Design Trade Studies for Turbo-electric Propulsive Fuselage Integration

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ABSTRACT

The present paper discusses intermediate results from activities performed within a European Commission funded collaborative research project CENTRELINE (“ConcEpt validatioN sTudy foR fuselage wakefillLIng propulsioN intEgration”). This project focuses on demonstrating the proof-of-concept for a ground-breaking approach to synergistic propulsion-airframe integration, the so-called Propulsive Fuselage Concept. Key feature of the investigated configuration is a turbo-electrically powered propulsor encircling the aft-fuselage, dedicated to the purpose of fuselage wake-filling. Apart from discussing the approach towards processing and integration of specialized, high-fidelity data in the overall system sizing framework, a series of aircraft-integrated parametric trade studies and sensitivity analyses are presented suitable for the derivation of important trends and characteristics. The optimisation of main power plant cooling air dependant on the fuselage fan operating strategy and improvement of the fuselage fan propulsor shaping show the potential for large efficiency gains.

Keywords: Boundary Layer Ingestion, Wake Filling, Propulsion System Integration, Propulsive Fuselage
## NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>APD</td>
<td>Aircraft Preliminary Design</td>
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<td>BHL</td>
<td>Bauhaus Luftfahrt e.V.</td>
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<td>BLI</td>
<td>Boundary Layer Ingestion</td>
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<td>CAD</td>
<td>Computer-aided design</td>
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<td>CAS</td>
<td>Calibrated Air Speed</td>
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<td>CENTRELINE</td>
<td>Concept validation study for fuselage wake-filling propulsion integration</td>
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<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>DES</td>
<td>Design</td>
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<td>EC</td>
<td>European Commission</td>
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<tr>
<td>FF</td>
<td>Fuselage Fan</td>
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<td>FPR</td>
<td>Fan Pressure Ratio of Fuselage Fan</td>
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<td>FUS</td>
<td>Fuselage</td>
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<td>GEN</td>
<td>Generator</td>
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<tr>
<td>GTF</td>
<td>Geared Turbo Fan</td>
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<td>HPT</td>
<td>High Pressure Turbine</td>
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<td>HTP</td>
<td>Horizontal Tail Plane</td>
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<tr>
<td>ISA</td>
<td>International Standard Atmosphere</td>
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<td>LHS</td>
<td>Latin Hypercube Sampling</td>
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<td>LPT</td>
<td>Low Pressure Turbine</td>
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<td>LTT</td>
<td>Low-Turbulence Tunnel</td>
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<td>MainPPS</td>
<td>Main Power Plant</td>
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<td>MTOW</td>
<td>Maximum Takeoff Weight</td>
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<td>MTU</td>
<td>MTU Aero Engines AG</td>
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<td>NPF</td>
<td>Net Propulsive Force</td>
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<td>NMI</td>
<td>Nautical Miles</td>
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<td>OEW</td>
<td>Operating Empty Weight</td>
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<td>OJF</td>
<td>Open Jet Facility</td>
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<td>PAX</td>
<td>Passengers</td>
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<td>PFC</td>
<td>Propulsive Fuselage Concept</td>
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<td>PPS</td>
<td>Propulsion System</td>
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<tr>
<td>PT</td>
<td>Power Turbine</td>
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<tr>
<td>RANS</td>
<td>Reynolds-Averaged Navier-Stokes</td>
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<tr>
<td>REQ</td>
<td>required</td>
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<tr>
<td>SAR</td>
<td>Specific Air Range</td>
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<td>SLS</td>
<td>Sea Level Static</td>
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<td>TLAR</td>
<td>Top Level Aircraft Requirement</td>
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<td>TU Delft</td>
<td>Technical University Delft</td>
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<tr>
<td>UCAM</td>
<td>University of Cambridge</td>
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<tr>
<td>VTP</td>
<td>Vertical Tail Plane</td>
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<td>WUT</td>
<td>Warsaw University of Technology</td>
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## Symbols

- $Alt$: Altitude
- $D_{PFC, bare}$: Drag of bare PFC configuration
- $d\Delta\text{ISA}$: ISA deviation
- $F$: Force
- $FN$: Net thrust
- $h$: Height
- $L$: Length
- $Ma$: Mach Number
- $N$: Rotation speed
- $p_2/p_0$: Intake freestream total pressure recovery ratio
- $P$: Power
Reducing the environmental impact of air travel is key in ensuring long-term sustainability of aviation. A series of challenging emission reduction targets have been declared by the European Commission (EC) through Flightpath 2050 [1] and the ACARE Strategic Research and Innovation Agenda [2], as well as by NASA with the N+ goals [3]. As generally acknowledged, reaching these ambitious target settings is not feasible by means of evolutionary improvement of the existing systems. The exploration of breakthrough technological advancements is necessary. In the field of propulsion and power, great potentials in terms of overall vehicular propulsive efficiency improvement may be expected from airframe wake-filling through the synergistic integration of Boundary Layer Ingesting (BLI) propulsor technology. Different from the thrust generation intrinsic to today’s propulsion systems installed in free stream air, the wake filling principle allows for reduced excess velocities in the propulsive jet, thereby yielding reduced kinetic energy losses in the aircraft wake, ultimately leading to propulsive power savings at the vehicular level.

