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SCALABILITY ANALYSIS OF RADICAL TECHNOLOGIES TO VARIOUS AIRCRAFT CLASS - PART I: INITIAL DESIGNS

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Abstract

Various research initiatives in hybrid-electric/sustainable aviation typically address only a single vehicle or single vehicle class. However, novel propulsion and energy solutions can be expected to be differently applied in different vehicle classes. The objective of the EU funded research project CHYLA (*Credible HYbrid eLectric Aircraft*) is to identify areas suitable for scaling, as well as limitations or challenges for development for the applications of key radical technologies on different classes of aircraft. This article provides an overview of the design approach followed for the CHYLA project, as well as initial radical designs and comparison to the CHYLA baselines. These provide the starting point for both the sensitivity study which will be presented in a later scalability assessment and economical assessments in the CHYLA project. A variety of regional, short medium range and large aircraft has been designed, all according to the same TLAR yet without detailed tuning of important power control variables. Results are distinguishable between concepts and provide sufficient detail to capture the necessary effects. The reduction of fuel consumption will require detailed assessment and fine tuning, though reductions may be achievable for regional and possibly SMR aircraft.

Keywords: hybrid-electric aircraft; distributed electric propulsion; aircraft design

Nomenclature

AR	=	Aspect Ratio (wing) ($\sim$)	MDO	=	Multidisciplinary Design
BLI	=	Boundary Layer Ingestion		=	Optimization
BM	=	Battery Mass (t)	MTOM	=	Maximum Take-Off Mass (t)
b	=	Wing span (m)	MZFM	=	Maximum Zero Fuel Mass (t)
C_{Di}	=	Induced drag coefficient ($\sim$)	NA	=	Not Applicable
CHYLA	=	Credible Hybrid Electric Aircraft	OEM	=	Operative Empty Mass (t)
C_{L}	=	Lift coefficient ($\sim$)	P	=	Power (kW)
Com	=	Commuter	P1	=	Primary propulsor/powertrain
CS	=	Certification Specification	P2	=	Secondary propulsor/powertrain
d_{fus}	=	Fuselage diameter (m)	PAR	=	Parallel
E	=	Energy (GJ)	PM	=	Payload mass (t)
FM	=	Fuel Mass (t)	PREE	=	Payload Range Energy
GA	=	General Aviation	PTE	=	Partial turbo electric
H2	=	Hydrogen		=	Efficiency ($\sim$)
h_{cr}	=	Cruise altitude (m)	R	=	Range (km)
LEDP	=	Leading Edge Distributed	REG	=	Regional Aircraft
	=	Propulsion	S	=	Wing area (m^2)
LH_2	=	Liquid Hydrogen	SMR	=	Short/Medium Range aircraft
LPA	=	Large Aircraft	SPPH	=	Series-parallel partial hybrid
l_{fus}	=	Fuselage length (m)	T	=	Thrust (kN)
M_{cr}	=	Cruise Mach number ($\sim$)	T/W	=	Thrust loading ($\sim$)

TF	=	Turbo fan	W/P	=	Power loading (kN/kW)
TLAR	=	Top Level Aircraft Requirement	W/S	=	Wing loading (kN/m^2)
TP	=	Turbo prop	WTMP	=	Wing Tip Mounted Propulsion

1. Introduction

Various research initiatives in hybrid-electric/sustainable aviation typically address only a single vehicle or single vehicle class [1, 2, 6, 8, 10, 12, 14, 18–21, 25, 28]. However, novel propulsion and energy solutions can be expected to be differently applied in different vehicle classes, and it is not unimaginable to try to reach a sufficient maturity level following an approach from the early days of aviation: starting small to prove the application of a certain radical technology and gradually scaling up to larger classes of vehicles. The objective of the EU funded research project CHYLA (*Credible HYbrid eLectric Aircraft*) is to identify areas suitable for scaling, as well as limitations or challenges for development for the applications of key radical technologies on different classes of aircraft. Therefore, the ultimate objective is to construct a landscape of technology applications that provides an overview of scaling opportunities, challenges and limitations. The objective of this article is to lay down the approach and conceptual design method for the CHYLA project, as well as to test the framework for its suitability to analyse a large variety of hybrid electric and hydrogen power aircraft in order to distinguish any scaling effects in later studies.

1.1 CHYLA background

In CHYLA, novel energy systems are applied to aircraft configurations and optimized to identify promising configurations in five different classes, i.e. 1) light aircraft - General Aviation, 2) commuter aircraft, 3) regional aircraft, 4) short-medium range and 5) large passenger aircraft. CHYLA is a collaboration between Delft University of Technology, Technische Universität Braunschweig and University of Southampton, funded by the EU H2020 program. The objective of the project is to identify the potential and challenges associated with the applications of hybrid electric powertrain technologies to aircraft of different classes. These technologies also extend to the application of different energy carriers and propulsion systems, linked to the particular powertrain architectures. To this end, the project identifies suitable technologies, suitable combinations of technologies and use an approach consisting of different phases to assess technology scalability/applicability. Additionally, economic and airline network aspects are analysed as well.

1.2 CHYLA approach

The approach followed in the CHYLA project is illustrated graphically in Figure 1. The project considers multiple stages of scalability assessment to analyse the different radical technology (applications). The development of radical aircraft feeds the conceptual design stage, of which the results will be discussed in this article, focusing particularly on the three largest classes of vehicles. These initial designs provide the input to a credibility based MDO approach, as detailed in Wahler et al. [27] — also presented at ICAS 2022. During this MDO study, the most feasible baseline designs for each category of aircraft will be optimized taking the credibility of reaching a certain technology level explicitly into account (e.g. confidence of reaching certain battery performance). This optimization is fed by a detailed energy network model, specifically designed to assess different combinations of electrical technologies to achieve required powertrain performance. The energy network model that has been developed is presented in Wahler et al. [26]. The last step uses aircraft designs from all stages to analyse the impact on operations, economics as well as airport integration. Each phase in the project is providing input to the scalability assessment, as each intermediate result provides information on the applicability and scalability of technology combinations. The initial designs presented in this article also form the baseline for the first step of sensitivity analysis and fine tuning of the designs.

