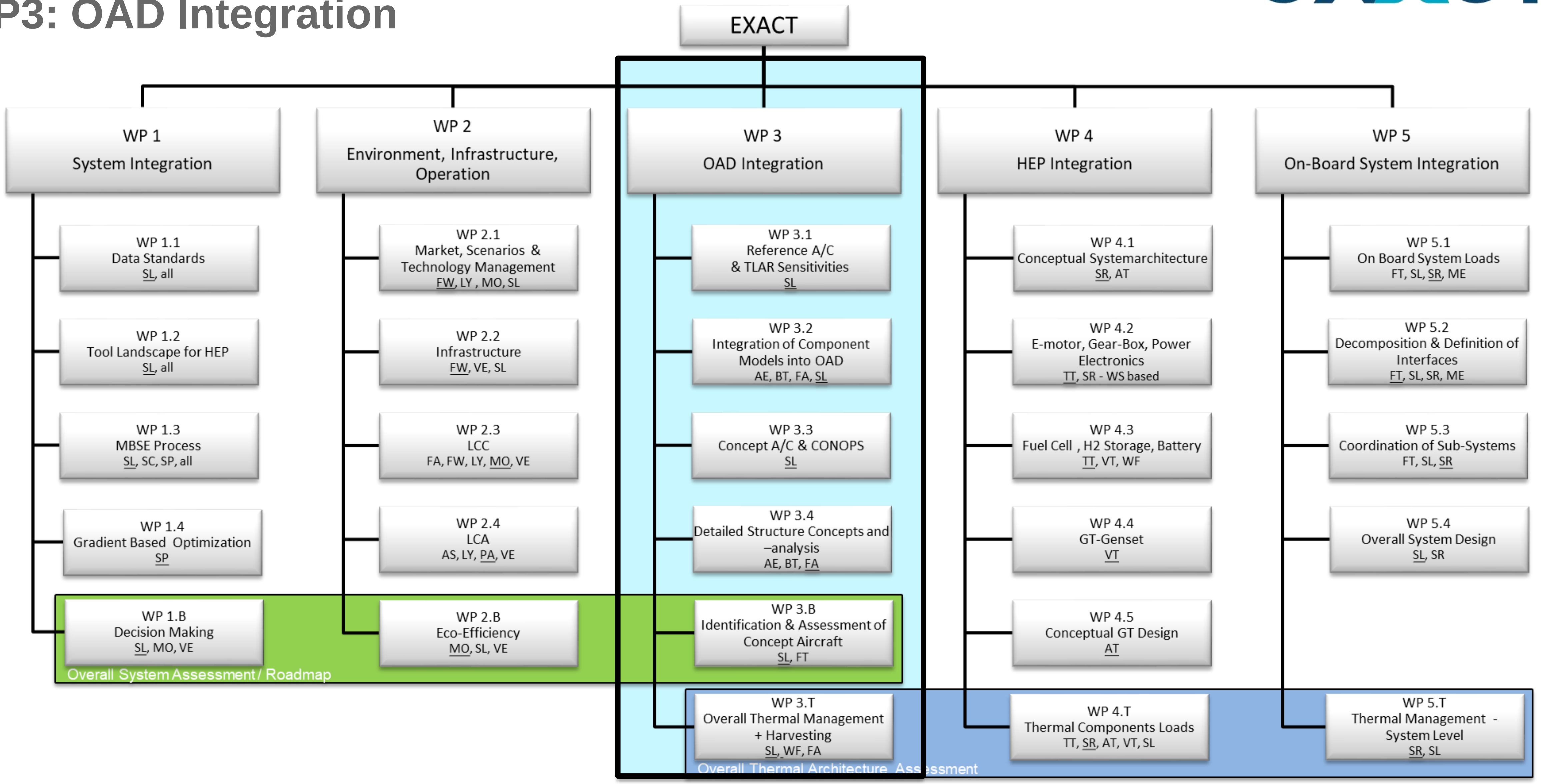
DLR Deutsches Zentrum für Luft- und Raumfahrt

Aircraft Modeling Results, Short-Range Turboprop Baselines (D250-321TP-2040, D220-320TP-2040)

Author: Georgi Atanasov

WP3: OAD Integration



EXACT

WP 1
System Integration
- WP 1.1 Data Standards SL, all
- WP 1.2 Tool Landscape for HEP SL, all
- WP 1.3 MBSE Process SL, SC, SP, all
- WP 1.4 Gradient Based Optimization SP
- WP 1.B Decision Making SL, MO, VE

WP 2
Environment, Infrastructure, Operation
- WP 2.1 Market, Scenarios & Technology Management FW, LY , MO, SL
- WP 2.2 Infrastructure FW, VE, SL
- WP 2.3 LCC FA, FW, LY, MO, VE
- WP 2.4 LCA AS, LY, PA, VE
- WP 2.B Eco-Efficiency MO, SL, VE

WP 3
OAD Integration
- WP 3.1 Reference A/C & TLAR Sensitivities SL
- WP 3.2 Integration of Component Models into OAD AE, BT, FA, SL
- WP 3.3 Concept A/C & CONOPS SL
- WP 3.4 Detailed Structure Concepts and –analysis AE, BT, FA
- WP 3.B Identification & Assessment of Concept Aircraft SL, FT
- WP 3.T Overall Thermal Management + Harvesting SL, WF, FA

WP 4
HEP Integration
- WP 4.1 Conceptual Systemarchitecture SR, AT
- WP 4.2 E-motor, Gear-Box, Power Electronics TT, SR - WS based
- WP 4.3 Fuel Cell , H2 Storage, Battery TT, VT, WF
- WP 4.4 GT-Genset VT
- WP 4.5 Conceptual GT Design AT
- WP 4.T Thermal Components Loads TT, SR, AT, VT, SL

WP 5
On-Board System Integration
- WP 5.1 On Board System Loads FT, SL, SR, ME
- WP 5.2 Decomposition & Definition of Interfaces FT, SL, SR, ME
- WP 5.3 Coordination of Sub-Systems FT, SL, SR
- WP 5.4 Overall System Design SL, SR
- WP 5.T Thermal Management - System Level SR, SL

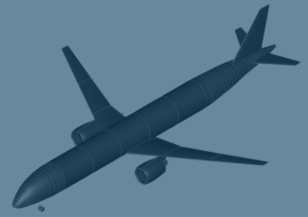
Overall System Assessment / Roadmap

Overall Thermal Architecture Assessment

Models Overview

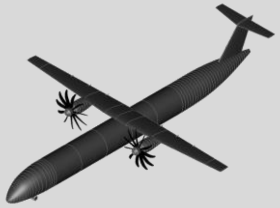
Baselines

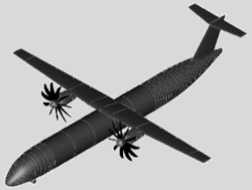
Baseline Turbofan Family


D250-321TF-2040


D220-320TF-2040

Baseline Turboprop Family


D250-321TP-2040


D220-320TP-2040

Regional Aircraft Baseline


D70-840-2040

LH2 Direct Burn

LH2 Turbofan Family


D250-TFLH2-2040


D220-TFLH2-2040

Mild-Hybrid LH2 Turboprop Family


D250-TPLH2-2040


D220-TPLH2-2040

Hybrid Electric

Mild-Hybrid LH2 Turbofan Family


D250-TFLH2-MHEP-2040


D220-TFLH2-MHEP-2040

Mild-Hybrid LH2 Turboprop Family


D250-TPLH2-MHEP-2040


D220-TPLH2-MHEP-2040

Fuel Cell LH2 Regional Aircraft


D70-FCLH2-2040

Plug-In Hybrid-Electric Aircraft


D70-PHEA-2040

Study Boundary Conditions

Reference A/C:

A321neo
interpretation
(EIS2016)

D239

Top-Level-Aircraft Requirements (TLARs)

Design Range	[nm]	2500
Design PAX (single class)	[-]	239
Mass per PAX	[kg]	95
Design Payload	[kg]	25000
Max. Payload	[kg]	25000
Cruise Mach number	[-]	0.78
Max. operating Mach number	[-]	0.8
Max. operating altitude	[ft]	40000
TOFL (ISA +0K SL)	[m]	2200
Rate of Climb @ TOC	[ft/min]	>300
Approach Speed (CAS)	[kt]	136
Wing span limit	[m]	<=36

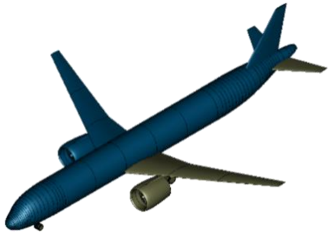
Redesign for EIS2040:

- TLARS ISO
- Engine Performance: -10% sfc
- Fuselage Mass: -5%
- Wing Structural Mass: -15%
- Empennage Mass: -3%
- Systems Mass: ISO
- Furnishings Mass: ISO
- Operator Items Mass: ISO

The goal of the modelling is to compare the performance characteristics between the turbofan and the turboprop baseline.

