IMOTHEP

GETTING HYBRID ELECTRIC

Design and performance of a turboelectric, distributed propulsion aircraft: Intermediate results from the European Project IMOTHEP

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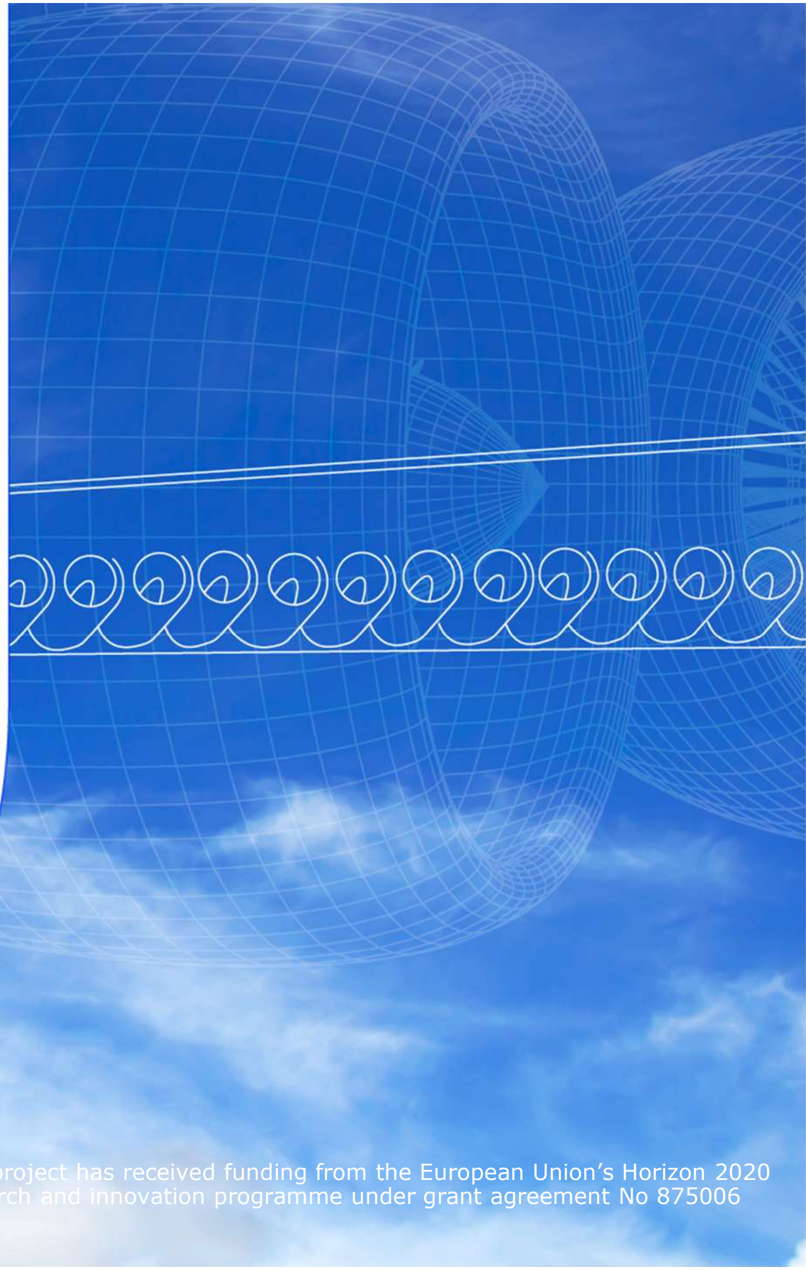
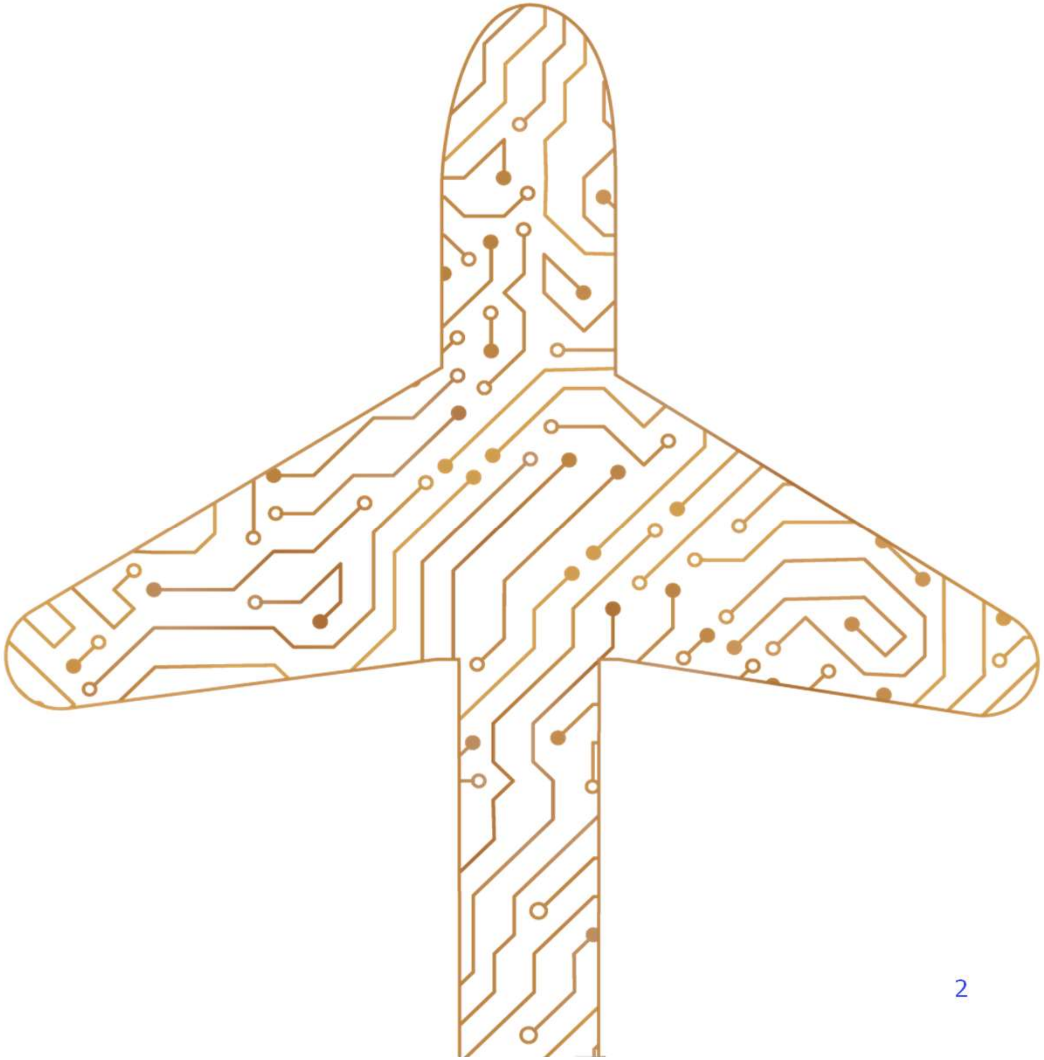


