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Conceptual Assessment of Hybrid Electric Aircraft with Distributed Propulsion and Boosted Turbofans

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This paper presents the results of a study into the effect of distributed hybrid-electric propulsion on aircraft performance and characteristics. To size these aircraft, a new preliminary sizing method for hybrid-electric aircraft with distributed propulsion, including aero-propulsive interaction, is combined with a modified Class-II weight estimation method where energy consumption is estimated through a mission analysis method. Comparison of the predictions from these new methods to the predictions from a traditional sizing method has shown to be within 5% agreement for a single-aisle aircraft powered by conventional turbofans in terms of wing loading, energy consumption and maximum take-off weight. A boosted turbofan aircraft as well as two aircraft with different distributed, hybrid-electric propulsion systems have been assessed for a 150-pax aircraft designed for a harmonic range of 800nmi. Each of these aircraft designs showed significant increases in propulsion system mass (up to 700%). The distributed-propulsion aircraft showed increases in energy consumption of 34% and 51%, respectively, over the conventional turbofan aircraft. However, the boosted-turbofan aircraft showed a 10% decrease in energy consumption and a 3% reduction in maximum take-off weight. Future studies have to be performed exploring the design space, including all powertrain components, thermal management components, mission parameters and propulsion system layout.

Nomenclature

Symbols

C_D = Drag coefficient (∼)
C_L = Lift coefficient (∼)
D = Drag (N)
E = Energy (J)
h = Altitude (m)
L = Lift (∼)
M_{cr} = Cruise Mach number (∼)
P = Power (W)
T = Thrust (N)
V = Velocity (m/s)
W = Weight (N)

Greek Symbols

η_p = Propulsive efficiency (∼)

Acronyms

ACN = Airport classification number
AHP = Analytical hierarchy process
APU = Auxiliary power unit
BC = Business class
CAS = Calibrated airspeed
DHEP = Distributed hybrid electric propulsion
DOC = Direct operating cost
DUUC = Delft university unconventional configuration)
EIS = Entry into service
FAR = Federal aviation regulations
HEP = Hybrid electric propulsion
ICA = Initial cruise altitude
ISA = International standard atmosphere
KCAS = Knots calibrated airspeed
MEA = More electric aircraft
MLM = Maximum landing mass
MRO = Maintenance, repair and overhaul
MTOM = Maximum take-off mass
OEI = One engine inoperative
OEM = Operational empty mass
SFC = Specific fuel consumption
SL = Sea-level
SPPH = Series/parallel partial hybrid
T/O = Take-off
TLAR = Top level aircraft requirement
TOFL = Take-off field length
TRL = Technology readiness level

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TSFC = Thrust specific fuel consumption
TTC = Time to climb
XML = Extensible markup language
YC = Economy class

I. Introduction

Environmental impact is one of the key focus areas of modern day aviation, with significant research efforts being invested in pursuit of, for example, the goals identified by the Air Transport Action Group[*] or the European Commission in its Flightpath 2050 [1] vision on aviation. This research involves, amongst others, hybrid electric propulsion (HEP) or even full electric flight. Some of the main challenges to be overcome are related to the specific power and power densities of the components in the (hybrid) electric powertrain, resulting in significant mass increases. Therefore much research (e.g. [2–11]) is performed in the area of distributed propulsion and hybrid-electric propulsion that is aimed at exploiting the synergistic benefit between distributed and (hybrid)-electric propulsion. The versatility that electrical systems offer when distributing powertrain components along the airframe, could result in aero-propulsive and airframe integration benefits.

However, most studies investigating distributed hybrid-electric propulsion (DHEP) do not consider the aero-propulsive interaction in the conceptual sizing process. Especially for distributed propulsion, these effects can have a large impact on the design points (i.e. wing loading, power loading, mass, etc.). Therefore, a new generic sizing method for DHEP aircraft, including these effects has been developed by de Vries et al. [12]. This development has been performed under the umbrella of the EU project NOVAIR. NOVAIR is part of work package 1.6.1.4 of the Clean Sky 2 program targeting Large Passenger Aircraft (LPA). The goal of NOVAIR is to investigate what synergistic effects between the propulsion system and the airframe can be exploited in future aircraft and what their impact is on key performance metrics such as overall energy consumption and characteristic weights. As a baseline for these comparisons, a tube-and-wing aircraft is used with conventional turbofan engines.

This paper presents the preliminary findings for three candidate hybrid-electric propulsion system architectures for a 150-pax aircraft designed for a harmonic range of 1100nmi. To this end, the new sizing method [12] has been implemented in the in-house-developed Aircraft Design Initiator (or simply *Initiator*), a conceptual design tool that synthesizes aircraft for any set of top-level aircraft requirements using a predefined convergence loop. This implementation links the new preliminary sizing method to an empirical weight estimation method as well as to a vortex lattice method for the wing aerodynamics. The main aim of this paper is to assess the synergy between HEP and distributed propulsors, to try to achieve environmental and performance benefits, though potentially at the cost of a higher weight.

The paper starts with a short overview of the concept generation phase and an explanation of the qualitative assessment (Section II), followed by a description of the new conceptual design method for hybrid electric aircraft with distributed propulsion (Section II.B) that has been used for the quantitative assessment. The implementation of this method inside the *Initiator* is briefly discussed in Section II.B as well. Verification and validation of the implementation can be found in Section III, prior to a discussion of the concept generation, and analysis and results in Section IV.

II. Design Process

The design process followed in this paper is schematically shown in Figure 1. First a large set of concepts is generated by a group of staff members from TU Delft, NLR, DLR and ONERA with a background in aerospace engineering, though with different specializations. The concepts were created during a joint workshop. Hence, they are shared between the three design teams, with each team having the liberty to assess different concepts, based on their interest. For the generation of the concepts, a spreadsheet is used that allows dragging and dropping aircraft geometrical components, to construct a top and front view of the concepts. Additionally, a powertrain layout (such as serial, parallel, etc.) is specified and extra notes on the expected benefits and characteristics of each concept are added. To compare the different aircraft concepts, a two-stage assessment approach is used. This assessment consists of a qualitative trade-off (or filtering) and a subsequent quantitative analysis of two of the chosen concepts (see sub-Section IV.D). Additionally, a reference aircraft based on the Airbus A320 and a boosted turbofan aircraft have been designed according to a common set of requirements.

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[*] Air transport action group, Facts & Figures, May 2016, `https://www.atag.org/facts-figures.html`, visited on 7 June 2018

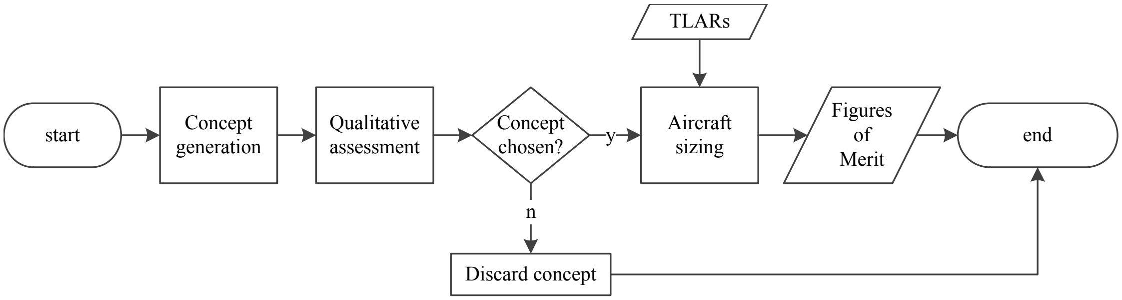


Fig. 1 Notional process flow followed in this paper.