EXACT Turbofan Baseline

D250TF

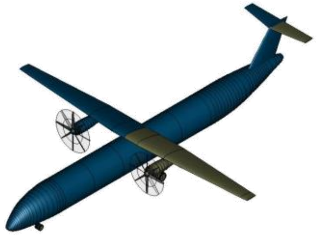


TLAR Changes:

- Range 1500nm
- 250 PAX; Design Payload 23750kg
- TOFL 1900m (SL, ISA), VLS < 140 KCAS

EXACT Turboprop Baseline

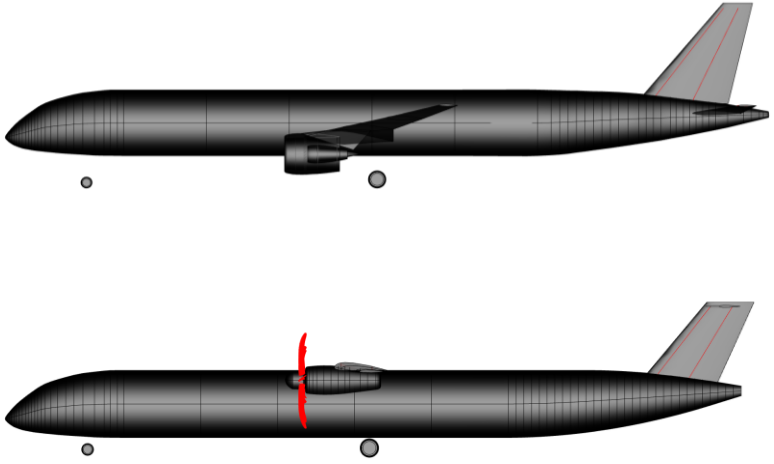
D250TP



TLAR Changes:

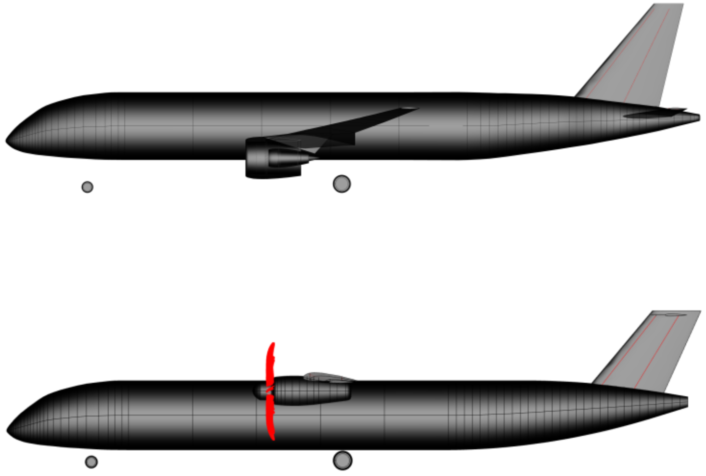
- Range 1500nm
- Mach 0.62
- 250 PAX & Design Payload 23750kg
- TOFL 1900m (SL, ISA), VLS < 140 KCAS

Family Concept Constraints



ISO Systems, except:
- Controls
- Hydraulics & Electrics
- Air conditioning

Components:
- ISO Wing (incl. High-Lift)
- ISO Empennage
- ISO Engines
- Lighter Landing Gear



TLARs:
- ISO design range (1500nm)
- Takeoff length and approach speed not additionally constrained → a result for ISO engines & wing

D250TP & D250TF:
- 250 PAX
- Standard Payload 23750kg
- Max Payload 25000kg

D220TP & D220TF:
- 220 PAX
- Standard Payload 20900kg
- Max Payload 24200kg
- Fuselage ~3.9m shorter

The overall aircraft design process and optimization take into account both family members.

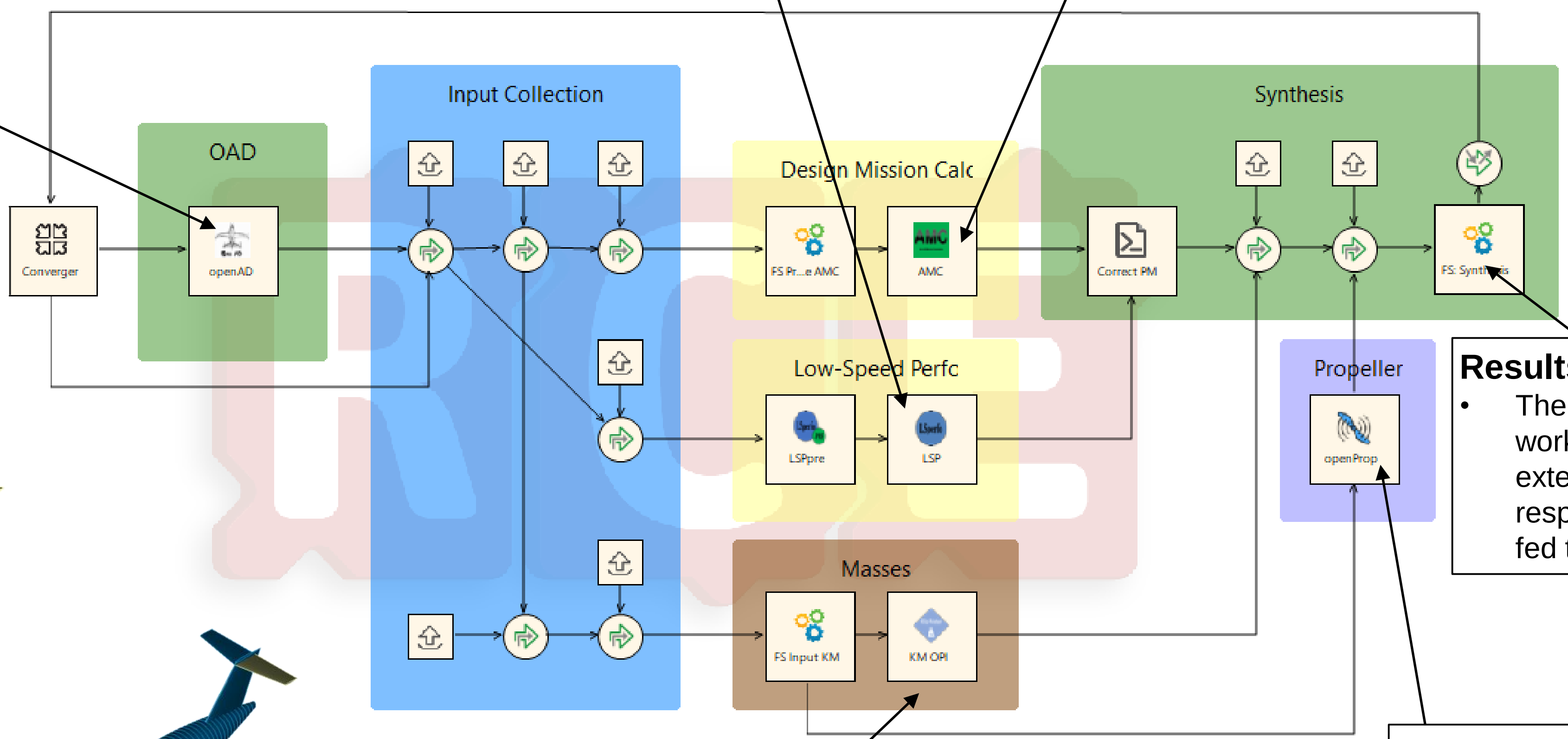
For more details:
“Cabin Modelling and Operator Item Assumptions for a Green Aircraft Family” by Y. Cabac, J.N. Walter, C. Hesse

