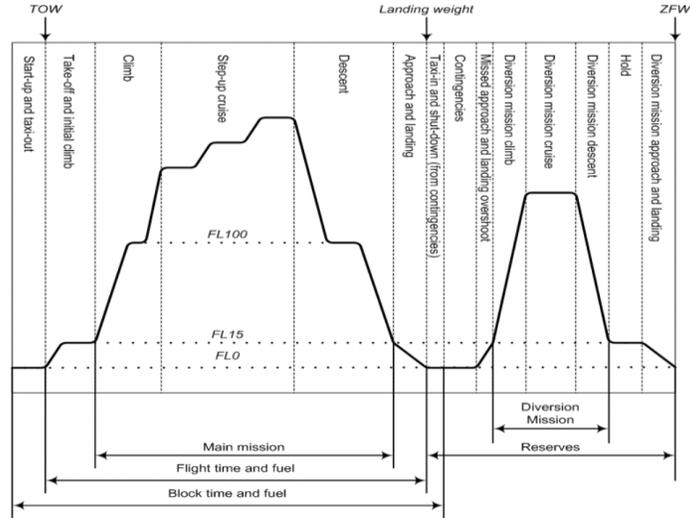
Fig. 12   Flight profile illustration

To be able to conduct detailed hybridization study, e.g. electrical power management at every mission segment, the mission model needs to work closely with the propulsion system models. Within the current TRADE platform, all the propulsion units are modelled in the gas turbine model. Hence, the gas turbine model is responsible to perform hundreds of operating points representing the flight profile with the capability of defining different hybridization for every mission segment. Hybridization of the diversion mission can be also defined independently. This could be used for interesting studies such as battery in-flight charging at the later stage of the mission and possible reduction in aircraft landing weight through charging the battery, etc.

F. Simulation and Optimisation Design Platform

A validation platform was implemented for two reasons. First, the validation platform served for quality assurance on the models delivered to project partners such as DLR. For this, the validation platform provided an integration platform to mock-up a range of high-level computation problems, it allowed stake holders to check model interface compliance and to test basic functionality, and it also showed that relevant computational problems can be solved successfully. Second, the validation platform was used for the analysis of integrated hybrid electric aircraft primary power systems provided to the project partners such as DLR. See [18] and [19] for example of such results.

A range of technical requirements resulted from the programming and modeling languages used for the implementation of sub-system models. Several models are system models in lumped or one-dimensional parameters (such as electrical power system). For all of them, the Modelica modeling language was used. The structural sizing model however requires field simulation using finite elements, and thus requires a different modeling formalism. It was therefore decided to implement the validation platform within the powerful yet user-friendly programming language Python. To protect intellectual property, system models were exchanged in compiled format via the Functional Mockup Interface ("pyFMI"). A generic and open source interface from Python to FMI and vice versa is already available. The structural model had to be interfaced using the Python language. The validation platform was then implemented in Python as a lean layer on top of OpenMDAO [52]. This lean layer consisted of Component and Group implementations leveraging the FMI interface, a model-based (instead of document-based) Interface Control Document, and continuous integration functionality [51] running simulation unit and integration tests automatically. See [18] for a more detailed overview of the implementation and a class diagram of the classes implemented on top of OpenMDAO.

IV.   Description of Simulation Workflow with Integrated TRADE Design Platform

In this section of the paper the integration of TRADE design platform into the DLR's RCE workflow is outlined. In Fig. 3 the DLR's RCE original workflow for sizing of hybrid electric aircraft is shown. In section III the TRADE models and validation platform are described and in Fig. 7 the modules within the design platform are shown. Here, the advanced structural model, the electric power system model, the gas turbine model, the thermal management system model, the operational and mission model and the simulation and optimization design platform is outlined.