The theoretical benefit of wake filling has been derived in numerous analytical and numerical studies using various levels of model fidelity, cf. e.g. [5], [6], [7] and [8]. Initial efforts to experimentally confirm these beneficial effects of wake ingestion have been conducted by means of low-speed wind tunnel test campaigns of generic bodies e.g. by ONERA [9], by TU Delft [10], and, by MIT for the D8 configuration (cf. [11] and [12]).

The EC-funded Horizon 2020 collaborative project CENTRELINE (“ConcEpt validatioN sTudy foR fusElage wake-filLIng propulsioN intEgration”) aims at demonstrating the proof of concept and performing an initial experimental validation for a particularly promising concept for airframe wake-filling, the so-called Propulsive Fuselage Concept (PFC) [4]. The concept features a turbo-electrically driven propulsive device integrated in the very aft-section of the fuselage (see Figure 1), dedicated to the purpose of fuselage wake-filling, i.e. the localized ingestion and re-energization of the viscosity-induced low-momentum wake flow of the wetted body via BLI.

An initial multidisciplinary investigation of the PFC focusing primarily on a purely gas turbine based drive train was conducted as part of the EC-funded FP7 research project “Distributed Propulsion and Ultra-high By-Pass Rotor Study at Aircraft Level” (DisPURSAL). Focusing on a medium-to-long range, wide-body application with 4800 nm design range, a nominal 9% fuel burn reduction was predicted relative to an equally advanced twin-engine reference aircraft [13]. Beyond a mechanically driven Fuselage Fan (FF) alternative options based on electrified drive train elements have been proposed [14-21] that ease on-board power transmission and help alleviating the aero-structural complexity associated with a mechanical fuselage propulsor drive.

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### 1.0 INTRODUCTION

**Engine inlet mass flow**

**HPC inlet mass flow**

**HPT cooling air mass flow**

**Fuel mass flow**
Constituted by the partners Airbus, ARTTIC, Bauhaus Luftfahrt e.V. (BHL) (Coordinator), Chalmers Tekniska Hogskola, MTU Aero Engines, Warsaw University of Technology (WUT), Siemens, Delft University of Technology (TU Delft) and the University of Cambridge (UCAM), the CENTRELINE consortium tackles the main challenges associated with efficient PFC aircraft design [4], i.e.:

- the obtaining of a thorough understanding of the aerodynamic effects of fuselage wake-filling propulsion integration;
- a synergistic aerostructural design integration of the BLI propulsor;
- a best and balanced architecture and design for the fuselage fan turbo-electric drive train; and,
- the multi-disciplinary systems design integration and optimisation at aircraft level.

Based on intermediate results from the ongoing design and analysis activities in the project, this paper presents and discusses the results of trade studies at the propulsion system and aircraft level that are necessary in order to identify a best and balanced PFC aircraft design.

2.0 MULTI-DISCIPLINARY DESIGN INTEGRATION

The foundation of the system-level design and performance studies presented in this paper is formed by the multi-disciplinary, multi-partner collaborative research conducted within the CENTRELINE project. This section of the present paper provides an overview of the roles, interfacing and data handling process between the project partners. Subsequently, the strategy implemented for the propagation of the multi-level, multi-disciplinary design and performance information to the level aircraft sizing and operational assessment is introduced.

2.1 Partner interfacing and information flow

In order to appropriately tackle the multi-disciplinary challenges of PFC aircraft design the scope of research in CENTRELINE includes activities at different levels of detail [4], i.e.

- system-level design definition and optimisation studies;
- high-end and high-fidelity numerical analyses of key aspects of the disciplinary design, including aerodynamics, structural design [22] as well as the architecture and main components of the turbo-electric propulsion and power system [23]; and,
- aerodynamic testing of the overall configuration in the Open Jet Facility (OJF) and Low-Turbulence Tunnel (LTT) facilities at TU Delft [24] as well as BLI propulsor testing on the low-speed fan rig at UCAM [25].

