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# Power Plant Pre-Design Exploration for a Turbo-Electric Propulsive Fuselage Concept

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**With intent to advance the exploration of a promising concept for synergistic wake filling propulsion system integration, the power plant characteristics associated with a Propulsive Fuselage Concept are investigated in this paper. In the targeted configuration a turbo electric power train is envisioned comprising an electrically driven, boundary layer ingesting fuselage propulsor in conjunction with two underwing podded Geared Turbofan engines providing electrical power offtake. Addressing the extraction of significant levels of power offtakes, upon the discussion of the modelling approach and simulation setup, a variety of parametric studies are presented with emphasis placed on discussing the operational space available for variations of power offtake as well as the effects on the design characteristics. In addition, exploratory studies on the design and performance characteristics of the fuselage propulsor are presented.**

## Nomenclature

*Symbols*
$A$ = area [m$^2$]
$F$ = thrust [N]
$F_N/w_2$ = specific thrust [m/s]
$M$ = Mach number [-]
$N$ = rotational speed [1/s]
$N_{H,corr}$ = rel. corrected HPC speed [-]
$N_{L,corr}$ = rel. corrected fan speed [-]
$P$ = power [W]
$p_2/p_0$ = intake total pressure recovery ratio [-]
$p_{16}/p_{13}$ = bypass duct pressure ratio [-]
$V$ = velocity [m/s]
$w$ = mass flow [kg/s]
$w_{cool}/w_{25}$ = relative cooling air mass flow [-]

$\xi$ = ratio of rel. power offtakes [-]

*Subscripts*
ds = design
f = fuel
HP = related to high pressure spool
LP = related to low pressure spool
N = net
off = offtake
rel = relative
supply = related to power supply system
T = turbine

*Acronyms*
BLI = Boundary Layer Ingestion
BPR = Bypass Ratio
FF = Fuselage Fan
FL = Flight Level
FPR = Fan Pressure Ratio
GTF = Geared Turbofan
HP = High Pressure
HPC = High Pressure Compressor
HPT = High Pressure Turbine
IATA = International Air Transport Association
ICAO = International Civil Aviation Organization
IPC = Intermediate Pressure Compressor
ISA = International Standard Atmosphere
LP = Low Pressure
LPT = Low Pressure Turbine
MCL = Maximum Climb
MTOW = Maximum Takeoff Weight
NASA = National Aeronautics and Space Administration
OPR = Overall Pressure Ratio
PFC = Propulsive Fuselage Concept
PSFC = Power Specific Fuel Consumption
R2035 = Reference 2035
SM = Surge Margin
TO = Takeoff
ToC = Top of Climb
TSFC = Thrust Specific Fuel Consumption
TSPC = Thrust Specific Power Consumption

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*Thermodynamic stations:*

0 = free stream
2 = fan inlet
25 = High Pressure Compressor inlet
3 = High Pressure Compressor exit
4 = burner exit
45 = Low Pressure Turbine inlet
13 = outer fan exit
16 = bypass exit
18 = bypass nozzle throat

## I. Introduction

The challenging long-term environmental targets outlined by multiple organizations worldwide including the European Commission,[1,2] NASA[3] and IATA[4] require in-depth investigation of aircraft and propulsion system break-through technologies. As attainable system efficiency gains are expected to flatten out when retaining the current propulsion system integration approach, the exploration of novel engine integration options is considered to be a key factor. In this respect, the perspective of introducing a more synergistic coupling of propulsion system and airframe is considered to offer potential for significant contributions to achieving these goals. The expected benefits cover various disciplines including overall vehicle aerodynamics, propulsion system design, structural optimization and aircraft control aspects. A particularly promising approach towards avoiding the weight and drag penalties of high propulsive efficiency levels that are intrinsically suffered in case of conventional systems integration paradigms is associated with the concept of distributing the propulsive thrust along main components of the airframe. This allows for the full exploitation of beneficial aero-propulsive interaction effects. As analytically derived and experimentally demonstrated in multiple studies (e.g. Refs. 5-8) one of the fundamental benefits of such more closely integrated arrangements is related to the localized ingestion and re-energization of the viscosity-induced low momentum wake flow of the wetted body via Boundary Layer Ingestion (BLI), which is also referred to as wake filling propulsion system integration.

As a most promising avenue towards a practical implementation of tightly-coupled airframe-propulsion integration, the Propulsive Fuselage Concept (PFC), has been identified.[9] Key element of the PFC is a propulsor encircling the aft of a cylindrical fuselage, the so-called Fuselage Fan (FF), with intent to ingest the fuselage boundary layer and provide aircraft wake filling, thereby reducing the propulsive power required onboard the aircraft.[10] An initial multidisciplinary investigation of the PFC focusing primarily on a gas turbine based FF drive train was conducted as part of the European Union-funded Framework 7 research project “Distributed Propulsion and Ultra-high By-Pass Rotor Study at Aircraft Level” (DisPURSAL).[11] Now, in order to alleviate the aero-structural complexity associated with a mechanical FF drive train, alternative options featuring an electric drive have been proposed.[9, 12-16] A solution based on a turbo-electric layout improves the FF integration,[17] as it facilitates the installation of the FF at the very aft-end of the fuselage body, thus maximizing the exploitation of the wake filling effect attainable from BLI, and allowing for an optimized structural integration of the propulsive device. In addition, the electric drive offers enhanced design freedom compared to a mechanically driven FF and thus enables the minimization of the FF net specific thrust and the electrical power installed. A multidisciplinary investigation of a turbo electrically driven PFC under realistic systems design and operating conditions has recently been started in the frame of the European Union-funded Horizon 2020 collaborative project CENTRELINE,[17, 18] which targets the proof of concept and initial experimental validation of this concept. Representing the most straightforward approach towards the realization of fuselage wake filling, a morphology based on a conventional tube-and-wing layout was down-selected from a variety of conceptual layouts.[19] In the selected configuration, two wing-mounted advanced Geared Turbofans (GTF) deliver the main share of the aircraft net thrust while providing the electrical power to drive the fuselage-installed propulsor, a single-rotating ducted fan, via generator offtakes. A widebody, long-range application scenario has been selected characterized by a 6500 nm design range and a cabin accommodation of 340 passengers in the baseline variant.[18] From a technology level point of view, a potential entry-into-service year 2035 is targeted.

In Figure 1, the general layout of the investigated PFC configuration is presented. In order to adequately evaluate the characteristics of the PFC, as part of the CENTRELINE project, reference systems appropriate for the targeted technology level have been defined. As such, an evolutionary improved twin-engine reference aircraft (“R2035”) featuring advanced Geared Turbofan power plants has conceptually been defined. Further information can be found in Ref. 18.

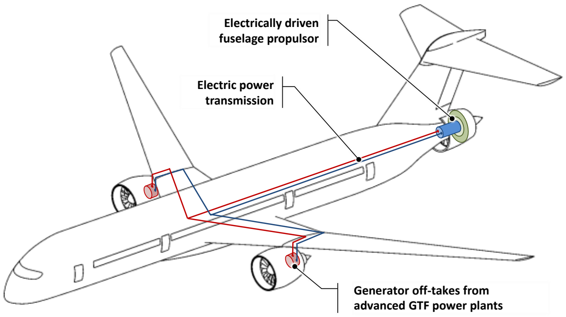


**Figure 1. Layout of Propulsive Fuselage Concept featuring turbo-electric drive train[17]**

The powering of the fuselage propulsor necessitates the extraction of significant amounts of power from the PFC main engines, thus requiring the power plants to feature specialized design optimization to cope with power offtakes in the multi-megawatt regime. As part of the early project work in CENTRELINE, an initial conceptualization and design definition effort of the PFC has been conducted serving as a starting point for more detailed analyses to be conducted over the course of the project. Associated with this initial design phase was a conceptualization of the drive train architecture as well as propulsion system studies of both the underwing podded power plants and the fuselage-installed propulsor. The present paper will elaborate exploratory analyses of all power plants installed on the PFC aircraft with focus on discussing the design characteristics and the operational behavior.

