PEASA 2025: Keynote Presentation

A Radical Regional Aircraft Concept in IMOTHEP: Lessons Learned in Propulsion System Architecture and Integration

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DLR

Background – the IMOTHEP Project

- **Four-year research project (2020-2024)** ⇨ ended in June 2024
  - Coordinated by ONERA
  - Funded as part of Horizon 2020 (European framework program)
- **29 partners**
  - **9 European countries + 2 international partners from Canada**
    - Effort equivalent to about 22 engineers full time

Background – the IMOTHEP Project

FOCUS OF THE PRESENTATION

Regional Radical:

- **Turbo-Electric + Distributed Electric Propulsion (DEP)**
- **Hybrid power – Gas Turbine + Battery**

Insights and Lessons learned from:

- How the aircraft configuration and the propulsion system architecture were defined.
- The overall modelling results
- The detailed propulsion system component modelling and integration into the airframe.

REG-RAD Configuration

Regional Radical (REG-RAD) Requirements:

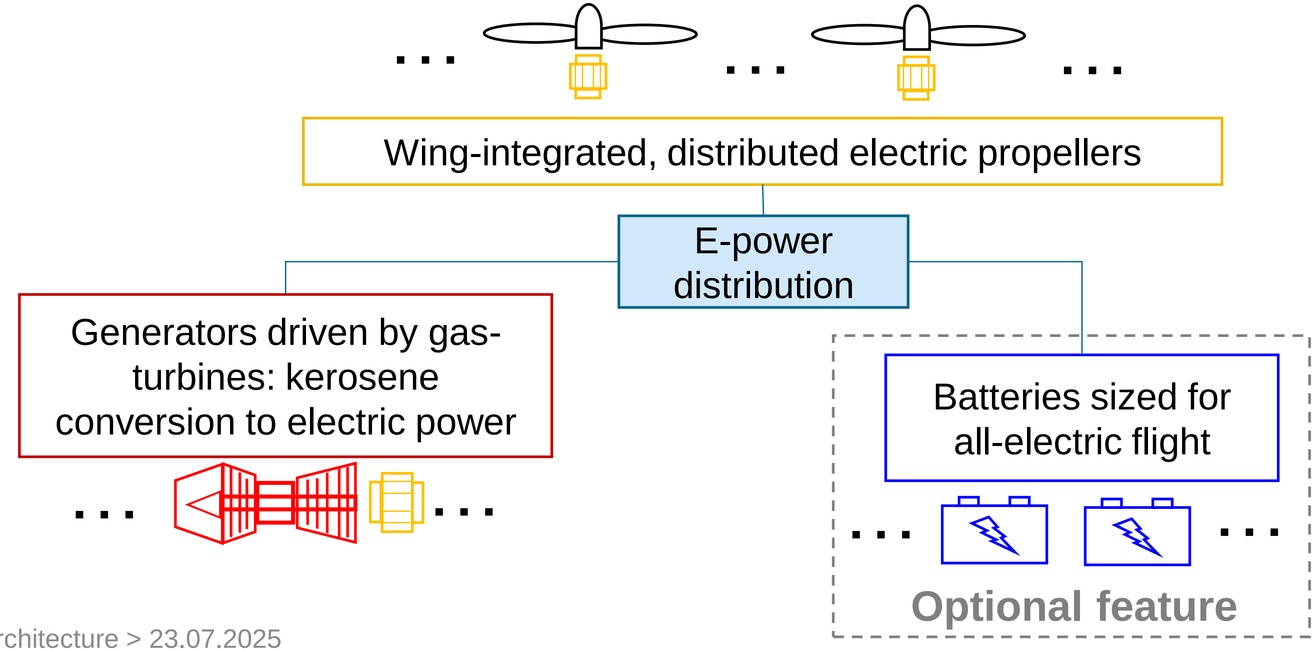
- Entry into Service of 2035+
- Similar class as the ATR42
  → 40 Passengers, 600 nmi range, Ma 0.4
- Radically different propulsion system?

REFERENCE AIRCRAFT

ATR42-500 (REG-REFX)

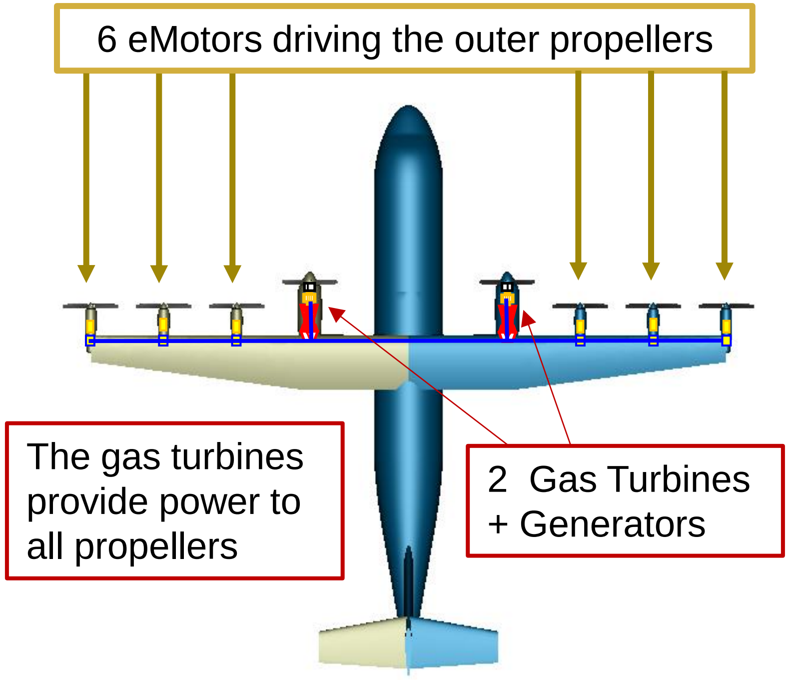
Modelling supported by LEONARDO

Project requirements for the RADICAL configuration:



Initial REG-RAD Configuration

REG-RAD_v0



Initial REG-RAD Configuration:
→ focus on turbo-electric propulsion, no battery

Potential advantages:

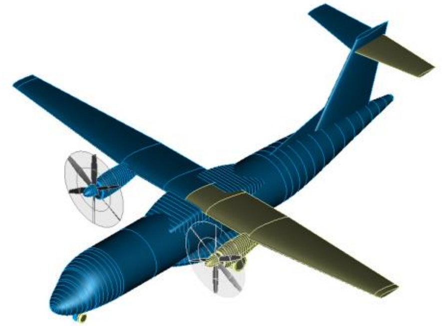
- Blown-wing effect
- Increased redundancy
- More propeller area

How did this configuration perform?