Modelling Workflow

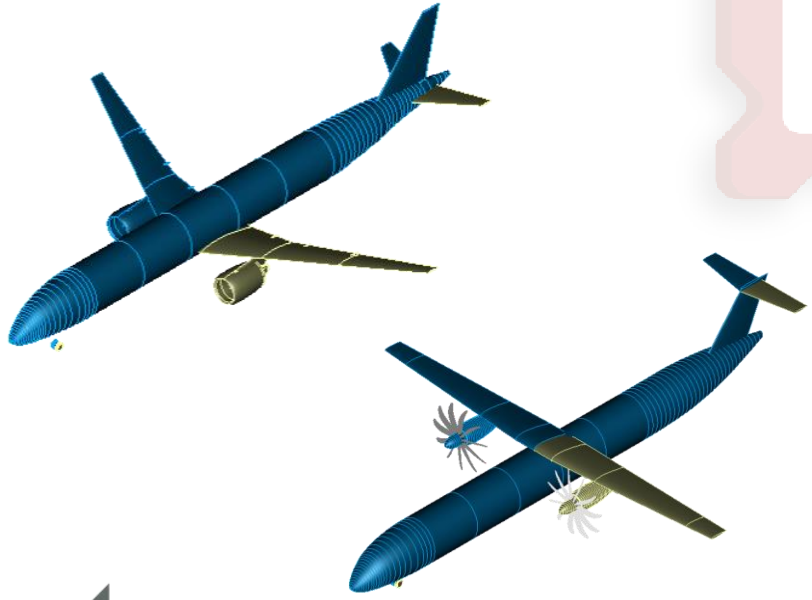
openAD:
- Overal Aircraft Design Model
- Handbook methods (can be overwritten with higher fidelity results)
- Creates an aero map and an engine map.
- Serves as a backbone and a synthesizer

LSP (Low-Speed Perfo):
- Calculates the low-speed trajectories of the aircraft
- Calculates the balanced field length

AMC (Aircraft Mission Calculator):
- Calculates the mission trajectories of the aircraft
- Flexible mission definitiion (incl. step cruise)



Results Synthesis:
- The results of all workflow tools and externally gereneted responce surfaces are fed to openAD

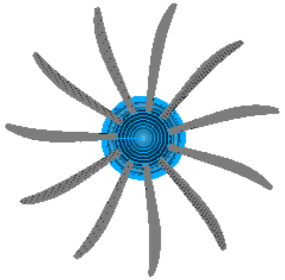


Kilo-Meter:
- Calculates the oprating items mass.
- Uses an off-workflow calculation of the fuselage primary structure and generates the mass of the secondary structure.

openProp (for Turboprop):
- Generates the propeller geometry
- Calculates the propeller efficiency at various points
- Presentation:

Modelling – Design Studies

- A propeller geometry study, resulting in an 11-bladed propeller design
  For more details:
  “Propeller Design and Analysis based on BEMT for Target Setting Purposes within the Aircraft Conceptual Design Phase” by Yannic Cabac, Georgi Atanasov



- Diameter = 5.9m
- AF = 77
- nBlades = 11

- The VTP size was determined by a responce surface generated by CASCOT. For more details:

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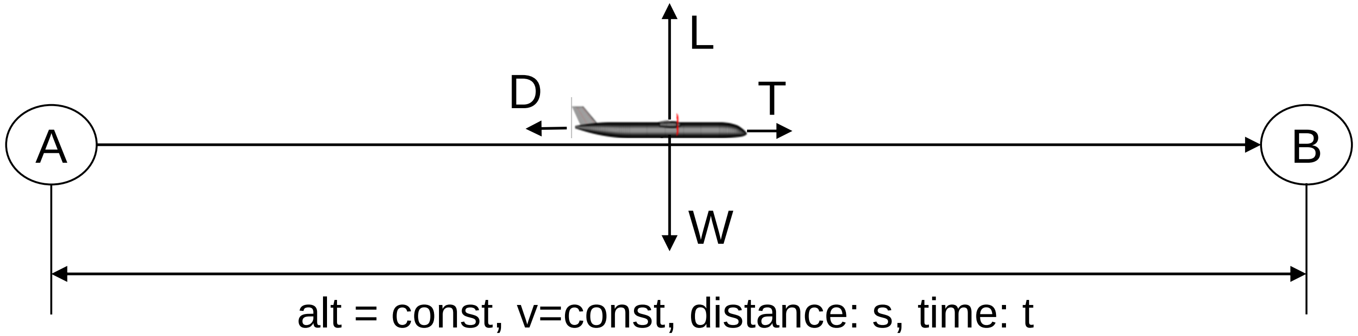
  “*Conceptual Loads Estimation and Assessment of Hydrogen Aircraft Configurations*” by Tobias Hecken

Turofan vs Turboprop Comparison

D250-321TF-2040
(D250TF)

D250-321TP-2040
(D250TP)

Effect of Speed on Efficiency



alt = const, v=const, distance: s, time: t

In Cruise:

$$L = W = m \cdot g$$

$$T = D = \frac{m \cdot g}{L/D}$$

Flight speed can affect these parameters, thus indirectly affecting fuel.

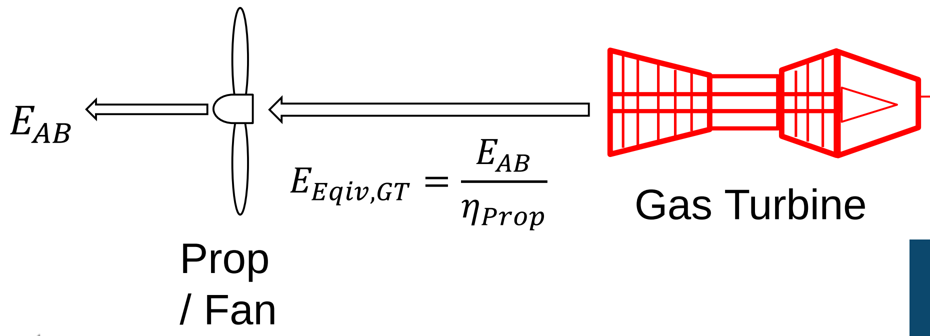
Energy (work) A->B: $E_{AB} \approx P_{ave} \cdot t = T_{ave} \cdot v \cdot t = T_{ave} \cdot \frac{s}{\cancel{t}} \cdot \cancel{t} = T_{ave} \cdot s$

(work equals force times distance)

The amount of work needed to move the aircraft is not directly dependent on the flight time.