## II. Propulsion System Modelling Approach

Prior to presenting study results, the propulsion system modelling strategy and important assumptions are discussed in the following. Power plant design and performance was conducted using an in-house developed Matlab®-based propulsion system simulation framework.[20] While it features a similar fidelity of component models as the commercial software GasTurb®,[21] it allows for a higher flexibility with regards to the simulation of uncommon engine architectures, and highly reduces the calculation time through extensive use of vectorization. Apart from the calculation of pre-defined, conventional architectures, the framework conveniently allows for the setup of unconventional cycles such as electrically ducted fans. Basic cycle sizing and performance heuristics as well as corresponding iteration schemes are employed based on Refs. 22 and 23 including the parametric evaluation of outer and inner fan pressure ratios, fan tip speed, bypass duct pressure ratio as well as nozzle thrust and discharge coefficients. The prediction of the required amount of turbine cooling air refers to the approach presented by Seitz.[23] Turbo component design efficiencies are mapped based on data given in Ref. 22 capturing the relevant first order effects including component size implications, Reynolds number effects, mean aerodynamic stage loading and, if applicable, the penalties resulting from turbine cooling air insertion, as well as the technology level. Typical component axial Mach numbers and hub/tip ratios at inlet and outlet indicated in Ref. 22 were applied. While at Top-of-Climb (ToC) conditions with Maximum Climb (MCL) thrust setting, maximum component corrected flow levels are obtained, thus constituting the relevant condition for cycle design and flow path sizing, temperatures, transmitted power levels and spool speeds are typically maximum at the representative take-off point. This motivates the consideration of multiple operating points within the engine sizing process. In the present context, appropriate multi-point based iteration strategies were implemented according to Ref. 24. Accordingly, component tip speeds are iteratively adjusted to yield a predefined maximum mechanical loading (i.e. the $AN^2$ metric) and the turbine cooling air demand is mapped according to the temperature levels exhibited during takeoff. The design efficiency of the fan drive gear system is determined according to Ref. 25 at maximum transmitted power (i.e. at takeoff), hence requiring iterative computation of the corresponding value at the engine sizing point. Handling bleed scheduling is based on the approach given in Ref. 23. The specific study results presented in the following are based on component maps used as standard maps in the software GasTurb 12®.[21]

The extraction of large amounts of shaft power from the turbofan spool beyond the levels required to satisfy the aircraft subsystem demand constitutes a severe impact on the overall High-Pressure (HP) or Low-Pressure (LP) spool power balance. From a model parameterization perspective, the direct prescription of the absolute power offtake level is considered inappropriate, in particular during off-design calculations. Instead, a set of relative descriptors was defined, which allow for full exploration of LP and HP spool offtake at design and off-design conditions and greatly improves the model convergence behavior. Firstly, the power offtake, $P_{off}$, relative to the respective turbine power output at a given engine operating point is introduced:

$$P_{rel} = \frac{P_{off}}{P_T} \tag{1}$$

Depending on the aspect studied, $P_{rel}$ may refer to the HP or LP spool. Similarly, for off-design simulation, the quantity

$$\xi = \frac{P_{rel}}{P_{rel,ds}} \tag{2}$$

is employed, indicating the fraction of relative power offtake compared to the respective design value. Again, $\xi$ may be defined with respect to the HP or LP spool.

The fuel efficiency of conventional turbofans is typically evaluated using the classic Thrust Specific Fuel Consumption (TSFC) metric, while for turboshaft engines often the Brake- (i.e. Power-) Specific Fuel Consumption is employed. In cases of turbofan engines where significant power levels are extracted with the intent of doing useful propulsive work in the overall system context, neither of these metrics serves the purpose of fully describing the true efficiency potential of the engine. Instead, the following extension of the Power Specific Fuel Consumption (PSFC) is proposed

$$PSFC = \frac{w_f}{F_N V_0 + P_{off,LP} + P_{off,HP}} \tag{3}$$

which relates the fuel flow, $w_f$, to the sum of net thrust power and the power extracted from the shafts, e.g. for powering the turbo electric drive train. Depending on the scope of the investigation, either or both of the last two terms may be zero. In the latter case, PSFC is directly linked to TSFC by the flight velocity, $V_0$. The net thrust, $F_N$, refers to the streamtube-corrected formulation, hence incorporating drag effects on the engine aft-body and core nozzle plug immersed in the bypass and core engine flow, respectively.

For the performance assessment of electrically powered propulsion systems both TSFC and PSFC metrics are inappropriate. Therefore, the Thrust Specific Power Consumption, TSPC, is employed which is defined as:[26]

$$TSPC = \frac{P_{supply}}{F_N} \tag{4}$$

where $P_{supply}$ denotes in general the power supplied by the energy source, independent of the type of power. For the analysis of electrically driven fan as studied in the Section IV, the system boundary is set to the fan shaft, i.e. $P_{supply}$ refers to the fan shaft power, $P_{shaft}$. Note that TSPC is inversely proportional to the power plant overall efficiency.

## III. Design and Performance Studies of PFC Main Power Plants

Upon the definition of study settings, cycle design studies are presented serving the purpose of identifying best and balanced key cycle parameters for the main power plants of the PFC. Thereafter, the impact of significant power offtakes on the design and operational characteristics are discussed.

### A. Cycle Design Study of Reference Power Plant

Using the methodological approach introduced above, the discussion of study results commences by presenting a cycle design study of a two-spool, boosted, short duct/separate flow GTF architecture without significant power off-takes, thereby establishing a suitable basis with regards to important cycle parameters for further system analyses. The investigation was conducted for the power plants of the reference aircraft. Accordingly, important study settings including requirements for net thrust were derived from aircraft-integrated studies on the R2035 aircraft.[18] In Table 1, a synopsis of the thrust and power offtake requirements is presented. In addition, requirements reflecting preliminary results of the PFC are presented including figures for net thrust as well as power required for the subsystems and for the turbo-electric drive train. As part of the discussed multi-point sizing strategy, a typical hot and high condition was assumed for the takeoff case. A relaxation of thrust requirement relative to the nominal takeoff point at M0.25, SL, ISA+15 K of 10% was assumed based on typical performance characteristics of contemporary widebody, twin-engine aircraft.[27]

| Parameter | Unit | R2035 Power Plants [a] | PFC Main Power Plants [a] |
|---|---|---|---|
| Net thrust at flow path sizing point (M0.82, FL350, ISA+10 K) | kN | 58 | 47 |
| Net thrust at takeoff point (M0.25, 5000ft, ISA+20 K) | kN | 246 | 201 |
| Power offtake for subsystems [a, b, c] | MW | 0.6 | 0.6 |
| Power offtake for FF drive train [a, b] | MW | - | 3.2 |
| Power offtake for FF drive train [a, c] | MW | - | 4.1 |

[a] per engine

[b] at flow path sizing point

[c] at takeoff point

**Table 1: Propulsion system thrust and power offtake requirements for R2035 and PFC main power plants**

In order to identify best and balanced key cycle parameters, design Overall Pressure Ratio ($OPR_{ds}$) and Turbine Entry Temperature ($T_{4,ds}$) were varied across a wide range of values. The fan diameter resulted from aircraft-integrated trade studies taking into account the corresponding weight and drag effects and was retained constant at 3.40 m. Figure 2 presents contour lines of design Thrust Specific Fuel Consumption (TSFC) against variations of $T_{4,ds}$ and $OPR_{ds}$.

