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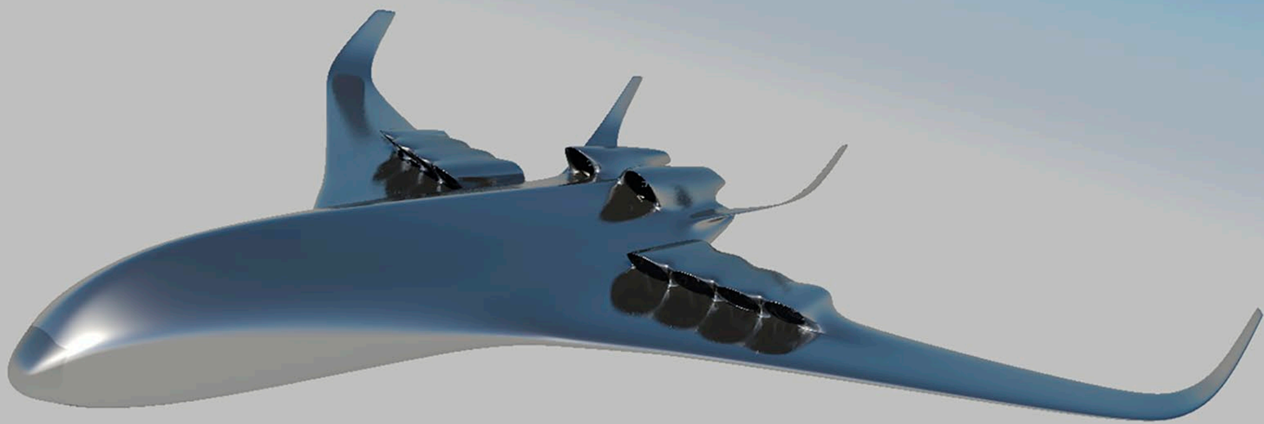
NLR-TP-2021-510 | January 2022

Conceptual design of a blended wing body aircraft with distributed electric propulsion

CUSTOMER: Royal Netherlands Aerospace Centre



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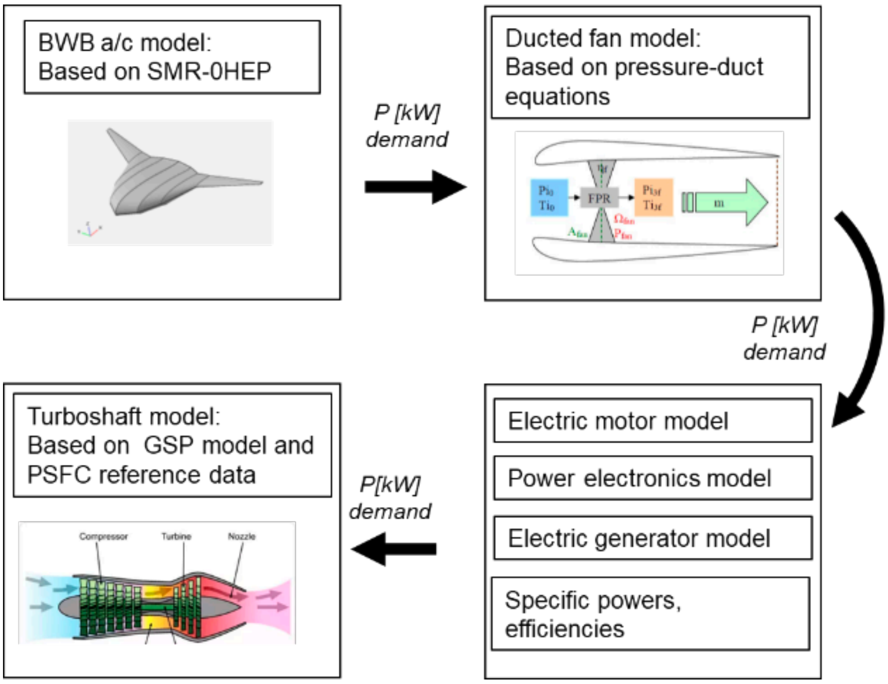

Power train performance and sizing in the conceptual design

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MASS
ducted fans

Problem area

Despite the COVID-19 pandemic global air travel is still expected to rise significantly in the coming decades. At the same time, climate neutral aviation by 2050 is a major objective of the European Green Deal. Therefore, reducing greenhouse gas emissions is one of the main challenges for the development of future commercial aircraft. This calls for ambitious research and disruptive technology solutions, well beyond the continuous improvement of current aircraft technologies. Radical aircraft concepts like blended wing body aircraft, taking advantage of distributed electric propulsion may significantly improve aerodynamic performance and reduce fuel consumption and emissions. But the potential of such concepts including the involved technology still requires substantial research.