A. Concept Filtering

The qualitative trade-off is performed by a group of experts. Together this group ranks all aircraft on a scale of 1 to 5, with respect to the reference aircraft (Airbus A320) in terms of a set of criteria. These criteria are categorized in quantitative and qualitative figures of merit. The quantitative figures of merit are: the operational empty mass (OEM), aerodynamic efficiency (L/D), the propulsive efficiency (η_p), energy conversion efficiency (efficiency of the powertrain up to the propulsor shaft) (η_{energy}), the cabin noise, and the community noise. The qualitative figures of merit are the ability to integrate the aircraft within existing airport facilities (Airport Integration), whether the concept can be easily stretched or shrunk (family) and whether the aircraft is maintainable (MRO). A weighting factor is assigned to each criterion. Three top-level constraints are also added (Table 1). These constraints are simple yes/no questions, asking the assessor whether she/he thinks the concept can indeed satisfy a particular constraint. Hence, if the assessor answers "no" to one of these questions, this can be considered a show-stopper for the concept at hand.

Table 1 Constraints on aircraft designs as part of the qualitative analysis

Handling Qualities	FAR	TRL/EIS
Y/N	Y/N	Y/N

To reduce the subjectivity of the decision-making process to pairwise comparisons, the weights are analyzed with the Analytical Hierarchy Process (AHP) [13]. In this case the Breguet range equation is used for the sensitivity of the energy-consumption related parameters in the ranking. The weights are recalculated using an eigenvector matrix, based on how much more important a criterion is considered with respect to another.

In addition to the AHP, an effort is made to reduce the subjectivity in the actual ranking of the concepts. To this end, all weighting criteria and configuration characteristics (e.g. canard, BLI or distributed propulsion) are recorded in a table where the deltas (as performance indicators) with respect to the reference aircraft are recorded. Adding or subtracting points (on the scale from 1 to 5) when the characteristic is assumed to have a positive or a negative effect on the weighting criterion, with respect to the reference. For example, a forward swept wing is assumed to have an OEM penalty (due to aero-elastic effects), but a better lift to drag ratio L/D (because of natural laminar flow). Recording these performance indices also means that the reasoning behind the trade-off is traceable. The characteristics have the same delta on any concept, hence, a particular concept will not be favored by the assessors.

B. Design Evaluation Method

The evaluation of the concepts that result from the qualitative concept selection is performed following a traditional aircraft design process, involving a design convergence of the main disciplines. This process follows a typical Class-I - Class-II iterative procedure, where a design point is chosen from a constraint diagram based on the point-performance requirements. To this end, a generic sizing method for the Class-I design process of hybrid-electric aircraft is employed, which differs from the traditional methods in the following manner:

1) Aerodynamic interaction effects are included.
2) Required shaft power is related to the power required at the energy source(s) through a powertrain model
3) The traditional Breguet range equation is replaced by a mission analysis where the aircraft is represented as a point mass.

The sizing methodology that is followed is illustrated graphically in Figure 2.

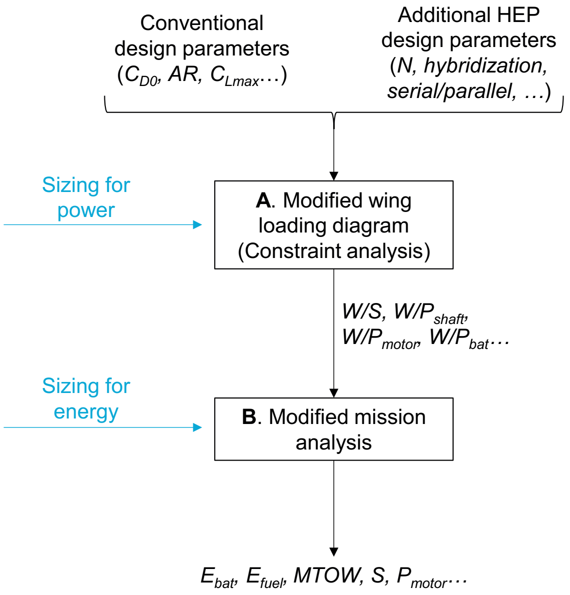


Fig. 2 Schematic flow of conceptual sizing for power and energy.

A key feature of this method is that it considers the aircraft as a point mass, balancing forces and accelerations for each performance requirement. For the representation of the powertrain a simplified model is used, following the six types of layouts proposed by Felder [2] and later adopted by the National Academy of Sciences [14]: Conventional, Series, Parallel, Turbo-electric, Partial turbo-electric and Series/Parallel partial hybrid. Additionally, three power controls are included in the model: Gas turbine throttle (ξ), Supplied power ratio (ψ) and Shaft power ratio (ϕ). This method is implemented in the Aircraft Design Initiator and coupled to a Class-II weight estimation method [15]. The integration of this new sizing method is described in Subsection II.C; a more detailed description of the *Initiator* can be found in Elmendorp et al. [16], the full description of the Class-I DHEP sizing method can be found in de Vries et al. [12]. The aero-propulsive effects of leading edge distributed propulsion are modeled using a simplified analytical model as reported in [12]. To include the effects of over-the-wing distributed propulsion, a rudimentary response based on a limited amount of experimental data obtained from Veldhuis [17] is employed. Current research focuses on improving this method.

Figure 3 illustrates the effect of propulsion-airframe interaction on a traditional power loading diagram. The design point for minimum wing size, Point A, shows no effect of propulsors on lift and drag. Point B is the design point for minimum wing size if distributed propulsion on wing is taken into account. Higher wing loading, hence a smaller wing area per unit weight, and higher power loading, hence smaller engines per unit weight, are enabled by distributed propulsion. The red curve is constructed by the intersection of the linear lines, which represent equilibrium along the longitudinal body axis, and the light red curves, representing equilibrium along the vertical body axis. For a given lift coefficient, there exists only a unique combination of wing loading and power loading where the cruise constraint is satisfied.

Additionally, because the increased complexity of the powertrain and the many components involved with power/thrust generation, a power-loading vs. wing-loading diagram is constructed for each component in the powertrain, as well as for the total propulsive power and shaft power. Different constraints can be active for different components from the powertrain and can hence size components differently. Here, one-engine-inoperative (OEI) is treated as failure of any one component in the powertrain; multiple different "OEI" constraints therefore exist for a given flight condition.

This is illustrated by Figure 4, which shows the "electro-motor power loading diagram" and the "gas-turbine power-loading diagram" for a hybrid-electric aircraft. These graphs clearly show that different constraints can be active for different components along the powertrain; because for the gas-turbine actually cruise power is sizing for this particular aircraft. Also indicated in this diagram are the different constraining points of the powertrain components. Note that these constraint diagrams are a result of the way shaft power is distributed between components and depend on the powertrain architecture that is employed.