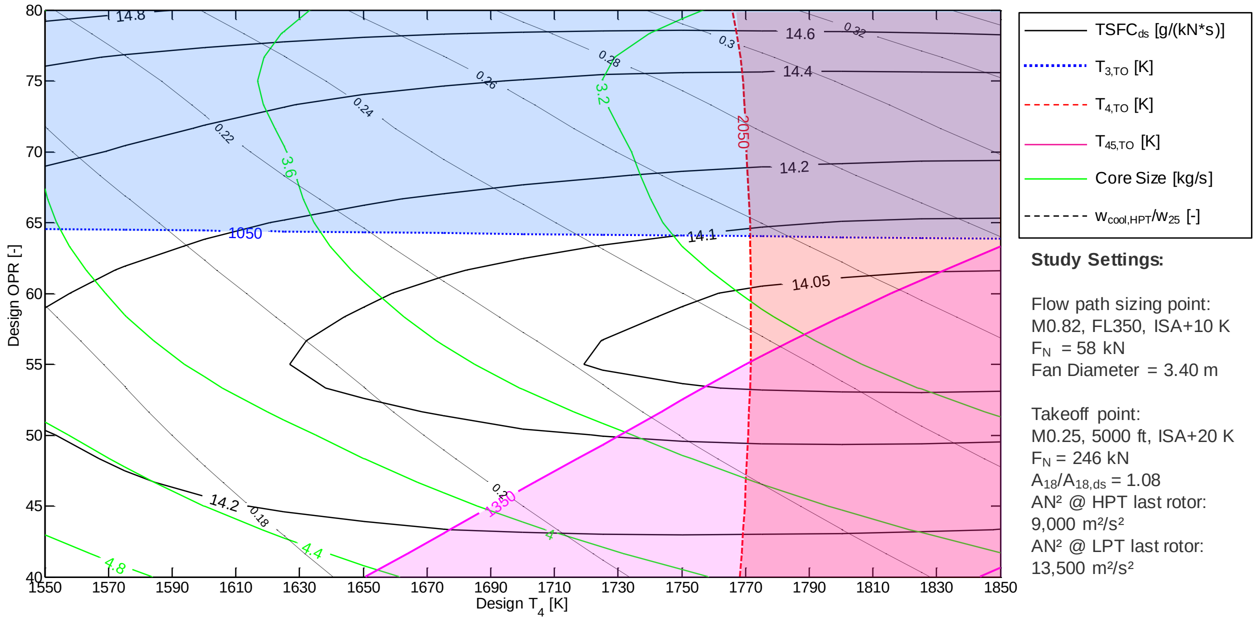


**Figure 2. Cycle design study for conventionally installed reference GTF power plant**

The two-dimensional design space is constrained through maximum limits of cycle temperatures occurring at hot day takeoff condition (see shaded regions). For the compressor exit temperature ($T_3$), $T_4$ and the Low Pressure Turbine (LPT) inlet temperature ($T_{45}$), maximum values appropriate for the considered timeframe of 1050 K, 2050 K and 1350 K, respectively, were assumed. The maximum turbine mechanical loading expressed using the $AN^2$ metric at the last rotor was set at 9000 m$^2$/s$^2$ for the High Pressure Turbine (HPT) and 13500 m$^2$/s$^2$ for the LPT, respectively. A relative area extension of the fan nozzle was assumed serving the purpose of increasing engine stability while by virtue of improved propulsive efficiency levels facilitating reduced temperature levels at takeoff. Intuitively, maximum $T_3$ levels are directly coupled to $OPR_{ds}$, thus emphasizing the upper limit of maximum feasible overall pressure ratios for given compressor material options and component efficiency levels. The $T_{45}$ iso-contours are a result of the amount of specific work required to be extracted from the HPT, thus varying with both $T_{4,ds}$ and $OPR_{ds}$. The loci of the $T_4$-limiter are approximately constant with the $OPR_{ds}$ levels. Also displayed in the chart are characteristics of the relative HPT cooling air demand, $w_{cool,HPT}/w_{25}$, featuring sensitivity with $OPR_{ds}$ and $T_{4,ds}$. In addition, the core size parameter is displayed. Within the range of parameters, only small changes in TSFC are observed. The location of the TSFC-optimal design values in $T_{4,ds}$ and $OPR_{ds}$ is strongly determined by the interplaying effects of basic cycle thermodynamics, turbine cooling air demand and component efficiencies, which are influenced by flow path dimensions, aerodynamic loading and turbine cooling air insertion. For the given study settings, the TSFC optimum is located beyond the permissible temperature levels. For further system analysis, a design at $OPR_{ds}$ = 60 and $T_{4,ds}$ = 1750 K was selected. These settings offer close to maximum fuel efficiency while providing sufficient margin with respect to each of the considered constraint, thus enabling development potential for future potential growth version. The turbo component stage configuration resulted from the application of typical stage loadings and mean pressure ratios according to information given in Ref. 22.

### B. Investigation of Significant Power Offtakes

This section discusses several exploratory studies of the underwing-podded main power plants of the PFC. A primary focus is set on discussing the implications of significant power offtakes on propulsion system design and performance characteristics. The net thrust requirements were applied as given in Table 1. Key cycle parameters including burner exit temperature, OPR, as well as constraints imposed at takeoff conditions were adopted from the reference power plant discussed in Section III.A, in the first instance. In addition, specific thrust was retained invariant, thereby yielding due to the reduced sizing net thrust a smaller fan diameter for the PFC application.

#### *1. Variation of Power Offtake at Cruise Condition*

As part of an initial study, the boundaries of feasible power extraction levels within the part power envelope were evaluated. As study parameters, at off-design conditions both the LP spool power offtake expressed as a fraction of the design value, $\xi_{LP}$, and the fan relative corrected speed, $N_{L,corr}$, were varied at a typical cruise flight condition. The part power study was conducted for different levels of relative design LP power offtake, $P_{LP,rel,ds}$, ranging from 0.15 to 0.30 in increments of 5%, while apart from the power required to satisfy the aircraft subsystem demand, additional power offtake from the HP spool was not considered in the frame of this study, i.e. $P_{HP,rel,ds} = 0$. The respective sub-plots are presented in Figure 3.

The characteristics are shown against the operational TSFC and net thrust ($F_N$). As a result of the introduction of the additional study parameter $\xi_{LP}$, the propulsion system operating line in the TSFC vs. $F_N$ diagram is extended to a carpet. The condition experienced at the ToC condition defined by $N_{L,corr} = 1$ and $\xi_{LP} = 1$ is indicated in each chart using a marker symbol. Also included in the plots are contours of absolute power offtake. The upper left chart of Figure 3 yields approximately the power offtake required for the investigated PFC design. As can be observed from the charts, for constant absolute power offtake a reduction of the engine thrust setting, i.e. reducing values of $N_{L,corr}$, yield due to the decreasing LPT power output strongly increasing levels of relative power offtake. As an example, for $P_{LP,rel,ds} = 0.15$, maintaining the design power for $N_{L,corr} = 0.85$ requires a relative power offtake of approximately $\xi_{LP} = 1.9$.

In order to explore the engine operational behavior against changes of operational power offtake, the parameter $\xi_{LP}$ was varied across a larger range covering values from 0.1 to values larger than the condition exhibited at the flow path sizing point. In general, for a given design power offtake, higher operational extraction ratios require an increase in LPT power output which is realized by increasing the burner exit temperature resulting in increasing spool speeds and OPR. The upper limit of feasible values of $\xi_{LP}$ was found constrained by the HPC corrected speed ($N_{H,corr}$) towards the higher end of engine thrust settings. For an assumed limit of $N_{H,corr} = 1.05$, the maximum feasible overpowering capability at the ToC condition ($N_{L,corr} = 1$) reduces from a factor of 1.44 at $P_{LP,rel,ds} = 0.15$ to 1.23 at $P_{LP,rel,ds} = 0.30$. To explain this behavior, it is expedient to compare two cases of relative design power extraction, $P_{LP,rel,ds} = 0.15$ and 0.25, both operated at a $\xi_{LP} = 1.2$. In order to accommodate the larger design offtake, the latter design requires an increased flow path size and hence results in an increased design LPT power. Hence, at a given ratio of $\xi_{LP} = P_{off}/P_{LPT}$ at off-design, an over-proportional increase in absolute power offtake between both design cases is yielded, specifically an increase from 4.09 MW to 8.13 MW (+98.8%), while relative design power offtake is only increased by 66.7%. This means, from the design with $P_{LP,rel,ds} = 0.25$ an over-proportionally larger amount of absolute power is extracted resulting in a higher burner exit temperature and thus increased HPC corrected spool speeds.

As can be seen from the figure, for constant levels of $\xi_{LP}$, the reduction of engine thrust setting is constrained by the stability limits of the compressor components. Following guidelines given in Refs. 22 and 28, a minimum required surge margin (SM) of 10% for the inner fan and 15% for the Intermediate Pressure Compressor (IPC) and the High Pressure Compressor (HPC) were applied. The surge margin of the HPC was found uncritical within the scope of this study. Note that the domain of surge margins below the stipulated constraint values is the region between the respective constraint line and the edge of the carpet.

A more practical operating mode is constituted in maintaining a constant absolute power offtake rather than a constant relative offtake. Inspection of Figure 3 reveals that in this case the engine thrust setting can be reduced down to the lower boundary of $N_{L,corr}$ values, which is, however, constrained within a relatively small bandwidth of $\xi_{LP}$ values. Also, while uncritical for low levels of $P_{LP,rel,ds}$, for higher values, limits are placed on the feasible reduction of power offtake during off-design operation. The complete suspension of power offtake, however, might constitute an important requirement for failure modes involving the FF being inoperative.