Description of work

Royal NLR has investigated the conceptual design of a short-medium range (SMR) aircraft for the 2035 timeframe, using its tool for conceptual aircraft sizing and for mission evaluation (MASS: Mission, Aircraft and Systems Simulation). The design is aimed at a blended-wing-body (BWB) aircraft configuration for 150 passengers, with a maximum range of 2750 NM, and with a typical operating range of 800 NM. A fully turboelectric (TE) power train has been applied to enable a distributed electric propulsion (DEP) configuration. This design study is part of the European Horizon 2020 project IMOTHEP (Investigation and Maturation of Technologies for Hybrid Electric Propulsion) which applies a holistic approach towards design of hybrid electric propulsion (HEP) aircraft. Integrated analyses with models of hybrid electric power train technologies are performed in close connection with propulsion systems and aircraft architectures (see the picture on the previous page). Simplified power train simulation models were applied in this conceptual design study.

Results and conclusions

From the conceptual design study it can be concluded that the BWB with DEP in combination with the TE power train architecture seems a promising approach for reduction of fuel consumption. For the 800 NM typical mission, fuel burn reduction potential up to 33% with respect to the current Airbus A320neo was found. In case of very optimistic technology assumptions this reduction could be even extended to 38%. The large reduction in fuel burn is mainly caused by the lower cruise thrust (because of the improved aerodynamics, compensating the increased weight), the increased propulsive efficiency of the distributed propulsors and the increased thermal efficiency of the turboshaft engine.

Applicability

The conceptual design of the BWB with DEP – with the involved simulation framework - can be used as a basis for further refinement in the following sequential design iterations of IMOTHEP. The design and mission evaluation tool MASS allows for easy integration of model updates, taking advantage of technology studies and involving increasing levels of fidelity.
The ultimate goal is to identify the key enablers and technology gaps that future research will have to bridge, to achieve radically improved HEP aircraft with much lower environmental impact.

GENERAL NOTE
This report is based on a presentation held at the MEA 2021 - More Electric Aircraft Conference, Bordeaux, 20/10/2021.

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Conceptual design of a blended wing body aircraft with distributed electric propulsion

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Abstract

This paper describes the conceptual design investigation for a short-medium range (SMR) aircraft. The design is aimed at a blended-wing-body (BWB) aircraft configuration with distributed electric propulsion (DEP). A fully turboelectric power train has been applied. This design study is part of the EU H2020 project IMOTHEP (Investigation and Maturation of Technologies for Hybrid Electric Propulsion) which applies a holistic approach towards design of hybrid electric propulsion aircraft. Integrated analyses of hybrid electric power train technology are performed in close connection with propulsion systems and aircraft architectures. This paper reports a selection of results of the first design loop in IMOTHEP. The results give a first indication of the potential fuel burn reduction for the BWB configuration in combination with DEP, compared to conventional SMR aircraft. Simplified power train simulation models were applied in this conceptual design loop. In follow-on design loops more refined models and data resulting from the project's technological studies of the power train components will be applied.

List of abbreviations

ANN	Artificial Neural Network
BAS	Baseline
BLI	Boundary Layer Ingestion
BWB	Blended-Wing-Body
CeRAS	Central Reference Aircraft Data System
CON	Conservative
CS	Cooling System
DEP	Distributed Electric Propulsion
DF	Ducted Fan
EIS	Entry Into Service
EM	Electric Motor
FPR	Fan Pressure Ratio
GSP	Gas-turbine Simulation Program
HEP	Hybrid Electric Propulsion
HPT	High Pressure Turbine
H2020	Horizon 2020
IMOTHEP	Investigation and Maturation of Technologies for Hybrid Electric Propulsion
ISA	International Standard Atmosphere
MASS	Mission, Aircraft and Systems Simulation (for HEP analysis)
MTOW	Maximum Take Off Weight
OEW	Operating Empty Weight
PE	Power Electronics
PSFC	Power Specific Fuel Consumption
PTO	Power Take-Off
RAD	Radical
REG	Regional
REF	Reference
SMR	Short-Medium Range
TAS	True Air Speed
TE	Turbo Electric
TLARs	Top Level Aircraft Requirements
TSFC	Thrust Specific Fuel Consumption
TS	Turbo Shaft
TT4	Total Temperature at HPT inlet

Introduction

Despite the COVID-19 pandemic global air travel is still expected to rise significantly in the coming decades. At the same time, climate neutral aviation by 2050 is a major objective of the European Green Deal. Therefore, reducing greenhouse gas emissions is one of the main challenges for the development of future commercial aircraft. This calls for ambitious research and disruptive technology solutions, well beyond the continuous improvement of current aircraft technologies. In the EU H2020 project IMOTHEP (Investigation and Maturation of Technologies for Hybrid Electric Propulsion) [1] the exploration of key technologies for hybrid electric propulsion (HEP) is under investigation.