For a consistent handling of multi-level and multi-disciplinary sets of design and operational parameters, ranging from the level of aircraft conceptual design definition to the level of component detailed design specification, efficient infrastructural measures, conventions and processes were established [26] including the versioning and exchange of information via a secure Git repository. Unified system definition and performance book-keeping standards were defined [27], that follow the requirements stated by the MIDAP Study Group [28], and thus, allow a rigorous benchmarking of the PFC against conventional aircraft without BLI propulsion. The roles of the individual partners within the collaborative, multi-disciplinary PFC pre-design exercise are discussed in the following. Therefore, key tasks and the basic flow of design information are visualised in Figure 2.
The multi-partner, multi-disciplinary workflow was initiated based on an initial target design for the PFC aircraft through which basic requirements and performance target settings for key aircraft components and subsystems had been defined in the very early phase of the project [4]. As can be seen in Figure 2, together with the aero-validation testing, the PFC aerodynamic analysis effort is shared by TU Delft and UCAM, with TU Delft in charge of the overall aircraft simulation and testing [29], and, UCAM performing the fuselage fan aerodynamic design, simulation and testing [30]. While the overall configuration aerodynamic simulation approximates the BLI propulsor using an actuator disk model, the 3D rotor and stator designs are fully taken into account within the fuselage fan aerodynamic analysis. The overall configuration aerodynamic simulation provides the fuselage fan inflow conditions and distortion patterns for the fan aerodynamics. The resultant fan aerodynamic design characteristics are fed back to the overall configuration aerodynamic simulation in order to refine and tailor the actuator disc model. BHL performs the fuselage fan propulsion system multidisciplinary conceptualisation. The aero-structural design and analysis of key parts of the PFC airframe is conducted by WUT [31]. Siemens in cooperation with BHL defined the turbo electric architecture, for which Siemens performs the pre-design of the turbo-electric power train components. Chalmers is in charge of the conceptual design and performance analysis of the main power plants [32] and MTU is responsible for the integration of the turbo-electric power generators into the main engines [33]. The multi-disciplinary design and analysis information is hosted on the central Git repository with a continuous knowledge integration from the detailed disciplinary investigations at the overall design level being performed by BHL.

PFC aircraft noise is assessed by Chalmers, with aerodynamic input for the fuselage fan provided by UCAM. The CAD modelling task of the aircraft is performed by WUT in cooperation with Airbus.

2.2 System-level knowledge integration

The knowledge on PFC aircraft design is incrementally refined during the CENTRELINIE project involving multiple levels of modelling fidelity. Incremental results from the various detailed design and analysis tasks need to be evaluated at aircraft-level in a continuous manner in order to provide adequate design guidance from an overall system optimality perspective. Therefore, a rapid-responding aircraft-level sizing and optimisation setup is required featuring

- robust parametric sensitivity for key design parameters from all relevant system components and disciplines;
- flexibility and extensibility in the parametric interfacing between the various design aspects; and,
- the capability of zooming by a quick inter-changeability of disciplinary models.
Given the nature of the design problem at hand, a fully-coupled multi-disciplinary, multipartner design optimisation process featuring the direct execution of the specialized disciplinary models seems widely impractical. Instead, decomposition of the overall system design and optimisation problem was performed. The individual disciplinary and component design optimisation subtasks were decoupled from the aircraft level, by imposing local objectives and constraints directly derived from the aircraft level design and optimisation task. This approach, commonly known as the “Bi-Level Integrated System Synthesis (BLISS) technique [34, 35], allows the handling of complex design optimisation problems based on a relatively small number of top-level variables effectively shared by the various subtasks. The optimum design solution at system level is guided by the derivatives of subtask responses and local design settings with regard to the shared global parameters.

For the interfacing between the system-level design optimisation and the local design optimisation activities, in the present context, surrogate modelling techniques – i.e. the approximation of complex system models through mathematical surrogates – were identified particularly attractive. Surrogate modelling techniques are best-suited for early design phases, when the ranges of parametric variation are large while the number of design variables is relatively small compared to more detailed design phases [34]. Due to their extremely fast response times, surrogate models enable rapid design space exploration and a quick gain of system behavioural knowledge. Surrogate model application intrinsically enforces quality assurance measures such as expert checks prior to the system level integration of subsystem analysis result data. The effectiveness of surrogate model application, however, is limited by the off-line computational effort required for surrogate model regression and validation which strongly increases with rising nonlinearity of system behaviour and the number of free variables to be fitted [36]. Hence, in order to ensure a best and balanced synthesis of surrogate model accuracy and sampling effort at the local level, for the present work, problem-oriented surrogate modelling approaches are employed. The design and performance characteristics of the main power plants systems as well as the BLI fuselage fan power plant are integrated using Feedforward Neural Networks (FNN), trained and validated by Latin Hypercube Sampled (LHS) [37] data as described in [36]. PFC aerodynamic performance properties, structural design characteristics as well as the design and efficiency properties of the turbo-electric power train components are integrated based on custom-developed non-linear regression models. In the following, the surrogate-based model integration strategy is discussed for the example of the bare PFC aerodynamic performance properties.