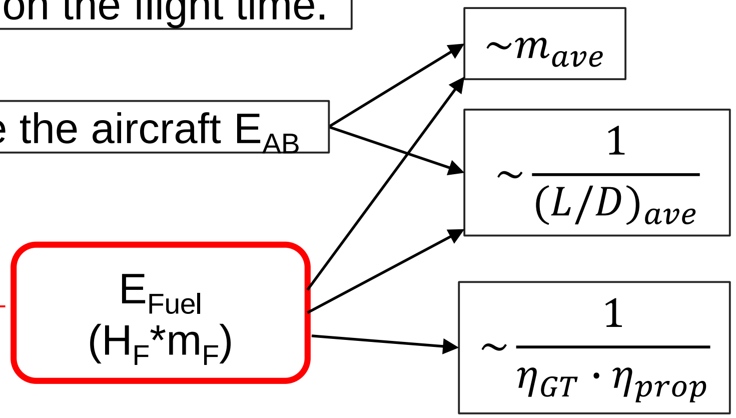
Energy (work) A->B: $E_{AB} \approx T_{ave} \cdot s = \frac{m_{ave} \cdot g}{(L/D)_{ave}} \cdot s \Rightarrow$

Work to move the aircraft E_{AB}



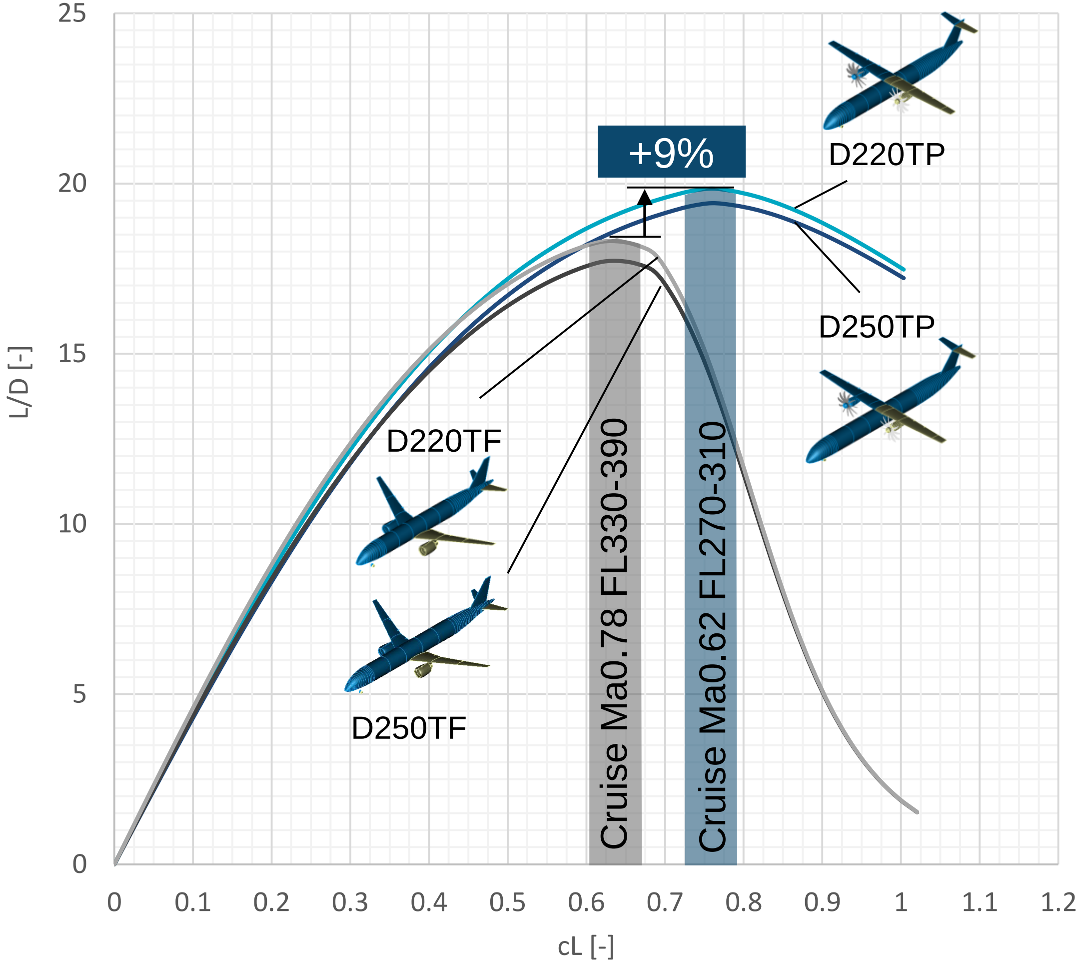
$E_{Eqiv,GT} = \frac{E_{AB}}{\eta_{Prop}}$

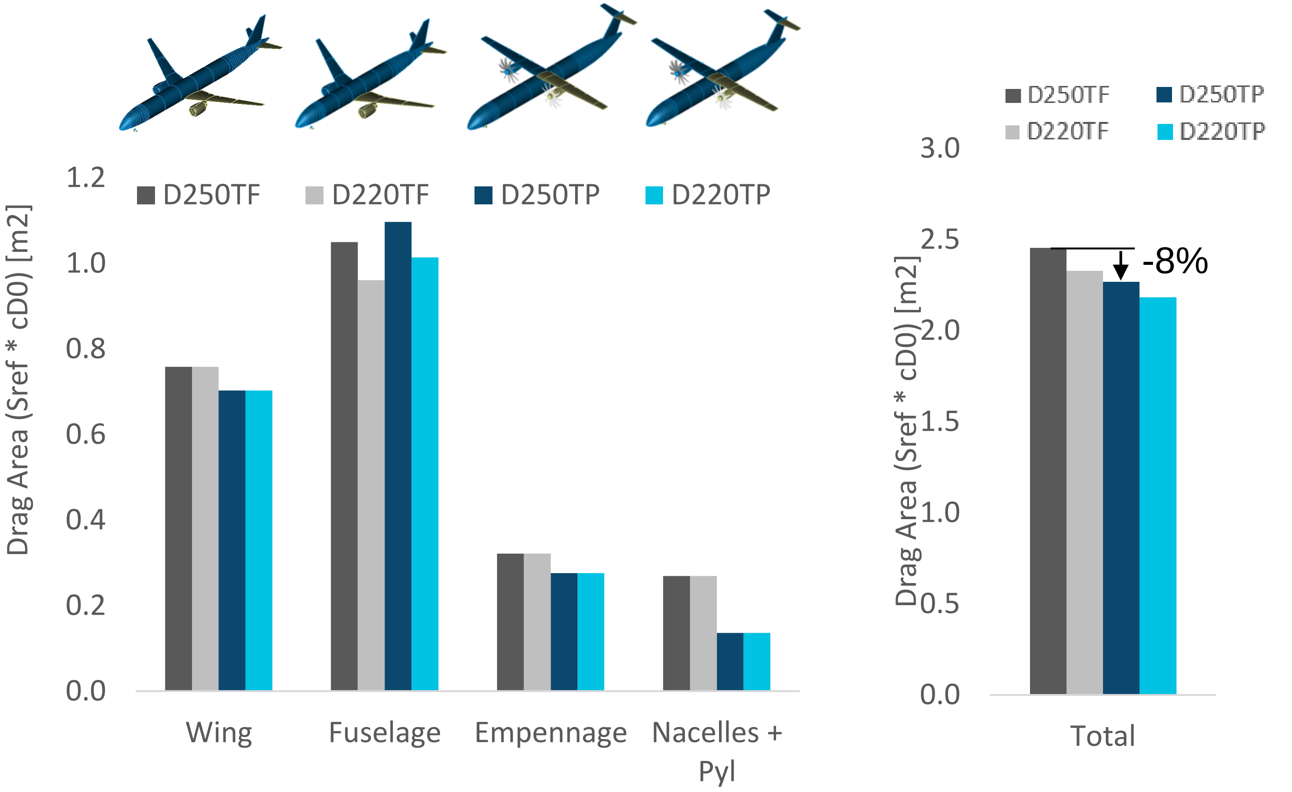
$E_{fuel} = \frac{E_{Eqiv,GT}}{\eta_{GT}} = \frac{E_{AB}}{\eta_{GT} \cdot \eta_{prop}}$



Cruise fuel is proportional to the aicraft mass and inversely proportional to L/D, poropulsor efficiency and gas turbine efficiency.