The IMOTHEP project started in January 2020 and applies a holistic approach towards HEP systems design. In-depth analyses of hybrid electric power train technology are performed in close connection with propulsion systems and aircraft architectures. In the first step, a set of initial aircraft configurations was developed based on top level aircraft requirements and technology assumptions, covering different missions and different levels of technology developments in airframe design. From there, technical specifications - such as the power needs and the operational constraints - are derived for the selection and investigation of the most suitable technologies for the hybrid electric power train and its components. Technological studies will provide refined components' characteristics and performance estimates, which will be synthesized through the aircraft performance analysis in sequential design loops involving increasing level of fidelity. In the end, the assessment of the vehicles' performances, as well as the sensitivity analysis to design parameters, will allow to identify key enablers and measure technology gaps that future research will have to bridge. In addition, an analysis of needs for tools, infrastructures and regulatory adaptations will be provided in order to elaborate the final roadmap.

IMOTHEP considers both regional (REG) aircraft and short-medium range (SMR) aircraft. For both aircraft types, different airframe and propulsion configurations are considered: conservative (CON) and radical (RAD), see Fig. 1.

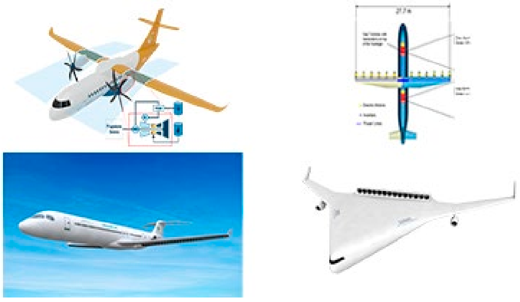

Fig. 1. Concepts under investigation for REG (top) and SMR (bottom), and CON (left) and RAD (right) [1].

In this paper the first results for the radical configuration for the short-medium range aircraft (SMR-RAD) are described. The aircraft concept is aimed at a blended-wing-body (BWB) configuration with distributed electric propulsion (DEP) and is partly based on [2], see Fig. 2.

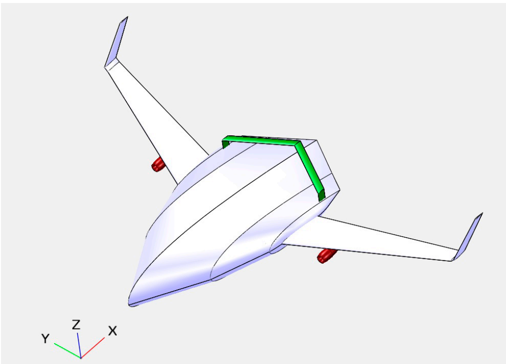

Fig. 2. Illustration of the BWB airframe adopted from [2].

Design approach

The conceptual design process starts from the top level aircraft requirements (TLARs) as formulated in IMOTHEP for the SMR aircraft. The main TLARs considered are:

- Design Range: between 1200 and 2750 NM;
- Typical Range: 800 NM;
- Design Payload: 15.9 t (150 passengers);
- Maximum Payload: 20 t;
- Design Mach number: 0.78.

An aircraft entry into service (EIS) in 2035 is envisaged. Therefore, the performance results of the SMR-RAD concept design – the BWB aircraft with DEP - are to be compared against

- a state-of-the-art SMR aircraft of today: the Airbus A320neo is used as reference aircraft (SMR-REF), slightly tailored to the TLARs;
- a version of the SMR-REF, projected to EIS in 2035, with corresponding technological advancements, but with conventional airframe and propulsion, is used as baseline (SMR-BAS);
- a version of the radical BWB aircraft with conventional propulsion (no DEP or HEP), called SMR-0HEP. For this the BWB configuration was adopted from an earlier study at ONERA [2] with comparable TLARs and with EIS 2035 technology assumptions.

The SMR-RAD concept design was derived by extending and re-sizing the SMR-0HEP, now with DEP. Ideas behind SMR-RAD are:

- An aerodynamically efficient airframe – such as a BWB with high lift over drag ratio - allows for larger Operating Empty Weight (OEW) and for heavier system installation for HEP.
- The potentially large fan area, achieved by many electric propulsors installed on large rear fuselage, with the potential for boundary layer ingestion (BLI) to increase the propulsive efficiency.

Several configurations of HEP architectures can be distinguished. Fig. 3 provides an overview. The SMR-RAD configuration applies the BWB airframe in combination with DEP, provided by a power train based on the all turboelectric architecture (TE).