The aerodynamic mapping at the present preliminary stage in the project is based on 2D axisymmetric RANS CFD simulations of the bare PFC configuration, i.e. the fuselage body including FF propulsive device (cf. [4]). Key result properties from the CFD computations include the flow field and corresponding freestream total pressure recovery ratio at the FF front face, $p_2/p_0$, the ideal power absorbed by the FF actuator disc, $P_{FF, disc}$, and, the Net Propulsive Force (NPF) of the bare PFC, being defined as

$$NPF = F_{FF, disc} - D_{PFC, bare}$$  (1)

where $F_{FF, disc}$ is the force produced by the FF disc and $D_{PFC, bare}$ is the drag produced by all other components of the bare PFC geometry. In order to efficiently integrate the bare PFC operational characteristics, a performance map was derived from CFD simulations of a representative PFC aero-shaping as performed by TU Delft. As illustrated in Figure 3, the off-design performance map is dependent on the actual FPR and flight conditions, which are explicitly the temperature deviation from norm atmosphere, $dT_{ISA}$, the altitude, $Alt$, and the Mach number, $Ma$. This off design performance deck is matched to parametric changes of the PFC design, such as FF blade height, $h_{blade}$, or design pressure ratio, $FPR_{Des}$, as well as fuselage length, $L_{Fus}$, and the design flight conditions through appropriate scaling, in the first instance. Whenever an updated aero-shaping is produced, the validity of the operational performance map is gauged and adaptation is applied if necessary.
The bare PFC off-design map was produced for the above listed key performance properties using a non-linear regression based surrogate model with sensitivity for operational Mach number, altitude and effective fuselage Fan Pressure Ratio (FPR). As an example, the response of the regression model for the NPF parameter within a typical flight envelope at constant fuselage FPR=1.4 is shown in Figure 4. The coloured contours indicate the operational NPF within the flight envelope relative to the sea level static NPF. The red markers indicate the CFD simulation based regression samples.

The mapping quality of the NPF parameter for different operational fuselage FPRs is shown in Figure 5 for two calibrated air speeds (CAS) in the relevant range for transversal flight phases, namely CAS=137 m/s (≈ 266 knots) and CAS=144 m/s (≈ 280 knots). The arithmetic mean deviation of the operational NPF surrogate model is 0.51% with a maximum absolute deviation from the CFD data of 0.18kN.
3.0 SYSTEM SIZING APPROACH

As a result of uncommon systems specific to the PFC layout and distinct boundary conditions – as the consideration of an aircraft family concept – this section will present interesting dependencies for system and aircraft sizing.

3.1 Aircraft sizing

The overall aircraft sizing process is implemented in the commercial modelling environment Pacelab Suite [38] using the Pacelab Aircraft Preliminary Design (APD) framework [38] as a baseline. APD offers a set of handbook methods for aircraft conceptual design mostly based on Torenbeek [39]. As a starting point for the present activities, a customised version of the framework featuring comprehensively supplemented methodology based on BHL in-house developed semi-empirical and analytical methods was employed (cf. [40], [36], [41] and [42]). During the CENTRELINE project, these baseline methods are systematically replaced by surrogate models created from the in-depth analyses of the PFC-specific design and performance aspects performed by the CENTRELINE partners.

Key top-level parameters for the steering and direction of the overall PFC aircraft design, include the design fan pressure ratios and diameters, the thrust split ratio between the under-wing podded main and aft-fuselage BLI power plants, the FF relative axial position along the fuselage, the fuselage slenderness ratio and aft-body upsweep angle, maximum wing loading, and, the fuselage fan operational power scheduling. For the aircraft sizing and performance evaluation in this paper, a step cruise profile is adopted targeting maximum Specific Air Range (SAR) in each cruise point. International reserves are applied including 200nm diversion distance, 30 minutes hold and 5% final reserves.

Figure 6 shows the implemented logic for PFC aircraft propulsion point performance evaluation. With the actual thrust demand, $FN_{req}$, the altitude, $Alt$, temperature deviation from ISA, $dT_{ISA}$, and the Mach number, $Ma$, specified as inputs from the aircraft design loop, the PFC propulsion system point performance evaluation logic is triggered. Depending on the input parameter settings, the FPR schedule provides an FPR to the bare PFC aerodynamics. The NPF of the bare PFC as well as the fuselage fan inflow conditions and ideal disc power absorption, $P_{Disc}$, are predicted by the bare PFC aerodynamics surrogate model. The FF performance model derives the actual power consumption, $P_{Shaft}$, of the FF. With this shaft power and the shaft speed, $N_{Shaft}$, the electrical system model calculates the requested generator power offtakes from the main power.