Turbofan vs Turboprop: Aerodynamics

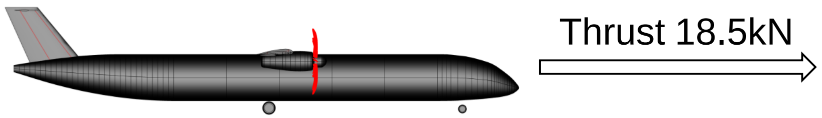




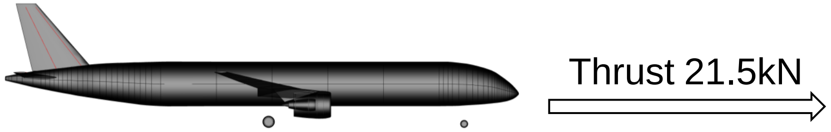
~9% improvement in L/D due to:

- smaller nacelles, wing and empennage
- increase in cruise CL due to less transonic effects limitations for the wing design, as well as relaxter engine-aero matching due to the lower speed.

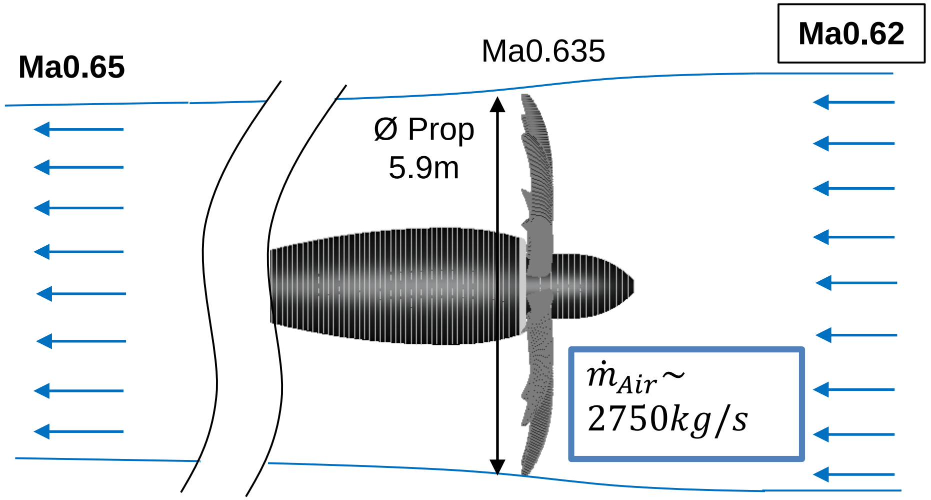
Turbofan vs Turboprop: Propulsor Efficiency

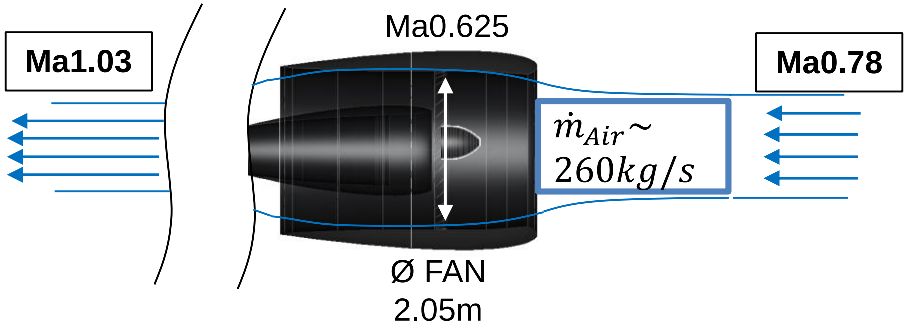


Cruise: 27000ft, Ma0.62



Cruise: 33000ft, Ma0.78





$\eta_{Propulsive} = \frac{2}{1+v_e/v_0} = 0.99$ → Propeller Losses → $\eta_{Propeller} \approx 0.85$

$\eta_{Propulsive} = \frac{2}{1+v_e/v_0} = 0.86$ → Fan & Duct Losses → $\eta_{DuctedFan} \approx 0.76$

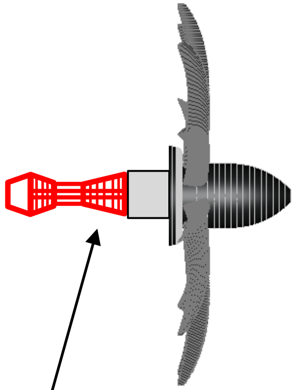
The propeller is ~12% (relatively) more efficient than the fan, mainly due to the large diameter.

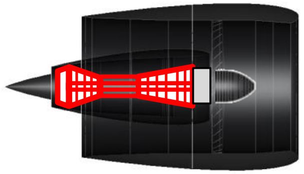
Turbofan vs Turboprop: Engines

Top of Climb Point (FL270, Ma0.6):
- TET = 1600K
- Thrust ~21.5kN
- etaProp = 84%

=> **Gas Turbine Equivalent Power* = 4.6MW**

*Equiv. Power is the total useful power including residual thrust





Top of Climb Point (FL330, Ma0.76)
- TET = 1600K
- Thrust ~24.5kN
- etaFan = 75%

=> **Gas Turbine Equivalent Power* * = 7.5MW**

*Equiv. Power is the total useful power including core thrust.

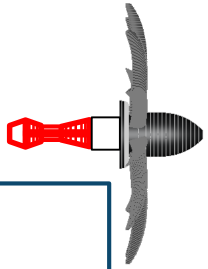
Gas turbine model efficiency:
- Equivalent power efficiency*: 52.5%
- 2-Stage Gearbox: 98.5% efficiency
- **Total equivalent efficiency**: 51.6%**

**Equiv. efficiency is defined as the fraction of the fuel heating energy that can be transformed into equivalent power.

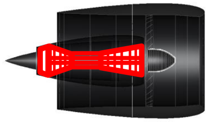
Gas turbine model efficiency:
- Equivalent power efficiency*: 55.5% (more efficient due to size effect)
- 1-Stage Gearbox: 99.4% efficiency
- **Total equivalent efficiency**: 55.1%**

The gas turbines of the turboprop are smaller and the propeller requires a 2-stage gearbox, which results in ~7% (relatively) lower efficiency of the power generation compared to the geared turbofan.

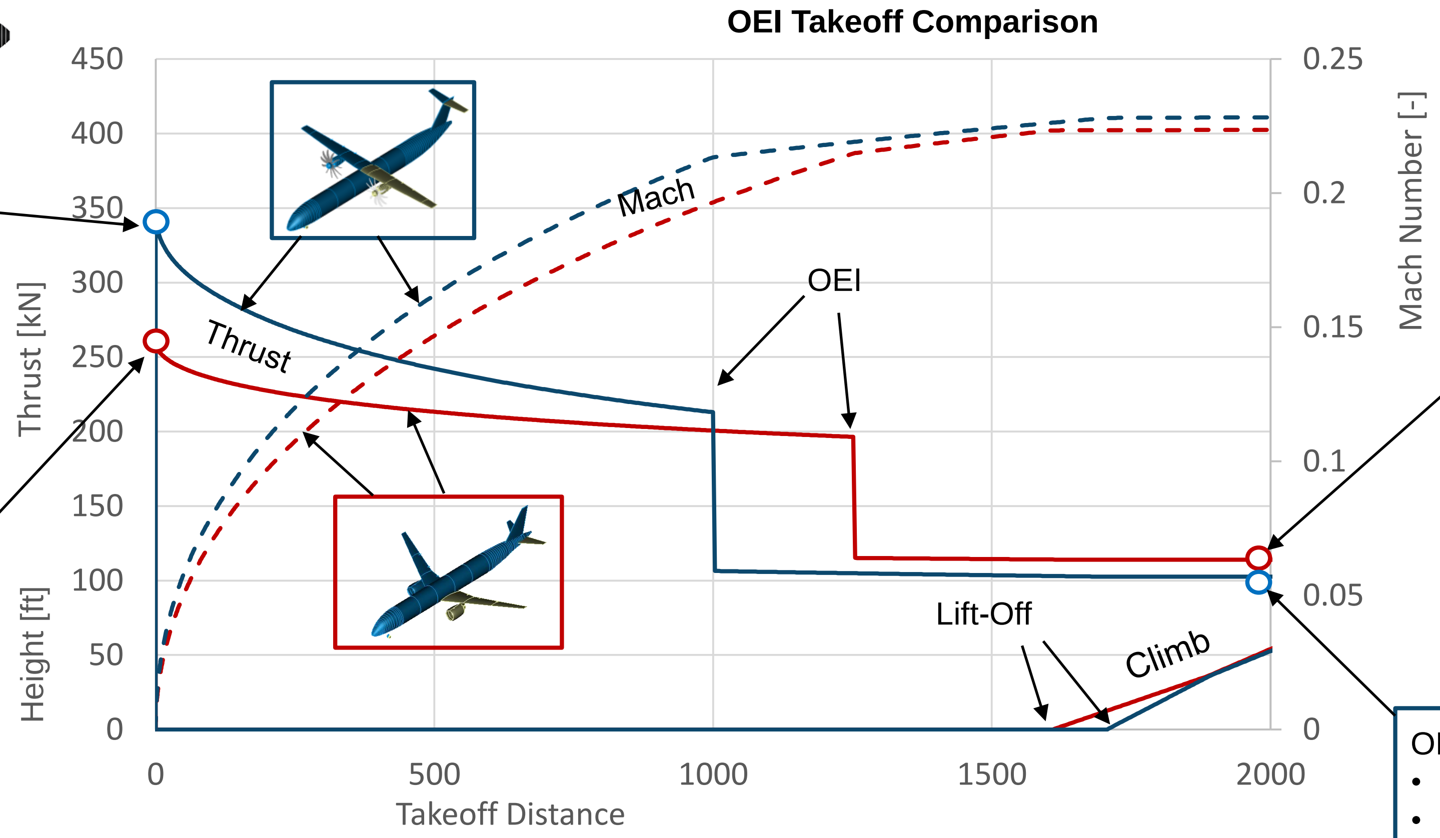
Turbofan vs Turboprop: Engines Low-Speed