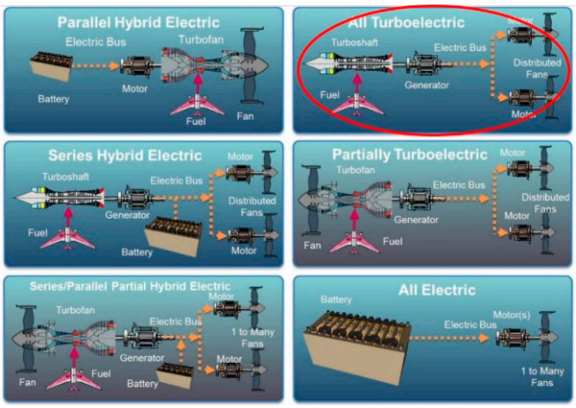

Fig. 3. Overview of HEP architectures, picture adopted from [3].

A multi-fidelity analysis approach is deployed in the incremental design process. During the conceptual design loop simplified models were applied. In follow-on design loops more refined models and data resulting from the technological studies of the power train components will be applied.

Modelling and simulation

The investigations for the SMR-RAD configuration were performed using the NLR tool for conceptual aircraft design and for mission evaluation (MASS: Mission, Aircraft and Systems Simulation for HEP analysis [4]). MASS includes models coming from various other tools, such as for flight mission modelling, airframe modelling, electric components modelling and engine modelling (GSP: Gas-turbine Simulation Program [5]) and predicts fuel and energy consumption and emissions, see Fig. 4. The application of the MASS tool was validated with A320neo data of SMR-REF.

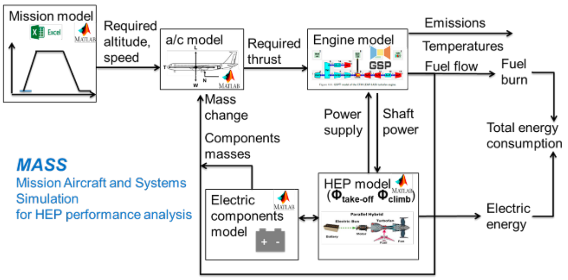

Fig. 4. Illustration of the analysis process in MASS.

For the sizing and assessment of the TE-based power train in SMR-RAD (see Fig. 9) MASS was extended with specific performance models that are described below.

Turboshaft model

A numerical approximation of a turboshaft (TS) model based on the CFM-LEAP [6] was derived, which predicts fuel flow and HPT inlet total temperature (TT4) as function of shaft power demand, altitude, Mach and offtakes:

$$\begin{pmatrix} \dot{m}_{fuel} \\ TT4 \end{pmatrix} = f_{TS}(P_{shaft}, h, M, \dot{m}_{bleed}, PTO) \qquad \text{Eq. 1}$$

Based on previous work [4] a GSP model of the CFM-LEAP engine was applied, with a corresponding multi-dimensional data set for variations in altitude, Mach, thrust, bleed and power offtakes. From this data set the relations in Eq. 1 were derived. The thrust variable is now replaced by (fan) shaft power which is the dominating input variable in Eq. 1. The relation of shaft power with fuel flow and TT4 is illustrated by the scattered data plot in Fig. 5. The scatter is caused by the impact of the other inputs (altitude, Mach, and engine offtakes).

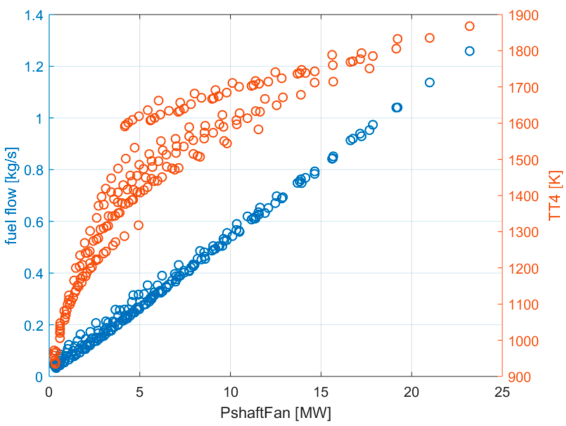

Fig. 5. Scattered data plot of the CFM-LEAP core model, with fuel flow and TT4 as function of shaft power.

Eq. 1 was implemented by fitting an Artificial Neural Network (ANN) through the data, with one hidden layer of size 14. The relative prediction errors were less than 1%, both on the training and test sets. Finally the fuel flow prediction was scaled to 2035 EIS technology estimations, applying a cruise power specific fuel consumption (PSFC) of 0.163 kg/kWh.

Electric power train component models

During the first design loop simplified models were used for the weight and performance of the generator, power electronics (PE), electric motor (EM) and cooling system (CS). Fixed specific power and efficiency estimations for 2035 were used. As these values are still subject to uncertainty both conservative and disruptive technology estimations were applied, see Table 1.

Table 1. Electric power train 2035 technology estimations.