Since the TRADE design platform consists of the aforementioned models for the investigation of the "Boosted Turbofan" but not to drive overall aircraft studies with resizing the airframe, the integration of the design platform into the workflow by replacing several modules of DLR is the next reasonable step. Therefore, the hybrid electric propulsion module, the aerodynamics, the wing mass estimation and the mission model are replaced. The wing twist optimization and the module to calculate the residual masses, resizing the airframe and to do performance calculation remain unchanged. The design platform is implemented as an entire tool into the RCE chain right after the twist optimization. Also python based tools are used to set the interface between the design platform and the remaining tools in RCE. They are designed to read the CPACS data and pass on the information to the design platform to write the results of the design platform back to the CPACS data. Since models of higher fidelity are used in the modified workflow the computation time for the optimization and the overall aircraft design is significantly increased.

While the airframe and wing geometries are resized during the modified workflow and the operational and mission model estimates the lift and drag with fixed values for an A320-like aircraft, the effects of the improved wing aerodynamic due to a higher aspect ratio is not captured.

To get a better comparability of the modified workflow to the original DLR's RCE workflow, the assumptions regarding the battery technology, system voltage for the electrical power system of the hybrid powertrain and the material used for the aircraft airframe and wing is kept the same. Since this value has a great impact on the hybridization of an aircraft. EIS2035. Therefore, the results for the "Boosted Turbofan" according to [15] are not suitable for a comparison since the technology assumptions are different. Furthermore, the modelling of the electrical motor and power electronic converter with respect to the power density and efficiencies is done differently. In TRADE the power density as well as efficiency is adjusted with respect to the required electrical power. This means, if the electrical system getting larger the power density and efficiency increases. In ADEC a fixed value for the power density and efficiency is used. To have a slightly better comparability the mean value of the minimum and maximum values used in TRADE are consulted.

In ADEC, the estimation of the wing mass is done with the tool Concept Loads Analysis (CLA). This tool is based on reduced order models from aero-elastic analyses for different wing configurations. In TRADE, empirical methods as mentioned in section IV A are used. This should lead to higher wing masses compared to ADEC.

Another aspect to be mentioned is that due to difficulties regarding convergence for the redesign of the gas turbine without and with hybridization, only a fixed gas turbine is used for the studies. Even if the gas turbine design and off-design points are moved towards critical operating points and therefore violates the constraints, the gas turbine and mission model estimates the relevant values. This assumption might have a huge impact on the evaluation of the block fuel because the gas turbine will not be designed for the specific hybridized case. But further studies will be done in the future to consider a gas turbine redesign. This will be done by using an improved design platform within the DLR's RCE workflow, increasing the design variables and adjusting the optimizer in openMDAO. Therefore, this work is still an ongoing process. Furthermore, in ADEC the gas turbine design is based on a linear scaling of the respective gas turbine map according to the degree of hybridization. This leads to a potential better gas turbine in cruise flight and a lighter engine in the DLR's original RCE workflow.

To evaluate and compare the results of the two different workflows, it is necessary to introduce the degree of electric energy (DOEE). It is calculated as the maximum ratio of battery energy and required total energy for the block mission according to Eq. (2). Note that the reserve state of charge of battery is set to 20% for both workflows. Therefore, the fuel of the diversion mission and the reserve energy is not considered. The effect of battery charging in specific flight phases is neglected.

$$DOEE = \left(\frac{E_{bat,blcok}}{E_{fuel,block} + E_{bat,block}} \right) \tag{2}$$

V. Description of Configuration in the Scope Of this Work

The "Boosted Turbofan" configuration for a design mission of 2500 NM is analyzed in the scope of the studies presented in this paper. The reference aircraft are used as a benchmark. But since the modified workflow is yet not evaluated the comparison serves only to get trends. The conventional reference configuration was built with the same original workflow as used in [15]. The DLR's RCE workflow with the integrated TRADE design platform is used for the reference and the "Boosted Turbofan" configuration. Furthermore, results of the original DLR's RCE workflow are consulted. Here, also a reference and a "Boosted Turbofan" configuration are considered. Due to the different assumptions of those workflows a head-to-head comparison might be not suitable. However, to illustrate the differences of the configurations and workflows it should be sufficient. Note that a calibration of the sizing process with the CSR-01 aircraft from the publically accessible "Central Reference Aircraft Data System" CeRAS

[14] is not done for the modified workflow. An overview of the configurations is shown in Fig. 2. The configurations are described in detail hereafter.