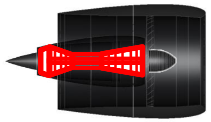


TO Static Point:
- TET = 1810K
- Thrust = 170kN
- P_Equiv* = 11.5MW

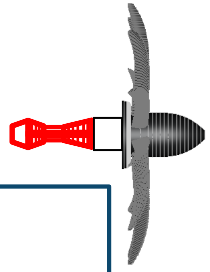


TO Static Point:
- TET = 1855K
- Thrust = 130kN
- P_Equiv* = 18.5MW





OEI Point:
- TET = 1900K
- Thrust ~114kN
- etaFan = 37%
- P_Equiv* = 22.8MW

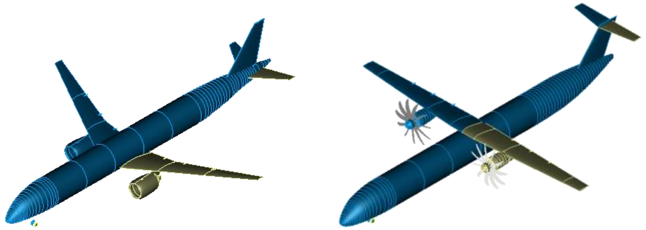


OEI Point
- TET = 1800K
- Thrust ~102kN
- etaFan = 65%
- P_Equiv* = 11.5MW

*Equiv. Power is the total useful power including residual (core) thrust

The large propeller requires significantly less power for thrust production compared to the turbofan.

Turbofan vs Turboprop: Allowances



Fuel Allowances	Units	D250TF	D250TP	Rel.
Taxi-Out (9min)	kg	92	61	-33%
Take-Off and Climb to 1500ft	kg	212	139	-35%
Approach (from 1500ft) & Landing (5min)	kg	100	63	-37%
Taxi-In (5min)	kg	51	35	-31%
Total	**kg**	**455**	**298**	**-35%**

Taxi Idle assumes 10% of take-off fuel flow

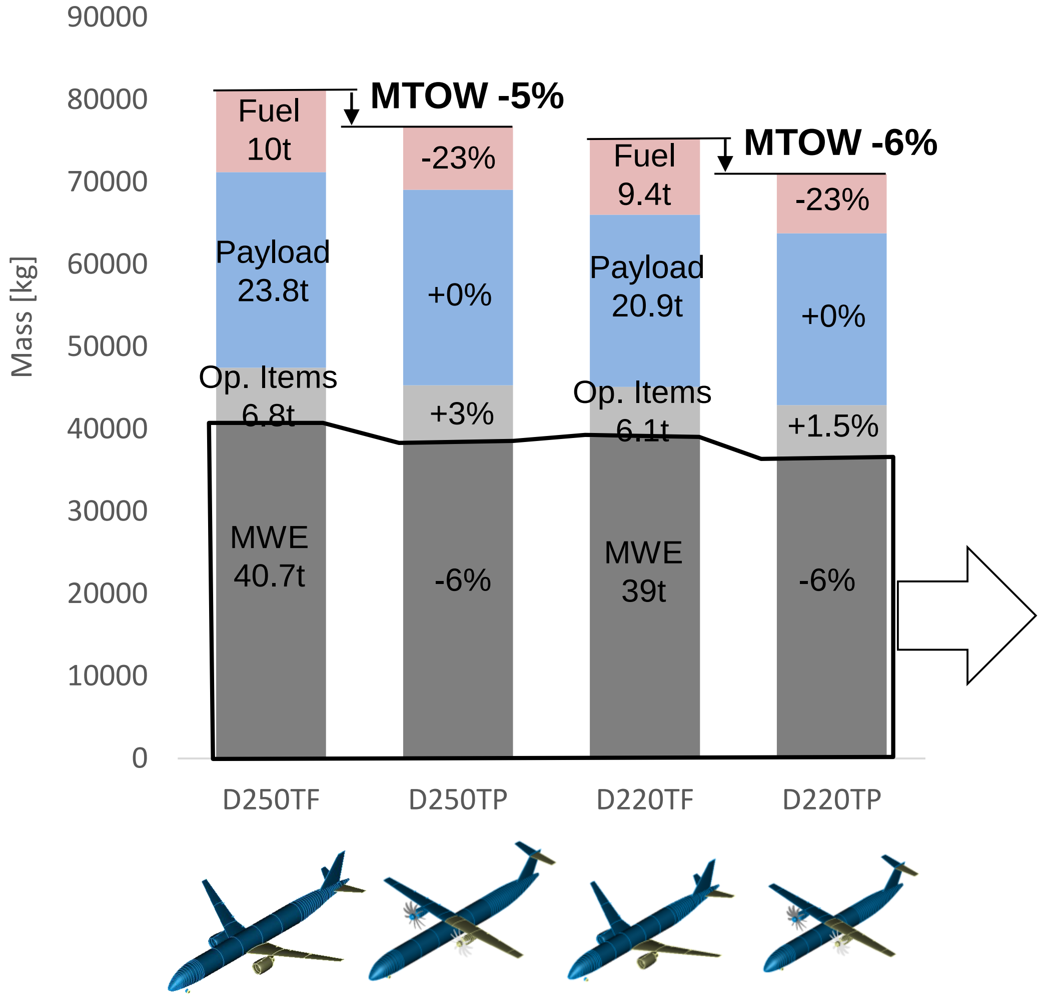
Calculated with LSP (Low-Speed Perfo Tool)