Parameter	**Conservative**	**Disruptive**
EM specific power [kW/kg]	11	17
EM power factor	0.95	0.95
EM efficiency	0.96	0.98
PE specific power [kVA/kg]	20	30
PE efficiency	0.99	0.99
CS specific power [kW/kg]	0.68	0.68
Generator specific power [kW/kg]	20	20
Generator efficiency	0.98	0.98

Ducted fan model

A ducted fan (DF) model was derived from [7] that predicts fan (total) pressure ratio (FPR), DF shaft power and propulsive efficiency as function of thrust demand, true air speed (TAS), altitude and fan area (in this case ducted fan exhaust area):

$$\begin{pmatrix} FPR \\ P_{shaft,DF} \\ \eta_{prop} \end{pmatrix} = f_{DF}(V_{TAS}, h, Fn, A_{exh}) \qquad \text{Eq. 2}$$

The DF is modelled as a duct (see Fig. 6) with air passing through, with perfectly adapted nozzle (i.e. static inlet and outlet pressure are equal), where quasi-isentropic transformation takes place.

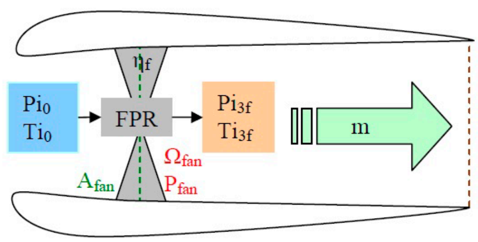

Fig. 6. Schematic depiction of DF model (adopted from [7]).

The corresponding equations (based on the model in

[7]) are given below, for completeness.

$$M_0 = {V_0}/{c_0} \quad \text{Eq. 3}$$
$$Tt_0 = Ts_0\left(1+\frac{\gamma-1}{2}\,{M_0}^2\right) \quad \text{Eq. 4}$$
$$pt_0 = ps_0\left(1+\frac{\gamma-1}{2}\,{M_0}^2\right)^{\frac{\gamma}{\gamma-1}} \quad \text{Eq. 5}$$

With $\gamma = 1.4$ the ratio between the specific heats for air and with V_0, c_0, M_0, Ts_0, Tt_0, ps_0 and pt_0, the true air speed, speed of sound, Mach number, static and total temperature, and static and total pressure respectively, all at the fan inlet condition. c_0, Ts_0, and ps_0 are derived from the altitude using the International Standard Atmosphere (ISA) [8] profile:

$$\begin{pmatrix} c_0 \\ Ts_0 \\ ps_0 \end{pmatrix} = f_{ISA}(h) \quad \text{Eq. 6}$$

The fan polytropic efficiency is approximated by a simplified linear relation with FPR [7]:

$$\eta_{poly} = 0.98 - 0.08(FPR-1) \quad \text{Eq. 7}$$

At the DF outlet the following equations are applied:

$$M_3 = \sqrt{\left(\left(1+\frac{\gamma-1}{2}\,{M_0}^2\right)\cdot FPR^{\left(\frac{\gamma-1}{\gamma}\right)}-1\right)\cdot\frac{2}{\gamma-1}} \quad \text{Eq. 8}$$
$$V_3 = M_3 c_0 \sqrt{\left(FPR^{\left(\frac{\gamma-1}{\eta_{poly}\cdot\gamma}\right)}-1\right)\cdot\frac{1+\frac{\gamma-1}{2}{M_0}^2}{1+\frac{\gamma-1}{2}{M_3}^2}} \quad \text{Eq. 9}$$
$$pt_3 = pt_0 \cdot FPR \quad \text{Eq. 10}$$
$$Tt_3 = Tt_0 \cdot FPR^{\left(\frac{\gamma-1}{\eta_{poly}\cdot\gamma}\right)} \quad \text{Eq. 11}$$
$$Ts_3 = Tt_3/\left(1+\frac{\gamma-1}{2}\,{M_3}^2\right) \quad \text{Eq. 12}$$
$$ps_3 = ps_0 \quad \text{Eq. 13}$$
$$\rho_3 = ps_3/(R\cdot Ts_3) \quad \text{Eq. 14}$$

With V_3, M_3, ρ_3 Ts_3, Tt_3, ps_3 and pt_3, the air velocity, Mach number, air density, static and total temperature, and static and total pressure respectively, all at the fan exhaust condition. The fan exhaust area follows from the net thrust per DF (taking into account $ps_3 = ps_0$):

$$\dot{m} = Fn/(V_3 - V_0) \quad \text{Eq. 15}$$
$$A_{exh} = \dot{m}/(\rho_3 \cdot V_3) \quad \text{Eq. 16}$$

With $\dot{m}$ the air mass flow through the DF, *Fn* the net thrust per DF and A_{exh} the fan exhaust area.
With Eq. 7 – 16 A_{exh} can be calculated as function of FPR and *Fn*. Using numerical approximation these equations were inverted and combined with Eq. 3 – 6 to predict FPR as function of A_{exh}, *Fn*, V_0 and altitude (Eq. 2). Fig. 7 illustrates the relation of FPR with fan A_{exh}, and *Fn* at cruise conditions adopted from the Central Reference Aircraft Data System (CeRAS) [9]. It can be seen that scaling of the DF (with respect to A_{exh} and *Fn*, e.g. with factor 5) results in the same FPR.