Table 1   Description of design missions

Mission	Range	Payload	Mach cruise	Alternate range	Loiter duration
1	2500 NM	17.0 t	0.78	200 NM	30 min

A. Conventional reference configurations

The conventional reference configuration of the paper [15] is used. This configuration was sized within the original DLR's RCE workflow. The CSR-01 which represents an Airbus A320-like aircraft with the technology level for entry into service in 1990 was consulted to validate and calibrate the original workflow. In Table 2, the reference data of the calculated conventional reference configuration is shown. Further information is given in [15].

Table 2   Conventional reference configuration [15]

Parameter	Unit	Conventional reference configuration
MTOM	[t]	77.1
OEM	[t]	42.0
wing area	[m²]	122.5
wing aspect ratio	[-]	9.5
mission fuel	[t]	18.06
block fuel	[t]	14.24

B. Advanced reference configuration for Design Range of 2500 NM and 17 t of Payload

The reference configurations in the scope of this workflow are based on a conventional airframe layout. They are equipped with turbofan engines and are sized under consideration of the same requirements and constraints as the "Boosted Turbofan" configuration. One design mission is taken into account. Consequently, for the design mission a dedicated reference configuration is provided for each workflow. They serve as a benchmark.

For these configurations, the same design mission as for the conventional reference configuration is applied. The results show the impact of the technology assumptions. In Table 3, the corresponding data is summarized and a comparison to the conventional reference configuration from section A is included. Here, the main parameters and the comparison of the two reference configurations to the conventional reference are shown.

In case of the reference configuration of the original workflow, the reduced specific fuel consumption of the turbofan engine and a resized airframe lead to a significant reduction in the block fuel mass of 23.4%. The MTOM is reduced by 2.0% which leads to a reduced reference area of the wing. This enables an increase in aspect ratio by 13.9% under consideration of the typical wing span constraint of 36 m. Aspects that are associated with changes in the wing design resulting in problems for the integration of the landing gear due to the combination of a high aspect ratio and a constant taper ratio of the wing are according to [15] neglected in the scope of this work. It is assumed that these problems do not affect the influence of the hybrid electric propulsion notably.

In case of the reference configuration of the modified workflow, the reduced specific fuel consumption of the turbofan engine lead to a significant reduction of the block fuel mass of 20.8%. The MTOM is increased by 2.7% which leads to an increased reference wing area. The aspect ratio is increased by 7.7% under consideration of the typical wing span constraint of 36 m.

Comparing the two reference configurations with each other, it is noticeable that the MTOM and the OEW differs by 4.7% and 8.9%, respectively. According to Table 3, the wing mass is strongly affected by the empirical methods used in the structural model of TRADE. Here, the wing mass of the TRADE configuration is increased by 42.5% compared to the conventional reference and by 38.4% compared to the other reference configuration. Also the combined mass of the furnishing and fuselage is slightly increased by 5.5%. Furthermore, the estimation of the individual system masses such as the auxiliary power unit, the air conditioning, the flight controls and other systems is done empirically in the original workflow as well as in the TRADE models. In the original workflow these masses are calculated by the OAD-tool "VAMPzero" [54] which utilizes semi-empirical methods provided by Raymer in [55] and Torenbeek in [26]. The advanced structural model of the TRADE consortium is based on Torenbeek´s

16

methods [26]. Therefore, here slightly different methods are used and depends on the technology factor used. This also leads to a mass penalty in case of the TRADE configuration and has an impact on the overall aircraft design. For further studies the impact of the system masses and structural masses should be removed to get a better comparability between both workflows.