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 875006

Summary

- Introduction: the IMOTHEP project
- SMR-CON: Concept and design tool
- Turboelectric propulsion
- Aircraft performance and design exploration
- Conclusion



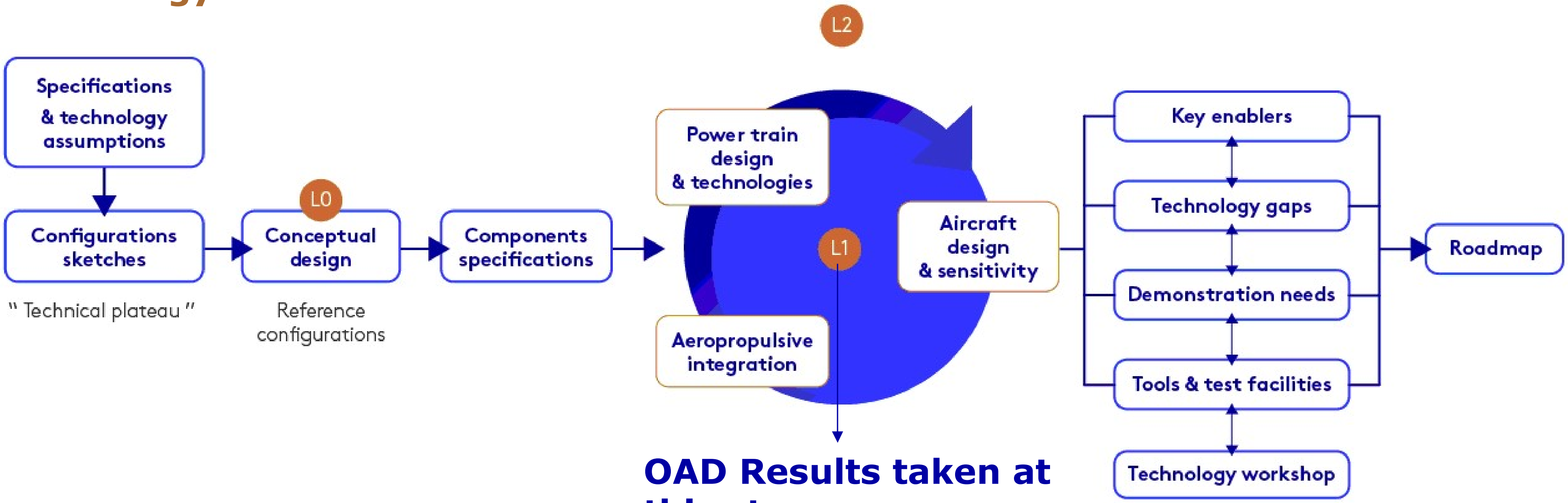
INTRODUCTION: THE IMOTHEP PROJECT

Imothep objectives and methodologies

Top level ambition

To significantly improve the estimation of Hybrid-Electric Propulsion potential to reduce transport aircraft carbon footprint.

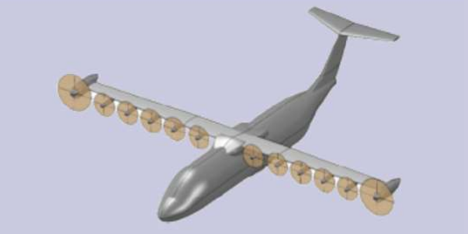
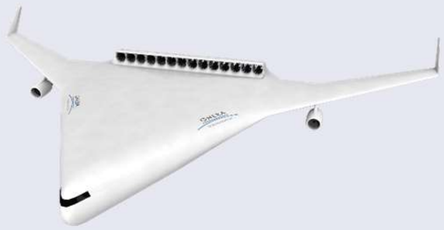
Methodology



OAD Results taken at this stage

Imothep configurations

Four aircraft configurations divided in two segments

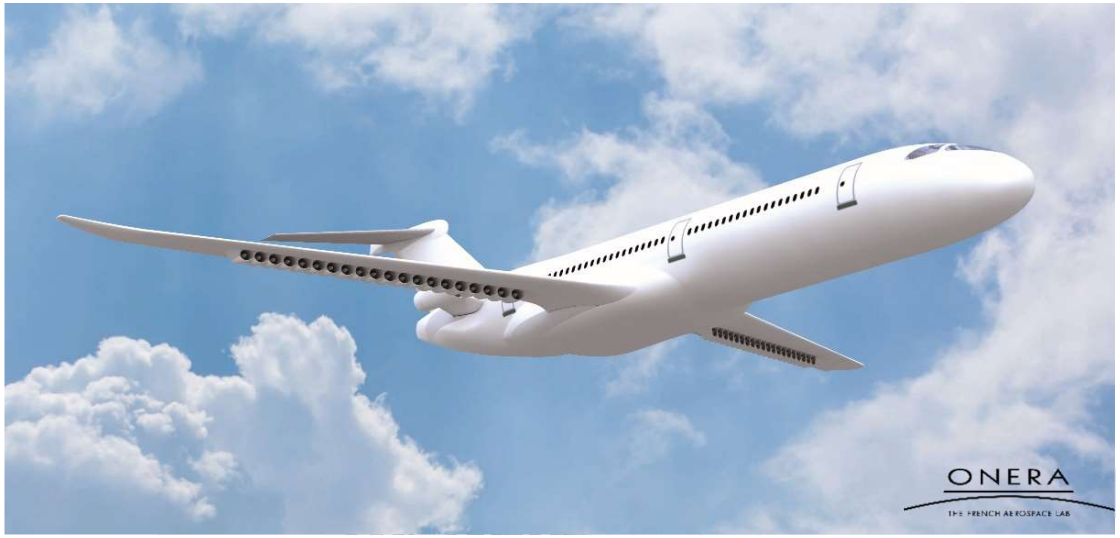
	CONservative	RADical	Mission
Regional	 Credit: Bauhaus-Luftfahrt	 Credit: Safran	40 pax @ 106kg/pax 600NM Mach 0,4
SMR	 Credit: ONERA	 Credit: ONERA	150 pax @ 106kg/pax 2750NM Mach 0,78

