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Conceptual design study for a radical short-medium range hybrid aircraft

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Abstract
The European research project IMOTHEP (Investigation and Maturation of Technologies for Hybrid Electric Propulsion) explores key technologies for hybrid electric propulsion in close relation with developments of aircraft mission and configuration. This paper presents the conceptual level design investigations on radical aircraft and propulsion configurations for short-medium range missions. A blended-wing-body configuration with turbo-electric powertrain and distributed electric propulsion is investigated using the NLR tool MASS. For the design, representative top-level aircraft requirements have been defined in IMOTHEP and the reference aircraft for the assessment of potential benefits is based on the A320neo aircraft.

1. Introduction

The further reduction of greenhouse gas emissions is essential for aviation to accommodate the expected increase in air travel and at the same time to pursue its service to society and environment. This calls for ambitious research and disruptive technology solutions, well beyond the continuous improvement of current aircraft technologies. In the European Horizon 2020 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. This has to be addressed in close relation with developments of aircraft mission and configuration, to derive relevant specifications for the investigation of electric components, such as the power needs and the operational constraints. This interrelation in IMOTHEP between the integrated design on aircraft vehicle level and the developments of key technologies for HEP components is illustrated in Figure 1.

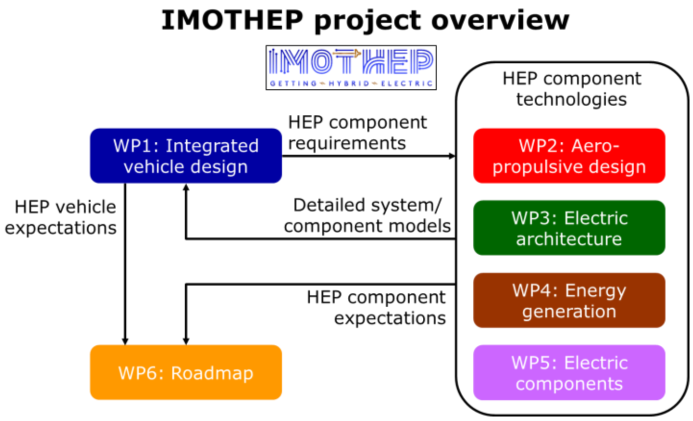

Figure 1: Global overview of the IMOTHEP project, illustrating the interrelation between the integrated design on aircraft vehicle level and the developments of HEP components technologies.

As part of the IMOTHEP project's activities on integrated vehicle design, conceptual level design investigations are executed on various aircraft configurations. These configurations are targeted for missions that contribute significantly to unwanted aviation emissions, i.e. regional (REG) missions and short-medium range (SMR) missions. For both mission types, different types of aircraft- and propulsion configurations are considered: conservative (CON) and radical (RAD). The conservative configurations include moderate technology developments without substantial design changes in the airframe. The radical configurations include more advanced technology developments in combination with unconventional airframe design. For the radical (RAD) configuration for the short-medium range

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(SMR) mission, in particular, a blended-wing-body (BWB) configuration with turbo-electric (TE) powertrain and distributed electric propulsion (DEP) is investigated.

The conceptual design investigations are based on representative top-level aircraft requirements (TLARs) that have been defined in the IMOTHEP project by the industrial airframers who are partners in IMOTHEP. The reference aircraft for the SMR mission is based on the A320neo aircraft, slightly adapted to comply with the IMOTHEP TLARs for SMR. The design objectives for the conceptual investigations are based on the IMOTHEP project targets. These project targets are expressed as criteria for emission reductions. These criteria are set for all design studies and are based on the ambition to achieve 10% more reduction than the targets that were set for 2035 in the European research program Clean Sky 2 (CS2) [2]. This means for IMOTHEP a reduction of 40% in CO2 emissions for SMR aircraft in comparison with 2014 State of Art [1].

The NLR investigations for the SMR-RAD configuration are done using the NLR tools for conceptual aircraft design and for mission evaluation MASS (Mission, Aircraft and Systems Simulation for HEP analysis) [3]. MASS includes models coming from various other tools, such as for flight mission modelling, aircraft modelling, electric components modelling and engine modelling (e.g. as provided by GSP: Gas-turbine Simulation Program [4]) and predicts fuel and energy consumption and emissions. This paper presents the conceptual level aircraft design investigations of HEP architectures for the SMR-RAD configuration. From these investigations, the main results for fuel consumption, emissions and propulsive equipment sizing for the BWB airframe in combination with a power train based on the all TE architecture are given.

2. Approach and Methods

In the IMOTHEP project, the conceptual level design evaluations for each of the aircraft configurations (i.e. the conservative (CON) and radical (RAD) configurations for the regional (REG) and short-medium range (SMR) missions) are executed in the same way according to the overall IMOTHEP design logic. All the aircraft design studies must comply with the TLARs that are defined in the project, separately for the REG and for SMR. The overall aircraft design (OAD) approach and tools that are operational at the project partners, are used for the modelling of aircraft and HEP components. Fast modelling methods are used to rapidly assess and compare the different aircraft configurations and propulsion options. The same technology assumptions on HEP components are consistently used in the various configuration studies. Specialised partners from industry and research provide the specific inputs for the HEP components in the power train, like advanced or simplified models or estimates of performances and masses for the different components and assumptions of technology developments in 2035.

The aircraft level conceptual design activities are executed by different partners of the IMOTHEP project:

- BHL (Bauhaus Luftfahrt, Germany) focus on the regional-conservative (REG-CON) configuration;
- DLR (German Aerospace Centre, Germany) focus on the regional-radical (REG-RAD) configuration;
- ONERA (French Aerospace Lab, France) focus on the short-medium-range-conservative (SMR-CON) configuration;
- NLR (Netherlands Aerospace Centre, Netherlands) focus on the short-medium-range-radical (SMR-RAD) configuration.

The different partners' tools are used for the study of the radical and conservative concepts. The quality and consistency of these tools is ensured by benchmarking the tools on the reference and baseline configurations. The actual HEP design studies yield the intended HEP aircraft configuration. This implementation of the IMOTHEP design logic is expressed in the Figure 2 below.

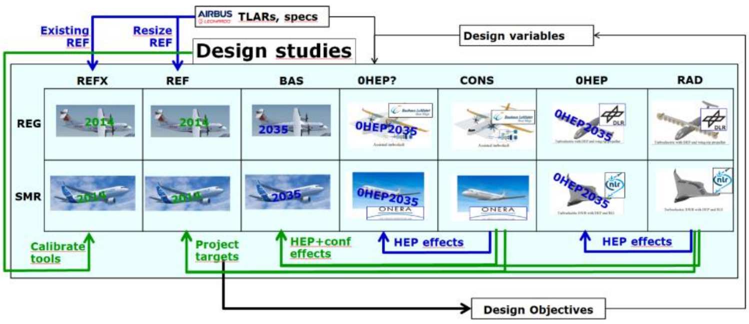

Figure 2: Illustration of the various configurations and their variants, and the design evaluations and assessments envisaged in the IMOTHEP design logic.