2. Aircraft Conceptual Design

The aircraft conceptual design makes use an in-house developed framework, which has been modified to incorporate the contributions of distributed (hybrid-) electric propulsion and can be used for novel configurations as well as hydrogen combustion [16]. The following sub-Sections provide a short

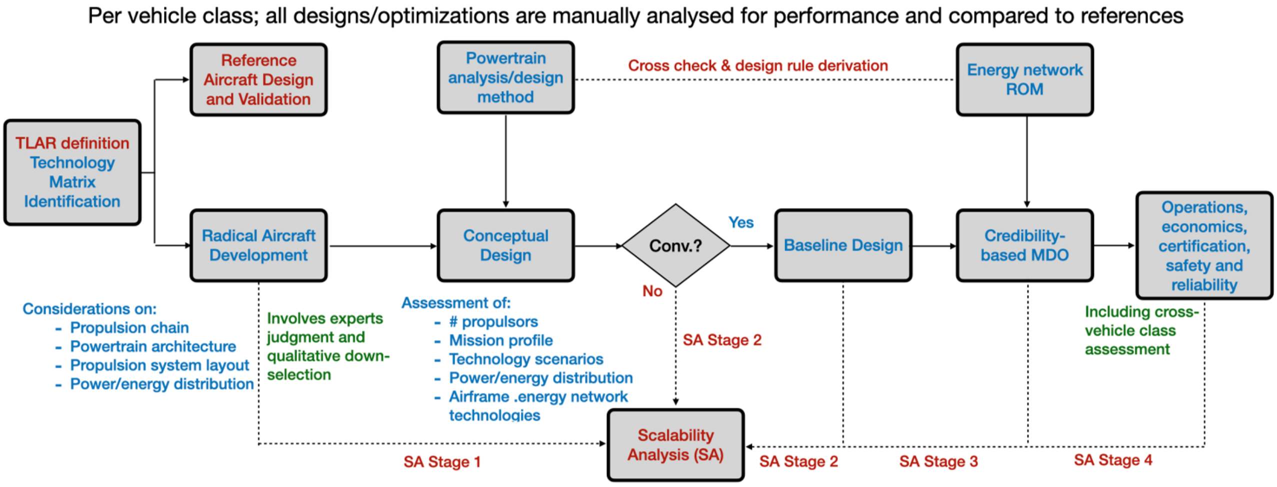

Figure 1 – Illustration of the approach followed in the CHYLA project for aircraft design and scalability assessment

overview of the design method and tools, as well as an overview of the top-level aircraft requirements (TLAR) for the CHYLA studies.

2.1 Preliminary Design Method

The design process used in this research is based on the work from De Vries et al. [4, 5], which forms a modified preliminary sizing method complementing a more traditional conceptual design approach based on the work of Torenbeek [22], Obert [15] and Roskam [17]. The modified preliminary sizing methods enable application to any configuration with aero-propulsive interactions, as are for example found in aircraft with distributed electric propulsion. In the preliminary sizing method by [4], the thrust, lift and drag decompositions account for aero-propulsive interactions leading to a set of modified equations of motion for the constraint analysis (or wing-power loading diagram) because for distributed propulsion, the equations for equilibrium flight can become coupled with lift and drag depending on thrust. This process is illustrated in Figure 2.

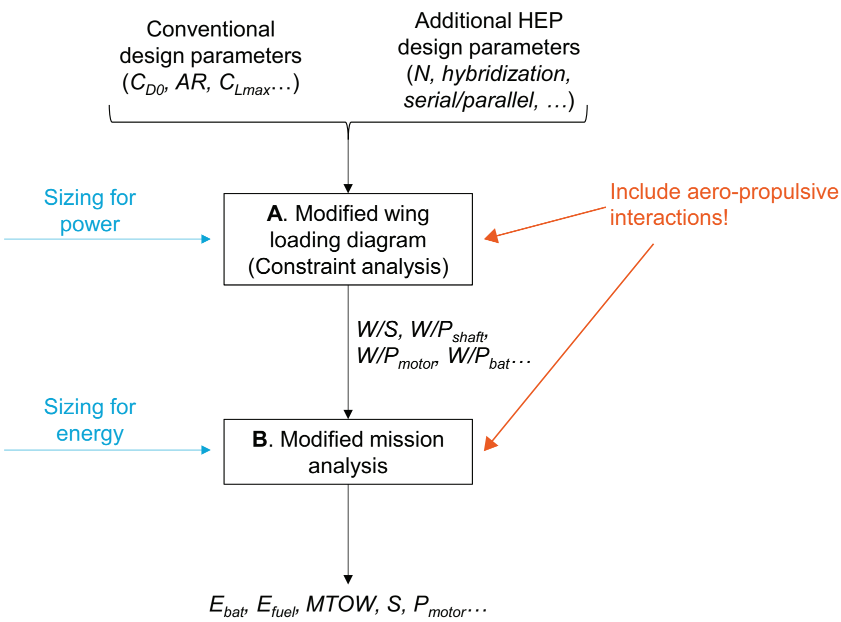

Figure 2 – Schematic flow of conceptual sizing for power and energy, originally presented by the authors in Hoogreef et al. [11]

Another aspect is the included powertrain model (for all kinds of powertrains with single or dual energy sources, see [3]) which is modelled as a chain of components/efficiencies. This powertrain model is controllable for different flight phases for different operating modes (of a hybrid electric powertrain) and can be configured with different power control parameters (Gas turbine throttle setting, Supplied power ratio, i.e. by a secondary energy storage in case of a hybrid powertrain, and the Shaft power ratio, which determines the power provided to the distributed electric motors).
The *supplied power ratio* [4, 13] is used as a power-split parameter to define how the power coming from the two energy sources is shared at the node:

$$\Phi = \frac{P_{\text{bat}}}{P_{\text{bat}} + P_{\text{f}}}. \tag{1}$$

The *shaft power ratio* is defined as:

$$\varphi = \frac{P_{\text{s2}}}{P_{\text{s1}} + P_{\text{s2}}}. \tag{2}$$

Combining both modifications allows constructing a power-loading diagram for every powertrain component to clearly show the influence of different constraints on different parts of the powertrain, as opposed to the traditional constraint (or power/thrust vs wing loading diagram) which is only derived for maximum take-off conditions for a single combustion engine. This set of diagrams determines the design point for the aircraft sizing process, which at aircraft level is still the point of maximum wingloading in an attempt to minimize MTOM althouh different points can be sizing for different components. Ultimately, the aircraft maximum take-off mass (MTOM) is determined for the limiting total power and energy requirements to perform the specified mission. An additional mission analysis is included as a point model, using time steps and a summation over mission, depending on the different control parameters that are specified. The analysis solves a power balance across the (hybrid) propulsion system (instead of conventional Breguet range equation), where constant component efficiencies per phase are used.