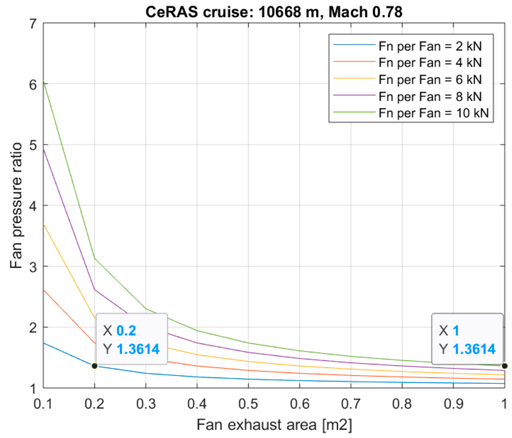

Fig. 7. FPR as function of A_{exh} *Fn* per DF in cruise.

Assuming a fan mechanical efficiency of 1, the DF shaft power and propulsive efficiency are derived using:

$$P_{shaft,DF} = \dot{m}\cdot c_p \cdot (Tt_3 - Tt_0) \quad \text{Eq. 17}$$
$$c_p = \frac{R\cdot\gamma}{\gamma-1} \quad \text{Eq. 18}$$
$$\eta_{prop} = \frac{Fn\cdot V_0}{P_{fan}} \quad \text{Eq. 19}$$

With c_p the specific heat constant for air and *R* the specific gas constant for air. This completes the details of Eq. 2.

Airframe model
The airframe model is inherited from the SMR-0HEP configuration, which incorporates the aerodynamic behaviour and aircraft weights, runs the prescribed mission and predicts the total thrust demand. The cruise drag polar for the optimized conventional configuration in [2] was extended for other flight conditions. Scaled drag polars for different Mach numbers were derived (adopting the relation between Mach and drag coefficient *CD* in [2]). The resulting drag polars are depicted in Fig. 8.

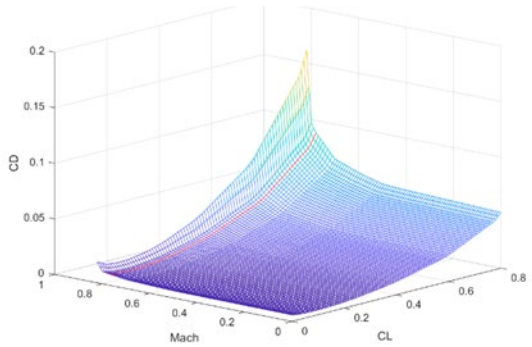

Fig. 8. SMR-RAD drag polars for varied Mach numbers.

Optionally, a very simplified Boundary Layer Ingestion (BLI) model can be applied which applies a small overall drag reduction if this parameter is set.

Using MASS, the models described above were coupled into a chain (see Fig. 9) to perform the sizing and assessment of the TE-based power train in SMR-RAD. In the SMR-RAD design process the power train components are sized iteratively from maximum power levels demanded by the mission. The component efficiencies (see Table 1) are taken into account in this process. The power train mass is derived from the maximum power demand for each component and the applied specific power.

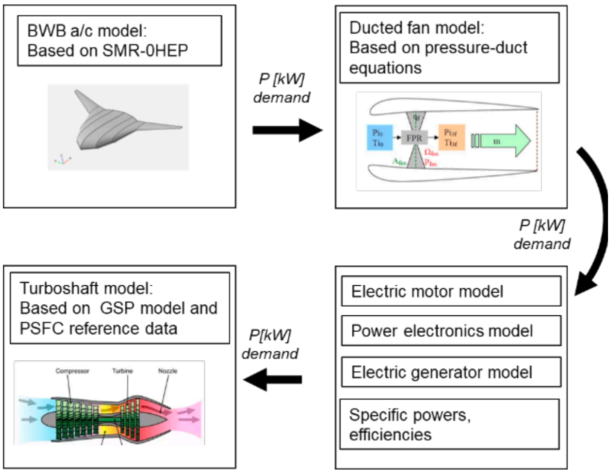

Fig. 9. Power train performance modelling logic (illustrations adapted from [2])

Results

Two variants of the SMR-RAD concept design were investigated:

- SMR-RAD-v1: for the longer design mission (2750 NM)
- SMR-RAD-v2: for the shorter design mission (1200 NM).