Baseline (Benchmark) Configuration – REG-BAS

STATE OF THE ART

REFERENCE AIRCRAFT



REG-REFX
(ATR42-500)

Remodelling for the Project Boundary Conditions

Requirements:

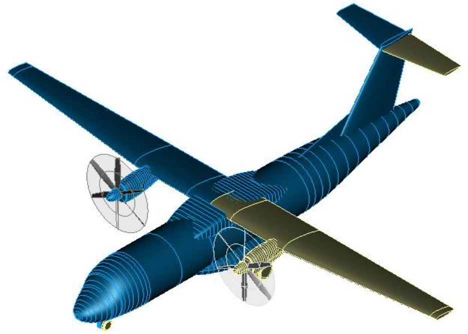
- 40 PAX
- 600 nm range
- Ma 0.4 (cruise speed)

2035+ technology improvements:

- Higher wing aspect ratio
- Reduced airframe drag
- Better engines
- Lighter structure

EIS 2035+ Models

BASELINE AIRCRAFT



REG-BAS

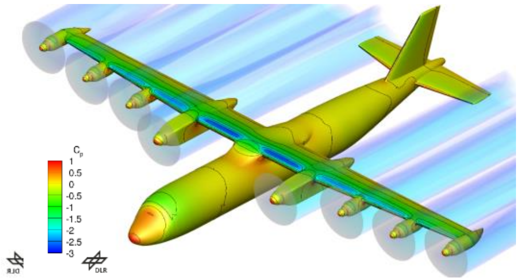
CONCEPT AIRCRAFT

REG-RAD_v0

The REG-RAD is assessed vs the Baseline Aircraft

Takeaway – Blown Wing Effect Application

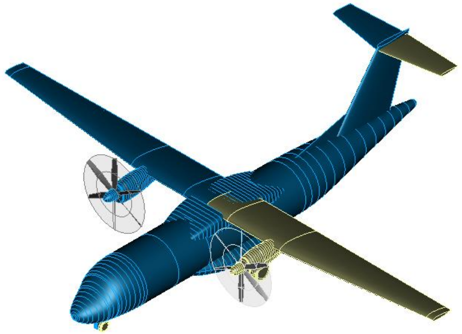
Benefits



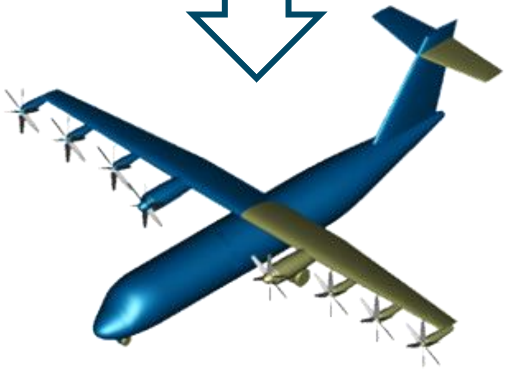
Blown-wing effect:

- Smaller wing
  - → -3% fuel burn
- Larger propeller area (better efficiency)
  - → -3% fuel burn
- Positive wing-prop interaction:
  - → -2% fuel burn

Total benefits: -8% fuel burn

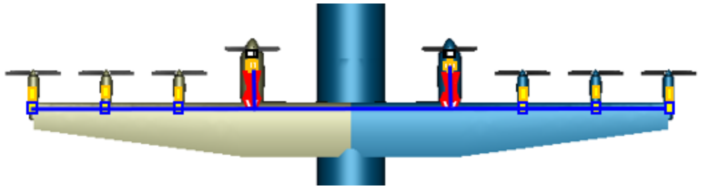


REG-BAS



REG-RAD_v0

Penalties



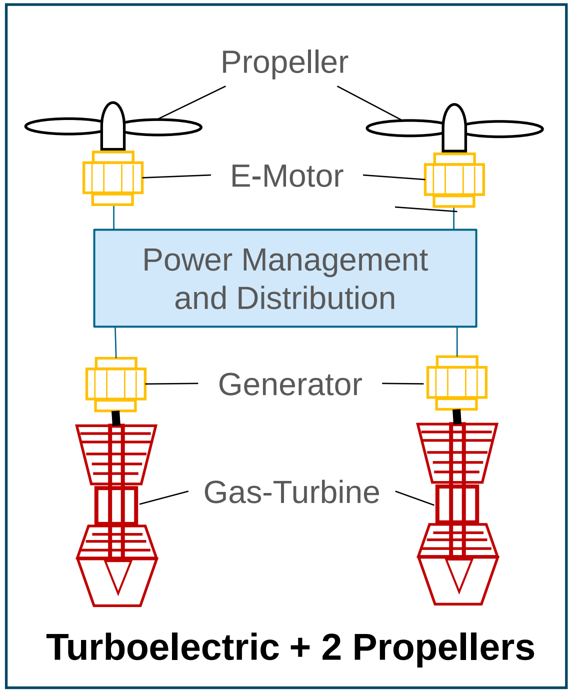
Heavy turbo-electric propulsion system:

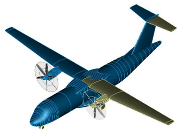
- Added propulsion mass:
  - → +6% fuel burn
- Larger nacelle wetted area
  - → +2% fuel burn
- Turbo-electric chain efficiency
  - → +7% fuel burn

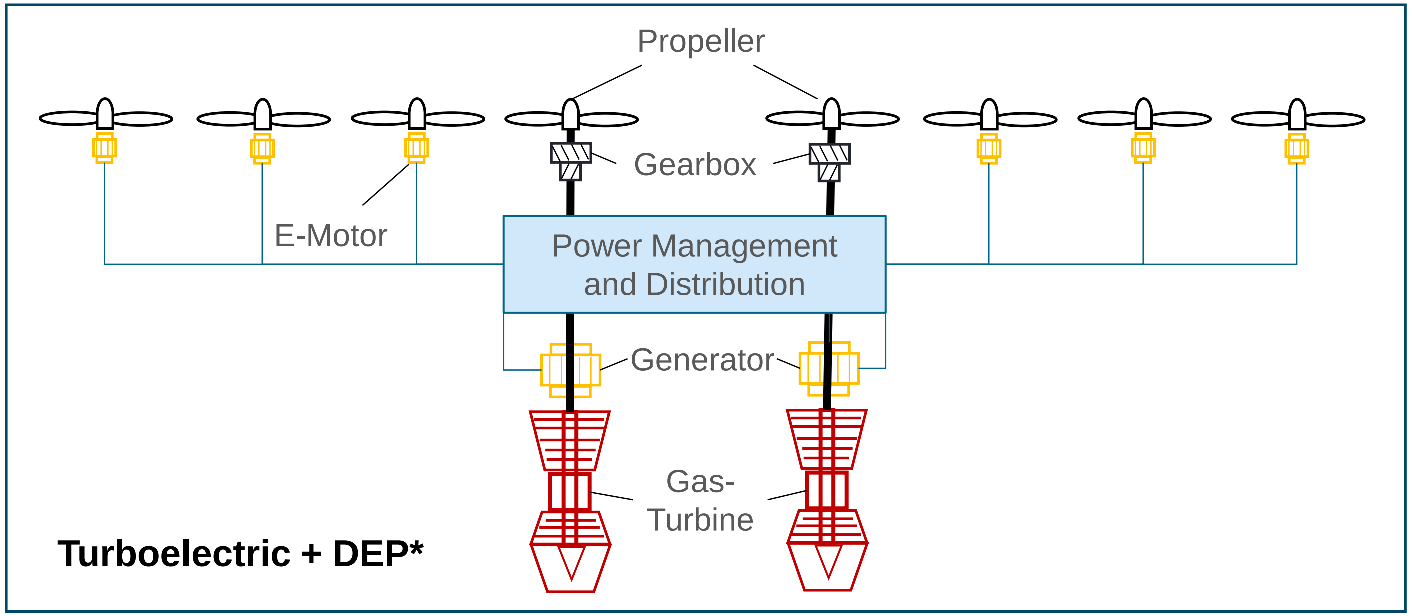
Total penalties: +15% fuel burn

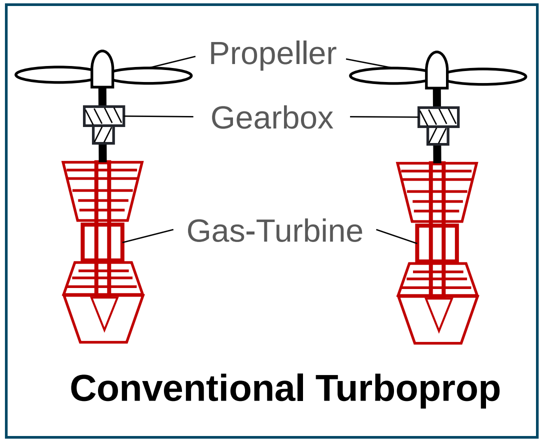
The penalties outweighed the benefits.