SMR-CON : CONCEPT AND DESIGN TOOL

SMR-CON : Turboelectric, distributed propulsion

Motivations for distributed electric propulsion

- **Incremental improvement of SMR aircraft includes:**
  - Increase of propulsive efficiency
  - Larger engine for By-Pass Ratio increase from 5.5 to 11
- **Next propulsive improvement limited by aircraft geometry.**
- **Distributed electric propulsion:**
  - Distributed Electric Fans at the pressure side of the wing
  - Large increase in propulsive efficiency with By-Pass Ratio up to 40.



P. Schmollgruber *et al.*, 'Multidisciplinary Exploration of DRAGON: an ONERA Hybrid Electric Distributed Propulsion Concept', in *AIAA Scitech 2019 Forum*, San Diego, California, doi: 10.2514/6.2019-1585

SMR-CON : Turboelectric, distributed propulsion, the disadvantages.

Disadvantages of DEP:

- Losses in electrical power transmission,
- Added weight,
- Aerodynamic interactions at transonic speed and added wet area.

DEP impacts on all disciplines of aircraft design

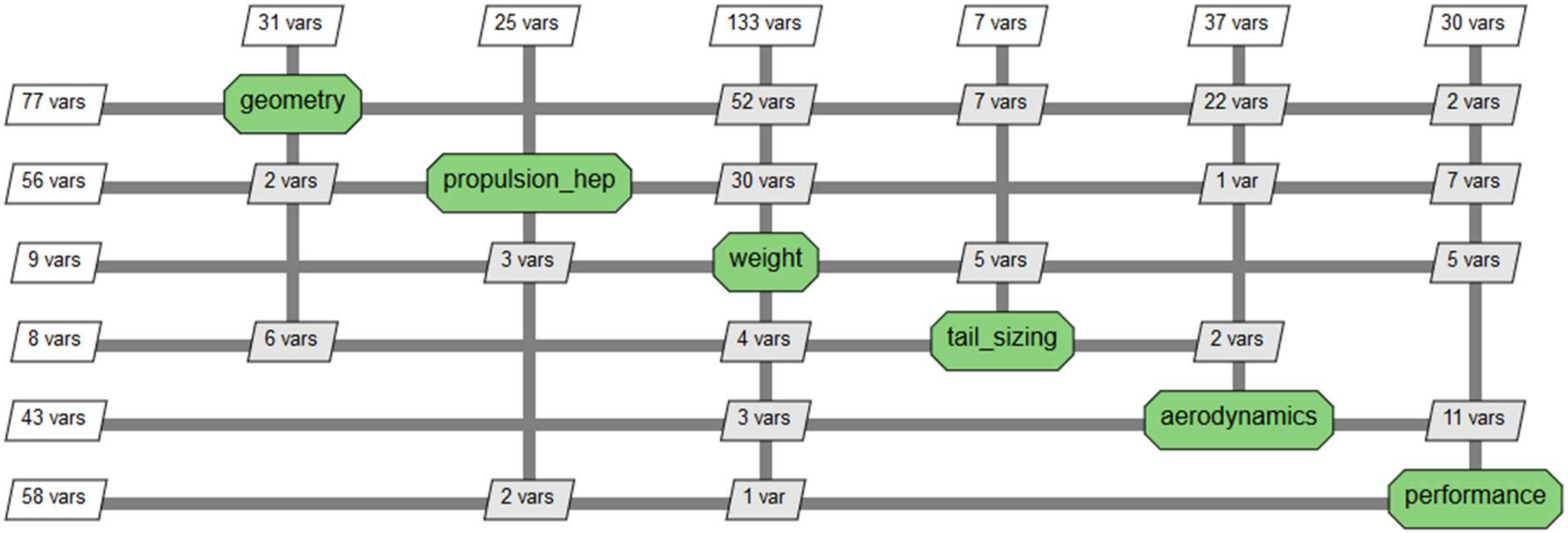
SMR-CON configuration analysed with an Overall Aircraft Design software: FAST-OAD[1]

(1) C. David, S. Delbecq, S. Defoort, P. Schmollgruber, E. Benard, and V. Pommier-Budinger, 'From FAST to FAST-OAD: An open source framework for rapid Overall Aircraft Design', *IOP Conf.*, vol. 1024, p. 012062, Jan. 2021, doi: 10.1088/1757-899X/1024/1/012062.