2.2 Conceptual design: Aircraft Design Initiator

All sizing methods are implemented as an analysis software in an in-house developed Matlab tool, containing a design convergence loop over several disciplinary analyses, including handbook methods, empirical data and physics based methods. This software, called the *Aircraft Design Initiator* (or *Initiator* in short) has been under development for over a decade and is capable of sizing both conventional and unconventional configurations (such as blended wing body aircraft and box-wing aircraft), with the latest additions being made to also design hybrid-electric and distributed propulsion, as well as hydrogen aircraft. The process flow of the Initiator is shown schematically in Figure 3. It should also be noted that the synthesis process is a process of convergence, not optimization. Hence, 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 constraints. Figure 3 only shows the process flow at an aggregate level, many of the blocks contain multiple design, analysis or sizing modules/methods. The Initiator was initially conceived as part of the European project Aerodesign (FP7) and has supported other European projects such as RECREATE (H2020), Smart Fixed Wing Aircraft (Clean Sky) as well as more recently in Clean Sky 2 (NOVAIR/LPA) and currently CHYLA (Clean Sky 2 Thematic Topic). The goal is to quickly conceive realistic aircraft designs to investigate the effect of new technologies and aircraft configurations. The tool consists of a series of disciplinary analysis and sizing modules that are combined in an efficient framework. The individual analysis modules are continuously updated by improved analysis methods to enhance the reliability or flexibility of the Initiator. A complete description of the Initiator and its development is presented by Elmendorp et al. [7]. More information on the employed overall sizing process for hybrid electric aircraft, with distributed propulsion, and its inputs is presented in [11].

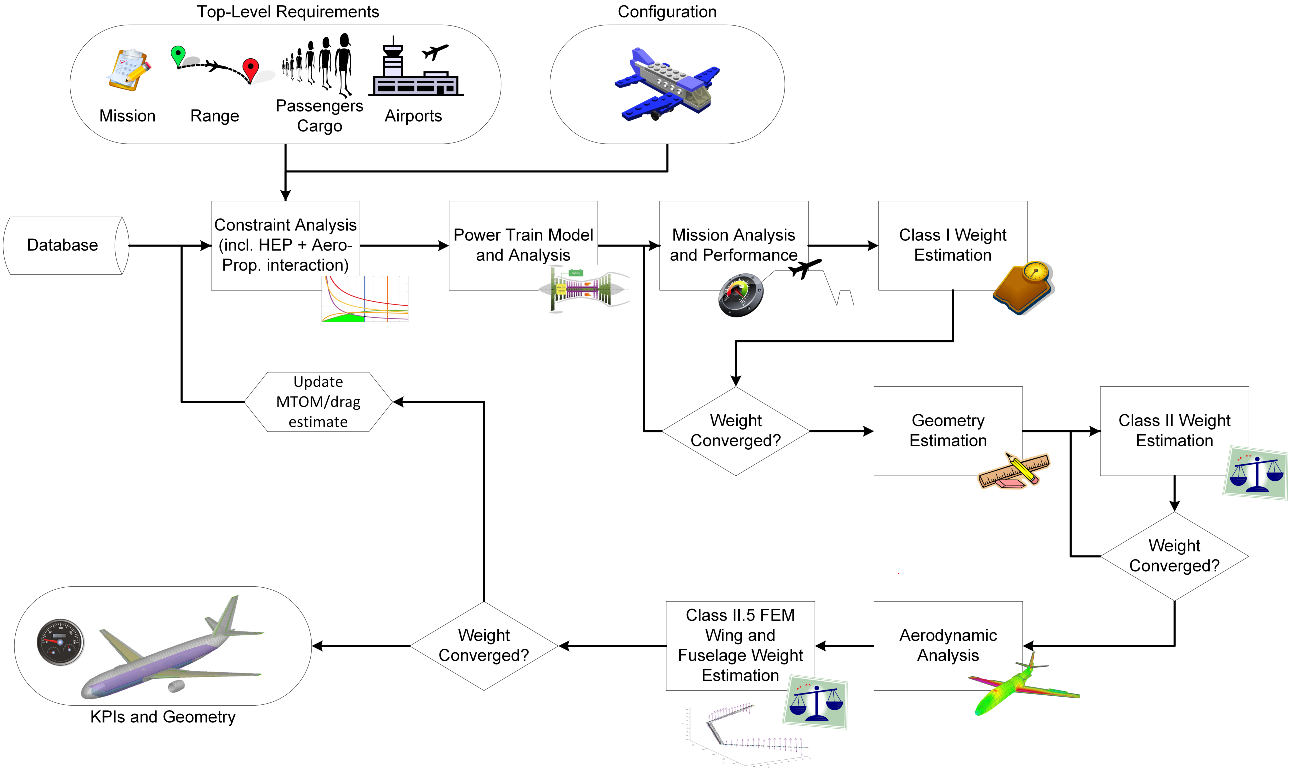

Figure 3 – Illustration of the *Initiator* process flow for the design of DHEP aircraft [11]

2.3 Aircraft TLAR

The Top-Level Aircraft Requirements (TLAR) determined for the baseline designs of the CHYLA project have been derived from current, class-leading examples as well as reference aircraft that have been selected in other European and national research initiatives (a.o. FUTPRINT50, Flying-V, GLOWOPT, IRON, MAHEPA, NOVAIR, UNIFIER19). An important consideration for the selection of suitable reference aircraft is the definition of the vehicle classes. For some, boundaries between classes are more obvious than others (e.g. CS-23 vs. CS-25 is a policy-based division in terms of MTOM and capacity) whereas for others, the boundaries actually may shift and the division is more based on vehicle concept/capacity rather than vehicle range (e.g. regional turboprop versus typical usage of thin-haul narrow bodies). In the latter example, a shift in technology use is not unimaginable, having turboprop aircraft with narrow-body capacity/range as a consequence. However, this will be driven by regulations and market demand. Nevertheless, the following classification of vehicles is proposed with an indicative payload capacity, as well as the selected reference aircraft:

- Regional (REG), 40-100 pax, ATR72-600
- Short/medium range (SMR), 150 pax, Airbus A320NEO
- Large aircraft (LPA), 300 pax, Airbus A350-900

Since payload capacity can have a significant impact on the overall aircraft design, it will be considered in sensitivity studies to further detail the scalability assessment of technologies. The TLAR are provided in Table 1.