Figure 5: Fitting quality of operational NPF surrogate model against FPR and altitude
plants, $P_{Gen}$. The main power plant model predicts the fuel flow $w_{fuel}$ dependant on this power offtake and thrust, $F_{NMainPPS}$. The implemented point performance evaluation scheme allows for the optimisation of FPR scheduling for optimum fuel flow.

Figure 6: Implemented logic for PFC aircraft propulsion point performance evaluation

### 3.2 Special implications of aircraft family sizing
Reflecting contemporary product development practice, the PFC aircraft is part of a family concept existing of a baseline (340 PAX), a stretch (391 PAX) and a shrink (296 PAX) family member, where the shrink and stretch variants are derived from the baseline through addition or removal of fuselage sections. This strategy increases operational flexibility to serve various market segments with a platform featuring a high degree of commonality in structures and systems. In the devised aircraft family concept, all three members have the following common assemblies:

- Undercarriage
- Wing
- Pylons and main power plants
- Empennage
- Turbo electric powertrain including FF power plant
- Aircraft subsystems

The stretch family member sizes the wing, main engines, pylon and undercarriage while the shrink family member defines the empennage size. As a result of varying wing loadings, all three family members have a different optimum top-of-climb altitude. Therefore, all three aircraft cruise at different altitudes with the same Mach number and have a different fuselage length equipped with the same fuselage fan. The implications of this sizing strategy have to be carefully taken into account with respect to the sizing of the FF and turboelectric powertrain.

### 3.3 Propulsion system sizing
In order to provide the flexibility of the main engines model to enable a sizing procedure, the design space of the main engines was described by multiple variables, including e.g. design net thrust, design specific thrust, relative HPT cooling air demand ($w_{c}/w_{25}$) and design power of the power turbine (PT). For simulation of the engine operational behaviour, this set of variables was supplemented by a series of typical off-design variables including e.g. flight Mach number, altitude, relative fan corrected speed and the PT offtake relative to the respective design power offtake. Utilising an experimental plan based on Latin Hypercube Sampling (LHS) provided by BHL comprising in total 16 design and off-design variables, power plant characteristics were computed by Chalmers. A description of the engine sizing process can be found in [32].

The net thrust of the main engines is sized to meet the stretch variant’s critical top level aircraft requirement (TLAR) performance targets. In this case, the climb time of 25
minutes is the most critical TLAR defining engine sizing. As outlined in Section 2, the aero-propulsive optimization of the PFC fuselage including the fuselage propulsor was an iterative process carried out in collaboration of TUD and BHL. In this study, the bare PFC aero-propulsive characteristics pertaining to the aero-shaping of a recent design iteration is integrated in the overall aircraft model and sensitivities regarding key characteristics of the FF are investigated in more depth. The FF shaft power demand is tracked during the whole mission. The FF electric drive motor is sized to the critical torque and critical speed values which most likely do not occur at the same time. This results in an oversizing of the motor but ensures that the motor is always operated outside the field weakening area. The power management and distribution system is sized for the maximum power demand during the mission, usually during take-off. Hereby, the resulting turbo electric drive train is able to safely withstand possible failure loads during malfunctions.

A high torque requirement at take-off entails a largely oversized electrical system during cruise. In order to minimize oversizing of the electrical system, an FPR schedule for the FF is defined. During take-off, the FPR should be as small as possible to prevent oversizing of electric components. During cruise, the optimum FPR should be reached. For initial calculations and trade studies a linear FPR schedule characterized by a proportionality between operating FPR and altitude was chosen due to the strong impact of air density on FF power. As the project advances, an optimization of the operating FPR for every mission point has to be performed to minimize fuel flow.

For mapping the characteristics of the FF power plant – in particular shaft power demand and rotational speed – at aircraft level and thus enabling to investigate several FF operating strategies, a corresponding design and performance model was set up in the BHL in-house developed propulsion system simulation framework APSS [43,44]. The fuselage propulsor is characterized by a single-rotating ducted fan layout. Typical heuristics for design and off-design system description and corresponding iteration schemes were implemented. The geometric parameterisation was adapted to allow for the prescription of fan inlet hub diameter as a free variable, which was matched with the local fuselage radial contour coordinate. Due to the expected detrimental impact of the distorted inflow field on the efficiency of the FF propulsor, the polytropic design efficiency of this component was assumed to be degraded by nominally 1.0% relative to the podded power plants operated in free stream conditions. Operational fan performance was modelled based on the GasTurb [45] standard fan map, in the first instance. Details on the power plant modelling strategy can be found in [46]. As the project progresses, fan performance maps specifically derived by UCAM for the considered application will be incorporated.