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Besides the CON and RAD configurations, also several other configurations for the REG and SMR missions must be evaluated in order to make the right assessments according to the IMOTHEP design logic. These assessments are mentioned and illustrated by the green and blue arrows in the bottom of the Figure 2. The other configurations are the REFX, REF, BAS, and 0HEP configurations, as also illustrated in Figure 2. Each of the considered configurations are motivated and explained as follows:

- REFX = existing reference aircraft, operational in 2014, i.e. ATR42 for REG and A320neo for SMR:
    - intended for calibration (or validation) of all partners' tools against aircraft level performance values that are provided by the airframers in the IMOTHEP consortium.
- REF = reference aircraft, i.e. with 2014 technologies assumptions, but adapted to comply with IMOTHEP TLARs:
    - intended for assessment of the resulting performance values of the RAD and CON aircraft with HEP powertrains in comparison to 2014 state of the art aircraft performance.
- BAS = baseline aircraft, i.e. the same as REF but with 2035 technology assumptions:
    - intended for assessment of the resulting performance values of the RAD and CON aircraft with HEP powertrains in comparison to the performance of 2035 technologies in conventional aircraft powertrains.
- CON = conservative aircraft configuration with HEP and with 2035 technology assumptions:
    - intended for evaluation and assessment of the resulting performance values for the CON aircraft with HEP powertrains for the REG and SMR missions.
- RAD = radical aircraft configuration with HEP and with 2035 technology assumptions:
    - intended for evaluation and assessment of the resulting performance values for the RAD aircraft with HEP powertrains for the REG and SMR missions.
- 0HEP = aircraft with an innovative architecture (e.g. blended-wing-body (BWB) for SMR) but with conventional turboprop or turbofan propulsion, with no hybridization:
    - intended for assessment of the isolated configuration effects. This 0HEP is mainly relevant for the RAD configurations; their airframe configuration stems from the considered HEP aircraft. For the CON configurations, this 0HEP has appeared to be not relevant because it has no substantial difference with BAS.

The Table 1 below gives an overview of all these configurations that are considered in the IMOTHEP design logic, and the technologies, or requirements, that they cover.

Table 1 : All the configurations in the IMOTHEP design logic, and the technologies or requirements that they cover.

Technologies included:	REFX	REF	BAS	CON	RAD	0HEP
Existing operational reference aircraft	✓					
With compliance to IMOTHEP TLARs		✓	✓	✓	✓	✓
With 2035 technology assumptions			✓	✓	✓	✓
With HEP powertrain				✓	✓	
With radical aircraft configuration					✓	✓

With this implementation of the IMOTHEP design logic (Figure 2) the concept design studies of the various aircraft configurations are executed. The specifications from the airframers for the reference configurations (REF) and for the TLARs are key inputs for these design studies. The full list of TLARs is long and includes several detailed values for operational requirements and is beyond scope of this paper. The main TLARs to be satisfied are summarized in the following Table 2, where all given values shall be considered as lower limit.

Table 2: The main TLARs considered in the concept design studies in IMOTHEP.

TLARs	REG	SMR
Design Range	400-600 NM (741-1111 km)	1200-2750 NM (2222-5093 km)
Typical Range	200 NM (370 km)	800 NM (1482 km)
Number of PAX (Design Payload)	40 (4240 kg)	150 (15900 kg)
Design Cruise Mach number	0.4 [0.4, 0.48]	0.78 [0.78, 0.82]
Seat pitch	30 in (0.762 m)	30 in (0.762 m)

It must be noted that the bandwidths specified for the design range and cruise Mach number are considered in IMOTHEP in order to account for certain flexibility in the aircraft capabilities. The reason is that some variation of a certain TLAR (e.g. the design range) may result in substantial benefits for the design objective (i.e. Typical Range

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mission fuel burn). These variations in TLARS are assessed to some extent through sensitivity evaluations. Also, although the Typical Range is listed in the Table 2, it is not a TLAR per se but it is included here because it represents the range for which several additional requirements shall be fulfilled and for which the design objectives are evaluated. These requirements and objectives will be further explained below.
The IMOTHEP project's targets are the basis for the design objectives in the concept design studies, as indicated in Figure 2. The IMOTHEP project targets are based on the targets that were set for 2035 in Clean Sky 2 (CS2) [2], with an additional 10% reduction. The main target that is considered in IMOTHEP is the reduction of CO2 emissions [1], which is directly proportional to fuel consumption. This leads to the following fuel reduction targets for IMOTHEP:

- for REG: -50% fuel consumption for Typical Range missions.
- for SMR: -40% fuel consumption for Typical Range missions.

All values given here are in comparison with 2014 State of Art aircraft. Technology assumptions for the different sub-systems in the various configurations are targeted at technology readiness level (TRL) 6 in 2035.
This paper deals mainly with the concept design study of the SMR-RAD configuration, which is executed according to the IMOTHEP design logic. Besides the SMR-RAD, also the SMR-REFX, -REF, -BAS and -0HEP configurations must be evaluated in order to make the intended assessments. This concept design study of the SMR-RAD and its related configurations will be further elaborated in the following sections.

3. Aircraft configurations for short-medium range (SMR)

3.1 Simulation tools for conceptual aircraft design and mission evaluation

The investigations for the SMR-RAD configuration and its variants are done using the NLR tool for conceptual aircraft design and mission evaluation: MASS (Mission, Aircraft and Systems Simulation for HEP analysis, [3]) (Figure 3). 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 [4]). Besides for sizing of aircraft and powertrain components, MASS can be used for prediction of fuel and energy consumption and emissions for a given flight. Any HEP architecture can be modelled in MASS, including parallel HEP as illustrated in the schema in Figure 3, but also series HEP and TE architectures.

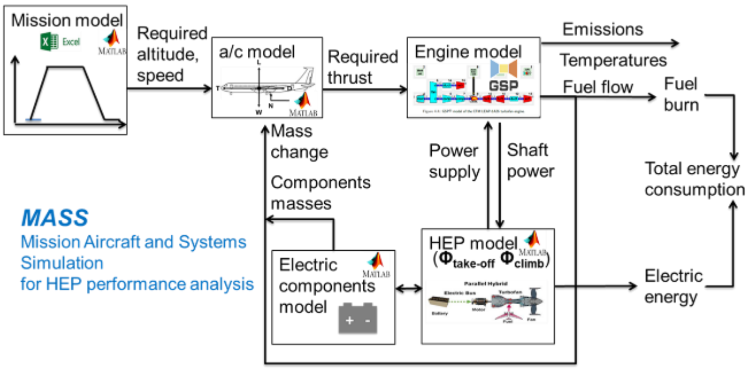

Figure 3: Illustration of the modelling and analysis process in MASS [3].

3.2 Calibration against existing reference aircraft (SMR-REFX)

The calibration in IMOTHEP of the MASS tool is based on the evaluation of the existing reference configuration for SMR (SMR-REFX), which is the A320neo with its 2014 technologies as it is operational in service. The comparison is based on fuel consumption figures provided by Airbus for the Typical Range mission of 800 NM (1482 km). For the NLR evaluations of the SMR-REFX configuration, the aircraft model of the A320neo and engine model of the CFM-LEAP-1A turbofan are based on existing models available at NLR [3].

Assumptions for aircraft and mission

For the evaluations of the SMR-REFX configuration, the following assumptions are applied. These assumptions are also used for the evaluations of the SMR-REF, SMR-BAS, SMR-0HEP and SMR-RAD configurations. Some assumptions will be slightly modified for some of the configurations, which will be explained when relevant.