Table 1 – Overview of TLAR for CHYLA baseline aircraft and initial designs

	unit	Regional	Short/Medium range	Large passenger aircraft
Capacity (business + economy class)	-	70	150 (12 + 138)	315 (48 + 267)
Maximum payload mass	kg	7500	20000	53500
Harmonic range	nmi	500	2460	5830
Cruise speed	KTAS	M0.4	M0.78	M0.85
Cruise altitude	feet	23000	37000	40000
Rate of climb SL	ft/min	1355	2500	3000
Ceiling	feet	25000	40000	43000
Take-off distance	feet	4500	7200	8500
Landing distance	feet	3300	4900	6600
OEI ceiling	feet	14000	19500	20000
Reserves		45min + 100 nmi	45min + 200nmi	45min + 200nmi

2.4 Validation and Baseline Design

The analysis methods programmed in the various functions inside the Initiator aircraft design framework are often bench-marked against data from the open literature and comparisons are typically presented with every publication (e.g.[7, 11, 12, 24]). Additionally, a separate comparison of the preliminary sizing method for hybrid electric aircraft is performed in [9], where the reference case is a typical commuter aircraft (Dornier DO-228). The table below (2) illustrates the designed reference aircraft with the Initiator as well as there reference specifications from literature. (Reference values from airport planning manuals and Jane's "All the World's Aircraft")

Table 2 – Comparison table for the validated (and investigated) aircraft: ATR72-600[1], A320NEO (WV0055)[2], A350-900 (WV010)[2]

Parameters	**ATR72-600**	**Initiator ATR72-600**	Δ (%)	**A320-NEO**	**Initiator A320-NEO**	Δ (%)	**A350-900**	**Initiator A350-900**	Δ (%)
MTOM (t)	23.0	23.8	+3.5	79.0	79.0	0	280	290	+3.6
MZFM (t)	21.0	21.2	+1.0	64.3	63.5	-1.2	196	194	-1.0
FM (harmonic) (t)	2.0	2.6	+30	14.7	15.5	+5.4	84.3	96.3	+14
PM (max) (t)	7.5	7.5	0	19.3	19.3	0	53.5	53.5	0
OEM (t)	13.5	13.8	+2.2	45.0	44.2	-1.8	142	140	-1.4
W/S (kN/m^2)	3.70	3.70	0	6.33	6.26	-1.1	6.20	6.21	+0.2
T/W	-	-	-	0.31	0.29	-6.5	0.27	0.30	+11
W/P (N/kW)	61.1	47.9	-21.6	-	-	-	-	-	-
S (m^2)	61.0	63.2	+3.6	123	124	+0.8	443	458	+3.4
b (m)	27.0	27.5	+1.9	35.8	36.0	+0.6	64.8	65.9	+1.7
l_{fus} (m)	27.2	25.3	-7	37.6	36.1	-4.0	65.3	58.9	-9.8
d_{fus} (m)	2.87	2.77	+3.5	4.14	3.97	-4.1	5.96	5.73	-3.9

Analysis of the data in Table 2 shows that the methods generally are able to produce aircraft with fairly good accuracy, generally within the expected +/- 10% bandwidth that is typical for handbook methods.

[1]Data from Jane's "All the world's aircraft" and ATR 72-600 Fact sheet https://www.atr-aircraft.com/wp-content/uploads/2020/07/Factsheets_-_ATR_72-600.pdf - visited: 29 April 2022

[2]Data from Jane's "All the world's aircraft" and Airbus Aircraft characteristics airport and maintenance planning. https://www.airbus.com/en/airport-operations-and-technical-data/aircraft-characteristics - visited: 29 April 2022

However, some larger deviations were identified particularly for the thrust and power loading, and consequently for the fuel mass. For all CS-25 designs that are cruise limited, the thrust or power loading corrections for altitude yield larger engines than the reference values. This is likely caused by a too large effect of the density lapse rate with altitude on the available power lapse in the current version of the sizing framework, particularly for the hybrid version of the Initiator. In the article by Onorato et al. [16], results with the conventional preliminary sizing method (i.e. without using the method by [4]) are much more accurate. Notably, also the fuselage length for the large aircraft is underestimated which is primarily caused by the tailcone length, though this will have only a marginal impact with the current class 2 sizing methods. The results give sufficient confidence to proceed with the scalability assessment and baseline design.

3. Technology Combinations and Variations

Whilst the TLAR describe the requirements to be met by the individual designs, there is still a significant amount of freedom in terms of energy carriers, powertrain layout and propulsion layout, next to aircraft configurations. For CHYLA, traditional tube-and-wing configurations are prioritized given the entry into service of 2035. As a starting point, an analysis has been carried out to narrow down the feasible design space by eliminating unfeasible or unrealistic options (based on past experience and literature). Moreover, the design space that is left should still provide enough coverage of the various options to give a suitable basis for the scalability assessment.
Technology variations are performed in such a way that a comparison is always made to an improved baseline specification. This allows for a fair comparison of the employed technology and to track the impact of any changes in design variables across different studies. This approach is illustrated in Figure 4. For example, if the design cruise speed would be reduced in a certain radical concept, this is also reflected in a modified baseline aircraft. This should limit the impact of uncertainties in the design approach, plus it allows for a fairer comparison as the modified baseline can always be compared back to the initial design (and associated reference aircraft).