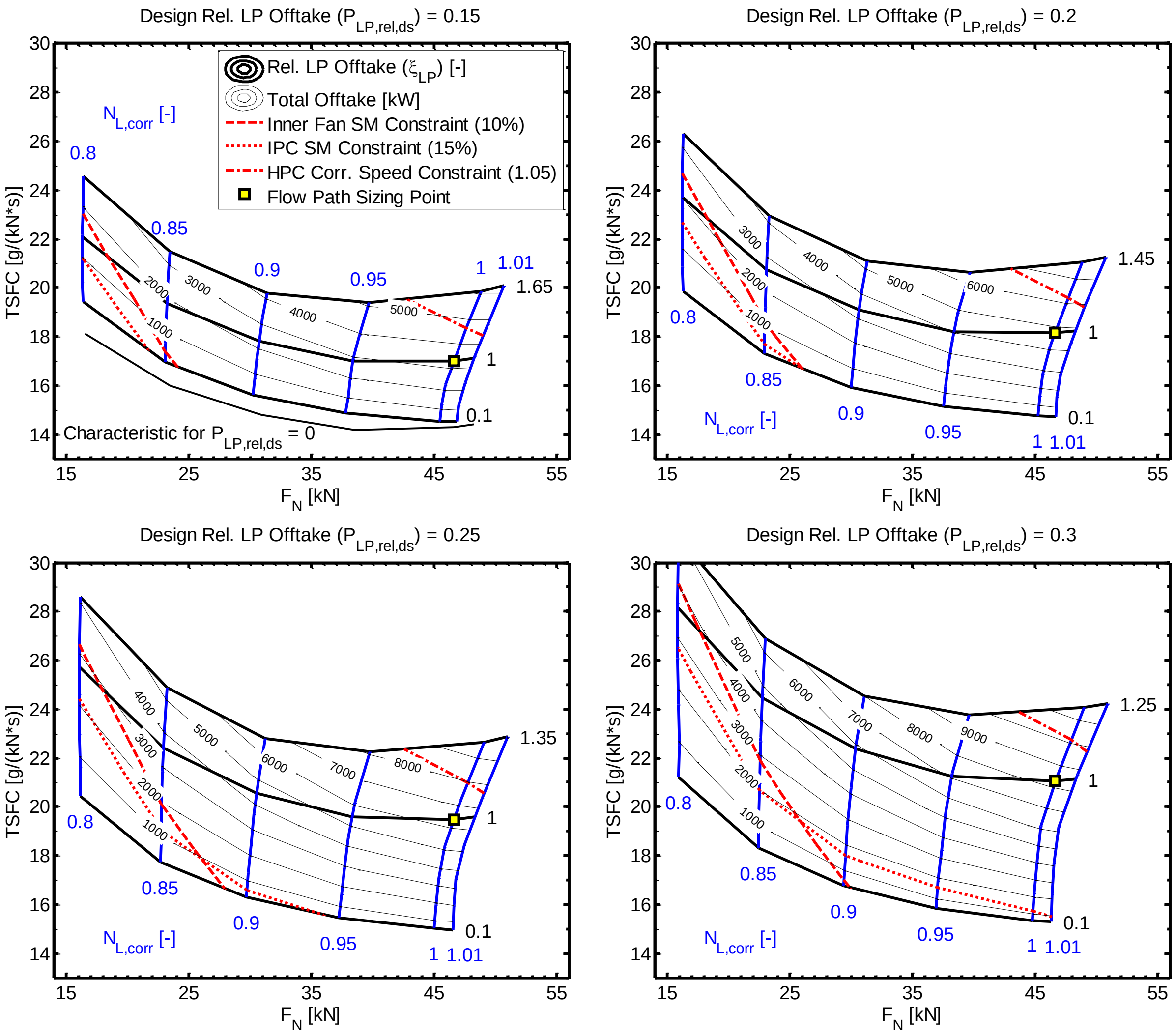


**Figure 3. Cruise part power study results for various levels of relative design LP power offtake (M0.82, FL350, ISA+10 K)**

It can be established that for all levels of design power offtake considered, the feasible variation in offtake during off-design operation is largely confined by the constraints applied, thus placing limits on the control law governing the power offtake along the mission. This, in general, requires increased flexibility in the operational space available and might require improved variability in the associated engine components, which has, however, not explicitly been modelled in the present context. It can be noted that this appears particularly relevant for low part power operation and even idle conditions.

Figure 3 signifies the drastic impact of power offtake on design TSFC, i.e. the value obtained at $N_{L,rel,corr}$ = 1 and $\xi_{LP}$ = 1. This appears intuitive since in this metric only net thrust is considered as useful work. In the shown case, an increase between 19% and 47% between the design points indicated in the chart and a hypothetical case of the same power plant with no LP power offtake is obtained. Moreover, for growing $P_{LP,rel,ds}$, the typical bucket shape of the TSFC curve becomes increasingly distorted and a monotonically increasing trend is obtained for reducing engine thrust settings. Note that this behavior is apparent for both constant relative and constant absolute power offtakes.

### 2. *Investigation of Combined HP and LP Power Extraction*

While in the previous study power extraction was limited to the LP spool, it is of interest to investigate the engine level impact when dividing the offtake to both LP and HP spools. Three scenarios are explicitly considered in the following:

- *Case A*: the previously studied scenario of sole drive train related power extraction from the LP spool
- *Case B*: the combined power extraction from LP and HP spools. As an initial assumption, here, the relative design power offtake was considered evenly distributed between both spools, while the overall absolute power offtake at design and takeoff point was retained identical to *Case A* as prescribed in Table 1.
- *Case C*: the hypothetical case of zero power offtake beyond the power required for subsystems. This case serves as a basis for comparison, in particular for assessing the impact of the different modes of power offtake on the design and performance characteristics.

In order to allow for consistent comparison of all cases, net thrust requirements including lapse rates between ToC and takeoff as well as key cycle settings and the fan diameter were kept invariant between all three scenarios considered. Tabulated data of these scenarios is provided in Table 2.

| | Unit | **Case A** | **Case B** | **Case C** |
|---|---|---|---|---|
| **Flow path sizing point** | | | | |
| Overall Pressure Ratio (OPR) | - | | 60.0 | |
| Burner Exit Temperature ($T_4$) | K | | 1750 | |
| Fan diameter | m | | 3.05 | |
| Rel. LP design power offtake ($P_{LP,rel,ds}$) | - | 0.146 | 0.072 | 0.0 |
| Rel. HP design power offtake ($P_{HP,rel,ds}$) | - | 0.0 | 0.072 | 0.0 |
| LP design power offtake [a] | MW | 3.2 | 1.5 | 0.0 |
| HP design power offtake [a] | MW | 0.0 | 1.7 | 0.0 |
| HP Power offtake for subsystems | MW | 0.6 | 0.6 | 0.6 |
| Overall power offtake | MW | 3.8 | 3.8 | 0.6 |
| HPT design power | MW | 20.3 | 23.7 | 18.5 |
| LPT design power | MW | 21.9 | 20.4 | 18.3 |
| Bypass ratio | - | 14.1 | 13.1 | 15.7 |
| Change in design TSFC [b] | % | +18.3% | +20.7% | base |
| Change in design PSFC [b] | % | -6.9% | -5.0% | base |
| Core size | kg/s | 3.02 | 3.25 | 2.71 |
| **Take-off point** | | | | |
| LP power offtake [a] | MW | 4.1 | 2.05 | 0.0 |
| HP power offtake [a] | MW | 0.0 | 2.05 | 0.0 |
| HP Power offtake for subsystems | MW | 0.6 | 0.6 | 0.6 |
| Overall power offtake | MW | 4.7 | 4.7 | 0.6 |
| $T_4$ at takeoff point | K | 1932 | 1995 | 2043 |

[a] designated for turbo electric power train

[b] relative to Case C

**Table 2: Comparison of different power extraction scenarios**

For *Case A*, $P_{LP,rel,ds}$ was adjusted to yield the required design power offtake. For *Case B*, $P_{HP,rel,ds}$ and $P_{LP,rel,ds}$ were conjointly manipulated to yield the desired overall power offtake. Closer examination of those two scenarios, in particular the HPT and LPT sizing power as well as the core size parameter, reveals that *Case B* requires a larger core engine than *Case A* yielding for constant fan diameter a diminished Bypass Ratio and giving evidence for increased core engine weight. This is rooted in the fact that for *Case B* a larger portion of the total design power offtake is extracted from the HP spool where the associated turbo components are intrinsically characterized by slightly lower efficiencies than the LP spool components. Hence, in particular at the takeoff point, higher levels of $T_4$ are required to produce the same total power offtake. The implemented multi-point sizing strategy captures the elevated thermal loading triggering increased turbine cooling air demand, which further contributes to the core engine increase. As a result, TSFC is penalized over *Case A* and a 7.6% larger core size is required. Note that the aerodynamic loading of the HPT strongly increases in *Case B* compare to *Case A*, thereby inhibiting a further increase of the HP power extraction share. In fact, a scenario where the given overall power extraction level is completely extracted from the HP spool would result in an unacceptably high HPC and HPT stage loading. Since from a practical perspective a HPT design featuring more than two stages is hardly justifiable, this scenario appears invalid and is thus not included in Table 2. In addition, this case would potentially affect the engine dynamic characteristics in a strongly negative way, in particular during transient maneuvers such as acceleration and start-up.