- Payload:

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  - According to the TLARs, the design-payload is 150 PAX@106 kg=15900 kg. The maximum payload is 20000 kg=189 PAX@106 kg, but that is not used in the REFX evaluations, only in some specific evaluations of the other configurations. The design-payload of 150 PAX@106 kg=15900 kg will be used in all SMR evaluations.
- Range:
  - The Typical Range mission at design-payload is evaluated, in which the distance on ground between take-off and landing is 800 NM (1482 km).
- Atmosphere:
  - In all mission evaluations, international standard atmosphere (ISA) [5] is assumed.
- Take-off and landing:
  - In all mission evaluations, take-off and landing are assumed at airports on sea level.
- Taxi:
  - The mission evaluation includes taxiing at airports, in which the taxi definitions given in CeRAS [6] are adopted: taxi-out is defined as 540 s taxiing at constant speed of 30 kts (15.4 m/s) yielding 8.33 km, and taxi-in is defined as 300 s taxiing at constant speed of 30kts (15.4 m/s) yielding 4.63 km. The total taxi distance results in 12.96 km and will be used in all SMR-RAD evaluations.
- Fuel burn:
  - The actual mission fuel burn figure that is calculated in NLR's mission evaluation is the "Block-off/Block-on fuel", i.e. trip-fuel + taxi-fuel. Here trip-fuel is the fuel consumption from brake release on takeoff at the departure aerodrome to the landing touchdown at the destination, and taxi-fuel is the fuel consumption during taxi-out and taxi-in. The "Block-off/Block-on fuel" will be evaluated in all SMR-RAD evaluations of NLR.
- Reserve-fuel:
  - Definitions given in CeRAS for reserve-fuel are as follows: reserve-fuel is the sum of contingency fuel, alternate fuel, final reserve fuel, additional fuel, extra fuel, i.e. total fuel on board minus trip-fuel and taxi-fuel. The reserve-fuel needed for the SMR Typical Range mission is approximately 3000 kg. Therefore, for simplification, the assumption in NLR's mission evaluation is to use a fixed reserve-fuel of 3000 kg, which will be used in all SMR-RAD evaluations of NLR.
- Cruise:
  - Definitions given in CeRAS for SMR cruise condition is Mach 0.78 flight speed at an initial altitude of 35 kft (10.7 km).
- Power-offtake (PTO):
  - Mechanical power off-takes from the low-pressure turbine (LPT) shaft, for power supply to non-propulsive on-board systems like pumps and generators, are taken into account. CeRAS applies a fixed PTO of 52 kW per engine. This value (104 kW in total) will be used in all SMR-RAD evaluations of NLR.
- Bleed-offtake:
  - Bleed air off-takes from the low-pressure and high-pressure compressors (LPC, HPC), for power supply to non-propulsive on-board systems like ECS and IPS, are taken into account. CeRAS applies a fixed bleed off-take of 0.98 kg/s per engine. This value (1.96 kg/s in total) will be used in all SMR-RAD evaluations of NLR.

With these assumptions, the existing reference configuration SMR-REFX has been evaluated with the NLR MASS tool for the Typical Range mission. The key results and conclusions from the evaluations of the SMR-REFX configuration are the following:

1. The SMR-REFX evaluation results in a Typical Range mission fuel burn of 4855 kg. This is an acceptable small deviation of less than 5% from the reference value for the Typical Range mission fuel burn.
2. From this result it is concluded that the MASS tool is sufficiently calibrated as conceptual design tool for the SMR-RAD study.

3.3 Evaluation of the reference SMR aircraft (SMR-REF)

For the evaluations of the SMR-REF configuration, the same aircraft and engine models are used as for the REFX configuration, i.e. the models of A320neo and CFM-LEAP-1A. But for the SMR-REF, the aircraft model is re-designed to comply with the IMOTHEP TLARs. The assumptions for aircraft and mission as described above for the SMR-REFX are also used for the SMR-REF evaluations.

TLARs

The re-design of the SMR-REF aircraft is simplified to the key design variable wing area (S_w), which is determined such that the mission fuel is minimized and the aircraft complies with the following TLARs:

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1. Wing span: must be lower than 36 m.
2. Payload:
   a. Design payload: is based on 150 PAX, i.e. 150 x 106 kg = 15900 kg.
   b. Maximum payload: 20 t = 20000 kg.
3. Design range: the bandwidth for the range, as indicated in Table 2, is considered as follows:
   a. a configuration Ref1 is defined that shall be able to fulfil a mission with a range of 2750 NM (i.e. 5093 km) at the design payload (i.e. 15900 kg).
   b. a configuration Ref2 is defined that shall be able to fulfil a mission with a range of 1200 NM (i.e. 2222 km) at the design payload (i.e. 15900 kg).
4. Design mission: an Initial Cruise Altitude (ICA) of 33 kft (10.06 km) at ISA+10 conditions shall be fulfilled:
   a. this is assumed to be fulfilled by the cruise altitude of 35kft (10.7 km) at ISA conditions that is used in all design missions, which is for density approximately equivalent to 33 kft (10.06 km) at ISA+10.
5. Take-off field length (TOFL): must be lower than 2200m at ISA+15 conditions:
   a. this is assumed to be fulfilled by the approximately equivalent TOFL of less than 2000 m at ISA conditions, which is used in all missions.
6. Climb time: must be lower than 35 min from 1500 ft (0.46 km) to 33kft (10.06 km) at ISA+10 conditions:
   a. this is assumed to be fulfilled by the approximately equivalent climb time of less than 35 min from 1500ft (0.46 km) to 35kft (10.7 km) at ISA conditions, which is used in all missions.
7. Approach speed: must be lower than 138 kts (71 m/s) in all missions.
8. Landing distance: must be lower than 1800 m in all missions.
9. Typical range:
   a. 800 NM (1482 km) at the default cruise conditions (Mach 0.78, 35 kft (10.7 km); CeRAS [6]).
   b. Additional Typical range missions are defined:
      i. default cruise conditions for max payload = 20 t (20000 kg)
      ii. default payload at high cruise speed conditions: Mach 0.82, 35 kft (10.7 km)
      iii. default payload, speed at high cruise conditions: 39 kft (11.9 km), with top of climb (TOC) climb rate of at least 100 ft/min (0.5 m/s) at ISA conditions.
10. One engine inoperative (OEI): SMR-REF shall be able to fulfil a mission at maximum take-off mass (MTOM) including take-off (TO) and climb until 15 kft (4.6 km) at a climb rate greater than 100 ft/min (0.51 m/s).

Design constraints

For all missions that shall comply with these TLARs, several design constraints are checked for violations in order to assess the feasibility of the design. These design constraints are based on the following criteria: the maximum allowable values of C_L (aircraft level lift coefficient), F_n (aircraft level net thrust force), N_1 (turbofan engine low pressure spool rotational speed) and T_{T4} (turbofan engine high pressure turbine inlet temperature) shall not be exceeded. The allowable values for N_1 and T_{T4} are based on or derived from EASA Type certification sheet of the CFM-LEAP-1A engine [7]. The design constraints are determined as follows:

- C_L: the values of C_L during the mission that are found from the MASS simulations shall always remain below the maximum possible C_L value. Because the current conceptual modelling does not include high fidelity methods to calculate the maximum possible C_L value, we estimate this value from the A320neo aircraft characteristics and mission specifications. This maximum possible C_L value occurs in the low speed mission segments of take-off and landing.
  - For rotation at take-off, the speed of A320neo shall be 150 kts (77.2 m/s) or more [8]. For straight-and-level flight at MTOM (i.e. 79 t (79000 kg) for the A320neo in REF) this leads to $C_L = \frac{MTOM \times g}{S_{wing} \times {}^1/_2 \rho v^2} = 1.73$. For the rotation we assume that 10% extra lift is needed for change of flight path angle, yielding $maxC_L = 1.9$.
  - For landing, we assume a final approach speed for A320neo of at least 131.5 kts (67.6 m/s) at maximum landing mass (MLM = 67400 kg [8]. For straight-and-level flight this leads to $maxC_L = \frac{MLM \times g}{S_{wing} \times {}^1/_2 \rho v^2} = 1.92$. The SMR TLARs require an approach speed v_{app} <138 kts (71 m/s), so v_{app}=137 kts (70.5 m/s) is used in all missions.
  - With these estimated $maxC_L$ values, the variations of the wing area (i.e. the key design variable) shall be made such that the design constraint $C_L < maxC_L$ is always fulfilled.
- F_n (net thrust force): the maximum take-off thrust of 120 kN per engine according to CFM-LEAP-1A type certificate [7] shall never be exceeded.
- N_1 (low pressure spool rotational speed): N_1 shall remain below 101% of the maximum design speed according to CFM-LEAP-1A type certificate [7].
- T_{T4} (high pressure turbine inlet temperature): T_{T4} shall remain below 1850 K.