4.0 DESCRIPTION OF BASELINE PFC AIRCRAFT

In order to facilitate critical assessment and benchmarking of the turbo-electric PFC technology in the CENTRELINE project, a realistic application scenario including advanced reference aircraft and propulsion systems for an aspired EIS year 2035 – dubbed “R2035” – was defined. Based on the analysis of forecast data, a wide-body long-range transport task featuring a 6500 nmi design range and a cabin capacity of 340 passengers was identified as particularly promising for a possible future PFC aircraft product family [4]. Equipped with advanced aerodynamic features, structural and systems technologies as well as Ultra High Bypass Ratio (UHBR) Geared Turbo Fan (GTF) engines, the R2035 reference aircraft is predicted to deliver a 27% design mission block fuel reduction versus a typical year 2000 aircraft serving the same transport task [4].

At the early stage of the project, an initial target design for the PFC aircraft was defined using simplified semi-empirical methodology, featuring an 11% block fuel reduction relative to the R2035 aircraft [4]. As part of this key requirements and challenging design targets for the PFC aero-shaping, the airframe structural concept as well as the design and performance characteristics of the main power plants and the fuselage fan including its turbo-electric power train were specified. The baseline PFC aircraft design presented in
this section represents the first iteration of the integrated overall systems design based on higher fidelity modelling.

4.1 Basic aircraft properties

This section presents dimensions and key characteristics of the PFC baseline aircraft. Figure 7 shows the 3-view of the PFC aircraft and a table with key specifications. The design Range is 6500 nmi and design payload is 34000 kg. The design cruise Mach number is 0.82.

![3-view of PFC aircraft](image)

Table 1: PFC Baseline Mass Breakdown

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<th>MTOW fraction [%]</th>
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<tr>
<td>Wing</td>
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<tr>
<td>Surface Controls</td>
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<tr>
<td>Fuselage</td>
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<tr>
<td>Horizontal Tailplane (HTP)</td>
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<tr>
<td>Vertical Tailplane (VTP)</td>
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<tr>
<td>Undercarriage</td>
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<tr>
<td>Pylons</td>
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<tr>
<td><strong>Structure Total</strong></td>
</tr>
<tr>
<td>Fuselage Fan Propulsion System*</td>
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<tr>
<td>Turbo - Electric Power Train</td>
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<tr>
<td>Main Power Plants*</td>
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<tr>
<td><strong>Propulsion Total</strong></td>
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<tr>
<td><strong>Systems</strong></td>
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<tr>
<td>OEW</td>
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<tr>
<td>Design Payload</td>
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<tr>
<td>Design Reserve Fuel</td>
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<tr>
<td>Design Trip Fuel</td>
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<tr>
<td><strong>Design TOW</strong></td>
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</tbody>
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*Including nacelles, excluding turbo electric generator/motor
4.2 Operational characteristics

As mentioned in Section 3.2, the family sizing has design implications on the turbo electric system. Figure 8 shows the flight profile during cruise along with the FF power consumption of the different family members. The different step cruise characteristics due to different wing loading can be seen very well. In the simulation of the aircraft, step climb is performed in order to optimize SAR

![Figure 8: Cruise altitude and fuselage fan power profile for different PFC family members (M0.82, ISA+10 K)](image)

Countercintuitively the motor sizing of the turbo electric drive train is not primarily defined by a certain family member. As can be seen from Figure 8 the FF power consumption of the different family members at the same altitude differ marginally. If resolved further during the mission, maximum torque and maximum RPM of the motor during the mission deviates less than 2% in-between the family members. This compares very well to the findings from Figure 8.

Figure 9 presents key characteristics of the PFC baseline aircraft during climb and cruise flight. In addition to the flight altitude, the shown parameters include NPF, FPR, FF shaft power and the fuel flow of the main power plants. The three steps during cruise are visible in the trend of each parameter. As a result of the applied FPR schedule, the FPR is directly proportional to altitude. Therefore, each altitude step results in a change in fuselage fan power consumption. Interestingly, this is associated with a reduction of the absorbed shaft power reflecting the strong effect of the reduction in air density. The gain in NPF of the bare PFC is connected to the FPR characteristic. The behavior of fuel flow results from the superposition of the individual effects and the visible peaks occur due to the en route climb maneuvers.

![Figure 9: Characteristics during design mission (climb and cruise)](image)
5.0 TRADE STUDY RESULTS

In order to provide guidance to the further design refinement activities and gauge the potential for further optimization of the actual design and to assess the plausibility of the present study, several sensitivity studies have to be performed. For the PFC concept especially trade studies regarding important parameters of the propulsion system and component weights are conducted. This will be trade studies regarding the following parameters:

- NPF
- FF blade height
- FF design FPR
- Main power plants cooling air
- FF efficiency compared to freestream flow conditions
- Turbo – electric power train efficiency
- Turbo – electric power train weight
- Main power plants specific thrust
- Main power plants design thrust
- VTP volume coefficient
- HTP volume coefficient
- Fuselage weight
- FF weight
- Empennage weight
- Wing weight
- Landing gear weight