Table 3: Reference configuration for 2500NM and 17t of payload

Parameter	Unit	Conventional reference configuration	Reference configuration for 2500NM, TRADE	Reference configuration for 2500NM, ADEC	TRADE Deviation	ADEC Deviation
MTOM	[t]	77.1	79.2	75.5	2.7%	-2.0%
OEM	[t]	42.0	48.2	44.4	14.7%	5.8%
wing reference area	[m²]	122.5	126.9	120.1	3.6%	-2.0%
wing aspect ratio	[-]	9.5	10.2	10.8	7.7%	13.9%
mission loaded fuel	[t]	18.06	14.0	14.1	-22.6%	-21.9%
block fuel	[t]	14.24	11.3	10.9	-20.8%	-23.4%
wing mass	[t]	8.2	11.6	8.5	42.5%	4.1%
fuselage mass	[t]	9.0	6.5	9.0	-27.3%	0.0%
furnishing mass	[t]	3.0	6.1	3.0	103.7%	0.0%
fuselage and furnishing mass	[t]	12.0	12.7	12.0	5.5%	0.0%
engine total mass	[t]	7.7	9.0	9.5	16.8%	23.6%

C. "Boosted turbofan" configuration for Design Range of 2500 NM and 17 t of Payload

For the "Boosted Turbofan" configuration, studies regarding the degree of hybridization or degree of electric energy and the wing aspect ratio are carried out with the DLR's RCE workflow with and without the TRADE design platform integrated. The consulted design mission is described in Table 1. The "Boosted Turbofan" incorporates a parallel hybrid powertrain (Fig. 5) with an electric motor connected to the fan shaft and electric energy stored in batteries. Since the electric motor at the fan mainly serve for assisting the gas turbines in off-design regions, this powertrain enables a more flexible sizing of gas turbines increasing their efficiency in cruise condition. Also, electrical energy can substitute fuel at costs of higher battery mass and the airframe of these configurations is not notably impacted by the HEP system. Hence, it is a reasonable step towards aircraft hybridization due to lower risk to development. To reduce the effects of the different technology assumptions of the workflows, as far as possible most of these parameters are set equal. As mentioned in section IV, the gas turbine is not redesigned during the studies because difficulties regarding convergence occurred. However, further studies with a gas turbine redesign will be done in the future.

Design space surveys are performed to evaluate the potential of the "Boosted Turbofan" configuration at the design range of 2500 NM considering the payload of 17 t. Furthermore, these design space surveys are considered to compare the methods of the original and modified workflow.