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SMR-REF design evaluations

Two separate REF configurations are considered for the different design ranges: the Ref1 configuration for the long design range of 2750 NM (5093 km) (TLARs 3.a in the list above) and the Ref2 configuration for the short design range of 1200 NM (2222 km) (TLARs 3.b in the list above). For both the Ref1 and Ref2 configurations, the re-design of the wing area is performed by checking the design constraints described above for the various missions as prescribed by the TLARs. Both the Ref1 and Ref2 configurations are used for the assessment of the SMR-RAD configuration.

The key results and conclusions from the evaluations of the SMR-REF configuration are the following:

1. For the SMR-Ref1 configuration, with maximum design range of 2750 NM@35 kft (5093 km@10.7 km), the wing area cannot be reduced below 123 m^2. The critical case is the failure case “OEI at TO with MTOM”.
2. For the SMR-Ref1 configuration the total mission fuel burn for the Typical Range mission is **4855 kg**.
3. For the SMR-Ref2 configuration, with maximum design range of 1200 NM@35 kft (2222 km@10.7 km), the wing area can be reduced to 113 m^2. The critical case is the mission evaluation for the TLARs of maximum payload (20000 kg).
4. For the SMR-Ref2 configuration the total mission fuel burn for the Typical Range mission is **4744 kg**.

3.4 Evaluation of the baseline SMR aircraft (SMR-BAS)

Also, for the evaluations of the SMR-BAS configuration, the aircraft model of the A320neo and engine model of the CFM-LEAP-1A turbofan are based on the existing models available at NLR. The assumptions for aircraft and mission and the TLARs and the design constraints as described above for the SMR-REFX and SMR-REF are also used for the SMR-BAS evaluations.

2035 technologies assumptions

The SMR-BAS models of aircraft and engine are first updated for 2035 aircraft EIS technologies and then re-designed for the IMOTHEP TLARs. This re-design of the SMR-BAS aircraft is also simplified to the key design variable wing area. The 2035 technologies are based on the assumptions described in Table 3.

Table 3: The 2035 aircraft EIS technologies and improvement assumptions for SMR-BAS, adopted from [9].

Aircraft Component	Improvement Measure	Affected parameter
Turbofan engine	Higher BPR, components improvement	PSFC -8,5% wrt NEO TSFC -10% wrt NEO T/W +3,7% wrt NEO Wetted area to be adjusted
Wing	Lightweight material	Mass -10% wrt 2014
Fuselage	Lightweight material	Mass -5% wrt 2014
Landing gear	Lightweight material	Mass -15% wrt 2014
Pylons	Lightweight material	Mass -5% wrt 2014
Furnitures (seats, galleys, catering,…)	Lightweight materials	Mass -25% wrt 2014
Aerodynamics	Morphing wing, turbulent coating, shock control, optimized winglet	+3.3% on L/D -5% on CD0 wing -50% on CD wave -10% on CD induced (all wrt. 2014).

These 2035 technologies assumptions were implemented in the SMR-BAS models in the following way:

- 2035 in comparison to 2014 turbofan engine assumptions:
    - Power specific fuel consumption (PSFC) -8.5% in comparison to NEO: apply 8.5% reduction on fuel consumption calculated with the 2014 CFM-LEAP-1A engine model. This has been implemented in the SMR-BAS models as a thrust specific fuel consumption (TSFC) reduction of 10%, accounting for the 8.5% reduction on shaft-power generation and additional 1.5% on thrust generation due to fan propulsive efficiency improvements.
    - Thrust-over-weight ratio (T/W) +3.7% in comparison to NEO: apply 3.7% reduction on engine mass, i.e. ~0.037*3000 kg=111 kg per engine, so 222 kg decreased mOE has been implemented in SMR-BAS models.
    - Wetted area to be adjusted: because UHBR engines have larger fan diameter but shorter length, the change in nacelle wetted area is a bit speculative. Therefore, no change in nacelle wetted area has been implemented in SMR-BAS models.

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- 2035 in comparison to 2014 component mass assumptions:
  - Wing mass -10%: i.e. ~0.1*8800 kg=880 kg decreased mOE has been implemented in SMR-BAS models.
  - Fuselage mass -5%: ~0.05*8800 kg=440 kg decreased mOE has been implemented in SMR-BAS models.
  - Landing gear mass -15%: ~0.15*2200 kg=330 kg decreased mOE has been implemented in SMR-BAS models.
  - Pylons mass -5%: ~0.05*650 kg=32.5 kg per pylon, so 65 kg decreased mOE has been implemented in SMR-BAS models.
  - Furnitures mass -25%: ~0.25*2440 kg=610 kg decreased mOE has been implemented in SMR-BAS models.
- 2035 in comparison to 2014 aerodynamics assumptions:
  - +3.3% on L/D: 3% reduction applied on CD has been implemented in SMR-BAS models.
  - -5% on CD0 wing: Decrease CD0_wing by 5% has been implemented in SMR-BAS models.
  - -50% on CD wave: Decrease CD_wave by 50% has been implemented in SMR-BAS models.
  - -10% on CD induced: Decrease CD_induced by 10% has been implemented in SMR-BAS models.

These 2035 technologies assumptions yield a total mass reduction on aircraft level (i.e. decreased mOE) of 2547 kg.

SMR-BAS design evaluations

Just like for the SMR-REF, also for the SMR-BAS two separate BAS configurations are considered for the different design ranges: the Bas1 configuration for the long design range of 2750 NM (5093 km) (TLARs 3.a in the list above) and the Bas2 configuration for the short design range of 1200 NM (2222 km) (TLARs 3.b in the list above). For both the Bas1 and Bas2 configurations, the re-design of the wing area is performed by checking the design constraints described above for the various missions as prescribed by the TLARs. Both the Bas1 and Bas2 configurations are used for the assessment of the SMR-RAD configuration. It is found that for SMR-BAS the Typical Range mission results do not depend on the design range requirement, because the maximum payload requirement is the sizing condition. The key results and conclusions from the evaluations of the SMR-BAS configuration are the following:

1. For the SMR-Bas1 configuration, with maximum design range of 2750 NM@35 kft (5093 km@10.7 km), the wing area can be reduced to 108 m^2. The critical case is the mission evaluation for the TLARs of maximum payload (20000 kg).
2. For the SMR-Bas1 configuration the total mission fuel burn for the Typical Range mission is **3773 kg**.
3. For the SMR-Bas2 configuration, with maximum design range of 1200 NM@35 kft (2222 km@10.7 km), the wing area can be reduced to 108 m^2. The critical case is the mission evaluation for the TLARs of maximum payload (20000 kg).
4. For the SMR-Bas2 configuration the total mission fuel burn for the Typical Range mission is **3773 kg**.