Comparison of *Cases A* and *B* with *Case C* (no powertrain-related extraction at all) reveals a substantial reduction in takeoff temperature levels. The explanation for this requires analysis of the relative levels of power offtake at takeoff condition: the given overall offtake yields values of $P_{LP,rel}$ which are at approximately 60% of their design value. Hence, for the larger-sized machines associated with *Cases A* and *B*, this operating condition is less demanding than for the reference case and therefore, a reduction of temperature levels ranging from 48 to 111 K is exhibited. While the associated benefit in cooling air demand counteracts the increase in TSFC, nonetheless, a penalty between 18.3% and 20.7% is obtained compared to *Case C*. If, however, the extracted shaft power is included in the balance of useful work, i.e. if the PSFC metric is applied, a benefit between 5% and 6.9% is achieved.

### 3. *Variation of Relative HP and LP Power Offtake at Part Power Operation in Cruise*

While the previous investigation was largely centered on analyzing the design and takeoff characteristics, as a next study, it is explored how the simultaneous extraction of LP and HP power offtake might improve the operational envelope with regards to increased variability during part power operation. Again, as in Section III.B.1, a typical cruise condition was considered. LP and HP power extraction levels were governed through variations of $\xi_{LP}$ and $\xi_{HP}$, respectively. The four charts presented in Figure 4 show various operational parameters, each at a given engine thrust setting prescribed by the fan relative corrected speed, $N_{L,corr}$. In addition to the respective level of $N_{L,corr}$, the mean value of the relative net thrust obtained for the operating domain of each chart with respect to the ToC point is provided in Figure 4. The abscissae and ordinates display the absolute power levels extracted from each spool and the overall power extraction is annotated using contour lines within each carpet. In addition, TSFC contours are included. Again, regions where the shown constraints would be violated reside towards the outer edges of the respective carpets. The study was conducted for the design described as *Case B* in Table 2, i.e. a balanced extraction of $P_{LP,rel,ds} = P_{HP,rel,ds} = 0.072$. This is confirmed by inspecting the power levels exhibited at the flow path sizing point in the lower right chart.

As an important result, it is determined that unlike in the case of sole power extraction from one shaft, now the operational space available for power extraction is substantially freed up and the criticality of the constraints becomes alleviated. As an example, at the ToC condition with MCL setting ($N_{L,corr} = 1$), the available over-powering capability with regards to power extraction is increased to a factor of more than two expressed in absolute power levels. This, however, is only possible by conjointly increasing $\xi_{LP}$ and $\xi_{HP}$ in a proportional manner towards the higher end. This constitutes an important characteristic when considering redundancy requirements during overall system sizing, in particular during failure modes where one of the PFC main power plants is inoperative.

Comparison of the four charts of Figure 4 demonstrates that depending on $N_{L,corr}$ the criticality of the individual constraints becomes amplified or alleviated. For lower thrust settings, the surge margin constraints of the inner fan, IPC and HPC become more dominating and restrict the extent of over-powering. As can be seen, due to higher operational HP extraction ratios yielding lower corrected HPC speeds, the operating points are shifted towards the surge line in the HPC map. Conversely, for reduced engine thrust levels, the HPC speed constraint becomes increasingly alleviated.

Figure 4 illustrates by the observed deviation from the purely orthogonal shape of the carpets a certain level of coupling between the absolute quantities of HP and LP power offtake. For example, at constant $\xi_{HP}$, increasing the LP offtake also triggers a small increase in LP offtake. This is due to the fact that the need for increased LPT power realized by increasing $T_4$ levels is accompanied by an increase in HPT power output and hence the absolute HP power offtake tends to increase.

In more detailed work it has to be established if the benefit offered by the increased operational flexibility associated with the combined LP and HP extraction compensates potentially increased complexity in the control system governing the offtake rates and the observed slight penalty in design performance.

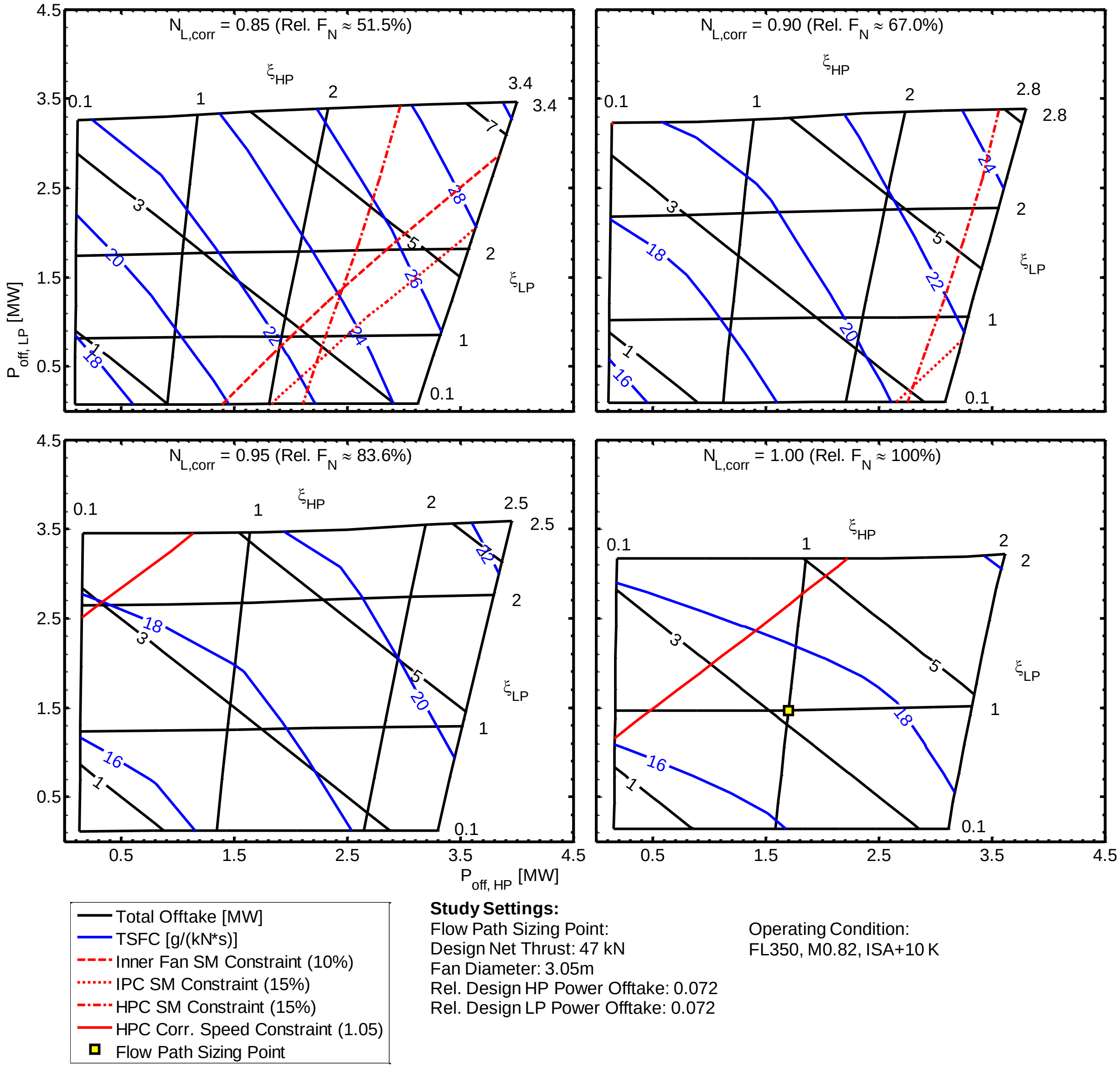
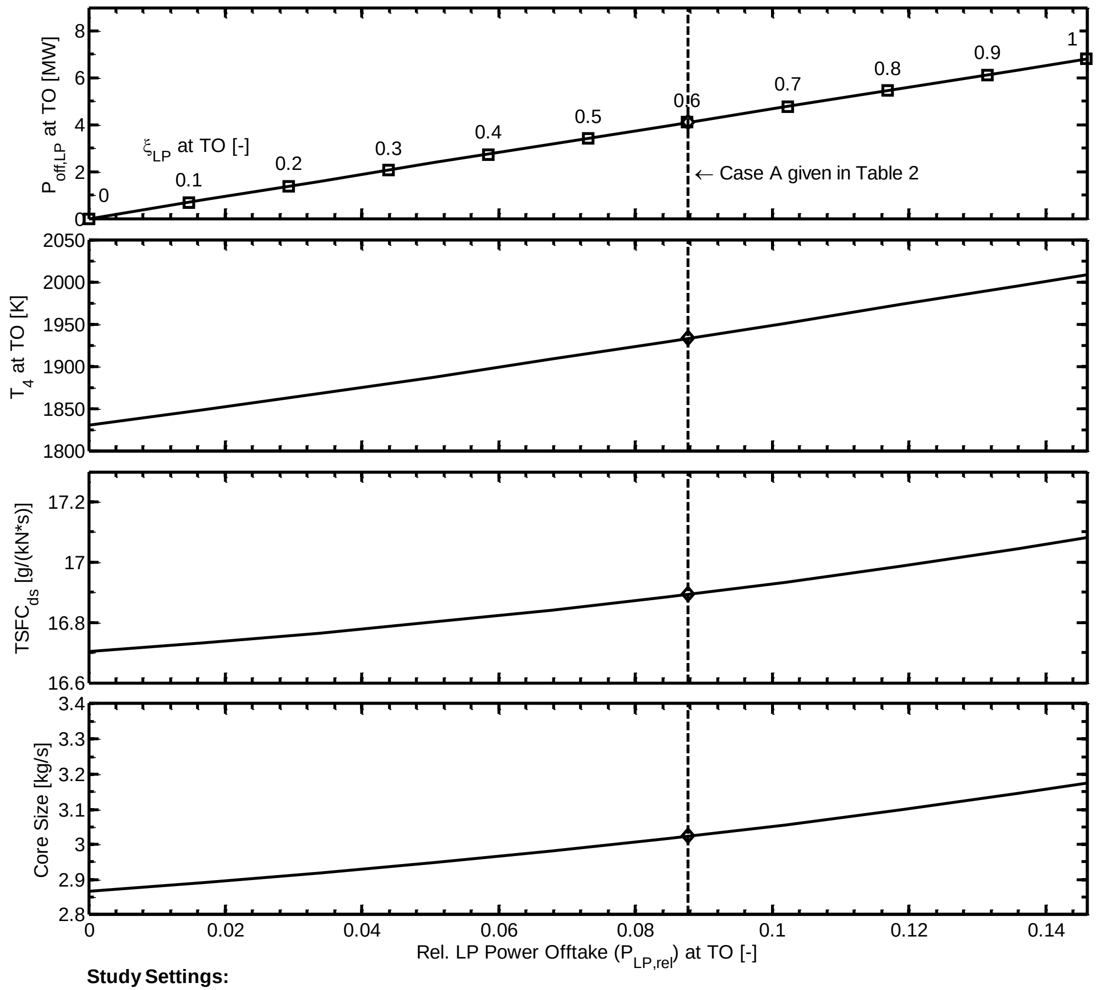