Overall Aircraft Design tool: FAST-OAD

Open source multidisciplinary design A/O software

- Analytical and semi-empirical models for tube and wing aircraft
- Open source release validated against the CSR1 Ceras[1] aircraft

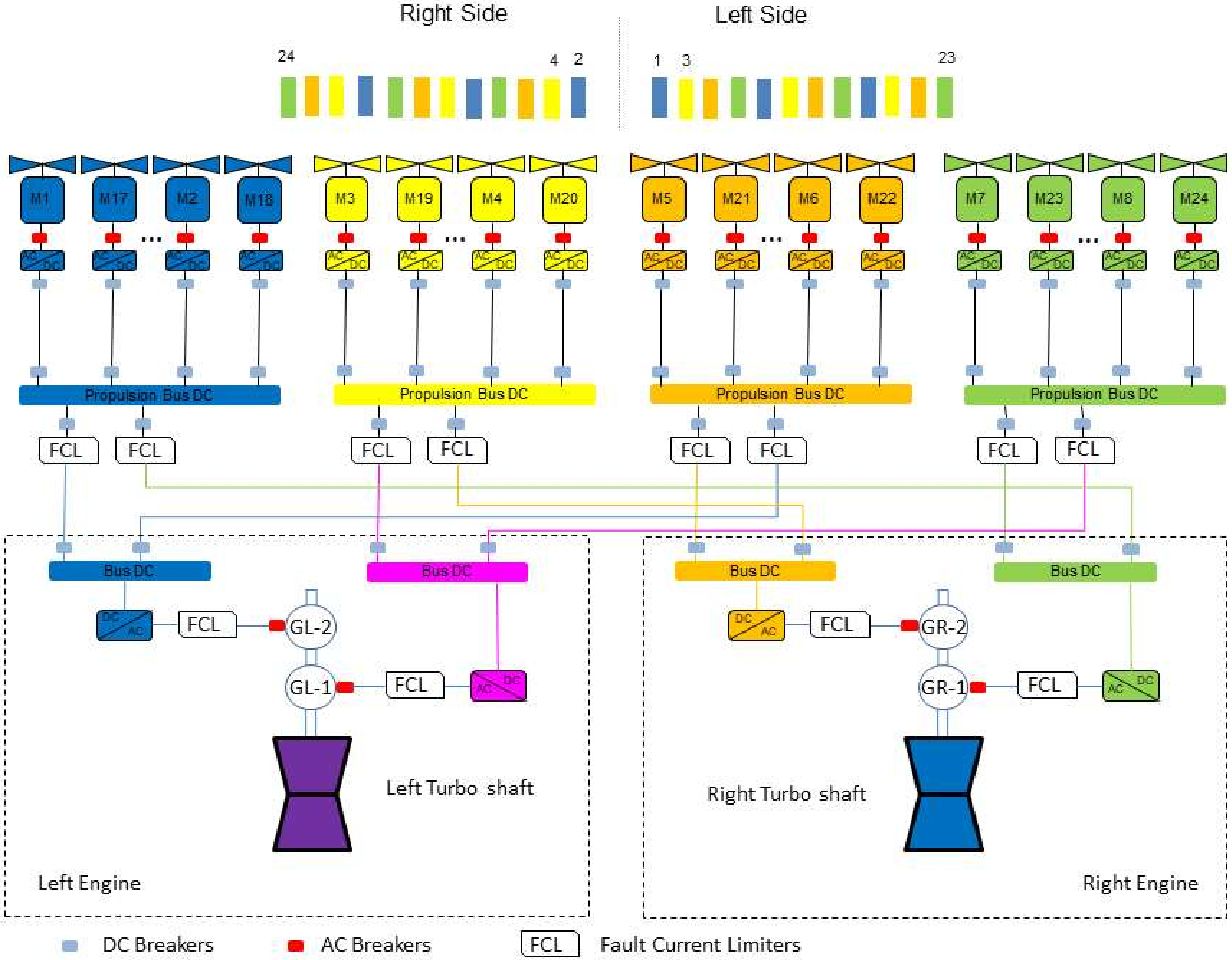


(1) Risse, Kristof & Schäfer, Katharina & Schueltke, Florian & Stumpf, Eike. (2015). Central Reference Aircraft data System (CeRAS) for research community. CEAS Aeronautical Journal. 7. 10.1007/s13272-015-0177-9.

(2) https://github.com/fast-aircraft-design

SMR-CON : PROPULSION COMPONENT DESIGN

Turbo-electric distributed architecture



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Component design

- **Electric Power Unit**
  - Integrated, direct drive design to fit in fan hub.
  - Reference efficiency, specific power and power density for liquid and air-cooled options.
- **Cables**
  - Aluminium cable design for 3000V operation and minimal weight.
- **Turbomachine**
  - Performance table (output power and specific consumption), weight and dimensions were provided.

Electric Power Unit	
Continuous output power	<1MW each
Specific power (liquid cooled)	9,2kW/kg
Efficiency	96,7%
Power density	6kW/L
Turbomachine	
Design power (@35kft)	7.95MW
Max OPR	48
Max T41	1900°K
Weight	1136kg

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Configuration status: SMR-CON

- **Generator**
  - Reference efficiency, specific power and power density.
- **Thermal management system**
  - Skin conduction for electric fans.
  - Compact heat exchanger for turbogenerator with puller fan.

Generator	
Continuous output power	11MW each
Specific power	9,65kW/kg
Efficiency	99%
Power density	25kW/L