3.5 Evaluation of the 0HEP SMR aircraft (SMR-0HEP)

SMR-0HEP BWB concept design

For the evaluations of the SMR-0HEP configuration a Blended Wing Body (BWB) aircraft concept was adopted from an earlier study at ONERA [10], see Figure 4. In this study, comparable TLARs and EIS 2035 technology assumptions were used as in the IMOTHEP SMR evaluations. In the SMR-0HEP evaluations, the inputs for the BWB aircraft definition are taken from ONERA's BWB concept study [10], which investigates the optimized BWB aircraft concept with conventional propulsion by two CFM-LEAP-1A turbofan engines with 2035 EIS technology assumptions. Because the TLARs that were used in ONERA's BWB concept study are not exactly the same as the TLARs in IMOTHEP, the SMR-0HEP design evaluations may yield constraints that are violated. Therefore in the SMR-0HEP evaluations, similar design variations are considered as for the REF and BAS configurations, i.e. only based on the variation of wing area.

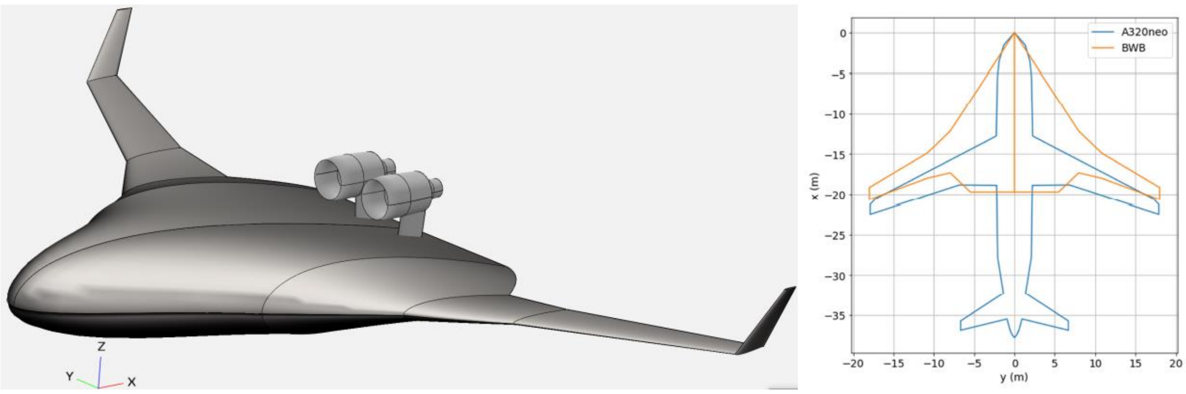

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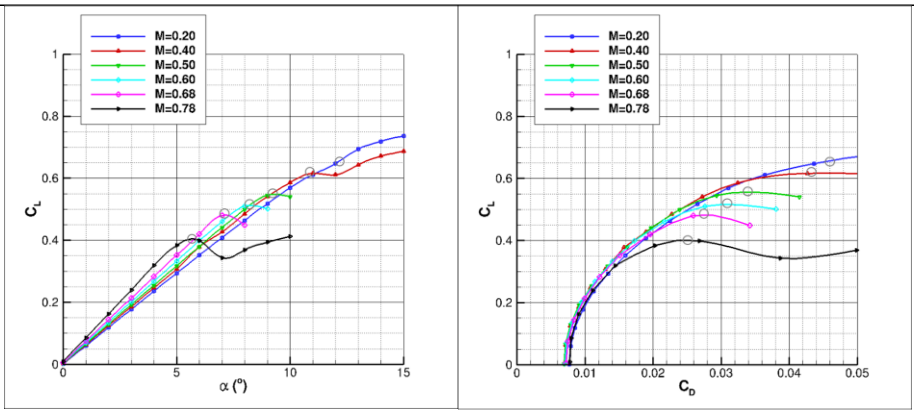
Figure 4: Illustration of the BWB SMILE aircraft geometry based on an ONERA concept study [10]. This geometry is the basis for the SMR-0HEP configuration. The figure presents the 3D shape with 2 CFM-LEAP-1A engines mounted on the rear center body (left picture) and the approximate planform (right picture, orange contour, in comparison with A320neo approximate planform in blue contour).

The main input parameters for the evaluations with NLR's MASS tool are the global aircraft sizing data like shape and global dimensions, masses, drag polars. The BWB shape and global dimensions are adopted from [10] and are illustrated in Figure 4. This BWB geometry accounts for a 150 PAX cabin layout and its projected wing area is 268.6 m^2. The mOE of the BWB is also adopted from [10]: mOE=36042 kg.

SMR-0HEP aerodynamic characterization

The drag polars for the BWB clean configuration without engines have been evaluated by Reynolds-averaged Navier-Stokes (RANS) analyses. The computational fluid dynamics (CFD) software ENSOLV [11] of NLR has been used for the calculations for the relevant flight conditions. These conditions comprise a number of speed-altitude combinations that are representative for the considered mission (Figure 5). These conditions are expressed by the Mach number and altitude in ISA. The resulting drag polars are depicted below in Figure 5. The drag polar data comprise the aircraft level lift coefficient (C_L) and drag coefficient (C_D) versus the angle of attack (α). The lift and drag coefficients have been evaluated for sequences of α. The data above certain maximum values of α have been excluded from further processing. These maximum values of α are indicated by the grey circles in Figure 5. The maximum C_L values in take-off and landing conditions on sea level are about 0.66. Of course, high-lift systems may well increase these maximum C_L values, but this is currently beyond the scope of this study. Furthermore, the BWB clean body has been aerodynamically designed for optimal cruise operation at around Mach 0.78 on 41 kft (12.6 km) altitude and C_L of about 0.27. Therefore this cruise condition is considered for the design range and the Typical Range missions of the SMR-0HEP configuration.



Mach	Alt (km)
0.2	0
0.4	1
0.5	3
0.6	6
0.68	8
0.78	10

Figure 5: Illustration of the drag polars for the BWB clean configuration (left), showing C_L versus α (the angle of attack) and versus C_D (the aircraft level drag coefficient), and based on a reference area $S_{ref} = 268.6$ m^2. Also, the maximum values of α are indicated by the grey circles, the data for higher values of α have been excluded from further processing. The speed-altitude combinations that are representative for the considered mission are listed on the right, expressed by the Mach number and altitude in ISA.

For an efficient incorporation of the drag polars in the MASS tool, a map of C_D as function of C_L and Mach number is generated using surrogate modelling methods. Polynomial methods of various orders and artificial neural networks (ANN) with various numbers of hidden nodes are evaluated. A feedforward ANN [12] with 9 hidden nodes is found to give the most accurate representation of the drag polar data and is therefore used in the MASS evaluations. On top of this drag polar representation of the BWB clean configuration, extra parasite drag contributions are added for the engines. A fixed value of 11.9 drag counts was estimated in [10] and has been used here too.

SMR-0HEP design evaluations

The SMR-0HEP configuration represents the radical airframe design of the BWB, but with conventional turbofan propulsion. Just like for SMR-BAS, also here the GSP based implementation of the CFM-LEAP-1A in MASS with 10% TSFC reduction due to 2035 technologies is used as turbofan model. Just like for the SMR-BAS, also for the SMR-0HEP two separate 0HEP configurations are considered for the different design ranges: the 0Hep1 configuration for the long design range of 2750NM (TLARs 3.a in the list above) and the 0Hep2 configuration for the short design range of 1200NM (2222 km) (TLARs 3.b in the list above). For both the 0Hep1 and 0Hep2

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configurations, the re-design of the wing area is performed by checking the design constraints described above for the various missions as prescribed by the TLARs. Both the 0Hep1 and 0Hep2 configurations are used for the assessment of the SMR-RAD configuration. Just like for SMR-BAS, also for SMR-0HEP it is found that the Typical Range mission results do not depend on the design range requirement, because the maximum payload requirement is the sizing condition. The key results and conclusions from the evaluations of the SMR-0HEP configuration are the following:

1. For the SMR-0Hep1 configuration, with maximum design range of 2750 NM@41 kft (5093 km@12.6 km), the wing area must be increased to 297 m^2. The critical case is the mission evaluation for the TLARs of maximum payload (20000 kg).
2. For the SMR-0Hep1 configuration the total mission fuel burn for the Typical Range mission is **3737 kg**.
3. For the SMR-0Hep2 configuration the total mission fuel burn for the Typical Range mission is **3737 kg**.