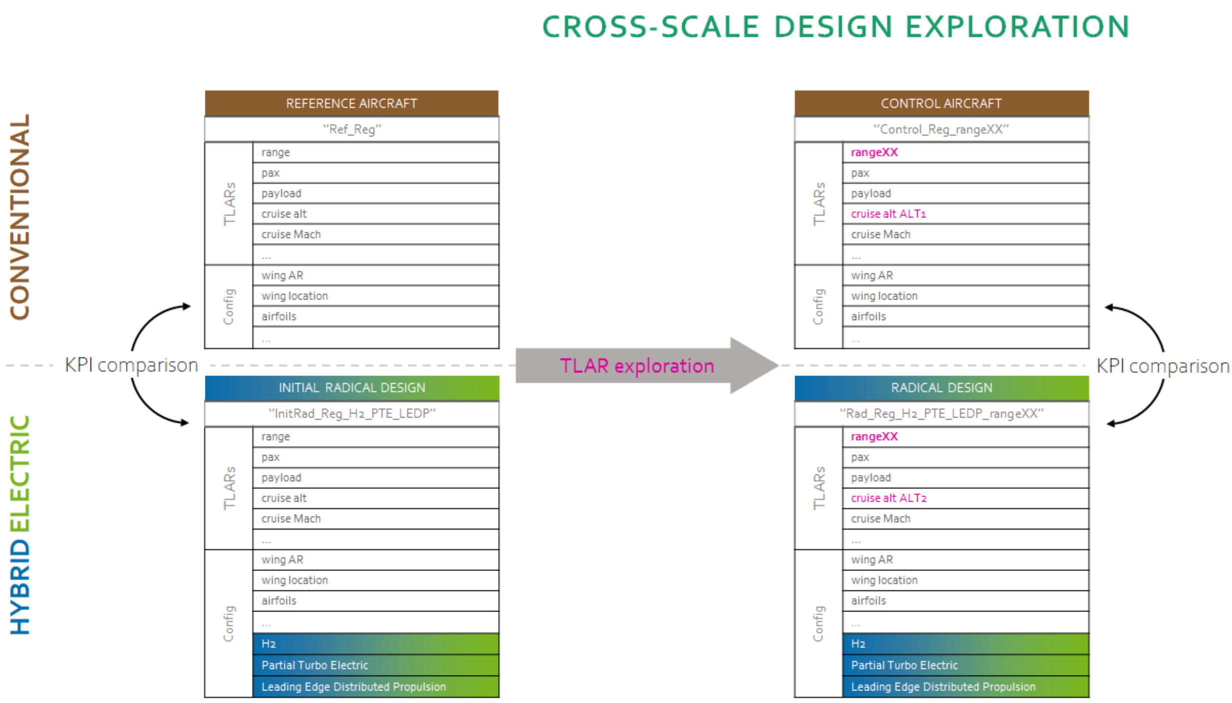

Figure 4 – Cross-scale design exploration approach for scalability assessment and fair comparison of aircraft design specification modifications.

3.1 Baseline designs

The figures and tables in this sub-Section present the results from the design of the CHYLA baseline aircraft according to the TLAR in Table 1, as well as a comparison to the reference aircraft sized by the same methods (but according to actual reference aircraft specifications). The reference specifications are provided for completeness.

3.1.1 Regional baseline aircraft

Figure 5 illustrates the baseline regional aircraft designed for CHYLA. The specifications largely follow those of the ATR72. However, some key differences exist that also impact the resulting KPIs (as shown in Table 3). Most important is the difference in cruise Mach number which significantly impacts the wing weight and hence MTOM, as well as the fuel used. Part of the fuel consumption increase due to higher Mach number is counteracted though by the higher cruise altitude.

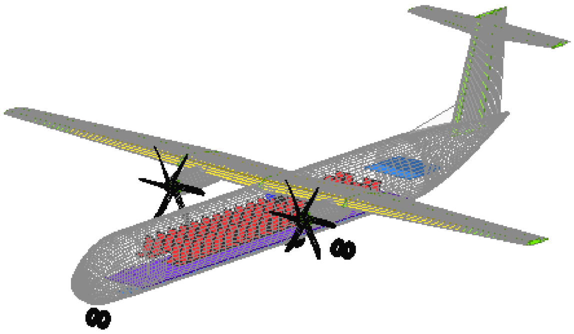

Figure 5 – 3D view of the CHYLA regional baseline designed with the Initiator

Table 3 – Overview of key performance indicators and design parameters for regional aircraft

	Unit	Initiator ATR72-600	Reference Values	CHYLA REG Baseline
W/S	kN/m^2	3.70	3.70	3.39
W/P	N/kW	47.9	61.1	57.5
MTOM	t	23.8	23.0	22.8
OEM	t	13.8	13.5	13.5
FM harmonic	t	2.60	2.10	1.78
S	m^2	63.2	61.0	66.0
R_{harmonic}	km	926	926	926
AR	-	12	12	12
M_{cr}	-	0.44	0.44	0.4
h_{cr}	km	5.2	5.2	7.0
PM	t	7.5	7.5	7.5

3.1.2 SMR baseline aircraft

The baseline SMR aircraft is illustrated in Figure 6 and its KPIs are presented in Table 4. The differences are all caused by the higher payload mass, which cascades on the MTOM and OEM and consequently impacts the fuel use of the aircraft. In general, the specifications are very similar to those of the A320.