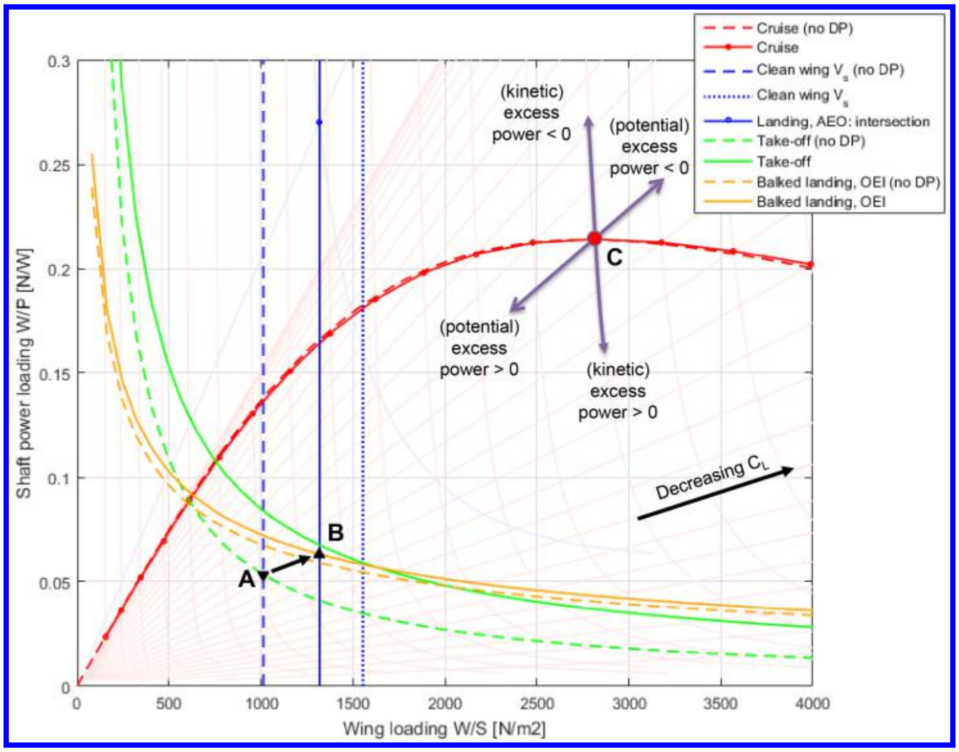


Fig. 3 Illustration of the effects of distributed propulsion on typical design points in a power loading diagram for shaft power.

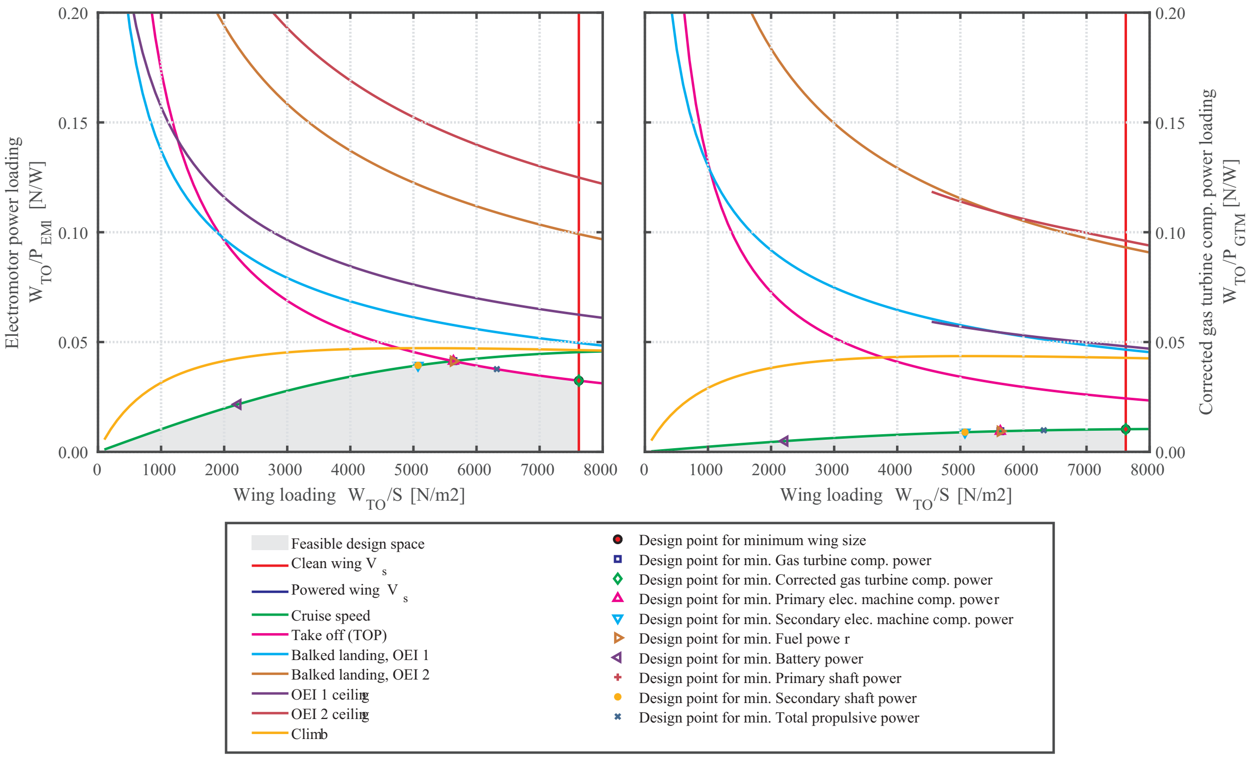


Fig. 4 Illustrative power-loading diagram for a hybrid-electric aircraft with distributed propulsion, for electromotor and gas-turbine (right) (corrected for sea-level conditions).

The power distribution is managed by the control parameters introduced earlier (gas-turbine throttle, supplied power ratio and shaft power ratio; see also de Vries et al. [12]), which are specified for each constraint in the power loading diagram and are also considered in the mission analysis. The mission analysis is implemented as a point model using a time step summation over the mission, through the power control parameters. Per flight phase, the control parameters are varied and the powertrain model is adapted for that particular flight phase to calculate the power balance across the entire (hybrid) propulsion system. From this power balance, the energy consumption is determined per component of the powertrain (in a way that is also suited to kerosene fueled aircraft). The model assumes constant component efficiencies per analysis. This is illustrated in Figure 5.