A change in design NPF maintaining constant design FF power is a measurement for the aero-propulsive design optimality. The improvement of that value is one of the most important tasks as the CENTRELINE project advances. Furthermore, FF blade height and FF design FPR are regarded as they are main design parameters influencing PFC performance characteristics. Afterwards the main power plant cooling air trade study is presented as it has a relatively big lever arm on block fuel and is dependent on FF operation strategy. The trade study regarding polytropic efficiency of the FF compared to operation in free stream condition follows. This efficiency deviation will subject to further detailed research. Afterwards trade studies regarding the turbo – electric power train efficiency as well as turbo electric – power train power density are presented. Subsequently the effect of a change of the empennage volume coefficients is investigated, as the current design does not incorporate any potentially stabilizing effect of the FF. Following are trade studies scrutinizing various component weights of the PFC aircraft. Especially the fuselage weight sensitivity is interesting, as the fuselage structural weight prediction will be refined when the project continues to move forward, as detailed structural strategies on how to implement the FF will be examined in depth.

All figures feature a red cross indicating the abscissa value corresponding to the baseline PFC aircraft, while the ordinate represents neutrality in all response values. In all studies, the sensitivities of OEW, MTOW and design mission block fuel on the varied parameter is assessed. Calculated points are marked with a square. The plotted lines represent a third degree polynomial fitting of the calculated points. The abscissa values are different for all trade studies as they represent a reasonable interval for each study.

5.1 Propulsion system parameters

This section aims at investigating the impact of important PFC propulsion system parameters on the overall system level. In addition, the sensitivity of key technology parameters are investigated to gain further knowledge on the reliability of the overall system results and to prioritize the criticality of certain system models regarding fidelity.

Figure 10 illustrates the substantial impact of NPF (see equation 1) on overall aircraft characteristics. As a theoretical scenario, this parameter was increased by up to +6 kN assuming constant FF power consumption. A higher NPF at constant power is the direct
result of further progress in the aero-propulsive optimization of the aft-fuselage and nacelle shaping.

![Diagram showing changes in design NPF with constant FF design power](image)

Figure 10: Aircraft design trade study of change in design NPF maintaining constant FF design power.

Figure 11 shows the results of varying FF blade height. A greater blade height than chosen for the actual PFC design seems beneficial. As can be seen, OEW is rising with increasing duct height because FF weight as well as fuselage weight increases. A larger duct also leads to a longer and heavier undercarriage and higher power offtakes at the main engines. The efficiency gain of the BLI effect seem to overcome these penalties until a duct height of approximately 0.8 meters. This must be further assessed in the future and could lead to a larger FF device as the project proceeds.

![Diagram showing FF blade height](image)

Figure 11: Aircraft design trade study FF blade height.

Figure 12 investigates the design FPR of the FF. The design FPR seems to be chosen close to its best value for the current aircraft since it is close to the block fuel minimum.

![Diagram showing Design FPR](image)

Figure 12: Aircraft design trade study of design fuselage FPR.
Figure 13 describes the impact of relative HPT cooling air demand, $w_c/w_{25}$. The value of 26% was chosen conservatively compared to 24% in the reference aircraft “R2035”. It can be seen that the relative amount of cooling air has a strong impact on the design mission fuel burn emanating from the significant impact on both TSFC and flow path dimensions. Further investigations related to a fuselage FPR schedule allowing for reduced main engine temperature levels and thus cooling air demand is advised. As mentioned in Section 2.0 the bare PFC aerodynamic data in the actual iteration of the PFC aircraft is derived from 2-D analysis. This analysis does not account for three dimensional effects during take-off rotation. As the project advances these effects will be assessed. Once incorporated, a further optimization taking into account cooling air dependency for varying design settings in combination with an optimized FPR schedule is advised.

Figure 14 shows the dependency of a variation of the fuselage fan design polytropic efficiency compared to a fan operating in freestream conditions. The assumption of a 1% degradation of FF design polytropic efficiency is based on computational and experimental results for BLI fans reported in the literature, cf. e.g. [47, 48]. As the CENTRELINE project advances this value will be substantiated through numerically computed results for the considered PFC configuration.

Figure 15 and Figure 16 can be used as direct indicators for improved turbo-electric power train efficiency and weight properties. It can be seen that an improvement in turbo-electric power train efficiency by 1% yields approximately the same block fuel benefit as 12% weight reduction in the turbo-electric power train.
In Figure 17, the effect of varying design specific thrust levels \( \frac{F_N}{w_2} \) of the main engines is visualised. Reducing values of \( \frac{F_N}{w_2} \) translate into growing fan diameters, thus yielding increasing values of OEW including cascading effects. Additionally, the study illustrates a direct trade-off with turbine cooling air requirements, which is kept constant in the present sensitivity study, but would need to be adjusted for varying power plant temperature levels at take-off as a result of design specific thrust implications on take-off performance.