SMR-CON: PERFORMANCE AND DESIGN EXPLORATION

OAD design and performance

Technology assumptions

Entry Into Service 2035

Design mission

150pax @106kg/pax

2750NM, M=0,78

Typical mission

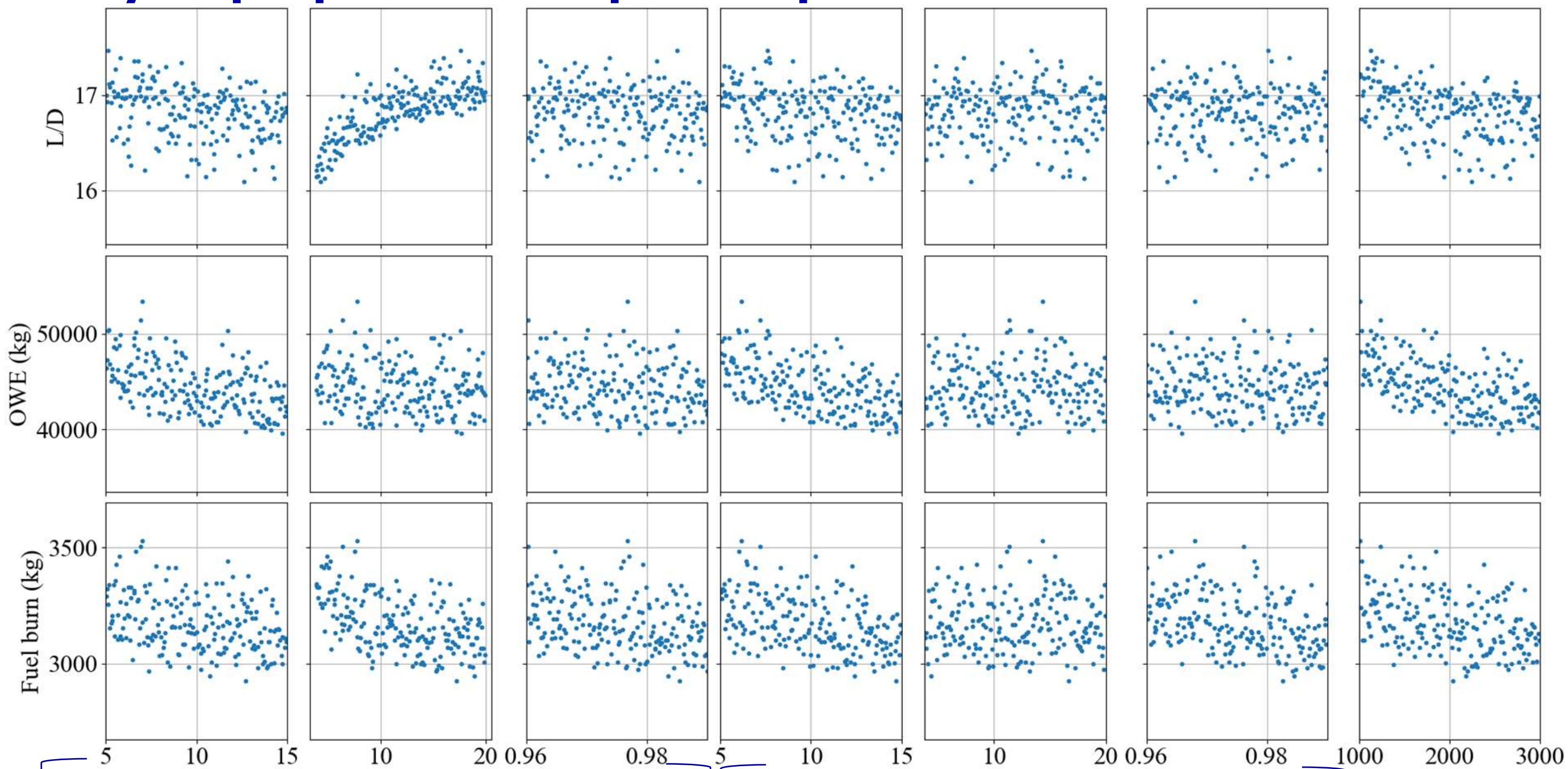
150pax @106kg/pax

800NM, M=0,78

Parameters	BASELINE	SMR-CON	SMR-CON wrt BAS (%)
MTOW (kg)	69 802	76 789	10.0
OWE (kg)	40 053	45 472	13.5
Propulsion weight (kg)	8 370	12 897	54.1
L/D max	18.0	17.1	-5.1
Fuel burn (kg)	**3828**	**3908**	**2.1**
TSFC (g/kNs)	**14.5**	**13.4**	**-7.5**
Wing area (m^2)	108	115.9	6.9

Design exploration

Sensitivity to propulsive component performance



Specific power (kW/kg)

Power density (kW/L)

Efficiency

EPU

Specific power (kW/kg)

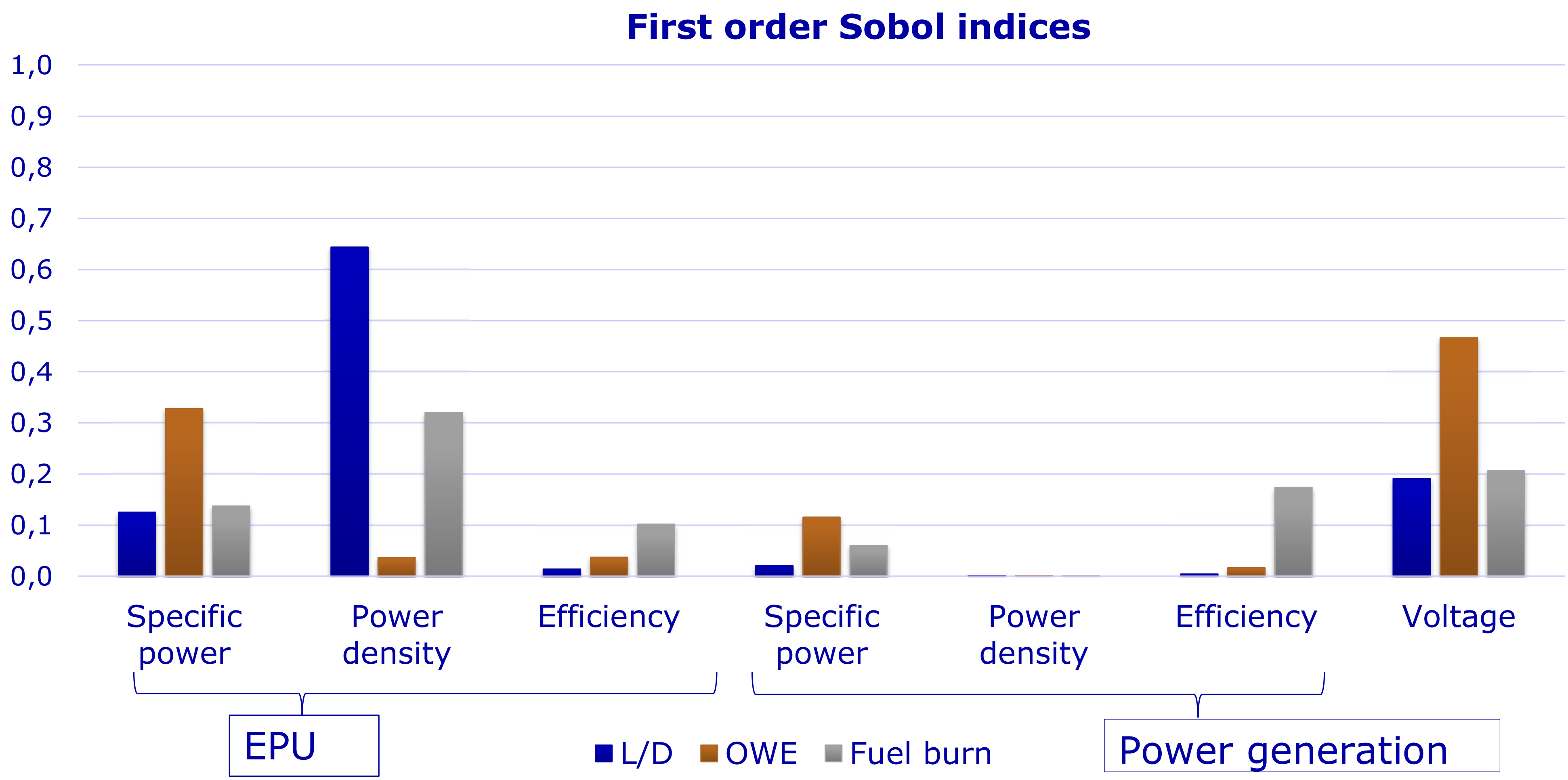
Power density (kW/L)