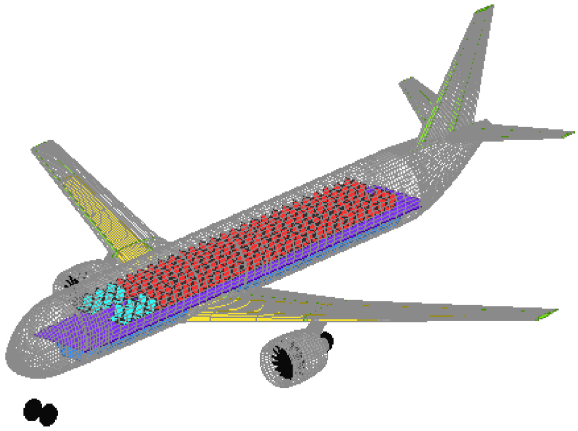

Figure 6 – 3D view of the CHYLA short/medium range baseline designed with the Initiator

Table 4 – Overview of key performance indicators and design parameters for short/medium range aircraft

	Unit	Initiator A320NEO	Reference Values	CHYLA SMR Baseline
W/S	kN/m^2	6.26	6.33	5.90
T/W	-	0.29	0.31	0.28
MTOM	t	79.0	79.0	82.4
OEM	t	44.2	45.0	45.9
FM harmonic	t	15.5	14.7	16.5
S	m^2	124	123	137
R_{harmonic}	km	$4.56e^3$	$4.56e^3$	$4.56e^3$
AR	-	10.5	10.5	10.5
M_{cr}	-	0.78	0.78	0.78
h_{cr}	km	11.3	11.3	11.3
PM	t	19.3	19.3	20.0

3.1.3 LPA baseline aircraft

The LPA aircraft specified in Table 5 and illustrated in Figure 7 is very similar to the A350, fulfilling almost the same set of TLAR except for the cruise altitude. Interestingly, this small change allows already for better fuel consumption and consequently a small weight reduction.

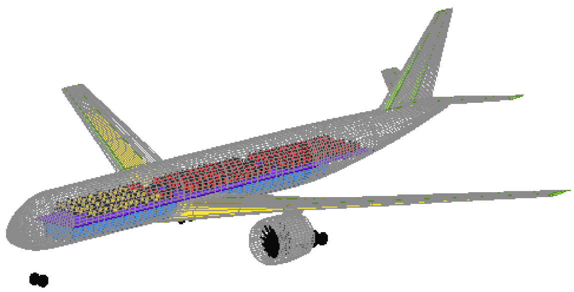

Figure 7 – 3D view of the CHYLA large passenger aircraft baseline designed with the Initiator

3.2 Design space matrix

In CHYLA, the design space is defined not only by aircraft configuration, but also by powertrain layout, and closely related, the energy carrier. Figure 8 offers a simplified representation of the set of powertrain architectures that covers combinations of energy source and nature of propulsive power. Powertrain architectures are composed of a "primary" powertrain, consisting of all components that are mechanically linked to the gas turbine, and an optional "secondary" powertrain. Combinations of

Table 5 – Overview of key performance indicators and design parameters for large passenger aircraft

	Unit	Initiator A350-900	Reference Values	CHYLA LPA Baseline
W/S	kN/m^2	6.21	6.20	6.21
T/W	-	0.30	0.27	0.30
MTOM	t	290	280	287
OEM	t	140	142	139
FM harmonic	t	96.3	84.1	94.8
S	m^2	458	443	453
R_{harmonic}	km	$10.8e^3$	$10.8e^3$	$10.8e^3$
AR	-	9.49	9.49	9.49
M_{cr}	-	0.85	0.85	0.85
h_{cr}	km	11.9	11.9	12.1
PM	t	53.5	53.5	53.5

these powertrains with matching energy carriers can be employed over a variety of vehicle classes, but may not be applicable across all. Hence, a design space matrix must be defined that combines energy source, powertrain layout and propulsion system with representative vehicle classes.

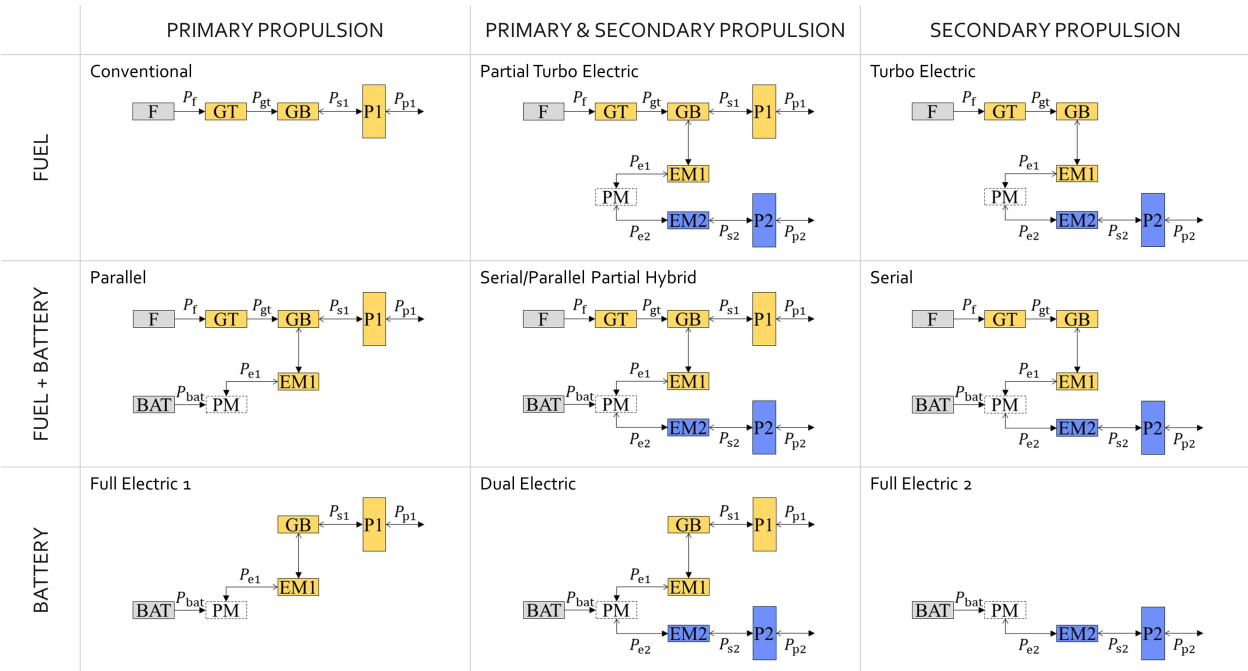

Figure 8 – Simplified representation of different powertrain architectures, adapted from [5]. "F" and "BAT" refer to fuel and battery respectively. As for powertrain components, "GT" stands for Gas Turbine, "GB" for Gear Box, "EM" for Electric Motor, "PM" for Power Management and "P" for propulsor. Upper-case letters are used for energy sources and powertrain components, while power paths are indicated with lower-case subscripts, with arrowheads indicating the feasible direction of the power flow

Figure 9 illustrates the reduced design space for which initial radical aircraft designs will be made. Note that not all possible combinations have been used, but a selection was made that allows to cover the entire design space without exhaustively testing all different options. It must be noted that the matrix shown here is not restricted to regional and larger aircraft, and additional studies will be made for commuter aircraft as well. That analysis allows to also evaluate some other forms of distributed propulsions systems and expand the design space. A more exhaustive study of propulsion layouts was performed before in [11]. The effect of varying power control settings on WTMP aircraft was studied in [23].