Another Perspective on the DEP Configuration









Distributed Electric Propellers (DEP) are actually better than 2 electric propellers

~ +15% Fuel Burn

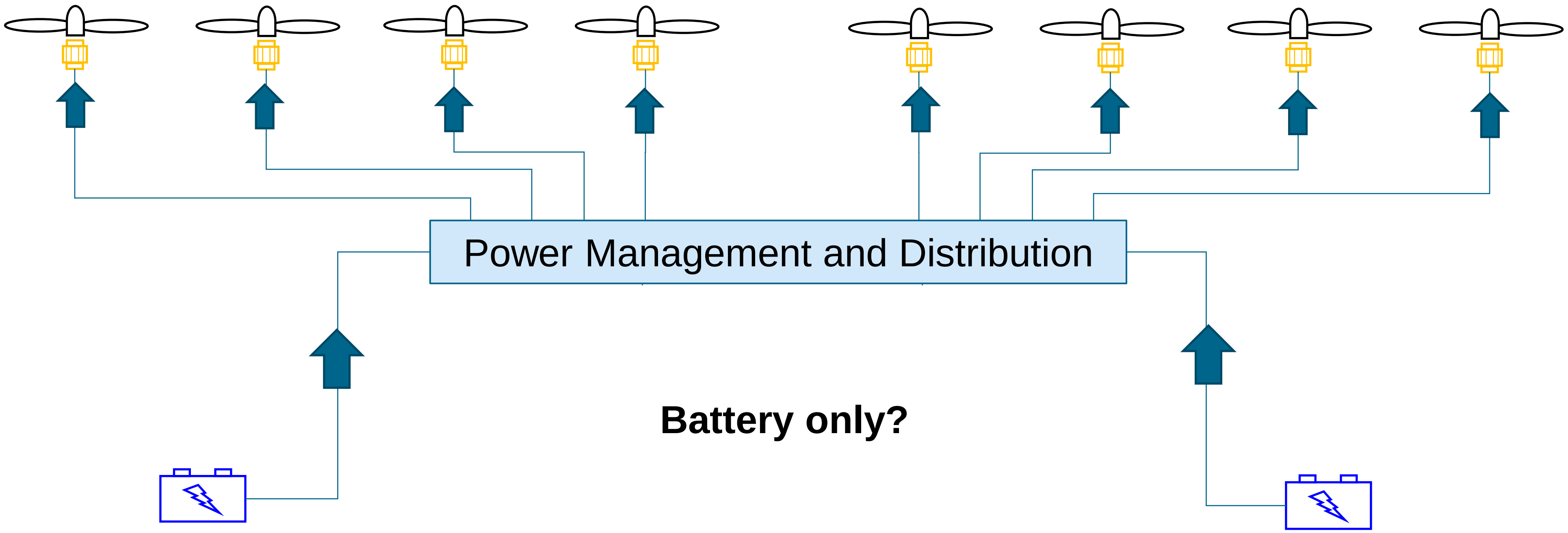
~ +6% Fuel Burn

But Turboelectric + DEP* is still worse than a normal turboprop!

Turbo-electric chain is much less efficient than simple turboprop.

Can hybrid propulsion be useful?

Further Improvements Possible?



Main Benefit → High Efficiency

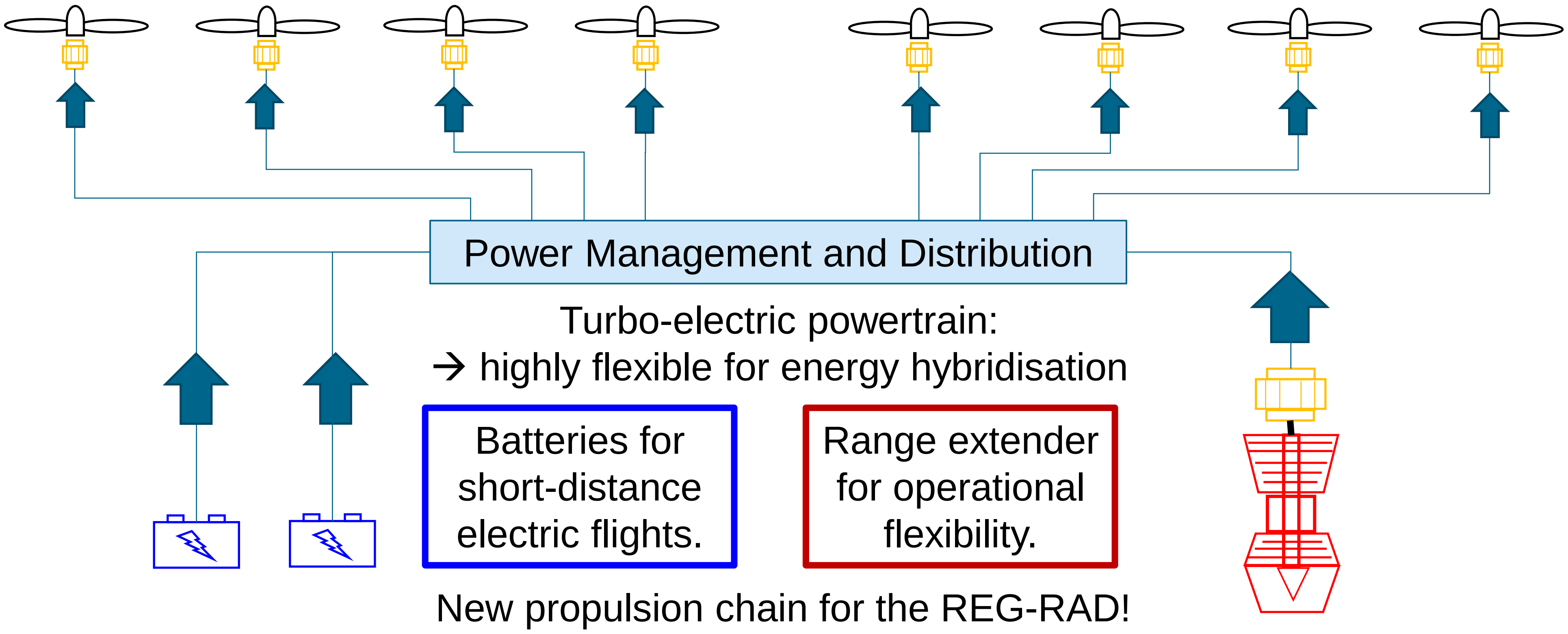
Battery Efficiency ~95%
Gas Turbine Efficiency ~35%

Not compatible with the 600 nmi design range requirement!

Main Drawback of Batteries:
→ Very heavy!

400 Wh/kg batteries are useful only up to ~400 nmi

New Energy Storage System for the REG-RAD_v1



The redundancy by the battery can allow only one range extender.

1 large range-extender is ~10% more efficient than 2 small ones.

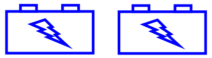
Plug-In Hybrid Propulsion Architecture

Why battery + range extender strategy?

~70% of ATR42 global operation < **200nmi!**

Project Evaluation Range: 200 nmi
(set by Leonardo)

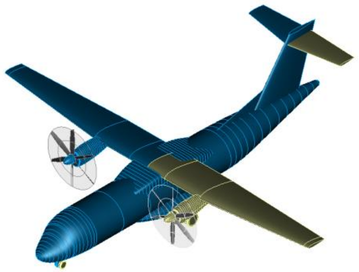
200 nmi is a feasible electric range!