Efficiency

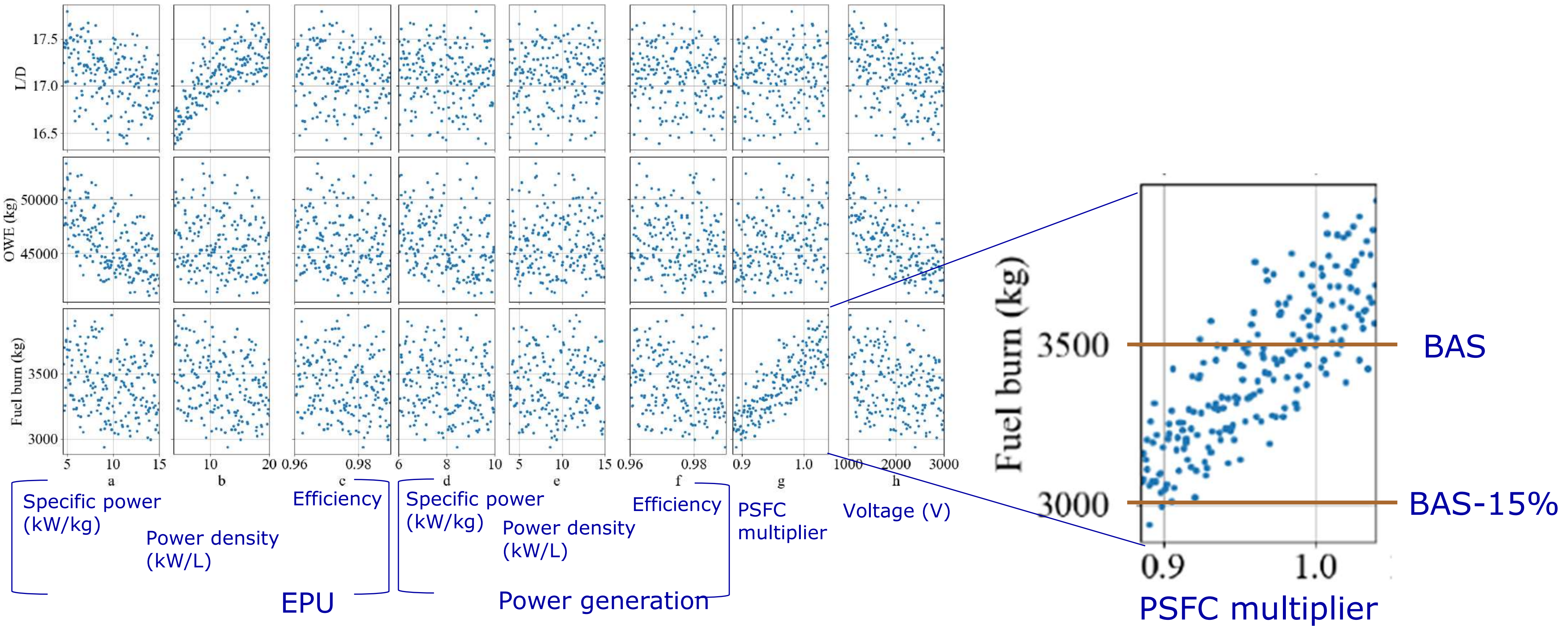
Power generation

Voltage (V)

Setting research directions



Expected improvements



Conclusion

SMR-CON Turbo-electric propulsion chain

- Turbo-electric propulsion showed better overall efficiency
- Overall aircraft performance limited by added weight and aerodynamics penalty.
- Research directions were identified for design loop 2:
  1. Thermal efficiency of turbomachine
  2. Power density of EPU (power electronics)
  3. Voltage
  4. Efficiency and specific power of electric components (which comes first?)
- Only qualitative recommendations, no quantified objective

Turboelectric propulsion should seek both propulsive efficiency and core efficiency increase

THANK YOU !