In Fig. 13, the relative deviations in MTOM, OEW, block fuel and block energy as well as the wing mass and total mass of the battery, electric and cooling system to the advanced reference for 2500 NM of the original workflow are shown. The wing span constraint of 36 m is not consulted because a comparison of the different workflows is done. The maximum benefit in fuel consumption and energy demand for a "Boosted Turbofan" is approximately 4% and is overserved for an aspect ratio of 13 and a DOEE of 0.0036. The main impact is the improved aerodynamic performance of the wing due to a higher aspect ratio. However, a "Boosted Turbofan" has a positive impact on the block fuel and energy demand for low hybridization even if masses for the HEP system are added. The additional mass of the electric propulsion system, the cooling system, and the battery is about 2.1 t and the MTOM is increased by 4% compared to the reference configuration.
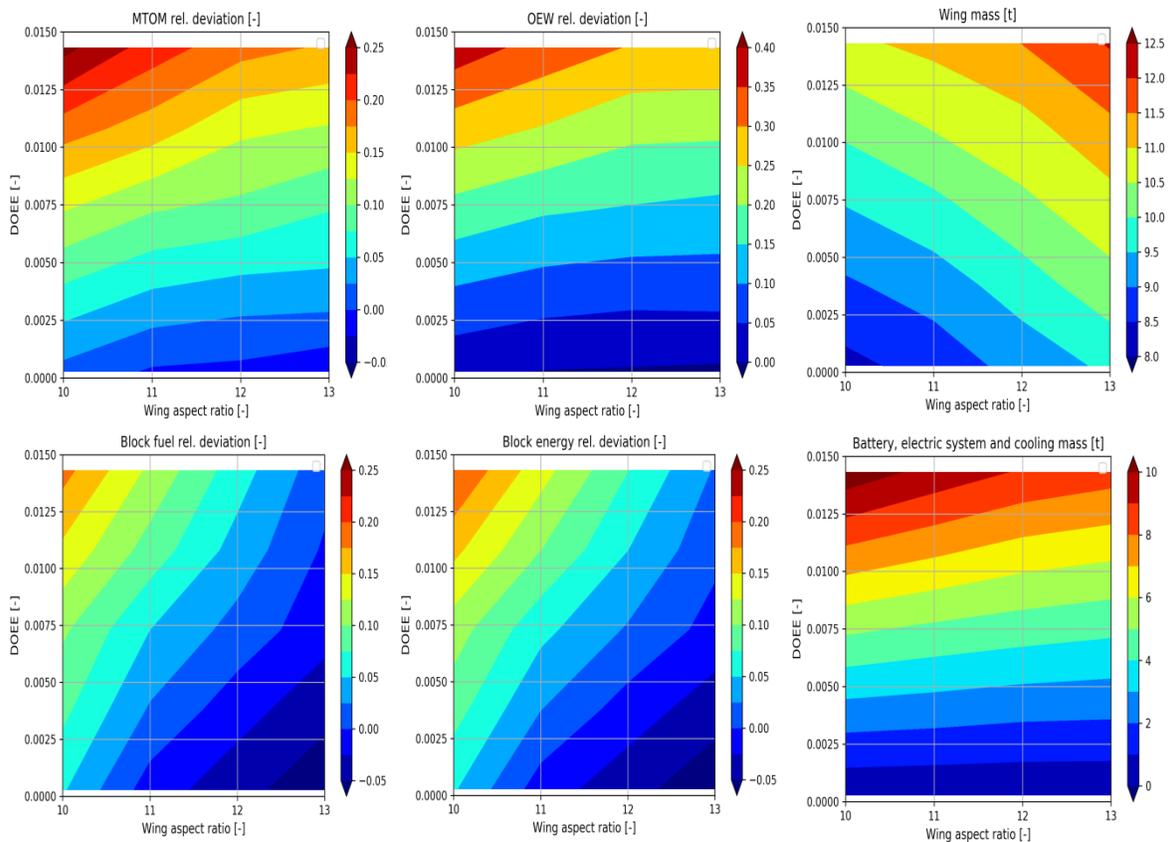
Fig. 13   Variation of degree of electric energy and aspect ratio for 2500 NM mission: impact on key parameters of original workflow (MTOM, OEW, wing mass, block fuel, block energy and the total mass of the battery, the electric system and the cooling system)

In Fig. 14, , the relative deviations in MTOM, OEW, block fuel and block energy as well as the wing mass and total mass of the battery, electric and cooling system to the advanced reference for 2500 NM of the modified workflow are shown. Here, no reduction in block fuel or energy demand is identified

As already mentioned, the wing mass is strongly affected by the empirical methods used in the structural model of TRADE. Furthermore, the estimation of the individual system masses such as the auxiliary power unit, the air conditioning, the flight controls and other systems is done slightly differently. In the original workflow these masses are calculated by the OAD-tool "VAMPzero" [54] which utilizes semi-empirical methods provided by Raymer in [55] and Torenbeek in [26]. The advanced structural model of the TRADE consortium is based on Torenbeek´s methods [26]. Both effects lead to a mass penalty in case of the TRADE configuration and have an impact on the overall aircraft design. Higher initial masses are consulted during the optimization. This leads to an increase in the block energy and block fuel due to greater thrust requirements. The high dependency of the MTOM and the block fuel and energy demand is observed in Fig. 14.

According to Fig. 13 and Fig. 14, the total mass of the battery, the electric system and the cooling system of the modified workflow increase as fast as in the study of the original workflow. Here, the efficiency and the power density of the electrical system improve by the size of the electrical system in the TRADE models while in the ADEC HEP system these values are kept constant. Therefore, a higher hybridization results in lower mass growth.