	Conventional H2 direct burn	Partial Turbo Electric	Parallel	Serial Parallel Partial Hybrid	Serial	Full-electric
Fuel (H2 or JetA1)	P1: TF. P2: NA **LPA; SMR** P1: TP. P2: NA **Reg**	P1: TF. P2: BLI-fan **LPA; SMR** P1: TP. P2: BLI-fan **Reg** P1: TP. P2: WtipMP **Reg**				
Fuel (JetA1) + Battery			P1: boosted TF. P2: NA **SMR** P1: boosted TP. P2: NA **Reg**	P1: TP. P2: BLI-fan **Reg** P1: TP. P2: WtipMP **Reg** P1: TP. P2: LEDP **Com**	P1: NA. P2: WtipMP **Com** P1: NA. P2: LEDP **Com**	
Fuel Cell + Battery					P1: elec fan **Reg** P1: WtipMP **Com, GA** P1: LEDP **Com; GA**	
Battery						P1: WMP. P2: WtipMP **GA** P1: NA. P2: LEDP **Com; GA**

Figure 9 – Combinations in energy source and powertrain architectures, for different aircraft classes and propulsion layouts, selected for the present work. In table cells, P1 and P2 refer to primary and secondary propulsion respectively. The corresponding propulsion layout considered are Turbo Fan (TF), Turbo Prop (TP), Boundary Layer Ingestion (BLI fan) and Wing Tip Mounted Propeller (WTMP), while "NA" refers to Non Applicable. In yellow are the CS-23 aircraft which are not part of this article but will be investigated in CHYLA.

3.3 Regional Aircraft studies

In addition to the CHYLA regional baseline aircraft, seven different radical designs have been made for the same TLAR. These aircraft include two aircraft with a partial turbo-electric (PTE) powertrain, two with a series-parallel partial-hybrid powertrain (SPPH), a boosted-turboprop with a parallel architecture as well as two hydrogen aircraft (one with direct combustion and one with a fuel cell). The KPIs of all these designs are reported in Table 6.

All aircraft ultimately converged, hence producing a consistent design. However, some key differences are obvious from the results. Most striking is the fact that almost all radical designs struggle to match the performance of the kerosene baseline. Even though most aircraft with some form of distributed propulsion achieve a benefit in terms of wing loading (under the assumption of powered stall speed), additional powertrain masses (propulsion system or energy carrier) trickle down on the OEM and MTOM, thus impacting performance. It must be noted that all these designs have so far been made for the same basic set of power control parameters, that are not yet optimized for the specific architecture, leaving some room for improvement as was illustrated in earlier work [23]. For example, when considering the induced drag effect of the WTMP configurations, it is important that, to achieve an induced drag reduction due to tip-vortex attenuation, the propeller is at efficient operating conditions. This also clearly indicates the required level of detail to fully exploit such radical configurations.

The hydrogen-based aircraft do show potential, not only in terms of emissions but for the fuel cell version even in terms of energy efficiency. However, the significant powertrain weight negatively impacts MTOM and OEM requiring an aircraft that is almost a class larger than its competitors. A large benefit can be achieved due to the electric fans not suffering from the density lapse rate (although this must be taken into account for the compressor part of the fuel cell). The other architectures leveraging distributed electric propulsion are also able to achieve a slightly higher power loading thanks to climb and cruise constraints being less limiting.

Table 6 – Overview of key performance indicators for novel regional aircraft. Drag count = 0.0001, lift count = 0.01; Δ's reported are due to aero-propulsive effects.

	Unit	REG Baseline	PTE BLI	PTE WTMP	PAR boost.	SPPH BLI	SPPH WTMP	LH_2	Fuel cell elec.
W/S	kN/m^2	3.39	3.39	3.39	3.38	3.39	3.39	3.39	3.39
W/P[1]	N/kW	99.6	99.6	99.6	101	99.1	98.7	98.7	101
MTOM	t	22.8	23.5	23.8	25.2	24.0	24.3	23.2	34.3
OEM	t	13.5	14.1	14.4	15.7	14.6	14.8	15.0	26.4
$FM_{\text{nominal mission}}$	t	1.19	1.29	1.29	1.35	1.32	1.33	0.45	0.33
BM	t	-	-	-	0.89	0.37	0.45	-	1.76
S	m^2	66.0	68.0	68.9	72.9	69.5	70.2	67.0	99.3
b	m	28.1	28.6	28.8	29.6	28.9	29.0	28.4	34.5
$PREE_{\text{nominal mission}}$	-	1.34	1.24	1.24	1.16	1.20	1.19	1.26	-
$E_{\text{nominal mission}}$	GJ	50.8	55.1	55.0	58.7	56.8	57.5	54.0	41.3
Fuselage Mass	t	2.42	2.44	2.43	2.43	2.49	2.43	2.89	2.84
Wing Mass	t	2.47	2.56	2.61	3.62	3.00	3.10	2.58	6.02
Propulsion System Mass	t	1.88	2.20	2.47	2.62	2.20	2.38	1.93	8.72
ΔC_L cruise	counts	0.68	0.62	1.83	0.95	0.64	1.84	0.75	0.81
ΔC_{D0} cruise	counts	-	0.86	-	-	0.54	-	-	-
ΔC_{Di} cruise	counts	-0.10	0.15	-8.73	-3.43	0.08	-8.88	-0.20	-0.88
Aero-Propulsive Efficiency cruise	-	17.6	17.7	18.4	17.7	17.7	18.4	17.0	18.3

3.4 SMR Aircraft studies

For short medium range aircraft, three additional radical aircraft were designed for the TLAR in Table 1 in addition to the CHYLA SMR baseline aircraft. These designs are reported in Table 7 and they include a PTE aircraft with an aft-mounted BLI fan, a parallel hybrid boosted turbofan concept and one SMR concept with hydrogen combustion.