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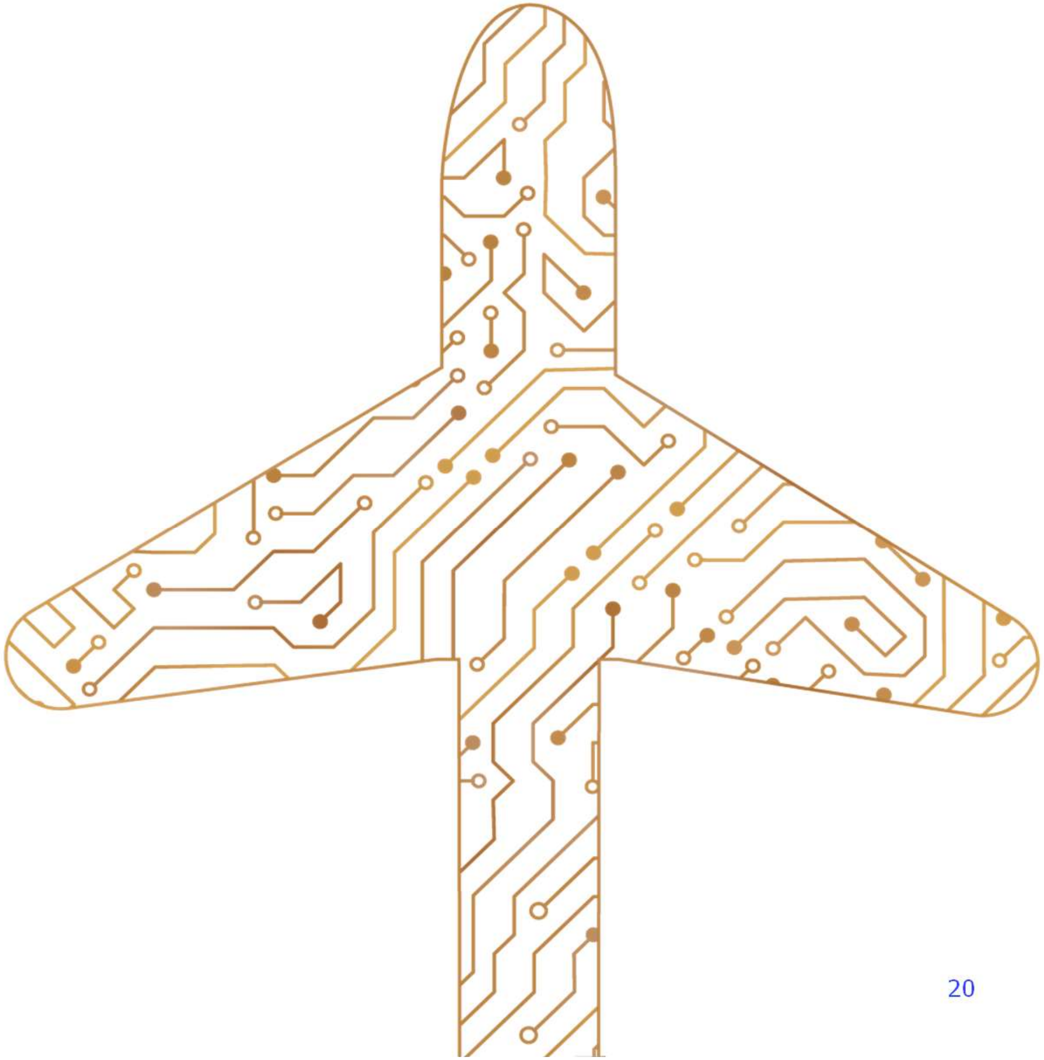

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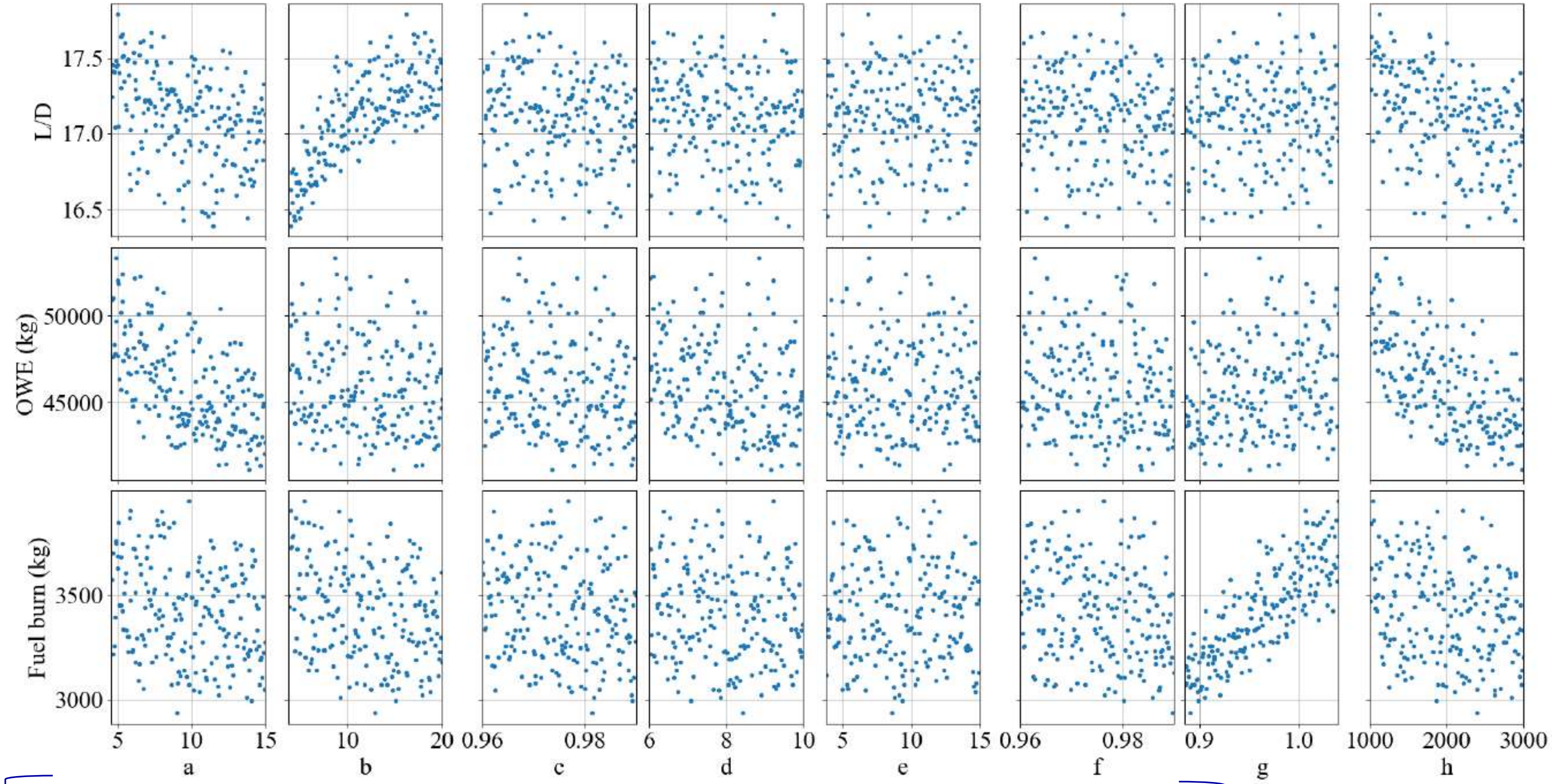
APPENDIX