3.6 Evaluation of the radical HEP SMR aircraft (SMR-RAD)

SMR-RAD BWB concept design

For the SMR-RAD initial configuration the same underlying assumptions are used as for the SMR-0HEP configuration. The BWB airframe with the updated wing area of 297 m^2 and updated mOE of 37934 kg that was found for the 0HEP is adopted here. This is because a sensible comparison between SMR-RAD and SMR-0HEP must be made. For SMR-RAD, only the propulsion system is changed from turbofan (i.e. the 2 CFM-LEAP-1A engines with 2035 EIS technology assumptions for 0HEP) to full turbo-electric. Of course, this change from turbofan to turbo-electric powertrain implies changes in mass and energetic efficiencies of the propulsion system, which will be addressed in this section.

Propulsion system mass estimations

The mass changes due to the update from turbofan propulsion of the 0HEP configuration to turbo-electric propulsion of the RAD configuration are partly estimated and partly resulting from the propulsion system sizing that is made with NLR's MASS tool. An overview of the components considered and their mass estimates is given in the Table 4. For the considered SMR-RAD turbo-electric configuration the 2 turbofan engines are replaced by turboshaft engines and electric generators, for power generation, and ducted electric fans for thrust generation. Each of these turboshaft engines and ducted fans requires a pylon and nacelle for proper installation on the BWB airframe. The location of each of these engines and fans is currently assumed extrados on the rear centre body of the BWB, symmetric in its centre-vertical symmetry plane, as illustrated in Figure 7. This location may yield benefits in terms of noise shielding and boundary layer ingestion (BLI) for the fans, but also may have disadvantages for maintenance or thrust vectoring. The positioning of these components on the BWB airframe is still under further investigation and not yet finally converged. Therefore these noise shielding and BLI aspects are beyond the scope of this paper. This paper is mainly focussed on the conceptual design and sizing of the propulsion components and the TE powertrain.

Table 4: Overview of the mass changes due to the update from turbofan propulsion of the 0HEP configuration to turbo-electric propulsion of the RAD configuration..

	**SMR-0HEP:** **2 x CFM-LEAP-1A powerplant** **with 2035 EIS technologies**		**SMR-RAD:** **2 x Turboshaft+Generator** **n x Ducted fan**
	**CFM-LEAP-1A:** **2879 kg**		**Turboshaft+power-turbine:** **700 kg+300 kg = 1000 kg**
	**Nacelle+auxiliary systems:** **1200 kg**		**Simplified diameter-specific nacelle mass for Turboshaft and Ducted fan: 200 kg/m** **Ducted fan diameter: variable** **Turboshaft diameter: fixed at 1m**
	**Pylon:** **625 kg**		**Simplified pylon for Turboshaft and Ducted fan:** **1250/(2+n) kg per pylon**
			**Simplified fan rotor for Ducted fan:** **32 kg per m^2 fan area**
		Electric generator model ACDC converter model Electric distribution model DCAC inverter model Electric motor model Simplified models, based on specific powers, efficiencies	**Electric components:** **Calculated from power train component sizing**

The mass estimation of the turbofan is based on actual data of the CFM-LEAP-1A engine, with a wet engine mass of 2990 kg [7]. For A320neo, the nacelle- and auxiliary systems have a mass of about 1200 kg [9] and the pylon mass is

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about 650 kg [14]. For 0HEP we take into account the mass reductions due to the 2035 EIS technology assumption (similar to BAS, as given in Table 3, section 3.4), yielding 2879 kg for the engine and 625 kg for the pylon.
For the SMR-RAD propulsion system, the masses of the turboshaft engine and the power turbine are estimated at about 700 kg and 300 kg, respectively. The masses of the nacelle and pylon components are estimated in the following way for the SMR-RAD configuration. The pylon mass is dominated by its structural sizing for transfer of thrust forces. Because the total thrust force on aircraft level for SMR-RAD is not very different from SMR-0HEP, the total mass of all pylons on SMR-RAD is assumed to be equal to the total mass of all pylons on SMR-0HEP, i.e. 1250 kg. The nacelle mass of a ducted electric fan, of the same size as the CFM-LEAP-1A nacelle with a fan diameter of about 2 m, is assumed to be one third of the mass of the CFM-LEAP-1A nacelle, i.e. 400 kg. This is because of the much simpler construction and system installation for the ducted electric fan. For example the thrust reverser, with a mass of about 400 kg for one CFM-LEAP-1A nacelle, is not needed in the ducted fans because of assumed reversed rotation capability of the electric fans. The ducted electric fans are sized on the basis of the fan area, which is an output of the ducted fan model. The nacelle mass is assumed to proportional to the nacelle wetted area, and therefore also proportional to the ducted fan diameter because the nacelle length is assumed to be constant. Consequently for the ducted electric fan nacelle, the diameter-specific nacelle mass is 400 kg divided by 2 m fan diameter yielding 200 kg/m.
For simplicity, the same structures for pylon and nacelle are assumed for the ducted fans and for the turbo-generators (i.e.: the assembly of turboshaft engine, power turbine and electric generator). For the SMR-RAD pylons this implies that the total pylon mass on aircraft level, i.e. 1250 kg, comprises n+2 pylons for n ducted fans and 2 turbo-generators. So for example for 8 ducted fans, the pylon mass is 1250 kg for 8+2=10 pylons, i.e. 125 kg per pylon. For the SMR-RAD nacelles for the ducted fans and turbo-generators the mass equals the nacelle diameter times the diameter-specific nacelle mass. The turbo-generators are assumed to have a nacelle of 1 m diameter. So for example for 8 ducted fans of 1.33 m diameter the nacelle mass is 200 kg/m times 1.33 m is 266 kg, and for the turbo-generators of 1 m diameter the nacelle mass is 200 kg/m times 1.0 m is 200 kg, so total nacelle mass on aircraft level is 8*266+2*200=2528 kg.
The mass of the fan rotor (i.e. 18 carbon composite blades and metallic rotor hub) of the CFM-LEAP-1A is estimated at 100 kg for a fan area of about 3.1 m^2. The fan rotor of the ducted electric fan is also assumed to consist of 18 composite fan blades and metallic rotor hub, at a similar areal mass of about 32 kg per m^2 fan area. The mass estimation of the electric powertrain components, like generators, power electronics and electric motors, is handled internally by the MASS tool in relation with the thrust requirements during the mission.