**Figure 4: Study results of HP and LP power extraction for $P_{LP,rel,ds}$ = 0.072 and $P_{HP,rel,ds}$ = 0.072 at various part power settings at cruise condition**

### 4. *Investigation of Takeoff Performance*

As a final trade study, the impact of power offtake variations at the takeoff point under presence of significant power offtakes is investigated. Accordingly, at the representative takeoff point indicated in Table 1, relative operating power offtake, $P_{LP,rel}$, was varied between zero and the design value. For this study, a scenario of 100% power extraction from the LP spool was considered (*Case A* in Table 2). The plots presented in Figure 5 show various parameters against the relative LP power offtake at takeoff. Intuitively, the absolute power offtake as well as $\xi_{LP}$ is linearly dependent on $P_{LP,rel}$.



**Study Settings:**
Flow Path Sizing Point:
Design Net Thrust: 47 kN
Fan Diameter: 3.05 m
Rel. Design HP Power Offtake: 0.0
Rel. Design LP Power Offtake: 0.146

Takeoff Point:
5000ft, M0.25, ISA+20 K
Net thrust: 201 kN
$AN^2$ @ HPT Last Rotor: 9000 $m^2/s^2$
$AN^2$ @ LPT Last Rotor: 13500 $m^2/s^2$
$A_{18}/A_{18,ds} = 1.08$

**Figure 5: Investigation of takeoff performance**

As an important outcome, a reduction of the operating $P_{LP,rel}$ offers a strong lever to reduce the temperature levels exhibited at takeoff. As outlined above, this emanates from the fact that compared to its design value, the power removed from the LP shaft reduces and hence the loading of the entire engine is relieved. While at $\xi_{LP} = 1.0$ a $T_4$ level of 2009 K is obtained, temperature is greatly reduced if $\xi_{LP} < 1$ is considered. Specifically, for $P_{off,LP} = 4.1$ MW ($\xi_{LP} = 0.6$) the result given in Table 2 is reproduced (see annotation). The remaining two sub-plots elucidate the impact of the repercussive effects captured by the implemented multi-point sizing strategy on the characteristics at the flow path sizing point, which greatly influences cruise performance. For decreasing $P_{LP,rel}$, the reduced temperature levels translate into smaller cooling air demands, thus improving TSFC at ToC conditions and yielding a smaller core size. While not explicitly analyzed yet, it should be noted that for the lower end of the considered levels of $P_{LP,rel}$, the cycle temperatures occurring at other flight phases (e.g. initial climb phase) may become more thermally demanding than the takeoff case, thus constituting an even more relevant condition for cooling air system design.

## IV. Design and Performance Studies of Electrically Driven Fuselage Fan

As a second part of the paper, conceptual studies on the electrically driven Fuselage Fan (FF) are presented in the following. In general, different approaches towards thrust and drag bookkeeping in case of boundary layer ingesting propulsion system integration have been proposed in the literature. In the present context, the thrust accounting is geared to the streamtube of air entering the engine. The adherence to this definition, which is commonly used in gas turbine simulation software[29] ensures conformity with the way conventionally installed power plants are typically bookkept. As a consequence, effects occurring within the streamtube ahead of the fan intake are incorporated within the power plant internal bookkeeping.[10] As an important characteristic of the propulsive device immersed in the fuselage boundary layer, a momentum deficit of the inlet flow is obtained translating into a penalized intake total pressure recovery ratio ($p_2/p_0$) compared to conventionally installed power plants.[10, 30, 31] Depending on the application case and study settings, in particular the radial dimension of the propulsor, the penalty may be significant. As a result of the fuselage momentum deficit being processed inside the power plant bookkeeping, the actual net thrust requirement of the aircraft is reduced accordingly.

Initially, an investigation of the impact of $p_2/p_0$ on both design characteristics and takeoff performance is discussed. Primary engine settings given in Table 3 were defined as part of the multi-disciplinary investigation outlined in Section I. Preliminary values for sizing net thrust requirements were derived from initial aircraft-integrated investigations.[18] The fan inlet hub diameter is an outcome of preliminary aerodynamic shape optimization studies of the aft-fuselage and FF nacelle geometry,[18] thus requiring iterative determination of the fan inlet hub/tip ratio. The fan axial Mach number was selected based on previous studies of FF arrangements described in Ref. 30. The value indicated in Table 3 is approximately 20% below the value typically expected for advanced conventionally installed turbofan engines indicated in Ref. 22. 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 1.0% relative to the podded power plants operated in free stream conditions. This is judged to be a conservative assumption since boundary layer ingesting fans operating in a flow field exhibiting both radial and circumferential distortion patterns have been numerically and experimentally assessed to be impaired by approximately 0.5 to 1.5% relative to the non-BLI case.[32-35]

| **Parameter** | **Unit** | **PFC Fuselage Fan** |
|---|---|---|
| **Flow path sizing point (M0.82, FL350, ISA+10 K)** | | |
| Net thrust | kN | 7.0 |
| Fan inlet hub diameter | m | 1.16 |
| Fan axial inlet Mach number | - | 0.56 |
| Bypass duct pressure ratio ($p_{16}/p_{13}$) | - | 0.99 |
| Delta in fan polytropic design efficiency [a] | % | -1.0 |