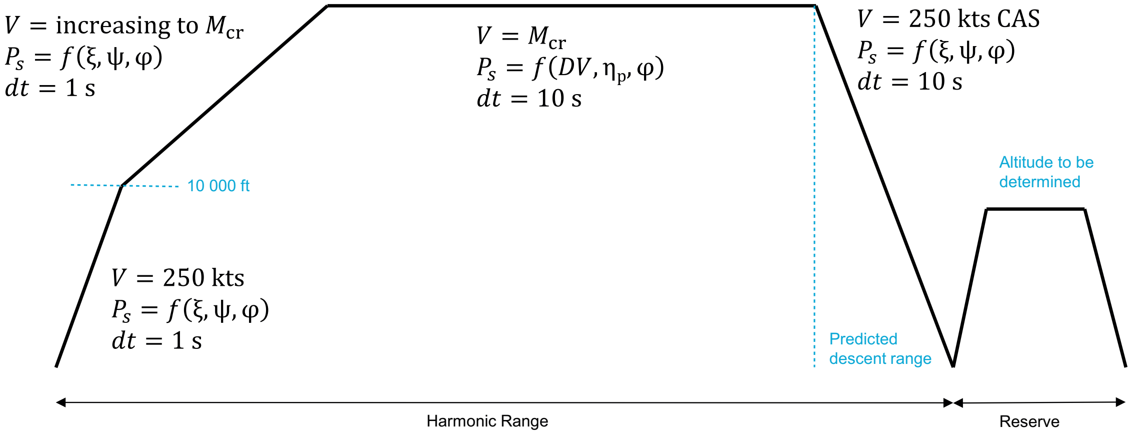


Fig. 5 Mission profile used during numerical energy consumption simulation

C. Software Implementation

The Aircraft Design Initiator is a software tool developed in-house in Matlab. The software contains a design convergence loop over several disciplinary analyses, including handbook methods, empirical data and physics based methods. This software is capable of sizing both conventional and unconventional configurations (such as blended wing body aircraft and box-wing aircraft). The Initiator was initially conceived as part of the European project Aerodesign (FP7) and has supported other European projects such as RECREATE (Horizon 2020) and Smart Fixed Wing Aircraft (CleanSky I). Currently, it is being used in Large Passenger Aircraft (CleanSky II) and Parsifal (Horizon 2020). The Initiator can be used to assess the impact of small and large changes to the aircraft on so-called key performance indicators. The latter include fuel efficiency, maximum take-off weight, life-cycle cost, and equivalent CO_2 emissions.

The Initiator is developed to be used for the conceptual design of CS-25 certified aircraft. It supports propeller-powered and turbofan-powered aircraft in the transport and business jet category. In terms of aircraft configuration, the Initiator supports conventional tube-and-wing aircraft and (to some degree) blended-wing-body aircraft, three-surface aircraft, and box-wing aircraft. A description of the Initiator can be found in Elmendorp et al. [16]. The following sections detail how the Initiator is currently used for the design of DHEP aircraft. In its current shape, the Initiator does not yet support DHEP aircraft to the same level as conventionally fueled aircraft. However, the DHEP version of the software does already include a Class-II weight estimation method and wing aerodynamic analysis. The process flow that is used for the assessment of DHEP aircraft in this paper is visualized in Figure 6.

The synthesis implemented in the Initiator is a process of convergence, where the design variables are altered in an iterative way until a predefined set of performance indicators converge below a certain threshold within a large set of (internal) constraints. In other words, the Initiator uses a process of design “feasilization”[18], rather than optimization to get a converged aircraft design. This also means that the constraints are not exposed to an optimizer and no explicit design variables exist that are under control of an optimizer.

Figure 6 only shows the process flow on an aggregated level; many of the analysis or sizing modules represent different smaller modules. For example, "Geometry Modules" contains more than 20 individual modules that dimension the aircraft geometry, ranging from engine position to wing taper ratio. Each of the modules requires input in order to complete its task. This input can come from an external source (i.e. user-defined input or reference data stored in a database) and/or can come from another module. Many modules have a dependency on other modules. For example,

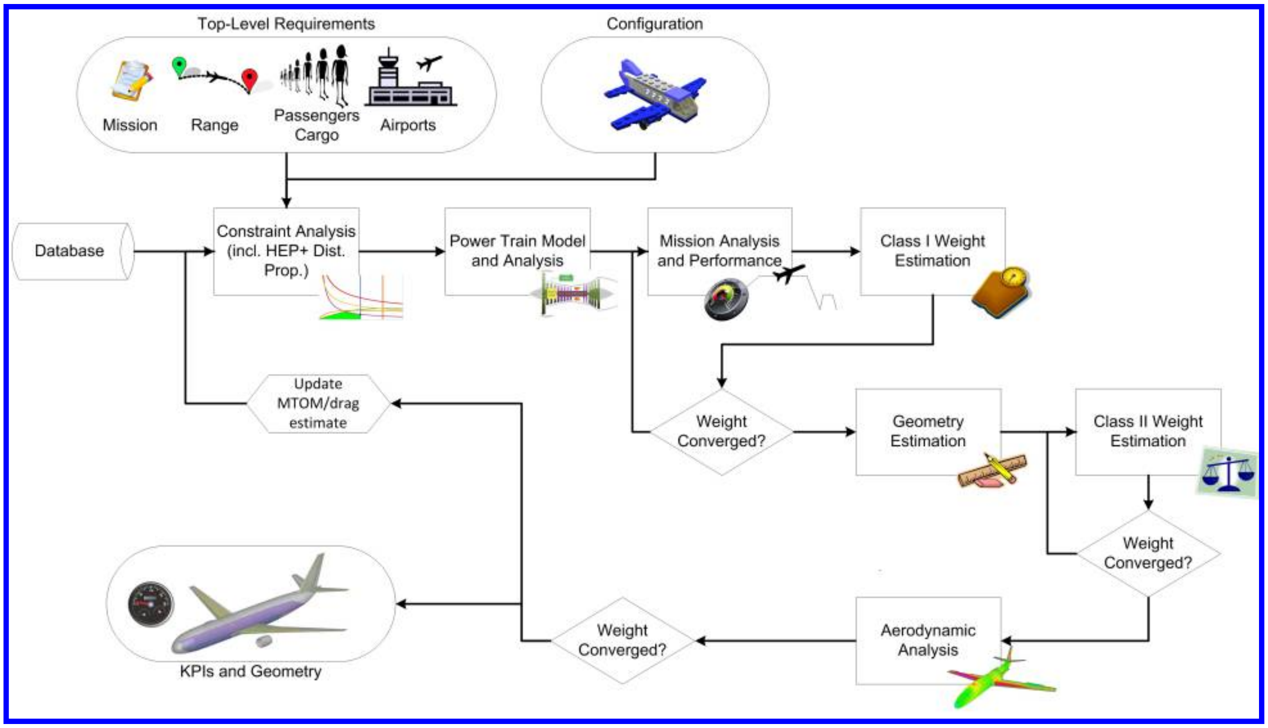


Fig. 6 Illustration of the *Initiator* process flow for the design of DHEP aircraft.

the "Class-I Weight Estimation" has a dependency on a database of aircraft data while the "Fuselage Configurator" (inside "Geometry Estimation") depends on the "Class-I Weight Estimation". These dependencies are documented in an XML-file. When a file is run that has a dependency on other modules, it automatically first runs these modules to generate the required input. For example, when only the module "Class-II Weight Estimation" is triggered, it first evaluates all the preceding modules, including the Class-I convergence.

The convergence loop for the DHEP aircraft design actually consists of multiple convergences; one on Class-I and mission analysis, one on the Class-II weight estimation and an overarching loop on the start of the process and the outcome of the Class-II loop. The latter converges on the maximum take-off mass (MTOM). Modifications have been made to the existing Initiator modules to accommodate the sizing of DHEP aircraft, such as mass estimations of electric motors and batteries.