Energetic efficiencies of the propulsion system

The energetic efficiencies of the CFM-LEAP-1A turbofan engines in the 0HEP configuration are incorporated in the GSP engine model. For the turbo-electric propulsion system, the energetic efficiencies of the powertrain components are incorporated in the turbo-electric component models. The main turbo-electric components are the turboshaft engine with power turbine, the electric generator with AC-DC converter, the electric distribution system with power cables, switches and buses, the electric motors with inverters and power electronics, the ducted fans. For each of these main components a more or less elaborate modelling approach is followed, as illustrated in Figure 6. The turboshaft engine is included as a gas turbine cycle model, developed with DLR's GTLab environment [15], and dedicated to the required approximate power levels. The gas turbine cycle model predicts the fuel mass flow ($\dot{m}_{fuel}$) and the HPT inlet temperature (T_{T4}) as a function of the required power, altitude and Mach number during the mission. The constraint for this turboshaft engine is only on HPT inlet temperature: T_{T4}<1900 K. The turboshaft engine drives a specific power turbine that is dedicated to power the electric generator through a direct drive shaft. The assembly of turboshaft, power turbine and electric generator constitutes the complete turbo-generator component. The SMR-RAD powertrain contains two of such turbo-generators in parallel for redundancy. The electric components in the powertrain comprise the generator with AC-DC converter, the electric distribution system and the electric motors with DC-AC inverters. These electric components are included by simplified models based on 2035 technology level estimates of specific power and efficiency values [13]. Also, the required cooling system (CS) equipment sizing is included in a similar simplified way. The assumed values are listen in Table 5. The pessimistic values listen in Table 5 are used in the initial evaluations of SMR-RAD. The optimistic values listen in Table 5 are used in the evaluations of the design variations for SMR-RAD that are described in the following section.

Table 5: Turbo-electric power train 2035 technology assumptions [13] for SMR-RAD. The pessimistic assumptions are rather conservative and close to current state of the art numbers. The pessimistic assumption are used in the initial SMR-RAD evaluations. The optimistic assumptions are estimates based on various public sources. The effects of these optimistic assumptions are assessed in the SMR-RAD design variations as described in the following section.

Parameter	Pessimistic	Optimistic
Electric motor specific power [kW/kg]	11	17
Electric motor power factor	0.95	0.95

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Electric motor efficiency	0.96	0.98
Converter/inverter specific power [kVA/kg]	20	30
Converter/inverter efficiency	0.99	0.99
Cooling system specific power [kW/kg]	0.68	0.68
Generator specific power [kW/kg]	20	20
Generator efficiency	0.98	0.98

The ducted fans are included by a simplified model based on polytropic pressure-duct equations [13]. With this model, the fan pressure ratio (FPR), the ducted fan shaft power ($P_{shaft,DF}$) and the propulsive efficiency (η_{prop}) can be predicted as a function of true air speed, altitude, net thrust force and ducted fan exhaust area ($V_{TAS}, h, F_{n,DF}, A_{exh}$). The total thrust force on aircraft level $F_{n,AC}$ follows from the BWB aircraft model for each point in the mission. This BWB aircraft model is described in the previous section for the SMR-0HEP configuration. The required ducted fan shaft power $P_{shaft,DF}$ shall be provided by the electric motor and the other electric components, for which the power values are summarized by the symbol for electric component power P_{EC}. The resulting power that is required by the electric generator is fed to the turboshaft model, together with the aircraft altitude and Mach number ($P_{shaft,TS}, h, M$). An overview of the turbo-electric propulsion system for SMR-RAD with all its components and variables is illustrated in Figure 6.

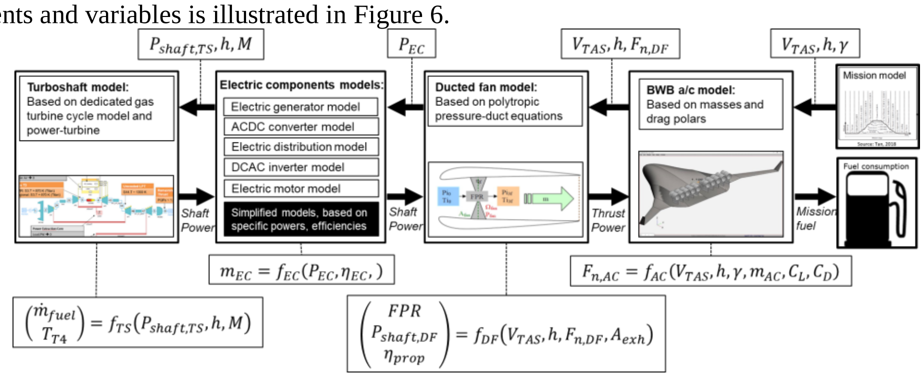

Figure 6: Illustration of the turbo-electric propulsion system for SMR-RAD, with the main powertrain components incorporated as more or less elaborate component models.

SMR-RAD design evaluations

The SMR-RAD design approach is different from the design for all the previous configurations. In the REF, BAS and 0HEP configurations only the wing area was considered as the global design variable, which was applied only to update the configurations such that all TLARs are fulfilled. The SMR-RAD design aims at optimizing the turbo-electric propulsion system, such that all TLARs are fulfilled and the Typical Range mission fuel consumption is minimized. The design variables considered in this study for SMR-RAD are the number, location and size of the ducted fans. In this way it is intended to maximize propulsive efficiency by maximizing total fan area. But the size and number of the propulsors will have limitations related to installation space and mass and drag of the fan casings, ducts and pylons. Another driver here may be the exploitation of boundary layer ingestion (BLI) benefits by installing the ducted fans extrados on the centre body. A low-fidelity modelling of BLI in ducted fans is also under investigation in the IMOTHEP project [16]. However, the modelling and analyses for incorporating the BLI effects are not yet completed and therefore the BLI benefits are out of scope for this paper.

An initial investigation of SMR-RAD is made for 8 ducted electric fans, as illustrated in Figure 7. This is a rather arbitrary choice, but it is made to start the investigations and make a first assessment of the feasibility of the chosen SMR-RAD concept. The key results and conclusions from the evaluations of the SMR-RAD configuration are the following:

1. For the SMR-Rad1 configuration, with maximum design range of 2750 NM@41 kft (5093 km@12.6 km), the wing area must be increased from 297 m^2 to 320 m^2. The critical case is the mission evaluation for the TLARs of maximum payload (20000 kg).
2. For the SMR-Rad1 configuration the total mission fuel burn for the Typical Range mission is **3798 kg**.
3. For the SMR-Rad2 configuration, with maximum design range of 1200 NM@41 kft (2222 km@12.6 km), the wing area must be increased from 297 m^2 to 317 m^2. This is slightly lower than for Rad1 because of the slightly lower mOE for the initial design range mission. The critical case is the mission evaluation for the TLARs of maximum payload (20000 kg).
4. For the SMR-Rad2 configuration the total mission fuel burn for the Typical Range mission is **3769 kg**.

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3.7 Evaluation of the design variations and optimization of SMR-RAD

Design variation of on-board system: More-electric aircraft (MEA) update of SMR-RAD
The initial SMR-RAD configuration includes the same bleed air off-takes and pneumatic- and hydraulic systems that were also assumed in all previous configurations (REFX, REF, BAS, 0HEP). In the SMR-RAD the bleed air is extracted from the HPC of the turboshaft engine. However, this turboshaft engine is not optimized for bleed extraction and therefore the energetic efficiency is relatively low. It is more efficient to extract all energy from the turboshaft's power turbine shaft, which is connected to the electric generator. Therefore a so-called MEA update is applied to SMR-RAD, which avoids the bleed air extraction from the HPC. Consequently the pneumatic systems that are the consumers of the bleed air, in particular the ice protection system (IPS) and environmental control system (ECS), must also be replaced by non-pneumatic systems. The pneumatic IPS can be replaced by electric heating systems and the bleed air supply to the pneumatic ECS can be replaced by electric air compressors. Besides the pneumatic systems, also the hydraulic systems, like flight control and landing gear actuators, can be replaced by electric alternatives. The changes in system masses and the power requirements for such a MEA architecture for an A320neo category aircraft has been previously investigated [17], and the following values are adopted in this study:

- The resulting total change in system mass on aircraft level is estimated at -980 kg, i.e. a reduction of 980 kg.
- The total electric power requirement for all the non-propulsive systems is estimated at 350 kW during the whole flight.