Batteries sized for 200 nmi range

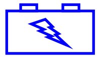
Extreme energy efficiency for the majority of the operation.

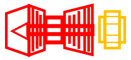
Reference Aircraft:
ATR42-500



Radical propulsion Concept for 2035+

REG-RAD_v1
Battery + Range Extender

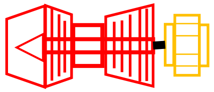




Longer range capability is important for range flexibility.

Project Design Range: 600 nmi
(set by Leonardo)

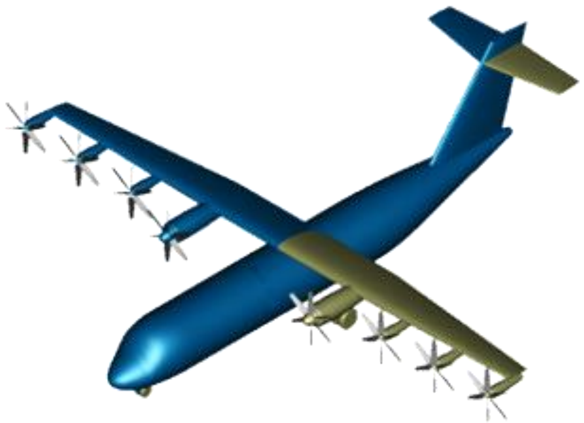
Unfeasible for batteries!



A Range-extender for longer distances

Operational flexibility

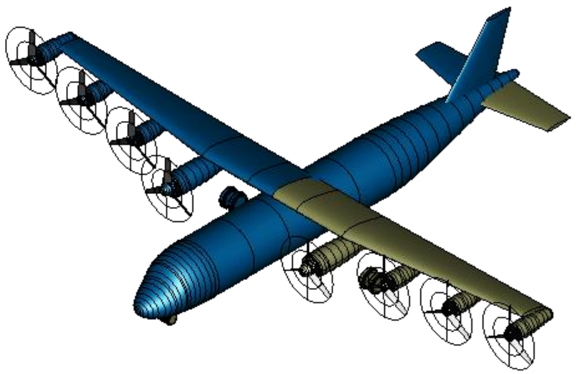
Radical Configuration Change



REG-RAD_v0

Only kerosene for energy storage

This concept performed worse than the conventional baseline aircraft



REG-RAD_v1

Battery for short flights

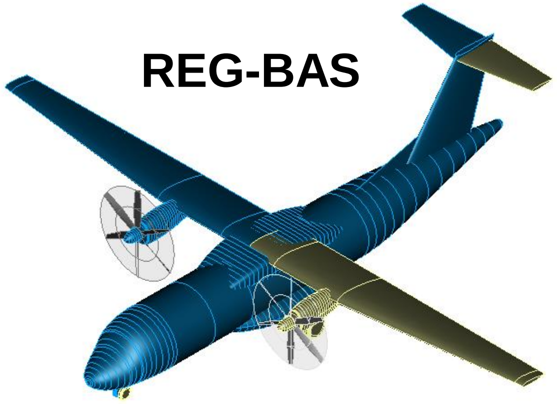
Kerosene range-extender for flight distance flexibility

How did this configuration perform?

Performance vs the Baseline

More than 70% of the fleet operation is projected < 200 nmi
Project evaluation range = 200 nmi

REG-BAS



Baseline Aircraft with EIS 2035+

Aircraft Mass: **15.5 t**
Block Fuel for 200 nmi: **375 kg**

REG-RAD_v0

Kerosene-driven turbo-electric concept

Aircraft Mass: **16.5 t**
Block Fuel for 200 nmi: **400 kg**

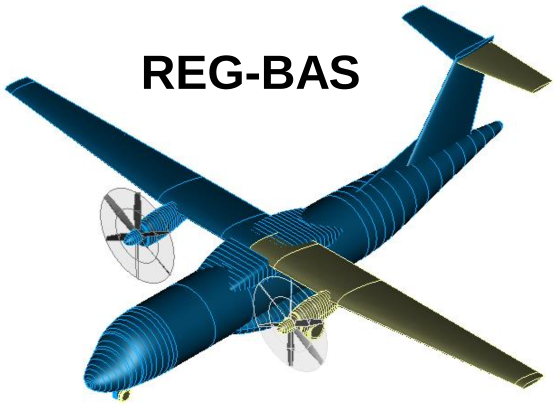
+6% Kerosene for the evaluation mission

Concept reworked to hybrid energy storage

Performance of the REG-RAD_v1

More than 70% of the fleet operation is projected < 200 nmi
Project evaluation range = 200 nmi

REG-BAS



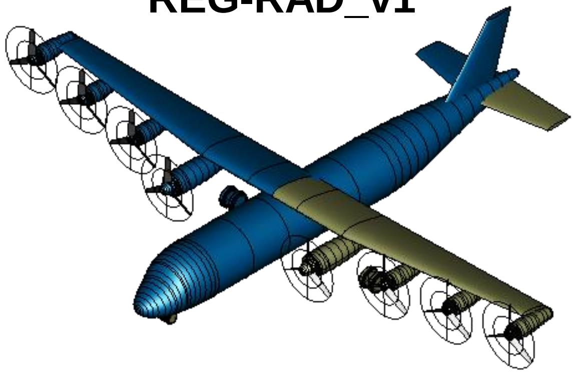
Baseline Aircraft with EIS 2035+

Aircraft Mass: **15.5 t**

Block Fuel for 200 nmi: **375 kg**

4500 kWh

REG-RAD_v1



Battery + Range-Extender Concept

Aircraft Mass: **23 t**

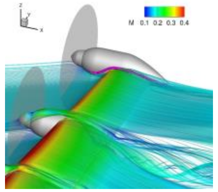
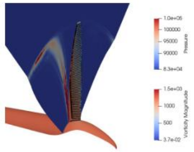
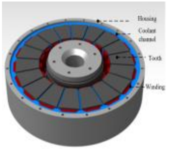
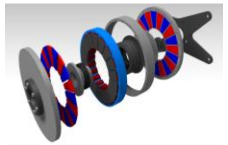
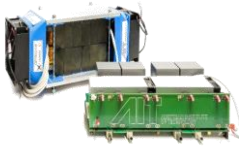
Block Fuel for 200 nmi: **0 kg**

Battery Energy for 200 nmi: **1800 kWh**

-60% block energy on 200 nmi

600 nmi hybrid range:
range-extender + battery

Project Iterations


Hi-Fi Studies on Aerodynamics, Propellers, and Powertrain Components

Aircraft Initialization

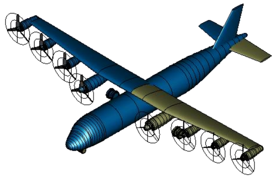
Initial REG-RAD & REG-BAS Concept
Lo-Fi modelling

REG-RAD_v0

REG-BAS_v0

Aircraft Iteration 1

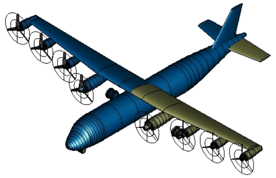
REG-RAD Re-Definition
Lo-Fi modelling
+ initial Hi-Fi results



REG-RAD_v1

Aircraft Iteration 2

REG-RAD Model Refinement
Lo-Fi modelling
+ initial Hi-Fi results



REG-RAD_v2

Aircraft Iteration 3

Aircraft Sensitivity and Optimisation Studies
Feed back of Hi-Fi disciplinary results