The first convergence loop commences with extracting data from a database of reference aircraft. With this information, an estimate of the maximum take-off mass (MTOM) is made. In the subsequent module, the required power and wing size are computed based on a user-specified set of top level aircraft requirements (TLARs) in addition to performance requirements stemming from regulations (FAR/CS 25).

III. Verification and Validation

To verify the new conceptual design method for DHEP aircraft, the *Initiator* designs have been compared against data from open literature. This has been performed both for an implementation with a conceptual design process using a traditional Class-I sizing and Breguet range equation, and an implementation using the new preliminary sizing for hybrid-electric aircraft [12]. This comparison also illustrates the performance of the new method to size conventional turbofan aircraft. These comparisons have been performed for an aircraft sized for Airbus A320-200ceo TLARs. In this case, a full convergence study has been performed that includes a detailed mission analysis and semi-analytical (Class-II.5) weight estimations for both the wing and fuselage.

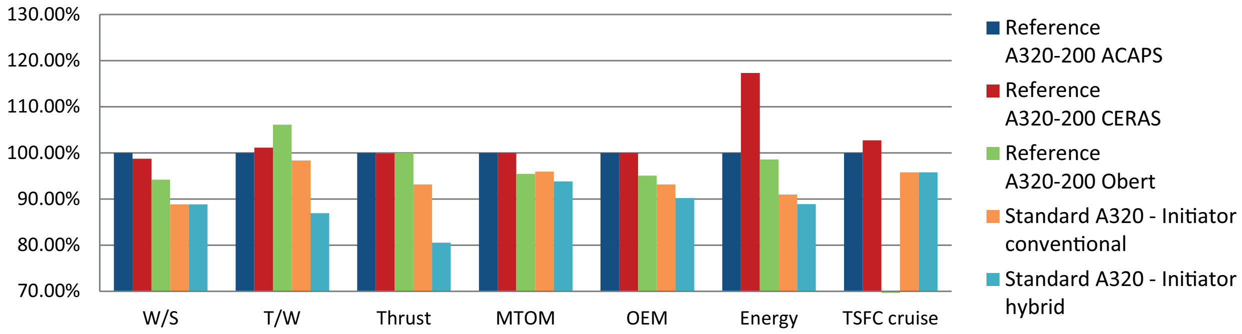


Fig. 7 Verification of the *Initiator* designs of an Airbus A320-200 compared to reference data of various sources. The *Initiator* has been used with both the "conventional" Class-I sizing, with a traditional wing-thrust-loading diagram and Breguet range equation, and the new preliminary sizing method for hybrid aircraft. N.B. in Obert [19], no data is available on the thrust-specific fuel consumption.

Figure 7 shows the comparison of the standard Initiator's performance , compared to A320 ACAPS data[†], CSR01 aircraft from the CERAS database[20][‡] and data available for the A320-200 in Obert [19]. Note that this figure has been scaled with respect to the ACAPS data, and that the y-axis only runs from 70% to 130%.

Since the Initiator is performing a design convergence and not an analysis, it is actually sizing an aircraft similar to an A320. The largest discrepancies are found in the values of thrust and energy (fuel) use. These differences can be attributed to the highly limited engine model, which is currently being updated. Important to note as well is the large deviation of the value of energy (fuel) use for the CERAS database. The wing loading constraint is also significantly different from the reference values, which results in a different design point. The landing constraint is sizing for this particular design, hence the lift coefficient in landing is probably underestimated. Figure 7 also highlights the difference between both preliminary sizing routines, when applied to a conventional turbofan. For the hybrid version (i.e. with the new preliminary sizing) this is attributed to an incorrect formulation of the take-off parameter (as specified in Raymer [21]. Hence, the take-off constraint is not sufficiently limiting and resulting in underestimated thrust requirements.

Similarly, the new DHEP conceptual sizing method has been compared to the traditional approach in the Initiator. For the comparison of the "hybrid" and "conventional" method, the A320 has been sized similar to Figure 7. Additionally, turbofan aircraft designed according to the requirements for the NOVAIR project are compared (these requirements will be further detailed in Table 2). The results are reported in Figure 8, here the dark blue and dark orange bars have been used as the normalized reference. Therefore, only blue bars can be compared to each other and similarly only orange bars.

From Figure 8 it can be concluded that both design methods yield very similar results. However, also some key differences are visible in thrust(-loading) and energy consumption. Interestingly, the difference for thrust-loading and thrust that is apparent for the A320 is not visible in the Novair A320. This difference is only visible in the design (Novair A320 hybrid method C2) that did not converge until the semi-analytical fuselage and wing weight estimation (Class-II.5), but only converged on the Class-II Torenbeek [15] weight estimation. Hence, the convergence loop should be checked for other parameters as well, as the main convergence loop of the Initiator is currently only comparing MTOM.

Overall, there seems to be a reasonable agreement between both methods. However, the differences do call for further analysis of the way the Initiator design loop is converging. Also, the differences in energy (fuel) usage between the empirical and semi-analytical convergences requires attention. The differences in thrust also directly translate to differences in the propulsion-system mass, which offsets both OEM and MTOM.

[†] Airbus A320 Aircraft Characteristics Airport And Maintenance Planning `http://www.airbus.com/aircraft/support-services/airport-operations-and-technical-data/aircraft-characteristics.html`; visited on 31 May 2018

[‡] CSR01 Aircraft; Central Reference Aircraft data System (CeRAS) for research community, available on-line: `https://ceras.ilr.rwth-aachen.de/trac/wiki/CeRAS/AircraftDesigns/CSR01`; visited on 22 March 2018

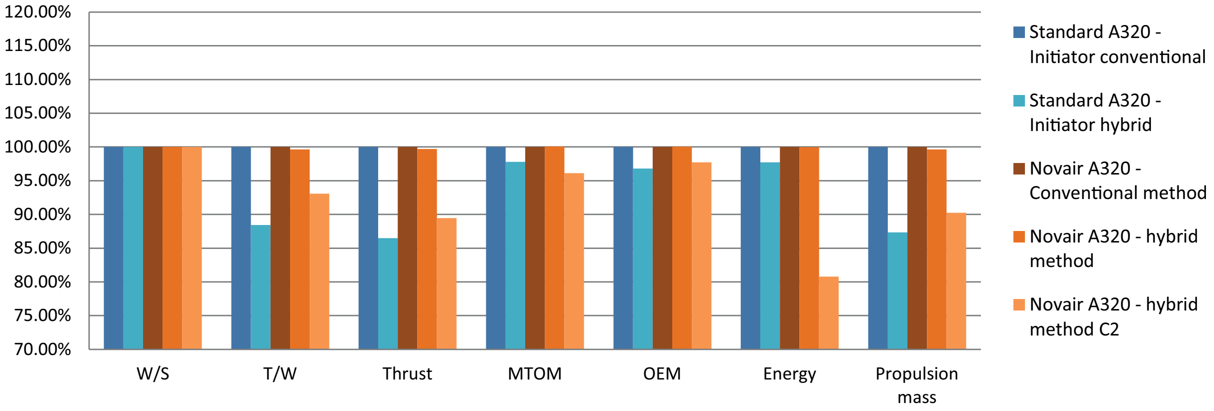


Fig. 8 Comparison between "hybrid" and "conventional" Initiator for an A320-like aircraft and an aircraft designed according to the requirements from Table 2. C2 refers to a convergence limited to the Class-II weight estimation.