[a] relative to conventionally installed fan

**Table 3: Settings and assumptions of Fuselage Fan propulsion system**

As a second sizing parameter, Fan Pressure Ratio ($FPR_{ds}$) was varied. The net thrust at takeoff was assumed constant for this study (32 kN) and chosen such that all design conditions considered in the study yielded valid results at the takeoff point. Reflecting the reduced flight velocity, intake pressure recovery ratio at takeoff was set to 0.98 and retained invariant throughout the study, in the first instance. This value was derived from preliminary aerodynamic analyses of the PFC fuselage considered in the present application.[18]

The results shown in Figure 6 indicate the implications with respect to design TSPC shown on the abscissa and fan inlet tip diameter on the ordinate. In addition, the design specific thrust ($F_N/w_{2,ds}$) is displayed as color contours. Apart from sizing parameters, important characteristics exhibited at the representative takeoff point are included in the chart. In order to directly allow for benchmarking the design and performance characteristics of the FF, the corresponding trend of TSPC is presented for an electrically powered fan operated under conventional propulsion system installation paradigms, i.e. when installed in free stream conditions. Accordingly, for this application, fan inlet hub/tip ratio was fixed at 0.26, design fan face axial Mach number was selected as typical for advanced turbofans[22] and the penalty in design fan efficiency was foregone. Moreover, for the propulsor installed in free stream, $p_2/p_0$ was set to 0.997. For this case specially highlighted in the chart, the typical characteristic for variations of $F_N/w_{2,ds}$ are obtained: initially, reductions in $F_N/w_{2,ds}$ yield improving propulsive efficiencies translating into increasing overall efficiency levels, i.e. reducing TSPC, while the necessary mass flow throughput, i.e. the fan diameter grows. However, for further reducing specific thrusts, overall efficiencies become increasingly impaired through degrading transmission efficiency levels. As an intrinsic characteristic of ducted propulsive devices, the impact of pressure losses in the transmission system scales inversely proportional to $F_N/w_2$. Consequently, a stationary point is encountered at approximately $F_N/w_2 = 50$ m/s.

For the case of wake filling propulsion system installation involving reduced intake total pressure recovery ratios, this effect becomes even more pronounced. Here, the degraded levels of transmission efficiency trigger a shift in the loci of TSPC-optimum specific thrust levels, which gradually appear at higher FPRs as $p_2/p_0$ decreases. Due to the increased hub radius, the carpet is located at larger fan diameters than experienced by the conventionally installed FF. As can be observed, for decreasing levels of $p_2/p_0$, maintaining a certain $FPR_{ds}$ results in a reduction in specific thrust as the pressure loss in the intake rises, thus requiring larger fan diameters. While in the present study $p_2/p_0$ was treated as a free variable, thus serving the purpose of evaluating its sensitivity, is has been established that $p_2/p_0$ is correlated to the amount of boundary layer momentum deficit captured within the propulsive device and hence depends on the size of the propulsor.[10, 14, 30]

Inspection of the takeoff related properties reveals the following trends: generally, the improving propulsive efficiency associated with low specific thrust designs translates into a stronger thrust lapse between takeoff and the flow path sizing point at ToC. Now, for fixed thrust requirements as considered in the present study, this behavior is reflected in significantly reduced shaft power demands at the takeoff point, $P_{shaft,TO}$. Accordingly, the fan is operated at a lower power setting at takeoff yielding decreased values of corrected speed ($N_{L,corr}$), which are visualized in the chart. In addition, the shift in takeoff operating point in the fan map associated with variations of $N_{L,corr}$ triggers slight changes in fan polytropic efficiencies, thereby further influencing the obtained characteristics in in shaft power. As one would suspect, for reducing specific thrusts, the susceptibility to fan stability issues at takeoff becomes pronounced as the surge margin limit (exemplary shown for 10%) is approached. Interestingly, this constraint is relieved once $p_2/p_0$ degrades.

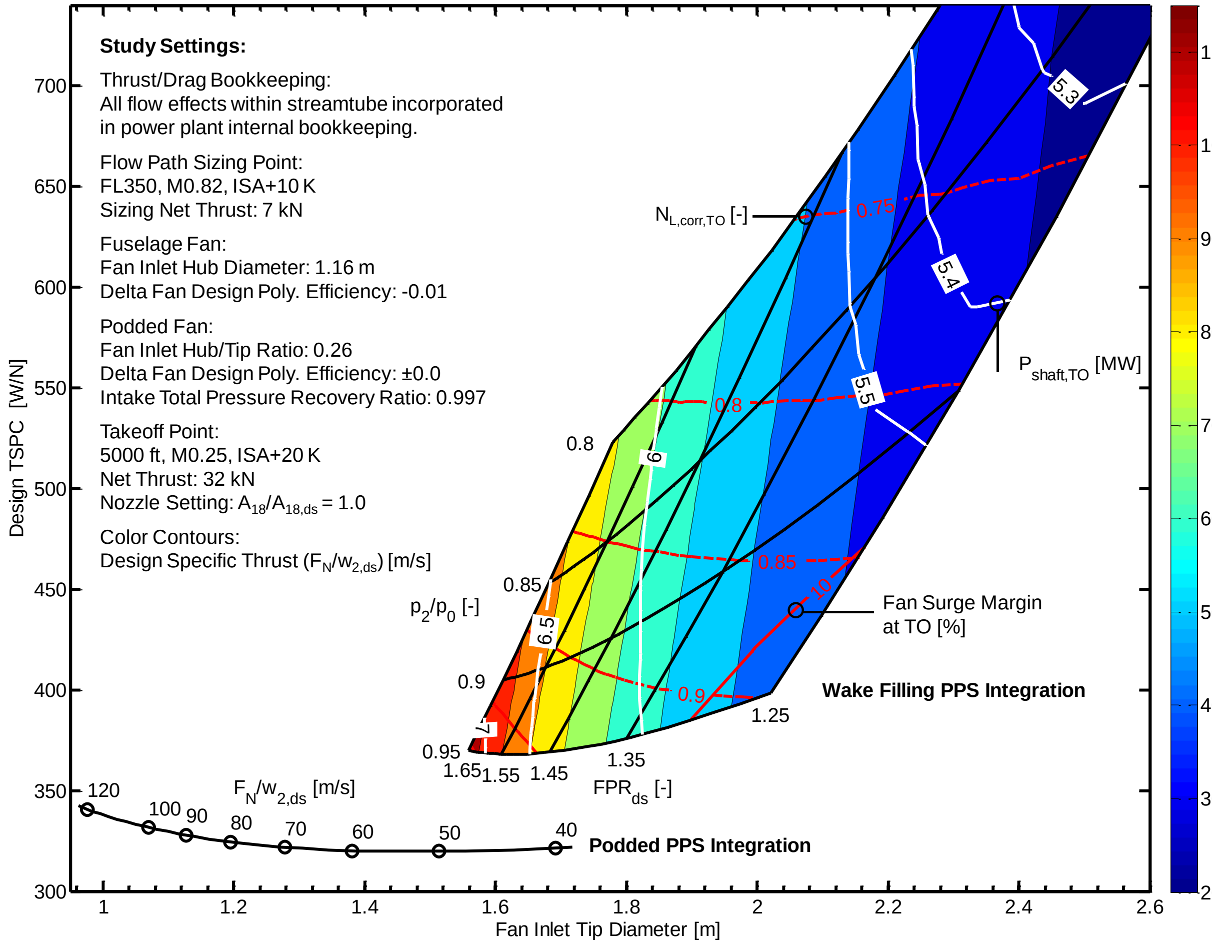


**Figure 6: Combined design and takeoff study of Fuselage Fan propulsor**

The chart may be useful for conceptual sizing purposes of the propulsive device: for a known intake total pressure recovery ratio and given thrust requirements, it allows for the direct tradeoff between cruise efficiency (i.e. TSPC), the propulsor size, which correlates with its mass, and the required takeoff power.