SMR-CON: Reduced design mission

Design exploration: Mission specifications

Parameters	REF (2750NM)	BAS (1200NM)	SMR-CON (1200NM)	BAS wrt REF (%)	SMR-CON wrt BAS (%)
MTOW (kg)	77031	61738	63428	-19.9	2.7
OWE (kg)	43228	38732	39672	-10.4	2.4
Propulsion weight(kg)	8712	8364	9978	-4.0	19.3
L/D max	16.1	17.9	16.9	10.9	-5.8
Fuel burn (kg)	4760	**3769**	**3712**	-20.8	**-1.5**
Reserve (kg)	2758	2193	2609	-20.5	18.9*
TSFC (g/kNs)	15.4	14.5	13.7	-5.8	-5.5
AR	9.45	10.9	10.9	15.3	0.0
Span (m)	34.1	33.6	34.0	1.1	-0.2
Wing area (m^2)	120	106	106	-11.4	-0.4

Overall aircraft sensitivity to the performance of propulsive components



Specific power (kW/kg)

Power density (kW/L)

Efficiency

EPU

Specific power (kW/kg)

Power density (kW/L)

Efficiency

Power generation

PSFC multiplier

Voltage (V)

27/05/2024

Turbofan vs turboelectric efficiency breakdown

	η_{core}	η_{PT}	η_e	η_{fan}	η_{tr}	η_{th}	η_p	η
Turbo-electric	0,57	0,91	0,93	0,88	0,74	0,42	0,93	0,39
Turbofan	0,6	0,91	1,0	0,875	0,85	0,51	0,74	0,377

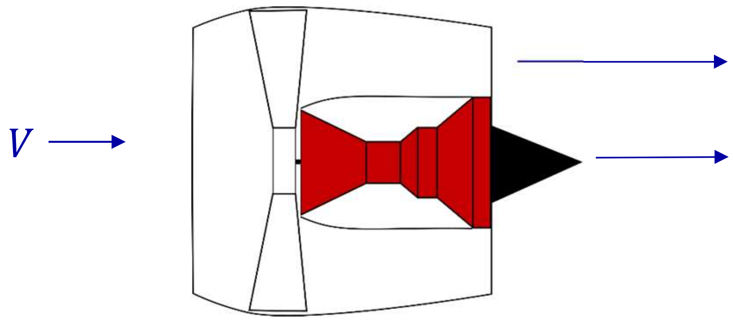
$$\eta = \eta_{th}\eta_p$$

$$\eta_{th} = \eta_{tr}\eta_{core} = \frac{\text{Rate of change kinetic energy}}{\text{Fuel power}}$$

$$\eta_{tr} = \eta_{PT}\eta_e\eta_{fan} = \frac{\text{Rate of change kinetic energy}}{\text{Power in flow at core exit}}$$

Turbofan analysis

- UHBR type
- Thrust 23700N @ 35kft, M=0,78
- BPR 16



	$\dot{m}$ (kg/s)	M	T (N)	$\eta_p = \frac{TV}{0,5\,\dot{m}(V_{ex}^2 - V_0^2)}$	Combined η_p	$\eta_{th} = \frac{V}{TSFC\,\eta_p\,LHV}$
Cold exhaust	235,8	1,03	17825	0,87	0,75	0,50~0,51
Hot exhaust	14,7	2,13	5875	0,54		

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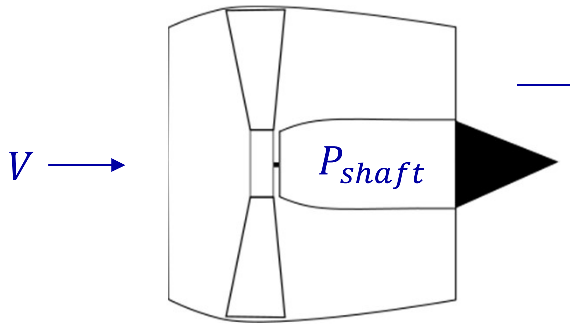
DEP analysis

- Thrust 23700N @ 35kft, M=0.78,
- No thrust from turboshaft,
- 12 efans,



	$\dot{m}$ (kg/s)	M	T (N)	$\eta_p = \frac{TV}{0,5\,\dot{m}(V_c^2 - V_0^2)}$	$\dot{m}_f = \frac{P_{shaft}}{\eta_{elec}} PSFC$	$\eta_{th} = \frac{0,5\,\dot{m}(V_c^2 - V_0^2)}{\dot{m}_f LHV}$
Cold exhaust	52,8	0,91	1975	0,93	101,4 kg/h	0,41

Exemplary configuration

Exemplary configuration ensuring 15% FB savings wrt to BAS:

- **10% comes from turboshaft PSFC improvement**
- **5% comes from electric propulsive chain**

	Fuel burn wrt BAS		Actual	-15%	Difference (%)
Results	L/D		17.1	16.8	-1.8
	OWE (T)		45.5	41	-9.9
Input parameters	EPU				
		Specific power (kW/kg)	9.2	10.5	14.1
		Power density (kW/L)	6	15.5	158
		Efficiency	0.967	0.979	1.2
	Power generation				
		Specific power (kW/kg)	6.55	11	67.9
		Power density (kW/L)	11	20	81.8
		Efficiency	0.97	0.985	1.5
	Voltage (V)		3000	2650	-11.7