IV. Concept generation, evaluation and analysis

A. Top-Level Aircraft Requirements

A set of top level aircraft requirements (TLARs) has been defined for the aircraft design exercise of LPA WP1.6.1.4. These TLARs are roughly based on an Airbus A320, with some modifications in terms of range, cruise speed and altitude to allow for more flexibility in the design studies of hybrid electric aircraft. These requirements are listed in Table 2.

Table 2 Top level aircraft requirements for hybrid electric aircraft as defined in LPA WP1.6.1.4

Parameter	Unit	Required Value	condition
Harmonic range	nmi	> 800	1100 nmi is used
Design payload	kg	13608 (see [20])	
DOC mission	nmi	800	
DOC payload	kg	15000	
Maximum payload	kg	20000	
Diversion range	nmi	250	h > FL130
(Initial) cruise Mach number	-	>0.6	
Initial Cruise Altitude (ICA)	ft	33000	after T/O @ MTOM, ISA+10°
Time-to-climb from 1500 ft to ICA (TT	min	<35	after T/O @ MTOM, ISA+10°
Max. operating (cruise) altitude	ft	>38500	~5000ft difference to ICA
Take-off Field Length (TOFL)	m	<2200	@ SL, ISA+15°
Approach speed (landing)	KCAS	<138	
Wing span limit	m	52	
One-engine-out (OEI) net ceiling	ft	>15000	
OEI range		half of design range	
ACN (flex B)	-	<42	
MLM (% MTOM)	-	100	
BC/YC	-	12/138	
Service life/cycles	-	100,000	

B. Concept Generation

During a joint workshop a total of 35 concepts for a cruise speed of Mach 0.78 are generated. A selection of some of the concepts generated is provided in Figure 9. Typical technologies of these designs include distributed propulsion, a propulsive empennage as well as electrically assisted turbofans.

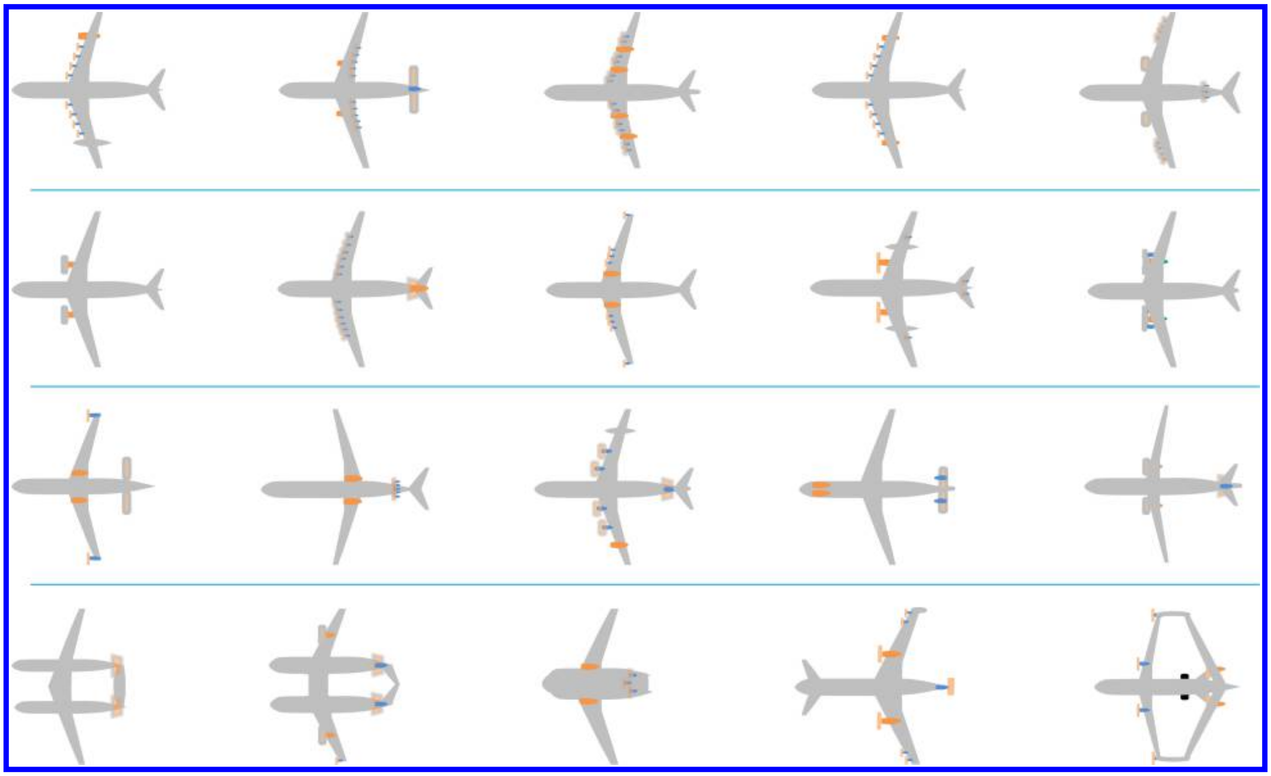


Fig. 9 Illustration of 15 out of a total of 35 generated concepts.

C. Concept Filtering

For the filtering of the concepts, each of the quantitative and qualitative figures of merit were assigned a weighting factor using the AHP method described above. The resulting factors are reported in Tables 3 and 4, respectively.

Table 3 Quantifiable figures of merit and weighting factor per criterion for the qualitative analysis

	Fuel/Energy consumption				Environment/Noise	
Figure of merit	OEM	L/D	η_p	η_{energy}	Cabin	Community
Weighting factor	0.148	0.074	0.074	0.074	0.124	0.041

Table 4 Qualitative figures of merit and weighting factor per criterion for the qualitative analysis

Figure of merit	Airport Integration	Family	MRO
Weighting factor	0.080	0.218	0.074

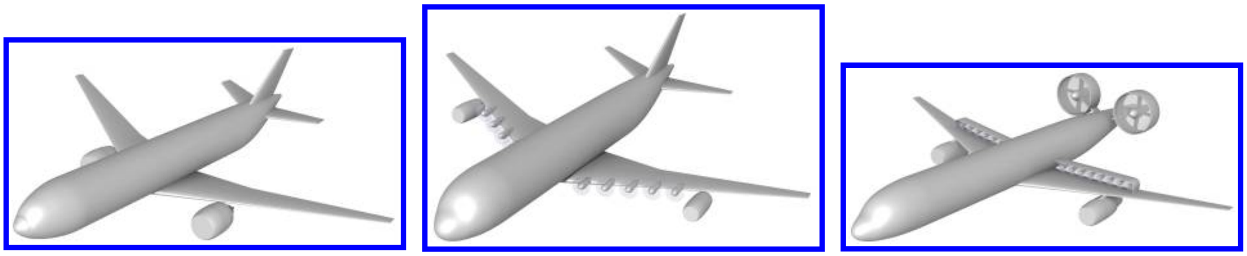
Several promising concepts, with different focus areas were selected for further quantitative assessment. These configurations have a certain number of commonalities; (1) Tube & Wing aircraft are preferred because the "family" criterion is considered important, these configurations can more easily be extended into a family of aircraft. Moreover, these aircraft are more feasible for 2035 and allow for isolating the impact (and the impact of the synergy) of HEP and distributed propulsion. (2) Use of distributed propulsion, either over-the-wing or leading-edge distributed propulsion, which may provide a high effective bypass ratio, a higher L/D, lower noise (when shielded) and easier family expansion. (3) A propulsive empennage, where a ring-wing doubles as propulsor and vertical/horizontal stabilizer. This has a potential drag benefit (through a reduction in wetted-area) and can provide shielding of propeller noise. An analysis of such a configuration with the Initiator is also presented in Vos and Hoogreef [22]. (4) Tip mounted propellers which can provide a drag reduction (induced drag a the tip, especially for lower aspect-ratio wings) and improved lateral control. The latter point may also be translated to a reduction in vertical tail-plane size.