Acknowledging the significant impact of the takeoff thrust requirements on the maximum shaft power exhibited by the FF propulsor, a second parametric study was conducted specifically focusing on the takeoff performance. For a given sizing net thrust and $FPR_{ds}$ of 1.40, fan corrected speed at takeoff was varied for a wide range of values. The design intake total pressure recovery ratio was aligned with the resulting size of the propulsor according to preliminary fuselage boundary layer flow analyses described in Ref. 18. In order to explore the impact of varying nozzle exit area ratios, the ratio $A_{18}/A_{18,ds}$ describing the nozzle exit area relative to its design value was treated as a second study parameter. The result of the study is visualized in Figure 7 showing operating lines of the fan for several nozzle settings. The power at takeoff is displayed at the y-axis and the corresponding net thrust indicated using color contours. Since for the sizing of electric machinery the maximum torque constitutes a key parameter, the torque measured at the fan shaft is included as contour lines.

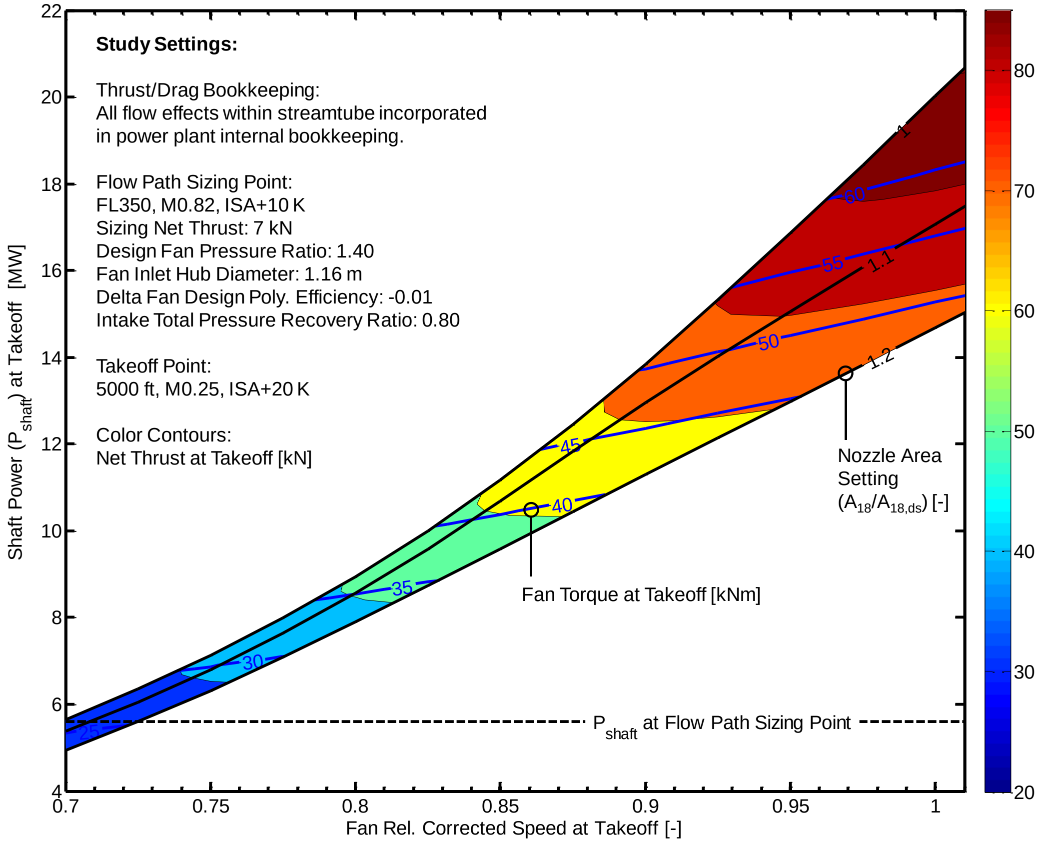


Figure 7: Takeoff study of Fuselage Fan propulsor

As expected, Figure 7 illustrates the strong dependency of the required shaft power with $N_{L,corr}$. As an interesting example, consider the case where $N_{L,corr}$ is reduced such that $P_{shaft}$ reaches the value exhibited at the ToC point. In this case, the reduced power and torque levels would potentially offer substantial benefits with respect to the mass of the electric drive motor connected to the FF. Obviously, in more detailed integrated studies at the overall aircraft level this has to be traded against the reduction of FF takeoff thrust and the cascading effects emanating from the sizing of the associated systems. It is recognized that due to the highly interacting nature of the associated propulsion systems installed on the PFC aircraft the integrated assessment at the vehicular level is necessary to quantify the true efficiency potential of the configuration.

The inspection of varying levels of nozzle area shows that for a given level of net thrust there is potential to reduce the required shaft power. From the perspective of minimizing $P_{shaft}$, the optimum setting of $A_{18}/A_{18,ds}$ is determined by the two primary effects: Depending on the level of $F_N$, the opening of $A_{18}/A_{18,ds}$ triggers a shift in the operating point away from the stall line, thereby resulting in varying fan polytropic efficiencies. Moreover, due to the reducing flow velocities, propulsive efficiency greatly improves with rising nozzle area ratios. As an example, for a takeoff net thrust of 45 kN a power reduction potential of 4.6% is obtained within the assumed boundaries of $A_{18}/A_{18,ds}$. While not critical for the study settings connected to Figure 7, the shift of operating points in addition may improve the fan stability.

# V. Conclusions and Future Work

With intent to explore the design and operational characteristics of the power plants involved in a turbo electrically driven Propulsive Fuselage Concept (PFC), this paper presented a variety of parametric studies on both conventionally installed advanced Geared Turbofan engines with significant power offtakes and the electrically driven Fuselage Fan. For the simulation and comparative evaluation of the power plants, metrics were introduced serving the purpose of describing the power offtake from the Low Pressure (LP) and/or High Pressure (HP) spool in relative terms. In order to establish a suitable basis for design and performance investigations, as a first step, a cycle design study was discussed and best and balanced key cycle parameters including Overall Pressure Ratio and burner exit temperature were identified.

Specifically addressing the extraction of large power offtakes beyond the amounts typical to satisfy the demand of the aircraft subsystems, several parametric studies were discussed in the following. Initially, the amount of power offtake was varied at a typical cruise condition, where firstly only power extraction from the LP spool was considered. Emphasis was placed on discussing the effects emanating from the operational constraints of the associated turbo components on the available operating space. It was established that for all levels of design power offtake the variability in offtake during off-design operation is bounded by several constraints, thus placing limits on the control law governing the power offtake along the mission. In order to relief this circumstance, thereafter, the combined extraction of power from both the LP and HP spool was investigated. Initially, a balanced approach characterized by identical relative power extraction ratios was pursued. A multi-dimensional parametric study conducted at various part power settings showed that the simultaneous extraction yielded significant benefits with regards to extending the operational space available for power extraction. Compared to the case of power extraction from the LP balance only, the constraints proved to be significantly alleviated. Specifically, for the boundary conditions applied for the study, an over-powering capability relative to the design value by a factor of more than two was determined to be feasible. In future work, optimal power offtake strategies identified by means of unified analyses on the PFC main engines and the fuselage propulsor on the overall vehicular level will be investigated. Associated with this is the exploration of alternative main power plant architectures potentially relieving the impact of power offtake on the overall system level. The focus of more detailed investigations should also be on investigating the transient behavior of significant power extraction rates. The identified impact of power offtake on the flow path dimensions will feed into the assessment of system weights, thus allowing for the identification of fuel burn optimality.

In a study dedicated to investigating the takeoff performance and the repercussive effects on the design point characteristics, it was found that the reduction of the power offtake at takeoff has a pronounced effect on the maximum temperate levels and hence the turbine cooling air demand. The implications on cruise performance were highlighted.

Finally, exploratory studies on the design and performance characteristics of the Fuselage Fan power plant were discussed. Based on a parametric study of design fan pressure ratio, the significant impact of intake total pressure recovery ratio – a parameter that is typically impaired in case of propulsors working in the boundary layer – on the overall system design and performance characteristics was signified. By including the trend of a conventionally installed electrically driven fan, it was elucidated in what extent this quantity affects the optimality of specific thrust levels. Also, takeoff performance and the levels of power and torque exhibited at this operating point were discussed under presence of variability in the fan nozzle. In more detailed studies, the performance benefits of a variable area fan nozzle need to be traded against the mass penalty of the associated actuation mechanisms and the additional system complexity introduced. As an alternative approach towards extending the operational space, a fuselage fan featuring variable blade pitch will be investigated.

It was highlighted that due to the highly interacting nature of the associated propulsion systems installed on the PFC aircraft the integrated assessment at the vehicular level is essential to quantify the true efficiency potential of the configuration.

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