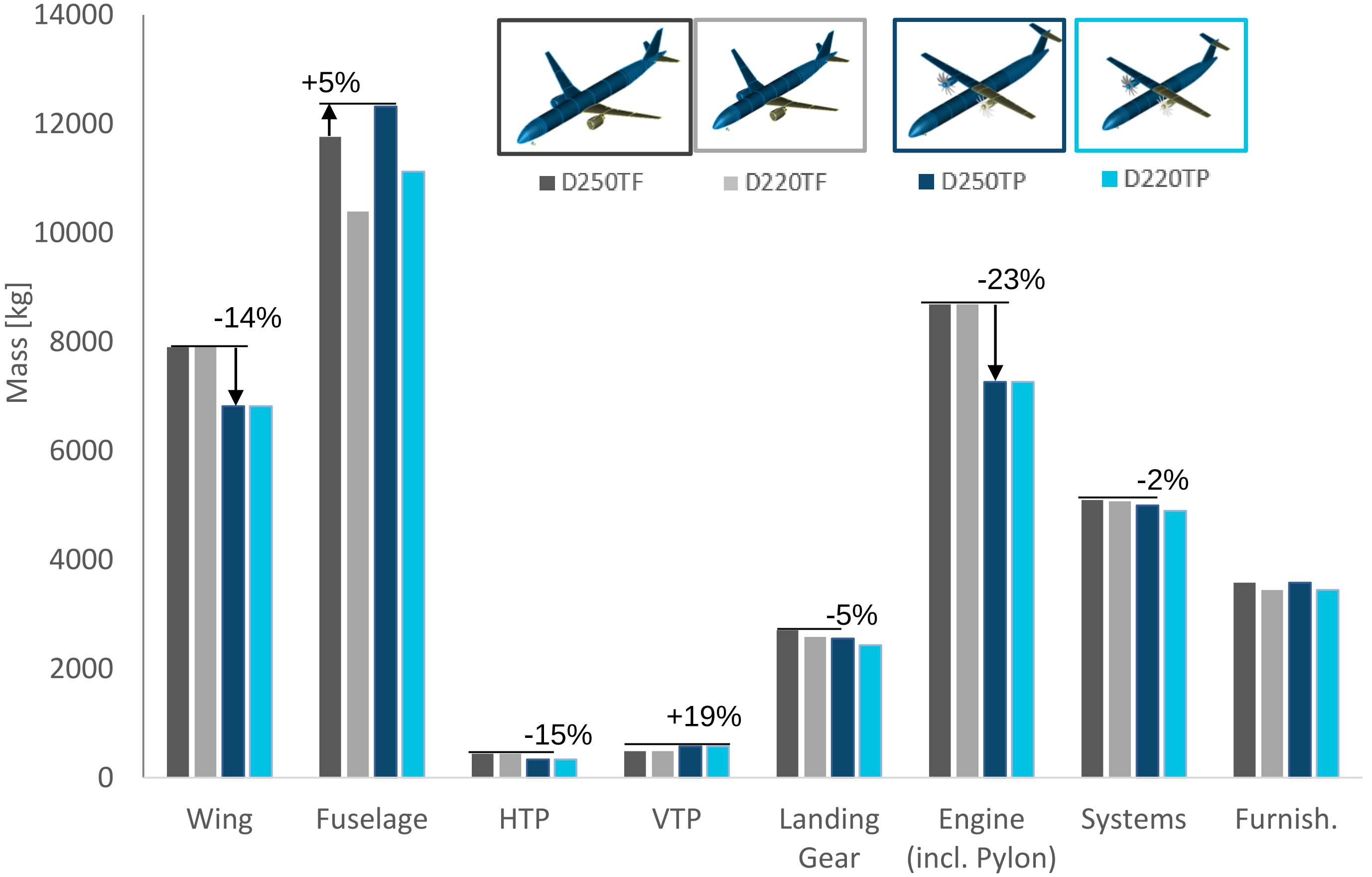
Taxi Idle assumes 10% of take-off fuel flow

The ~35% smaller gas turbines burn proportionally less fuel at idle power (taxi, approach&landing). The large propellers are significantly more efficient in producing thrust during take-off and initial climb.

The reduction of the fuel allowances is especially advantageous at shorter missions

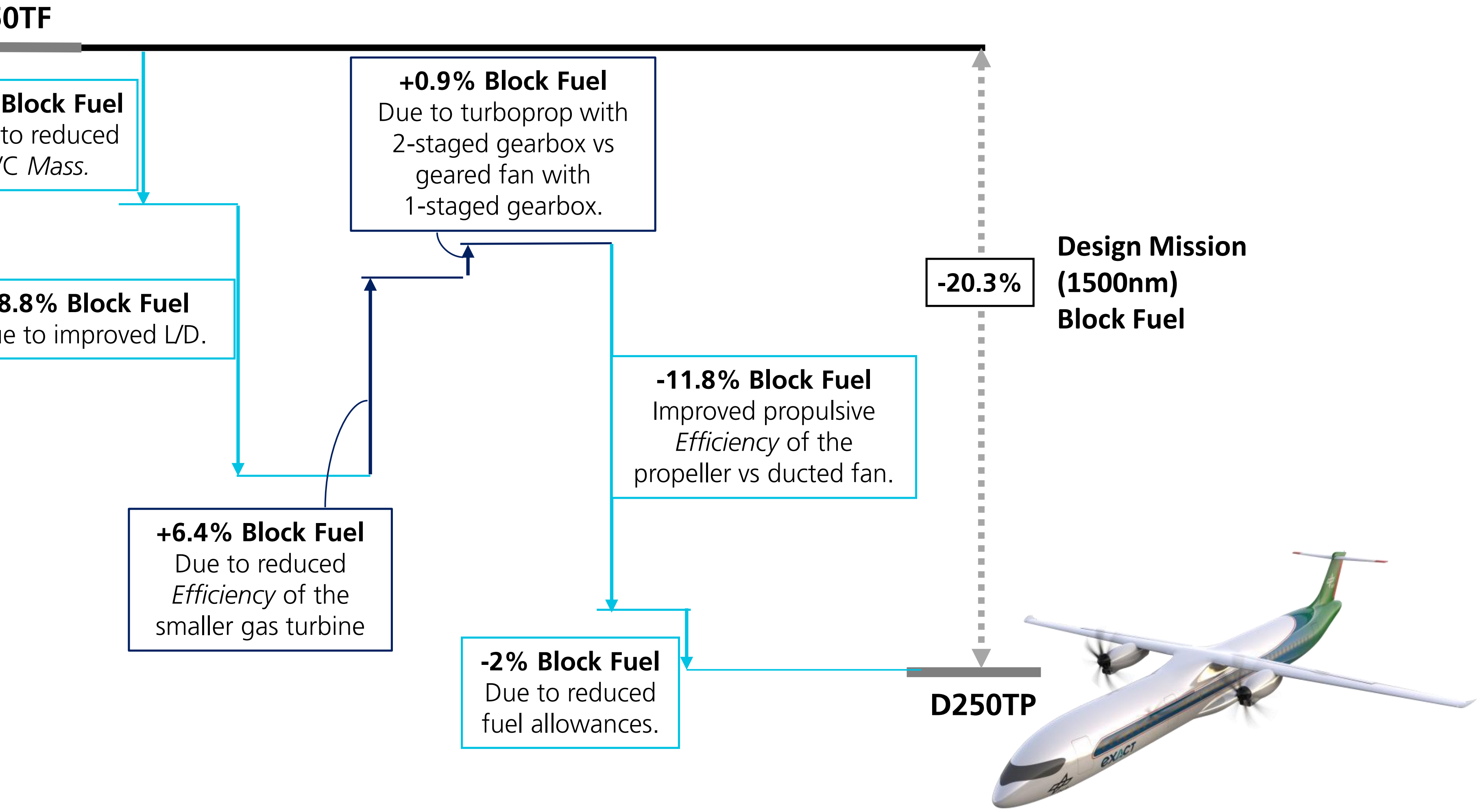
Turbofan vs Turboprop: Mass Breakdown





The MTOW of the turboprop is ~5% lighter, with ~6% empty mass reduction due to lighter wing and engies and ~23% less fuel.

Turbofan vs Turboprop: Design Block Fuel Comparison



D250TF

-5% Block Fuel
Due to reduced A/C *Mass.*

-8.8% Block Fuel
Due to improved L/D.

+6.4% Block Fuel
Due to reduced *Efficiency* of the smaller gas turbine

+0.9% Block Fuel
Due to turboprop with 2-staged gearbox vs geared fan with 1-staged gearbox.