REG-RAD_v3

REG-BAS_v3

Final Results

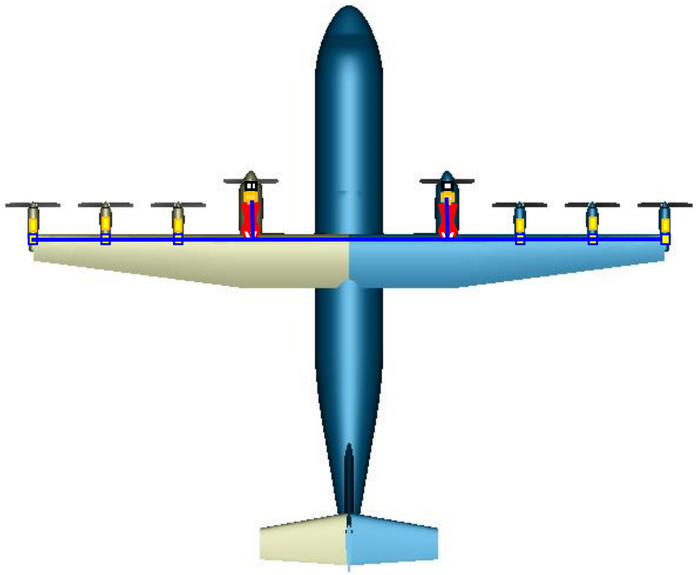
Concept Maturation and Consolidation
Integration of all Hi-Fi results into the aircraft model

REG-RAD_v4 (final)

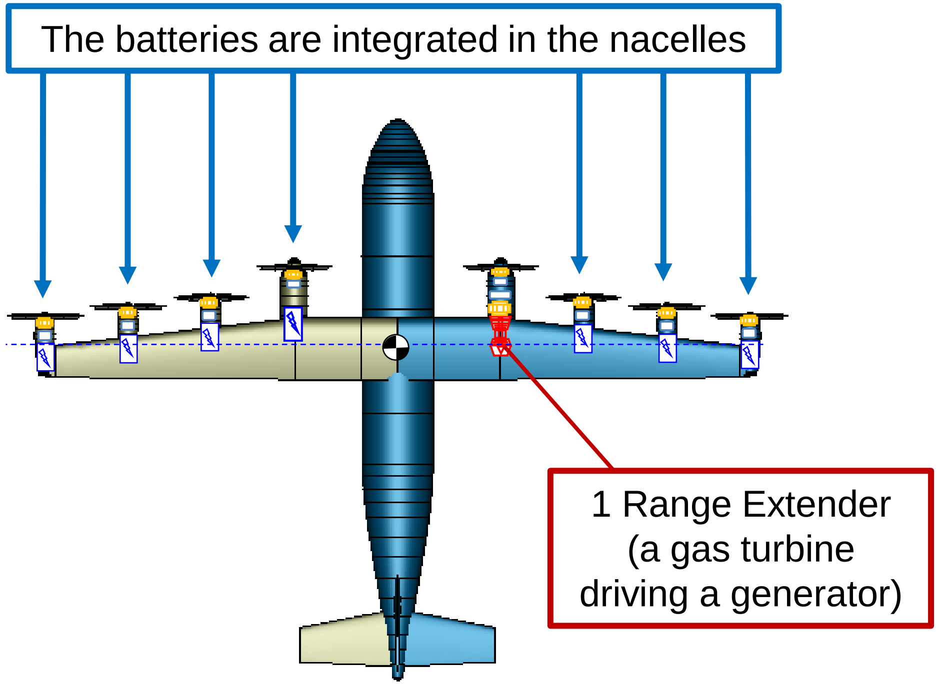
REG-BAS_v4 (final)

Propulsion System Architecture and Integration

Propulsion System Integration



REG-RAD_v0

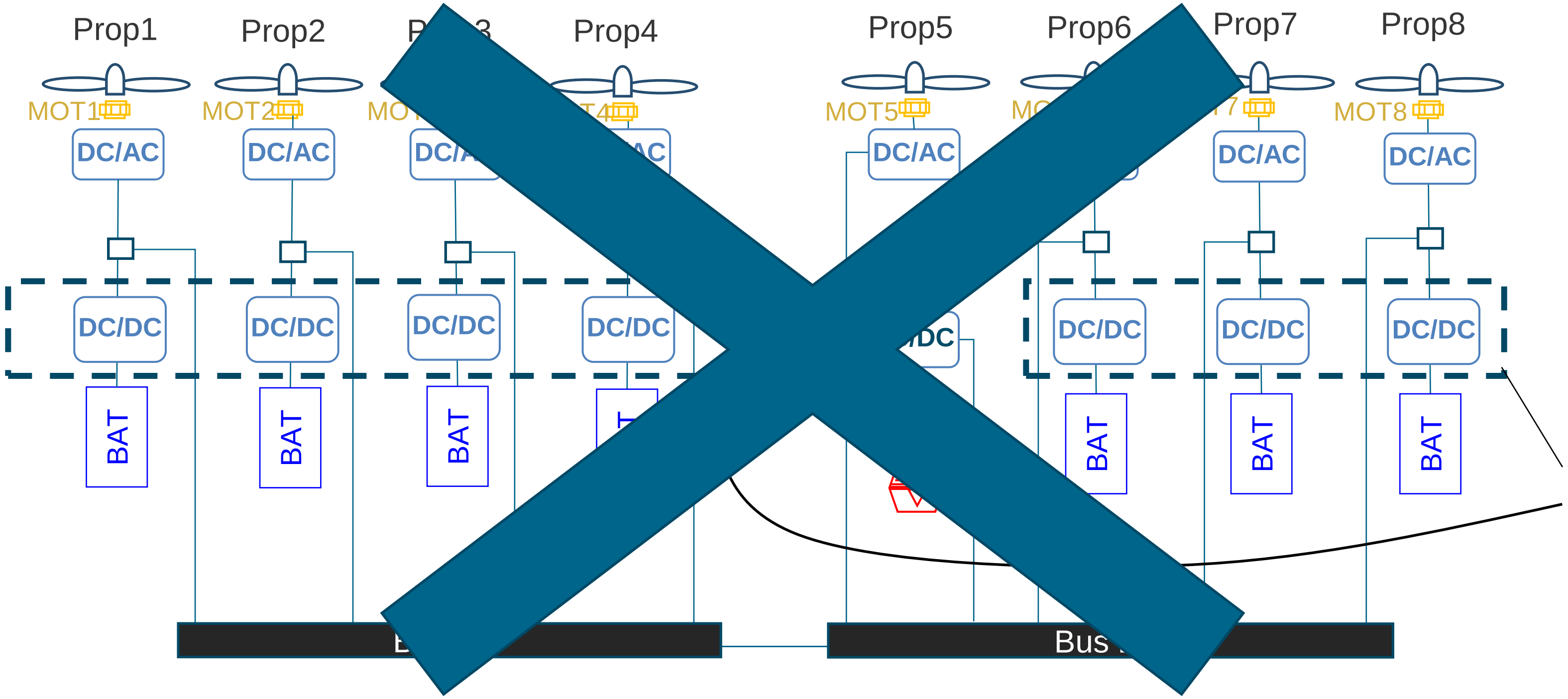


REG-RAD_v1

Priority on keeping propulsion and fuselage separated

Integration drawback: larger nacelles ~ +3% drag.

Initial Propulsion Architecture (REG-RAD_v1)



Main Challenge:

7 Batteries, 8 E-Motors: Assymetry!

→ **Crossfeed cables always active.**

Common point failure can become a certification problem.

Required measures:

→ Isolated DC-DC inverters (very heavy!)