Since a redesign of the gas turbine is not done yet within the modified workflow the gas turbine does not use the potential of a "Boosted Turbofan". Here, further studies with a redesign of the gas turbine must be carried out.
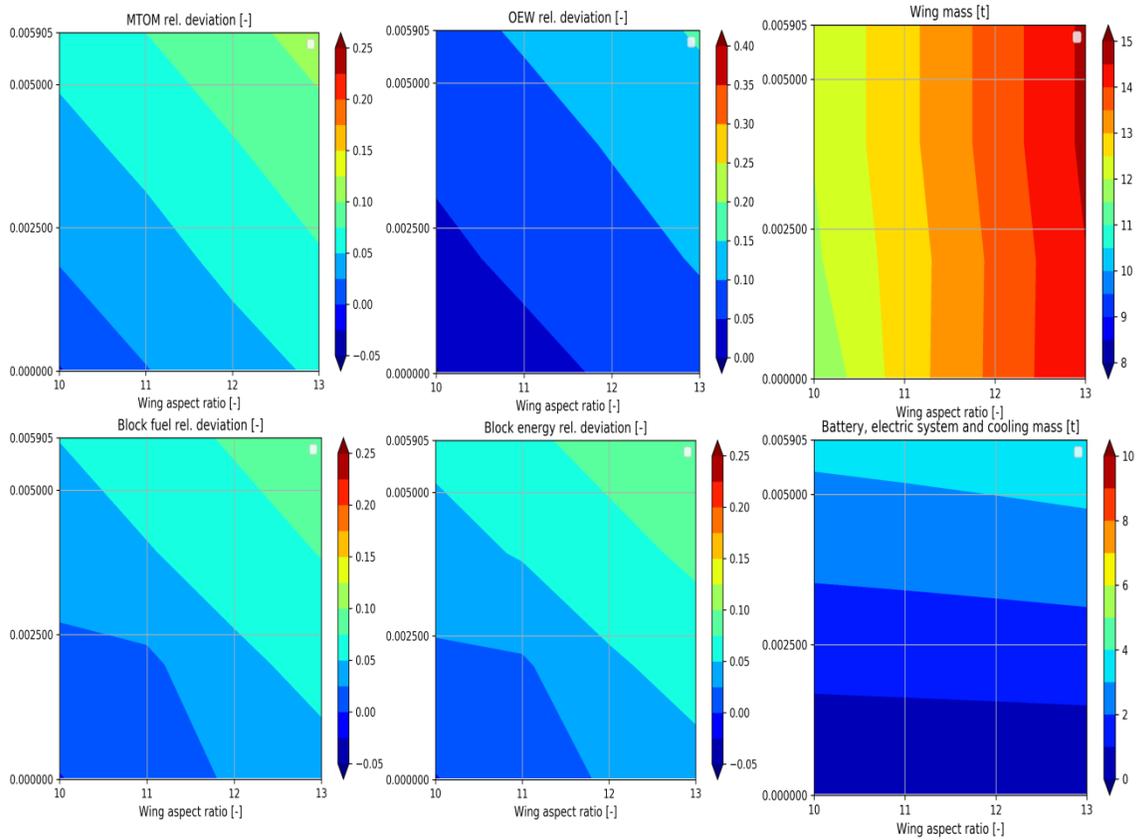
Fig. 14   Variation of degree of electric energy and aspect ratio for 2500 NM mission: impact on key parameters of modified workflow (MTOM, OEW, wing mass, block fuel, block energy and the total mass of the battery, the electric system and the cooling system)

VI.   Summary and Conclusion

In this paper, the activities of the German Aerospace Center (DLR) and the Turbo electRic Aircraft Design Environment (TRADE) consortium related to the conceptual design studies of the "Boosted Turbofan" configuration for a typical short range mission within the European project Clean Sky 2 are described. Furthermore, to understand the cooperation between the DLR and TRADE consortium a brief overview of the activities is given. For the analyses, two overall aircraft sizing workflow are utilized. First, the DLR's RCE workflow based on low level physics based and semi-empirical methods is used. Second, the DLR's RCE workflow with the simulation and optimization design platform developed by TRADE integrated is consulted. Here, the several models of the DLR are replaced by the TRADE models which incorporate methods of higher fidelity for the electrical power system, thermal management, mission and gas turbine.