As indicated in the results of SMR-RAD in [10], this non-propulsive power off-take of 350 kW has been included in the power demand from the main electric generators. The results for the MEA update of the initial SMR-RAD are listed in the results paragraph below.

Design variations of the ducted electric fans configuration
The SMR-RAD design aims at optimizing the turbo-electric propulsion system, where the design variables considered in this study for SMR-RAD are the number, location and size of the ducted fans. Because of the limited installation space on the rear centre body of the BWB, the sizing of the fan area shall be such that the ducted fans fit, i.e. that their size does not exceed approximately 16 m in span direction. Variations of the number of ducted fans are considered: besides the initial 8 fans configuration, also 10 slightly smaller fans and 6 slightly larger fans are considered. The 3 different configurations with the 8, 10 and 6 ducted fans are illustrated in the Figure 7.

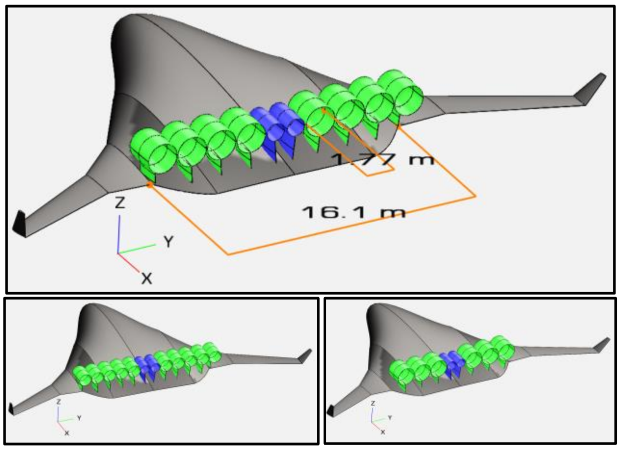

Figure 7: Illustration of the SMR-RAD with the various propulsion configurations: the initial configuration with 8 ducted fans each with 1.77 m fan diameter (upper picture), the variant with 10 ducted fans each with 1.41 m fan diameter (lower left picture), the variant with 6 ducted fans each with 2.06 m fan diameter (lower right picture). It must be noted that all the ducted fans and the two turbo-generators are all installed on the rear center body and the turbo-generators have a fixed diameter of 1.0 m. The ducted fans are indicated by the green nacelle+pylon and the turbo-generators are indicated by the blue nacelle+pylon.

The results for the 3 different SMR-RAD configurations with the 8, 10 and 6 ducted fans are listed in the results paragraph below.

Design variation of turbo-electric power train technology assumptions for SMR-RAD
The technology assumptions for the turbo-electric power train components for EIS in 2035 that are used so far for SMR-RAD are the pessimistic values listed in Table 5. Instead, more optimistic values may be considered, as also listed in Table 5. The effects of these optimistic assumptions are evaluated for the best performing SMR-RAD ducted

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fan configuration as found in the previous section. The results for SMR-RAD configuration with the optimistic technology assumptions are listed in the results paragraph below.

4. Assessments of potential benefits of SMR-RAD

The results from the initial SMR-RAD and all the design variation studies of SMR-RAD are summarized and comparison is made to all the other configurations (REF, BAS, 0HEP) in Table 6. Here only the key summary results of the configurations for the long design mission (2750 NM (5093 km)) are given. This is because the configurations for the short design mission (1200 NM (2222 km)), appear to have hardly any benefit in Typical Range mission fuel burn.

Table 6: Results overview for all the SMR-RAD design variation evaluations and comparison to all the other configurations (REF, BAS, 0HEP). Only the results for the long design mission (5093 km) configurations are shown. All values are given on aircraft level, i.e. based on summation of all engines and propulsors.

	REF	BAS	0HEP	RAD initial 8 Dfans	RAD MEA 8 Dfans	RAD MEA 10 Dfans	RAD MEA 6 Dfans	RAD MEA, 6 Dfans Optimistic assumptions
Design 2750 NM								
mOE [t]	44.3	40.7	37.9	42.4	40.6	40.3	40.1	38.0
mTO [t]	78.5	71.1	67.2	71.7	69.0	68.7	68.3	65.8
max Pshaft [MW]	33.6	29.6	24.9	19.6	19.2	19.1	19.0	17.9
Typical Range mission 800 NM								
Fn [kN] (mid flight)	39.7	32.1	28.0	30.2	29.3	29.1	29.0	28.0
TSFC [g/kNs] (mid flight)	15.46	14.39	14.18	13.06	12.23	12.40	12.24	12.04
PSFC [kg/kWh] (mid flight)	0.197	0.175	0.181	0.171	0.155	0.155	0.156	0.156
Fuel burn [kg]	4855	3773	3737	3798	3448	3463	3420	3263
Fuel burn relative to REF fuel burn [%]	100%	78%	77%	78%	71%	71%	70%	67%

5. Conclusions and further work

As part of the IMOTHEP project, the conceptual design investigations for the SMR-RAD configuration are done using the NLR tools for aircraft design and mission evaluation. The current findings show some potential for the considered project targets (-40% fuel consumption for SMR in comparison with 2014 State of Art). Reductions in Typical range mission fuel burn of up to 33% are predicted for the SMR-RAD configuration in comparison to the REF configuration. The project target of -40% fuel consumption is therefore assumed to be feasible. However, a major part of the reduced fuel burn results from the expected technology developments up to 2035, as can be concluded from the BAS configuration, for which a fuel burn reduction of 22% is found in comparison to the REF configuration. Only a small portion of 1% fuel reduction is achieved by the radical configuration of the BWB airframe. Another 10% fuel reduction is achieved actually due to the application of HEP and MEA technologies, of which about 7% is due to the MEA architecture.

The conceptual design investigations for the SMR-RAD configuration have shown that the BWB with DEP in combination with the TE power train architecture is a feasible approach for the reduction of fuel consumption. For the 800 NM Typical range mission, fuel burn reductions up to 30% with respect to SMR-REF are found. In case of optimistic technology assumptions (such as the optimistic values in Table 5) this reduction can be even extended to 33%. More advanced technology assumptions, such as the exploitation of drag reduction by BLI, may yield even further reductions beyond 33%.

Furthermore, it was found that reducing the design range from 2750 NM to 1200 NM has only very small impact on the Typical range fuel burn of all the SMR configurations; for SMR-RAD for example only about 1% reduction in Typical Range mission fuel burn can be achieved by the reduced design range requirement.

The resulting SMR-RAD configuration still has limitations and uncertainties that shall be further investigated. The ducted fan analyses are based on simplified modelling. For instance, the additional drag for the ducted fan was estimated by simplified modelling. Also the potential BLI benefits are out of scope for this paper. It is expected that improved aerodynamic and ducted fan models provided by higher fidelity analyses will decrease these uncertainties.Further aerodynamic analysis of the BWB airframe shall be improved to optimize the configuration. Simplified models were used for the power train sizing, based on the specific power and efficiency values. 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 dedicated for the considered mission requirements in terms of thrust and power. Possibly updated mission requirements may

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imply a further adapted turboshaft model, which would make the SMR-RAD analysis more accurate. Such an improved model is important as it directly impacts the Typical range fuel burn.

The application of batteries for energy storage has not been analyzed during this study. It is not expected currently that batteries will bring 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 the ongoing studies in the IMOTHEP project.

In the ongoing and following more detailed design studies in the IMOTHEP project the SMR-RAD design will be further refined, taking advantage of technological HEP design studies and including increasing levels of fidelity. The ultimate goal in IMOTHEP is – together with the REG and CON aircraft configurations under study - to identify for HEP the key enablers and technology gaps that future research will have to bridge.

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