In both cases 18 ducted fans - each with an exhaust area of 1 m^2 per fan - were applied and no BLI was assumed. Fig. 10 shows the resulting payload-range diagrams, compared to SMR-0HEP. The SMR-RAD-v2 has a lower Maximum Take Off Weight (MTOW) than SMR-RAD-v1, due to the lower design range. However with the lower MTOW the maximum payload TLAR (20 t) cannot be satisfied. A smaller maximum payload could be considered: e.g. 18 t. Then it follows from Fig. 10 that the maximum payload mission could be performed on a range of 600 NM. But, as the lower design range conflicts with the maximum payload requirement, SMR-RAD-v2 was not further considered in the frame of this study. SMR-RAD-v1 is named SMR-RAD hereafter.

Table 2 summarizes the sizing and performance results for SMR-RAD. The main performance metric is the Typical range fuel burn. It can be seen that all configurations have a lower fuel burn than SMR-REF, as expected. The Typical range fuel burn of SMR-0HEP is slightly higher than SMR-BAS, potentially because of the larger operating empty weight (OEW). The large reduction (32%) in fuel burn of SMR-RAD against SMR-REF is mainly caused by the lower cruise thrust[1] (because of the improved aerodynamics, compensating the increased OEW), the increased propulsive efficiency (due to the increased fan area and low FPR) and the decreased PSFC (17%). The last two are also expressed by the decrease in TSFC of 21%.

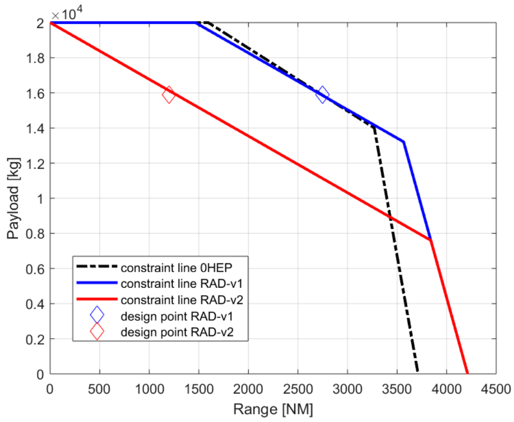

Fig. 10. Payload-Range diagrams of SMR-0HEP, SMR-RAD-v1 and SMR-RAD-v2.

Table 2. Comparison of SMR-RAD (initial design with 18 DFs of 1 m^2 exhaust area) against REF, BAS and HEP0.

	SMR-REF1	**SMR-BAS1**	**SMR-0HEP**	**SMR-RAD Initial**
Design 2750 NM				
OEW [t]	44.3	40.7	47.5	53.6
MTOW [t]	78.1	70.4	77.6	82.8
max Pshaft [MW]	34.1	29.5	29.9	21.9
Typical range 800 NM				
Fn [kN] (mid flight)	39.2	30.6	31.6	33.9
TSFC [g/kNs] (mid flight)	15.6	14.7	14.3	12.4
PSFC [kg/kWh] (mid flight)	0.197	0.175	0.179	0.164
Fuel burn [kg]	4925	3734	3821	3327
Fuel burn relative to REF fuel burn [%]	100%	76%	78%	68%

In addition Fig. 11 provides a simplified view of the design mission, including speed and total shaft power levels. These values can be used as indicated required performance levels in the power train technological studies.

[1] This cruise thrust reduction in relation to SMR-REF is also applicable to SMR-0HEP.

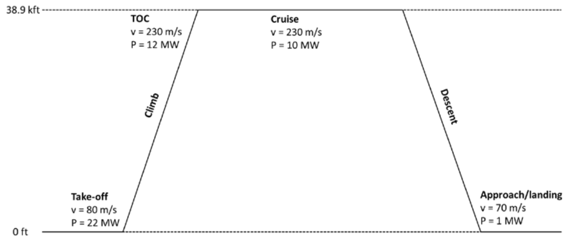

Fig. 11. Schematic view of SMR-RAD 2750 NM design mission, with TAS (v in m/s) and total shaft power (P in MW).

Additionally, several parametric explorations were performed with the initial SMR-RAD design: varying the number of DFs[2], varying the technology assumptions (conservative or disruptive, see Table 1) and assuming a small benefit of BLI or not. Fig. 12 depicts the results. The lowest Typical range fuel burn was found with 26 DFs, although with low sensitivity: choosing a number of DFs between 20 and 30 has little effect on the fuel burn. Furthermore it is remarked that geometrical constraints (e.g. DFs on outer wings or not) are not yet taken into account here.