D. Analyzed hybrid electric aircraft concepts

Using the implementation of the DHEP sizing method and the originally existing modules from the Initiator (those depicted in Figure 6), three different hybrid-electric aircraft have been designed. These include a boosted turbofan parallel-hybrid aircraft, where electric motors powered by batteries provide additional power during take-off and climb phases, and two serial-hybrid concepts with distributed propulsion. This section provides a description of the concepts, with artist impressions of their layout and an overview of the analysis results.

1. Concept HS1: Boosted turbofan

The boosted turbofan concept is the HEP configuration that requires least modifications to the airframe when compared to a conventional turbofan aircraft. The main difference is the presence of a battery and electro motor-generator in the powertrain providing additional power to a gearbox for specific flight conditions. The powertrain architecture therefore uses a parallel layout. Boosting is used during take-off and climb, hence limiting the battery mass (which presents a dead-weight that must still be carried once it is depleted) and allowing the gas-turbine efficiency to be improved during cruise. Visually, the concept does not appear different to a traditional turbofan aircraft, as illustrated in Figure 10a.



(a) Boosted turbofan parallel hybrid (HS1)

(b) Leading-edge distributed propulsion serial hybrid (HS2)

(c) Distributed over-the-wing propulsion, propulsive empennage serial hybrid (HS3)

Fig. 10 Artist impressions of hybrid-electric aircraft configurations.

2. Concept HS2: Distributed leading-edge propulsion

The HS2 concept is an aircraft using distributed tractor propellers arranged along the leading edge of the main wing, powered by two gas generators located under the wing. The distributed propulsion should assist in the high-lift conditions and provide additional bending relief to the main wing structure, though the outboard positioning of the engines could result in adverse aero-elastic effects. Distributed propulsion also has the potential to provide a large effective by-pass ratio. The concept uses a serial architecture. Figure 10b presents an artist impression of this aircraft concept.

3. Concept HS3: Over-the-wing distributed propulsion with propulsive empennage

This concept is an evolution of the DUUC[23, 24] (Delft University Unconventional Configuration), with additional distributed electric propulsion over the wing on the trailing edge. The power is solely coming from two gas generators mounted under the wing, which do not contribute to the propulsive force. The propulsive empennage takes over the role of the vertical and horizontal stabilizers. An artist impression of this concept is presented in Figure 10c. The concept uses a serial architecture. The propulsive empennage is expected to give a weight penalty, but a better efficiency and noise shielding because of the duct. Additionally, the absence of the regular empennage may result in a wetted-area reduction. Distributed propulsion provides bending relief and higher lift with deployed flaps. This allows for a smaller wing because of a high wing loading. Thrust vectoring added to the ducts may have a positive effect on upset recovery.

E. Assumptions and limitations

The designs have been assessed considering a set of assumptions and limitations specific to these (D)HEP configurations. These assumptions are listed below. Additionally, a set of values has been assumed for all powertrain components for their energy density or specific power.

Concept HS1:

- Gas-turbine thermal efficiency increased from 0.37 to 0.42 by constant operating point, this assumption can be invalidated by lighter loaded missions requiring less power to cruise and moving away from the design point
- Batteries assist in all phases except cruise (500 Wh/kg at pack level, 2 kW/kg)
- Secondary masses calculated with Torenbeek's equations [15]; nacelle mass contribution for electric motors and generators similar to normal nacelle mass estimation (7.5 and 12 kW/kg specific power, respectively)
- Cables, inverters, cooling and distribution systems for HEP are not yet included in Class-II
- Battery state of charge not yet accounted for
- MEA aircraft: reduced systems mass, 80% reduction in electrical system, 20% reduction of flight controls, no APU [25]

Concepts HS2 and HS3:

- Gas-turbine thermal efficiency increased from 0.37 to 0.42 by constant operating point
- Batteries assist in all phases except cruise (500 Wh/kg at pack level, 2 kW/kg)
- Wing mass has additional bending relief for distributed propulsion
- Secondary masses calculated with Torenbeek's equations [15]; nacelle mass contribution for electric motors and generators similar to normal nacelle mass estimation (7.5 and 12 kW/kg specific power, respectively)
- Increased power density of gas-turbine (10.5 kW/kg)
- Cables, inverters, cooling and distribution systems for HEP are not yet included in Class-II
- Battery state of charge not yet accounted for
- MEA aircraft: reduced systems mass, 80% reduction in electrical system, 20% reduction of flight controls, no APU [25]

F. Aircraft Sizing & and Results

Figure 11 and Table 5 present the results of the design studies performed for the three aforementioned aircraft configurations. "More-electric aircraft" (MEA) have been analyzed, assuming that the mass of the on-board electrical systems and auxiliary power unit (APU) can be reduced because of the presence of a hybrid-electric powertrain.

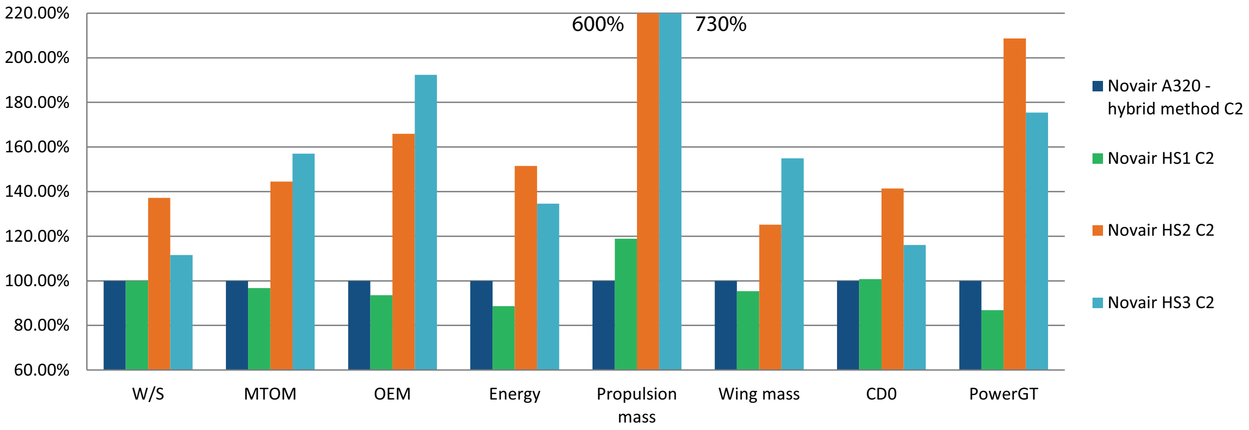


Fig. 11 Selection of results from design studies for three hybrid-electric aircraft normalized with respect to a traditional A320-like aircraft designed for the same TLARs. C2 refers to a convergence limited to the Class-II weight estimation.