Table 7 – Overview of key performance indicators for novel SMR aircraft.

	Unit	SMR Baseline	PTE BLI	PAR boost.	LH_2
W/S	kN/m^2	5.90	5.90	5.20	4.77
T/W	-	0.28	0.24	0.30	0.30
MTOM	t	82.4	87.9	97.4	81.6
OEM	t	45.9	48.2	58.2	54.5
FM harmonic	t	16.5	19.8	19.2	7.18
BM	t	-	-	7.72	-
S	m^2	137	146	162	148
b	m	37.9	39.2	41.2	39.4
T	kN	230	207	204	239
$PREE_{\text{nominal mission}}$	-	1.51	1.27	1.28	1.25
$E_{\text{nominal mission}}$	GJ	605	720	710	731
Fuselage Mass	t	10.1	10.5	9.76	12.8
Wing Mass	t	9.70	10.6	12.0	10.3
Propulsion System Mass	t	6.40	6.42	6.45	6.65

From Table 7 the most striking difference is the impact of the maximum landing mass ratio on the

[1] Propulsive power loading, corrected to MTOM

maximum achievable wing loading. The structural integration of the tank and lower fuel mass due to the higher gravimetric energy density of hydrogen increase the landing mass fraction. As a consequence, the hydrogen aircraft cannot achieve the same wing loading as its baseline and requires also more thrust (constrained by OEI balked landing). The MTOM for this aircraft is slightly lower, with higher OEM due to the tank installation but significantly reduced fuel mass. The overall design requires more energy but emits no carbon dioxide. For the boosted turbofan, a similar rationale may be followed, though a significantly higher fuel mass is still present. Consequently, the aircraft was sized for the original landing mass fraction (85%) as this was still achievable for the harmonic mission and the dead-weight penalty of the battery is impacting MTOM.

The other hybrid-electric designs also cannot match the kerosene baseline in terms of performance, due to the impact of the battery mass for the boosted turbofan and the slight increases in fuselage and consequently wing mass for the PTE version (due to the extra propulsor and extra required fuselage length). Similar to the regional aircraft, there is room for improvement left on the table through modification of the power control variables. Especially for the PTE version, where the lower thrust loading is currently not exploited.

3.5 Large Aircraft studies

The design space for large aircraft is the most restrictive, under the expectation that hybrid-electric (battery electric) powertrains are too heavy for long range operations. Consequently, only two additional radical designs have been made for this category, a hydrogen (combustion) and PTE with BLI fan aircraft. These are reported in Table 8 in addition to the CHYLA LPA baseline.

Table 8 – Overview of key performance indicators for novel large aircraft

	Unit	**LPA Baseline**	**PTE BLI**	**LH_2**
W/S	kN/m^2	6.21	6.21	5.11
T/W	-	0.30	0.29	0.30
MTOM	t	287	322	284
OEM	t	139	158	185
FM harmonic	t	94.8	111	45.0
S	m^2	453	508	544
b	m	65.6	69.5	71.8
T	kN	851	915	832
$\text{PREE}_{\text{nominal mission}}$	-	1.51	1.30	1.15
$E_{\text{nominal mission}}$	TJ	3.81	4.45	5.00
Fuselage Mass	t	32.3	38.1	52.2
Wing Mass	t	31.6	36.8	37.6
Propulsion System Mass	t	22.2	26.0	21.7

Similar to the SMR hydrogen aircraft, the LH_2 version of the LPA aircraft is constrained by the high landing mass ratio. However, because of the longer range the fuel mass benefit is outweighing negative effects in terms of MTOM and thrust. More information on the particular designs will be reported in [16]. The wing area is significantly increased due to the lower wing loading, also impacting the achievable aerodynamic efficiency. Hence, the PREE is lower, yet the combustion of hydrogen does not emit carbon dioxides.

The PTE aircraft with BLI is negatively impacted by the additional powertrain components and consequently is not able to match the performance of the kerosene aircraft. In contrast to the small aircraft categories, the difference is more significant and might not be possible to overcome by fine-tuning power control variables. The aft-mounted fan impact the fuselage mass and tail area negatively, hence impacting the overall aircraft weight and component masses.

4. Conclusions

This article presents an overview of the design approach followed for the CHYLA project, as well as initial radical designs and comparison to the CHYLA baselines. These provide the starting point for both the sensitivity study which will be presented in a later scalability assessment and economical assessments in the CHYLA project. A variety of regional, short medium range and large aircraft has been designed, all according to the same TLAR yet without detailed tuning of important power control variables.

Consequently, many radical designs are not yet able to match kerosene aircraft performance (which has been tuned through decades of development of design methods and the use of statistical data). In terms of carbon emission reduction, the LH_2 combustion appears to be the most feasible on short term. However, for regional aircraft fuel cells may be an option if a high MTOM is accepted. Generally, the addition of powertrain components for hybrid electric aircraft negatively impacts the designs. Hybrid electric architectures leveraging distributed electric propulsion are also able to achieve a slightly higher power loading thanks to climb and cruise constraints being less limiting. These results are in line with previous studies, which also showed that benefits are achievable with further fine tuning. At this stage, the converged designs mean that the starting points for further sensitivity studies and scalability assessment is provided, which aligns with the main objective to test the aircraft design framework for all kinds of powertrain architectures and configurations. Results are distinguishable between concepts and provide sufficient detail to capture the necessary effects. The reduction of fuel consumption will require detailed assessment and fine tuning though may be achievable for regional and possibly SMR aircraft.

In terms of scaling effects, benefits of hybrid electric propulsion tend to scale negatively with flight range, as seen when comparing similar architectures across classes. However, the benefits of hydrogen combustion become more pronounced with longer range, though other studies have shown that tank layout and design can be critical to feasibility of the designs.

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Copyright Statement

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