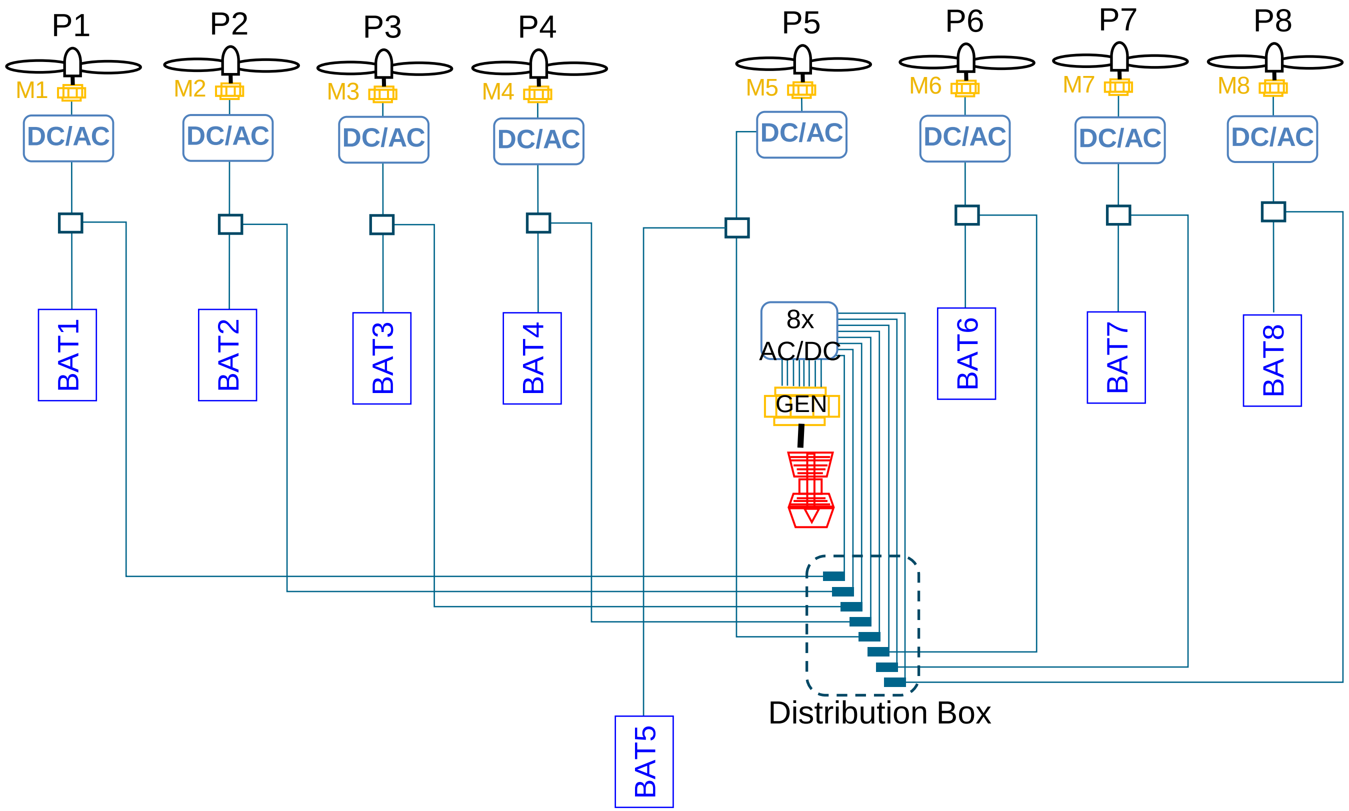
→ Alternatively very-short-reaction-time circuit breakers, e.g. pyro. (questionalble for certification)

Cross-expertise discussions concluded that a rework is needed!

Avoid cross-flow power.

Attempt to avoid common point failure modes

Final Propulsion Architecture



No DC-DC inverters needed for the batteries due to segregation of the opeation modes!

Consensus from the consortium-wide discussions:

Switch to electrically symmetrical architecture

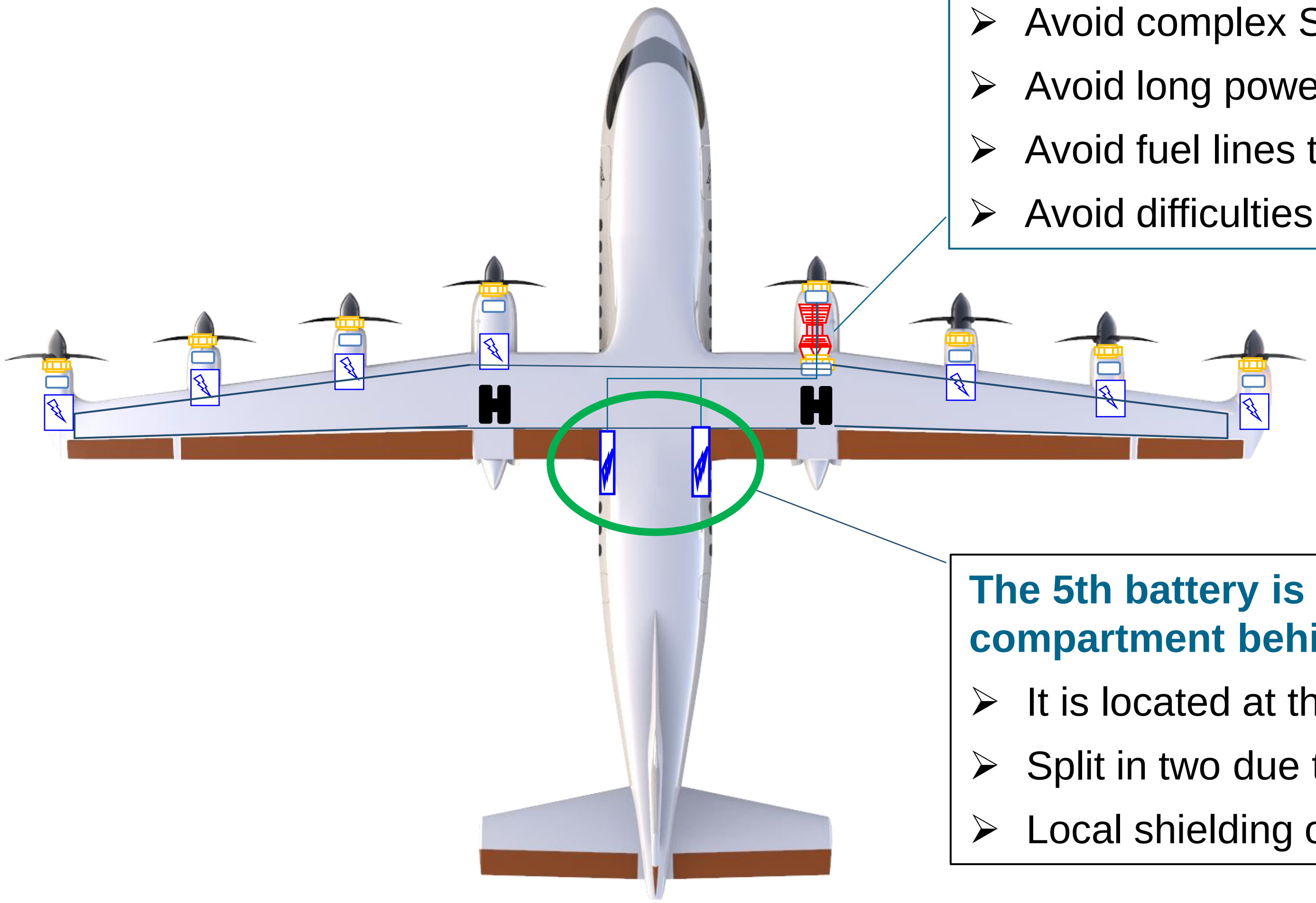
Boundary conditions:

- All e-propellers are identical (symmetrically)
- All e-propellers are powered by a dedicated battery.
- All batteries are of identical electric properties.
- Base architecture: 800V

No common failure points:

- No cross-feed during battery-powered flight.
- Generator with 8 separate pole pairs drives 8 rectifiers
- All batteries are inactive during range-extender operation.
- No battery recharging by the generator during flight (possible only at the airport).