As can be seen from the results in both Table 5 and Figure 11, the boosted turbofan aircraft is the most likely to provide a benefit in terms of mission fuel use and total energy consumption. The design resulted in a decreased total

Table 5 Results from design studies for three hybrid-electric aircraft in comparison to a traditional A320-like aircraft designed for the same TLARs.

Parameter	Unit	NOVAIR A320	HS1	HS2	HS3
W/S	N/m^2	5555	5555	7622	6195
Power (total propulsive)	MW	39.4	39.8	28.3	46.0
MTOM	tons	59.8	57.9	86.4	93.9
OEM	tons	32.8	30.7	54.5	63.1
Energy use	GJ	299	265	453	402
TSFC cruise	g/kNs	15.6	15.1	16.7	16.8
Fuel mass	tons	7.0	6.1	10.5	9.3
Battery mass	tons	-	1.0	1.4	1.4
Propulsion system mass	tons	3.9	4.6	23.4	28.4
Wing mass	tons	6.1	5.9	7.7	9.5
Power gas-turbine	MW	39.4	34.2	82.2	69.1
Power electro motor	MW	-	5.6	28.3	46.0

energy usage (±10%) and also reduced fuel mass because of the more efficient operation of the gas-turbine during the cruise phase. Using the MEA architecture, the possibility exists to even have a slightly lower MTOM and OEM as compared to the reference aircraft (designed for the same mission, by the same tool).

The boosted turbofan configuration uses a parallel hybrid configuration and achieves a small benefit in terms of maximum take-off mass and operative empty mass. This benefit can be attributed to the increased thermal efficiency of the gas-turbine (increased to 0.42) which is assumed to be possible because the operating point in cruise has improved (closer to design condition), since the engine is no longer sized for take-off. In take-off and climb, electric energy is provided by a battery and electro-motor. Additionally, the flight control mass has been decreased by 20% and the electric system mass by 80% because of the further electrification of the aircraft (due to the hybrid system). Also the auxiliary power unit has been removed, as its function can be taken over by the battery.

The lower weight also leads to a slightly smaller engine, though the battery and electro-motor increase the total mass of the powertrain again. It should be noted that cables, cooling, inverters and battery depth of discharge have not been taken into account yet, which will increase the weight again. The total effect of reduced masses and reduced power requirements, together with the improved gas-turbine lead to a slightly smaller empennage and wing (with better L/D) and a lower thrust-specific fuel consumption. The degree of hybridization of this configuration is still very low (<1% in terms of energy). All hybrid-electric concepts resulted in designs with limited battery mass, due to the strong impact of battery mass on MTOM for the values of specific energy and power assumed. These battery masses represent hybridization levels of less than 1%, because of the penalty of carrying the additional mass over the mission and the low specific energy compared to kerosene. Additionally, the serial-hybrid architecture is increasing the mass of all powertrain components.

This is also visible in the results of both more radical configurations, where the mass of the propulsion system is significantly increased because of the presence of all additional components. These effectively result in powertrain masses that are six or seven fold of a representative turbofan-powered aircraft, because of the presence of a set of many electric motors, propellers, gearboxes and gas-turbines. Both high speed serial configurations show that a serial powertrain architecture for a hybrid electric configuration leads to significant mass penalties, attributed to the increase in powertrain mass (even without cables, inverters, cooling and battery depth-of-discharge considerations).

However, it can be seen that the distributed propulsion does allow for a much more favorable design point, increasing wing loading by 10-20%. In particular, HS2 demonstrates that leading edge distributed propulsion can have a benefit in terms of high-lift capabilities, increasing $C_{L_{\max}}$ to allow higher wing loadings and higher power loadings (in essence, better design points for minimizing maximum take-off mass). However, all aero-propulsive benefits and benefits for gas-turbine operation are negated by the increased masses. Additionally, the design operates beyond the limit of the current aero-propulsive model. Hence, in landing condition, the effects are not fully taken into account. Similar to the HS2 configuration, also the HS3 configuration suffers in terms of mass increase due to the additional powertrain components.

Not all benefits of distributed propulsion have yet been taken into account and a relatively simple model for the ΔC_L and ΔC_D has been used. Hence, some benefit may still be achieved from the synergy between HEP and distributed propulsion. To investigate this, more detailed studies must be performed, also exploring the entire design space of e.g. number of propulsors, power-splits, mission profile and mission requirements, powertrain control parameters and using the gas-turbine for thrust generation as well. An initial effort of such a design space exploration is made in de Vries et al. [26]. In addition, parallel configurations will be studied.

V. Conclusions and Outlook

Using a new Class-I sizing method for hybrid-electric aircraft with distributed propulsion coupled to a Class-II weight estimation method inside a conceptual sizing tool, several hybrid electric aircraft concepts have been assessed. The sizing method has also been compared against a traditional Class-I sizing, showing a good agreement with the traditional sizing and literature references. These studies, involving a boosted turbofan aircraft and two concepts with distributed hybrid electric propulsion, have shown that the synergy between distributed and electric propulsion allows for the selection of a better design point. However, for the two DHEP aircraft, the powertrain mass significantly increases (more than quadruples). Consequently, the configurations with serial hybrid powertrains and distributed propulsion present a significant weight increase, which translates directly from the powertrain mass to the operative empty mass and maximum take-off mass. This offsets any potential improvement due to aero-propulsive benefits. These aero-propulsive benefits can be achieved if the mass penalty can be offset, either by lowering the powertrain mass (improved technology) or lowering the power requirement (lowering flight speed or payload requirements). Distributed propulsion (in particular leading edge) offers design point improvements, i.e. higher wing loadings and higher power loadings. The boosted turbofan has shown a potential fuel saving in the order of 10% on the evaluated mission. Because the HEP could allow for a reduced systems and APU masses, the resulting MTOM and OEM are comparable to the reference aircraft.

Future studies will explore the design space, including all powertrain components, cooling and insulation effects, mission parameters and propulsion system layout, to identify feasible combinations of distributed and hybrid electric propulsion. Additionally, an increase in the propulsive efficiency is expected for adapted wing configurations in which a rectangular duct is combined with wing airfoil shape optimization to arrive at a more uniform inflow field for the over-the-wing distributed fans. Additional numerical analysis on such a configuration is under way. Ongoing design activities and sensitivity studies focus on using the series/parallel partial hybrid (SPPH) powertrain, to provide potentially lower propulsion system masses. For all future design studies, detailed investigations on the different enabling technologies, such as aero-propulsive interaction of distributed over-the-wing propulsion, and mass estimations or stability characteristics of the propulsive empennage are key to unlocking the potential of these technologies on airframe level. Detailed investigations are required at subsystem level to provide the thorough understanding necessary for correct integration and interaction at system level.

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