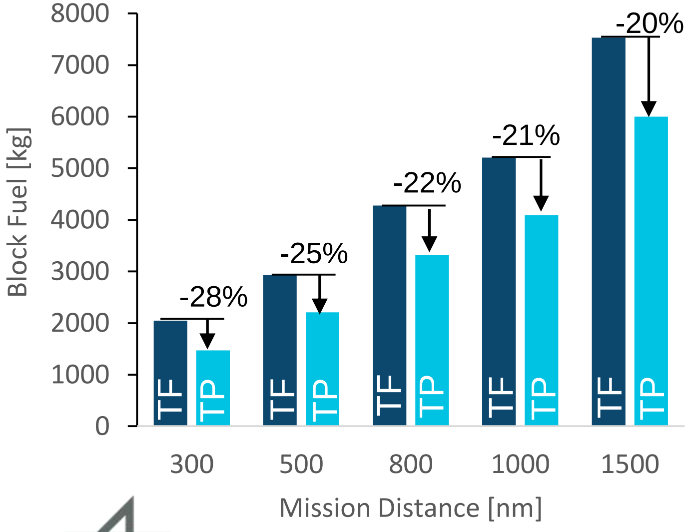
-11.8% Block Fuel
Improved propulsive *Efficiency* of the propeller vs ducted fan.

-2% Block Fuel
Due to reduced fuel allowances.

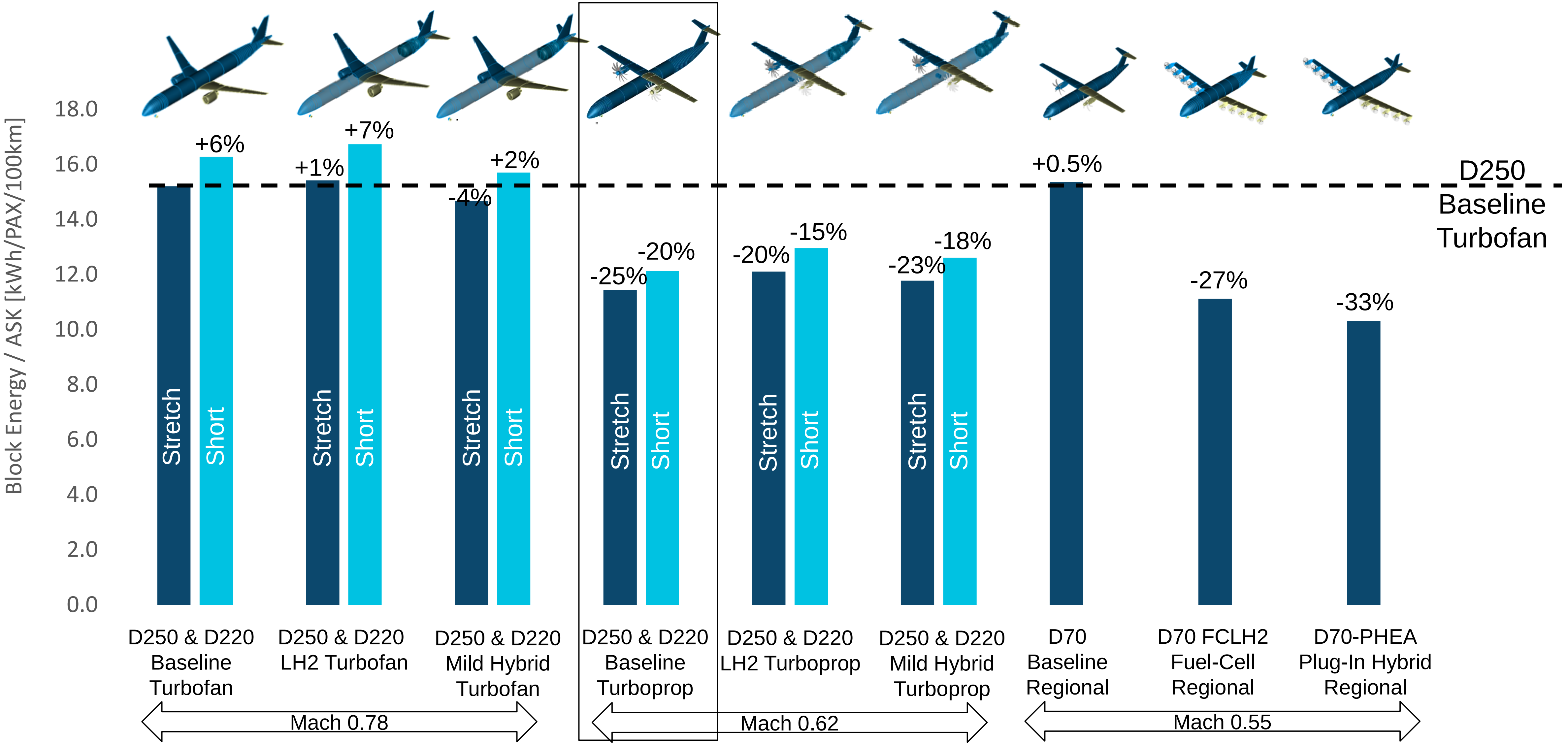
-20.3%

Design Mission (1500nm) Block Fuel

D250TP



Block Energy Comparison @ 500nm & Standard Payload



Summary and Outlook

- Summary
  - 20-25% block fuel reduction compared to a respective turbofan design.
  - Tendency for lower cruise altitudes → increased potential for climate impact reduction.

- Outlook
  - Higher-fidelity wing calculation.
  - Detailed Mach-number trade-off studies for the aircraft concepts.
  - Feeding back results from the other HAPs into the design.

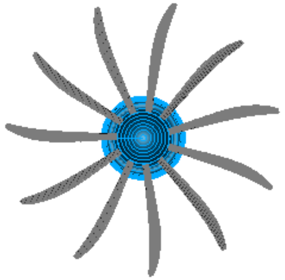
Thank you for your attention!

Reach out to: georgi.atanasov@dlr.de

All renderings by Line Winkler (DLR)

Modelling – Design Studies

- A propeller geometry study, resulting in an 11-bladed propeller design
  For more details:
  :*“Propeller Design and Analysis based on BEMT for Target Setting Purposes within the Aircraft Conceptual Design Phase” by Yannic Cabac, Georgi Atanasov*



- Diameter = 5.9m
- AF = 77
- nBlades = 11

- The VTP size was determined by a responce surface generated by CASCOT. For more details:
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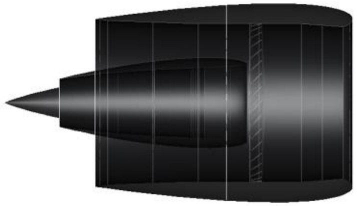
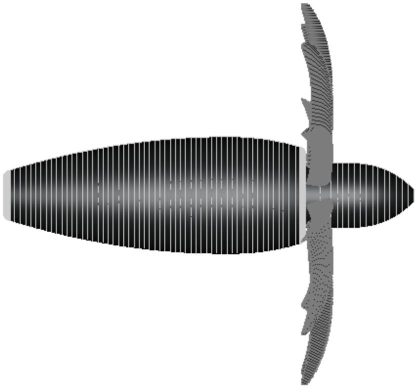
  “*Conceptual Loads Estimation and Assessment of Hydrogen Aircraft Configurations*” by Tobias Hecken

Backup Slide Engine Mass Breakdown



D250TF Engine Mass Breakdown

Total Engine Mass	*8800*
Gas Turbines	*4200*
Gearboxes	*700*
Fans (incl. inner ducts)	*600*
Nacelles (incl. thrust rev.)	*1830*
Pylons	*960*
Eng & Nacelle Systems	*510*



D250TP Engine Mass Breakdown

Total Engine Mass	7270
Gas Turbines	2720
Gearboxes	1280
Propellers	2100
Nacelles	410
Mounting Structure	340
Eng & Nacelle Systems	420