Integration of the Final Propulsion Architecture



The range extender remains in the nacelle, to avoid fuselage integration:

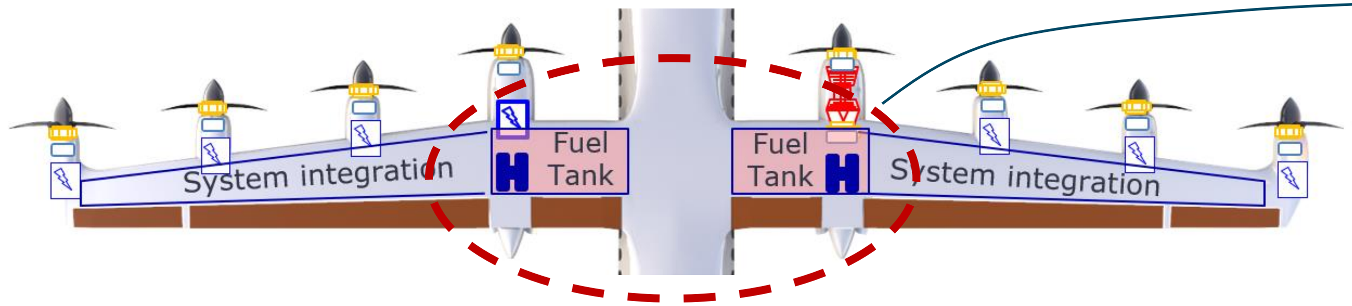
- Avoid complex S-duct inflow of the gas turbine
- Avoid long power cables throughout the rear cabin section
- Avoid fuel lines throughout the cabin.
- Avoid difficulties with cabin noise when range-extender is used

It is easier to integrate the 5th battery in the fuselage instead of the gas turbine!

The 5th battery is placed at the wing-fuselage fairing compartment behind the wing:

- It is located at the sides of the fuselage for crash case mitigation
- Split in two due to center of gravity.
- Local shielding of the fuselage structure in case of thermal runaway

Fuel and Power-Cable Integration

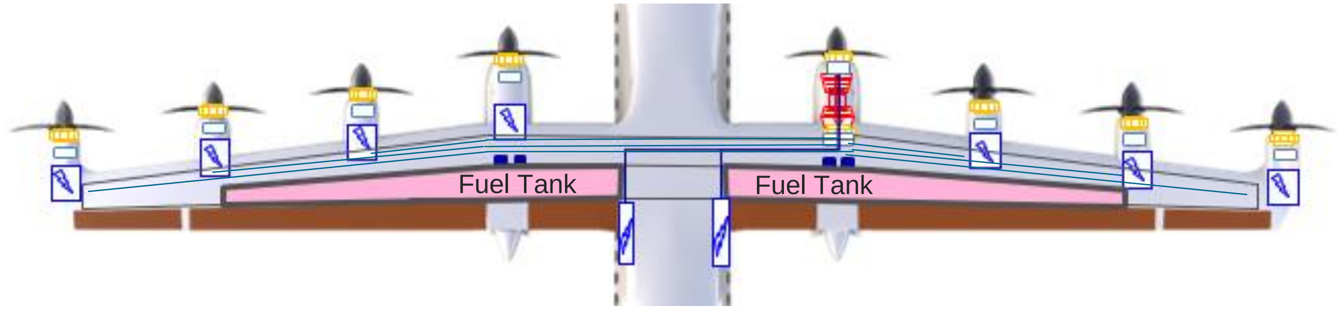


Initial Set-Up (REG-RAD_v1)

The center of the wing is too packed:

- Fuel tanks betwen the two spars
- De-icing system at the leading edge
- Flap system at the trailing edge

Difficult to integrate the cross-feed cables!

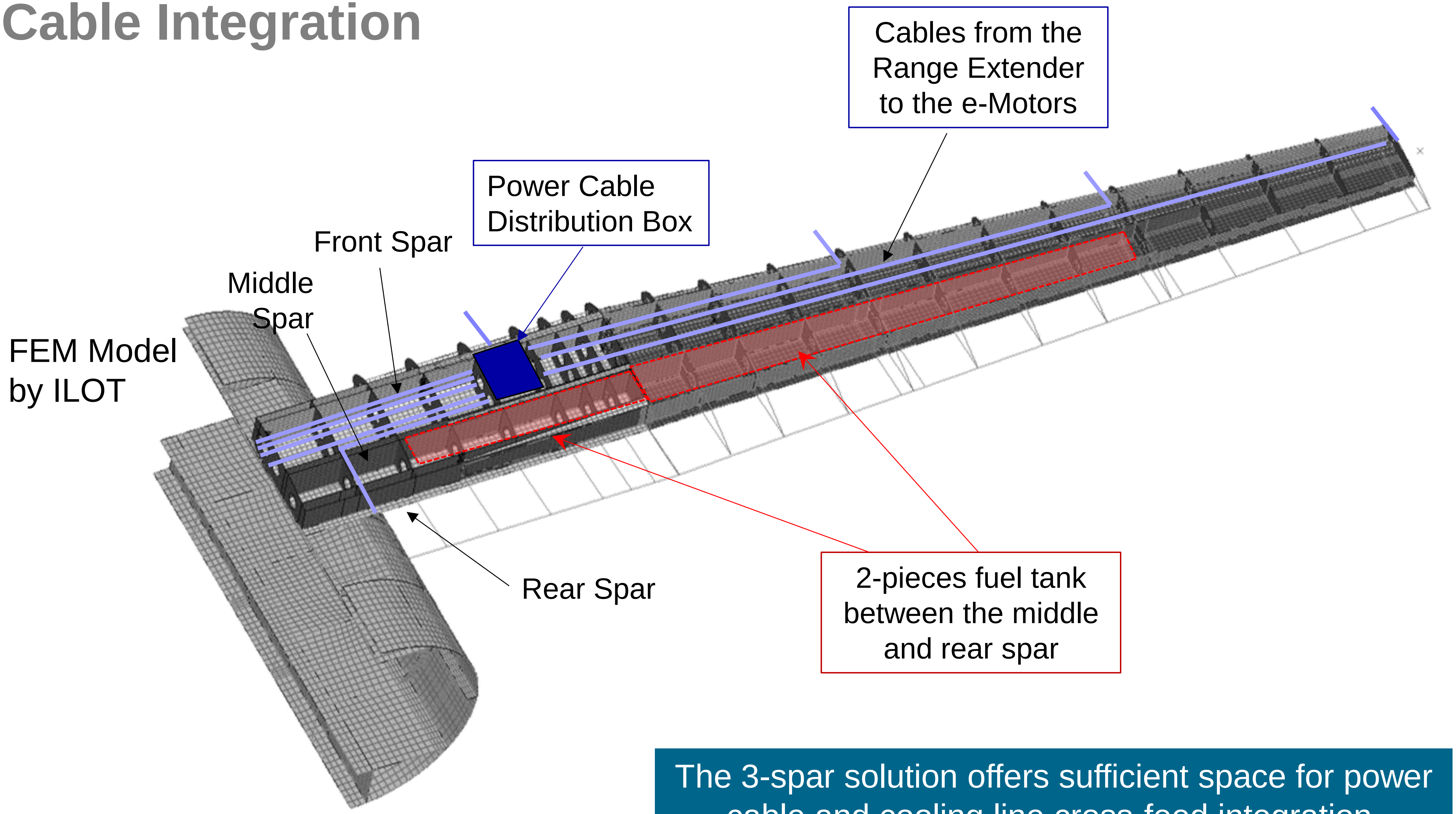


Final Configuration

Switch to a 3-spar wing structure:

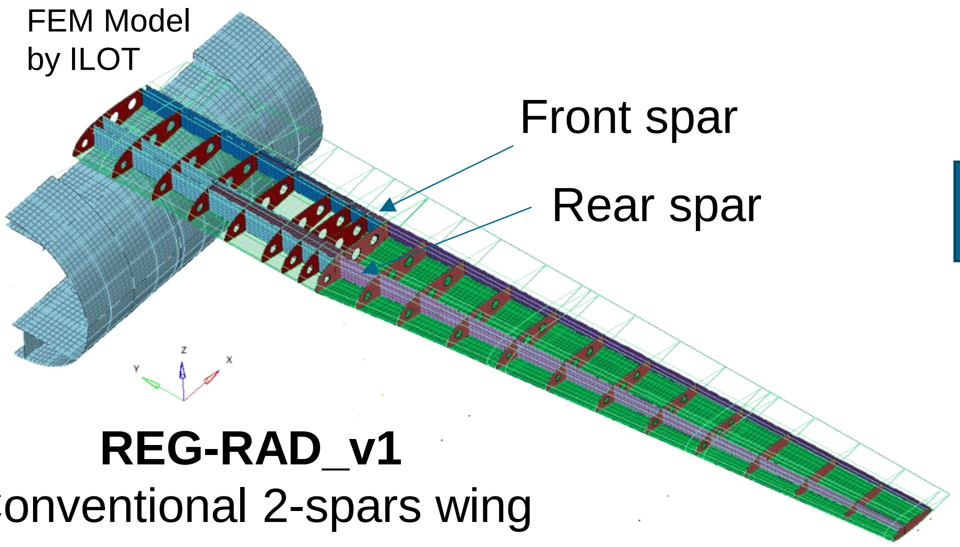
- The fuel is integrated between the rear and the middle spar.
- The cables are integrated between the front and the middle spar.

Cable Integration

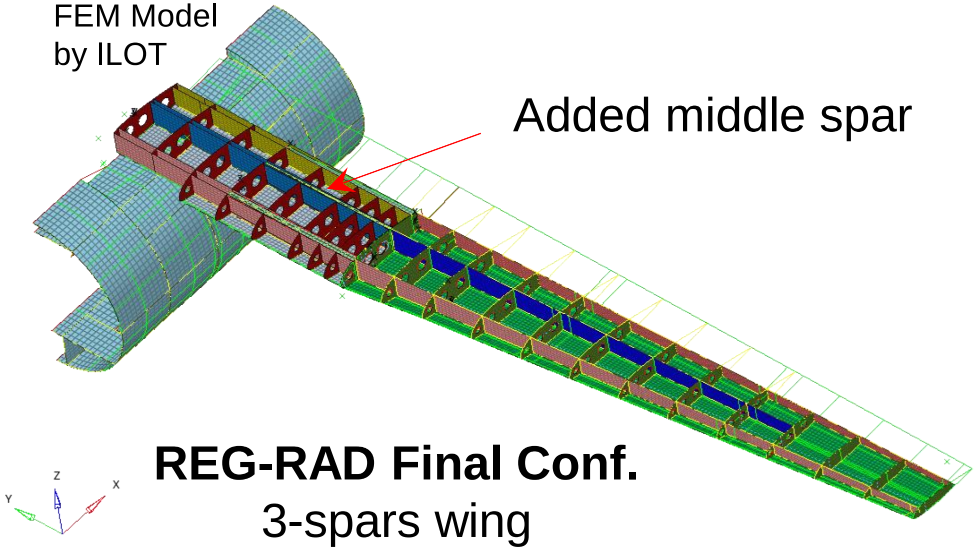


The 3-spar solution offers sufficient space for power cable and cooling line cross-feed integration.

Wing Structural Analysis



REG-RAD_v1
Conventional 2-spars wing



REG-RAD Final Conf.
3-spars wing

The structural and aerolastic analysis results in the project:

→ The heavy battery across the wing reduces the natural frequency of the wing structure
→ Switching to a 3-spar wing increases the natural frequency for the same structural mass.

The 3-spar solution is synergetic in terms of structure properties and propulsion integration.

Summary and Conclusions

Study Partners and Disciplines

Aircraft certification aspects: DLR, LEONARDO AIRCRAFT, EASA European Aviation Safety Agency

Aircraft operation aspects: DLR, LEONARDO AIRCRAFT, EUROCONTROL

Overal aircraft model
Industry oversight: LEONARDO AIRCRAFT

Aircraft design: DLR

Aerodynamics: DLR, CIRA Centro Italiano Ricerche Aerospaziali

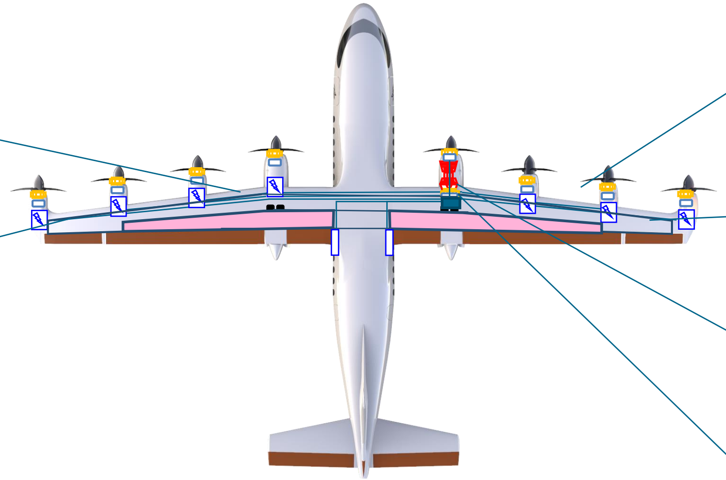
Propeller Modelling: SAFRAN

Wing Structure: Łukasiewicz Institute of Aviation

Cable Modelling: ONERA THE FRENCH AEROSPACE LAB

Cooling System Model: DLR

Failure Probability Analysis: University of Strathclyde Glasgow



Electric Machines and inverters: University of Nottingham UK | CHINA | MALAYSIA

Battery Design: AIT AUSTRIAN INSTITUTE OF TECHNOLOGY

Generator design: UNIVERSITÉ DE LORRAINE

Gas turbine design: DLR

Propulsion system model
industry oversight: SAFRAN, Avio Aero A GE Aviation Business, MTU Aero Engines

Lessons Learned – Summary

Do not underestimate the definition of the propulsion system architecture and integration.

- ➢ An interdisciplinary-consistent solution is difficult to achieve.
- ➢ Many different areas of expertise are required.

There is still much to be explored with regard to electric aircraft flight.

When assessing a radically new concept aircraft:

- ➢ Plan a longer concept definition / refinement / downselection phase.
- ➢ After the concept is chosen, define the following aspects as soon as possible:
  - Detailed propulsion architecture
  - Propulsion components integration
  - Operational constraints (refuelling / recharging / power management)
  - Detailed component failure analysis

OR

Prepare for many aircraft model iterations.

Thank you for your attention!