A set of reference configurations is consulted and generated to evaluate the configuration and to provide a benchmark configuration with conventional propulsion system at the same technology level as the investigated "Boosted Turbofan" configuration. As a result, for the configurations incorporating advanced technologies the block fuel mass is reduced by 23.4% and 20.8% for the configuration generated by the original DLR' RCE workflow and modified workflow, respectively. The main drivers for this difference are the advanced engine technology. Airframe technologies that are not directly related to hybrid electric propulsion are not applied. Main focus is on the impact of the hybrid electric propulsion system. Moreover, the MTOM of the reference configuration is reduced by 2.7% and increased by 2.0% for the reference configuration of the original and modified workflow, respectively. In addition, the OEW of is increased by 5.8% and 14.7%. The main driver for this behavior is the estimation of the wing structure and system masses done by the structural model of the TRADE design platform.

The "Boosted Turbofan" configuration for a design mission of 2500 NM is investigated in the scope of this work. A design spaces study is conducted to identify the differences. The results show that in the scope of this work

the improved sizing point of gas turbines due to hybridization leads to a reduction in block fuel by about 4% for the configuration generated by the original workflow. However, since no redesign of the gas turbine is done by the modified workflow yet and mass penalties are added within the advanced structural model no reduction in block fuel is identified in the study of the modified workflow.

VII. Outlook

The presented work is focused on the investigation of a "Boosted Turbofan" configuration and the comparison of the models developed by DLR and the TRADE consortium. Based on these results, studies related to the "Boosted Turbofan" configuration can be conducted taking into account a redesign of the gas turbine within the modified workflow. The suggestions for the next steps, based on the lessons learned during these studies, are summarized in this section.

For the modified workflow with the models and the design platform of the TRADE consortium, it is necessary to achieve a redesign of the gas turbine to evaluate the "Boosted Turbofan" with an optimized gas turbine. Here, an improved design platform is currently being developed in TRADE which will extend the models and increase the performance of the design platform. The interface between the TRADE design platform and the RCE workflow must be improved to get a better handling regarding the required design variables, their start values and the hybridization of the design as well as off-design points. Here, additional design variables have to be taken into account to achieve a convergence for the gas turbine because the hybridization of the gas turbine leads to critical operating points. Thus, design variables regarding the handling bleed flow and a possible power-off take during taxi, descent and approach and landing flight phases to charge the battery must be considered. Furthermore, the cooling flow for the high pressure and low pressure turbine must be adjusted to achieve the constraints of the maximum turbine blade temperature. The consideration of all these aforementioned points leads to a large set of design variables and a more complex optimization problem. Here, to achieve a convergence for the gas turbine redesign and to reduce the computation time the openMDAO driver and solvers must be adjusted.

Furthermore, since the estimation of the wing mass within the TRADE design platform has a huge impact on the MTOM as well as on the OEW the wing estimation tool of the DLR should be used to eliminate this influence and to get a better comparability between both workflows. But the modified workflow has been yet not calibrated with the CeRAS configuration. Here, if the technologies assumptions are adjusted to map the CeRAS configuration for the reference configuration the strong impact of the wing mass estimation might vanish.

In addition, to compare only the impact of the different hybrid electric propulsion system models of the TRADE consortium and the DLR on the overall aircraft design, only the gas turbine, electric power system and thermal management system should be implemented into the DLR's RCE workflow. Therefore, the impact of the mission and structural models on the OAD will remain unchanged. However, an implementation of only the HEP system into the DLR's RCE workflow is complicated by the fact that for the DLR mission model a separate map that contains the specific fuel consumption and other values as functions of altitude, mach number and thrust settings are needed. The gas turbine model of the TRADE consortium calculates such maps, but not in the required level of detail. Nevertheless, the DLR and the Mälardalen University are currently in contact and discuss a possible cooperation.

Acknowledgments

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