The benefit that can be expected from BLI is still uncertain. Various values can be found in literature (e.g. [10], [11]) depending on the particular assumptions of the study. As a first guess a 5% drag reduction by BLI was applied for the parametric study. This value is to be refined during subsequent design loops. Applying this drag reduction in combination with the disruptive instead of conservative technology assumptions for the electric power train (see Table 1) results in an additional reduction in fuel burn (i.e. 38% typical range fuel burn reduction with respect to SMR-REF). The results are also summarized in Table 3, applying the same metrics as in Table 2.

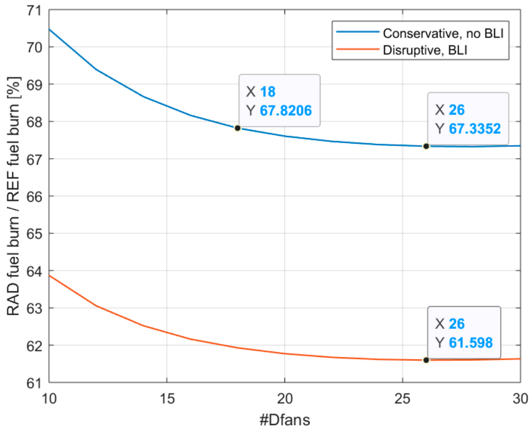

Fig. 12. Impact of number of DFs on Typical range fuel burn relative to SMR-REF, with conservative technology assumptions and with disruptive assumptions, including 5% overall drag reduction by BLI.

[2] A fixed 1 m^2 fan exhaust area was applied as only the total fan area impacts the performance with the current models.

Table 3. Summary of SMR-RAD exploration results.

	SMR-RAD initial: 18 DFs of 1 m^2	SMR-RAD optimized: 26 DFs of 1 m^2	SMR-RAD optimized, disruptive and 5% BLI drag reduction
Design 2750 NM			
OEW [t]	53.6	54.6	52.9
MTOW [t]	82.8	83.8	81.0
max Pshaft [MW]	21.9	21.5	19.2
Typical range 800 NM			
Fn [kN] (mid flight)	33.9	34.3	31.9
TSFC [g/kNs] (mid flight)	12.4	12.4	11.8
PSFC [kg/kWh] (mid flight)	0.164	0.164	0.163
Fuel burn [kg]	3327	3306	3025
Fuel burn relative to REF fuel burn [%]	68%	67%	62%

Conclusion, recommendations and perspective

The SMR-RAD analyses performed in the first design loop conclude that the BWB with DEP in combination with the TE power train architecture seems a promising approach for reduction of fuel consumption. For the 800 NM Typical range mission, fuel burn reductions up to 33% with respect to SMR-REF were found. In case of optimistic assumptions (such as the disruptive scenario in Table 1 in combination with drag reduction by BLI) this reduction could be even extended to 38%. The large reduction in fuel burn of SMR-RAD against SMR-REF is mainly caused by the lower cruise thrust (because of the improved aerodynamics, compensating the increased OEW), the increased propulsive efficiency (due to the increased fan area and low FPR) and the decreased PSFC.

Furthermore it was found that reducing the design range from 2750 NM to 1200 NM has only small impact on the Typical range fuel burn of SMR-RAD (~1%). Because also the max payload requirement is not feasible with the short design range variant (SMR-RAD-v2), this variant was not further analyzed.

The SMR-RAD configuration resulting from the first design loop still has limitations and uncertainties which

are to be improved during next design loops:
The DF analysis was based on simplified modelling. For instance, no additional drag was calculated for the DF. Also no BLI was taken into account, except during the exploration where the impact of assuming a 5% drag reduction was applied. It is expected that improved aerodynamic and DF models provided by higher fidelity analyses will decrease these uncertainties.
Further aerodynamic analysis of the BWB airframe will be needed to improve the drag polars and to optimize the configuration.
Simplified models were used for the power train sizing, based on the specific power and efficiency values. Cabling aspects were not considered yet. It is expected that more detailed electric component models (e.g. with shaft speed, power, voltage or temperature dependencies) will provide more insight into the feasibility of the current power train sizing.
The current turboshaft model was derived from the engine core behavior of the GSP CFM-LEAP1A model. A more detailed TS model, would make the SMR-RAD analysis more accurate. Such model is important as it directly impacts the Typical range fuel burn.
The application of a battery was not analyzed during this design loop. It is not expected currently that such extension will benefit to SMR-RAD in combination with TE, because batteries have much lower specific power than generators. However, alternative HEP architectures for SMR-RAD could still be further investigated during next design loops.

In the following sequential design loops of IMOTHEP the SMR-RAD design will be further refined, taking advantage of technological HEP design studies and involving increasing levels of fidelity. The ultimate goal is – together with the other aircraft configurations under study - to identify the HEP key enablers and technology gaps that future research will have to bridge.

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