As the engines are sized to meet the stretch variant’s climb time requirement, Figure 18 analyses the possible savings due to a smaller net thrust sizing. A downsizing of the engine may be possible if a correspondingly adapted FPR schedule is used for the stretch and the baseline family member.
Figure 18: Aircraft design trade study of design net thrust

5.2 Empennage sizing

Figure 19 and Figure 20 examine the sensitivity of changing volume coefficients of the empennage. In the aircraft design process the potentially stabilizing effect of the FF nacelle has not yet been taken into account. This means a reduction of the volume coefficient of the HTP and VTP might be possible.

Figure 19: HTP volume coefficient aircraft design trade study

Figure 20: VTP volume coefficient aircraft design trade study

Figure 21 assesses the empennage weight change. Since the VTP strongly contributes to the structural stability of the fuselage propulsor nacelle, the empennage weight may be subject to changes in further design iterations, which will incorporate high-fidelity aero-structural computation results. The gradient of the results show trends which would also be expected for conventional aircraft.
5.3 General component weight sensitivities

The fuselage weight impact is analysed in Figure 22. The structural integration of the fuselage fan has an impact on fuselage weight. As structural requirements also feed back into the fuselage fan design the fuselage weight and structural strategies will be numerically analysed by WUT in more depth as the CENTRELINE project moves forward.

Figure 23 assesses the sensitivity of the results for a change of the fuselage fan weight technology factor. The resulting trends are almost linear.

In Figure 24 a variation of wing weight technology factor is conducted. The trend for OEW, block fuel and MTOW is also almost linear.
Figure 24: Aircraft design trade study of wing weight

Figure 25 shows a variation of the landing gear weight technology factor. The sizing for the landing gear is conducted in the stretch version to meet the take-off rotation requirement. In this respect, the critical sizing case is constituted by the ground strike of the nacelle of the FF. As can be seen in the mass breakdown of the PFC aircraft the landing gear seems to have a slightly higher MTOW fraction than comparable standard aircraft. This means that a variation of the landing gear weight has a higher impact on MTOW, OEW and block fuel as would be expected for conventional aircraft.

Apart from the landing gear, the conventional component trade studies in this section behave as expected for conventional aircraft configurations. Due to the FF, the design space for a family design is larger than for conventional aircraft, which could allow for a reduction of some penalties derived for standard aircraft family designs.

6.0 CONCLUSION

This paper presented a multidisciplinary assessment approach along with interim findings and integrated design results for tube and wing aircraft configuration employing fuselage wake-filling propulsion integration, the so-called Propulsive Fuselage Concept (PFC). The configuration investigated as part of the EC-funded Horizon 2020 collaborative project CENTRELINE is characterized by a turbo electrically driven, aft-fuselage installed ducted, boundary layer ingesting propulsor, while the main share of the aircraft’s net thrust is provided by underwing podded Geared Turbofan power plants.

The paper commenced with the discussion of the approach used for the integration of specialized data corresponding to the different disciplines. Thereafter, the integrated sizing process including an aircraft design process is described and the used methods are discussed. Based on this methodological framework, several trade studies investigating the impact of considerations for product family implications in the integrated sizing process were presented. Furthermore, the influence of important propulsion system sizing
parameters was elaborated. As a major result, it was established that the system level sensitivities for conventional components, sized as part of the family sizing process, behave similar to those expected for conventional aircraft family design. In contrast to conventional aircraft family sizing, the fuselage fan could offer the freedom to decrease family sizing penalties through application of different fuselage fan operating strategies in the different family members. Regarding propulsion system sizing parameters, the turbine cooling air demand was found to have a strong impact on fuel burn. As part of further studies in CENTRELINE, the cooling air demand will be evaluated parametrically, taking into account the temperature levels at the relevant power plant operating conditions. Together with optimized operating schedules of the fuselage propulsor, this will allow for the investigation of the impact of fuselage fan sizing and performance parameters on the required net thrust and hence temperature levels demanded of the PFC main engines. The optimization of the aero shaping of the fuselage fan propulsor is one of the main tasks as the sensitivity study showed a large potential to further decrease fuel burn with a better design. Additionally, further investigation of a variable blade pitch fuselage fan device as well as variable nozzle area could widen the FF operating range and improve FF efficiency. Also, it is advised to analyse the structure of fuselage and fuselage fan in more detail. To further improve model accuracy, 3D CFD calculations especially during take-off rotation are needed. Smaller empennage sizing could be possible after investigating the stabilizing effect of the FF nacelle. To find the most beneficial application for BLI, a variation of payload and range as well as cruise Mach number is recommended.

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