Conceptual design of passenger aircraft for in-flight refueling operations

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Introduction

• One of the biggest challenges for future aviation is represented by the increasing **cost and scarcity of fossil fuel**.

• The demand of air transportation is steadily increasing, while the constraints on the allowed environmental impact by authorities are getting more stringent.

• New designs and operational concepts are required to meet the ambitious challenges devised by ACARE.
In the RECREATE (REsearch on a CRuiser EEnabled Air Transport Environment) project, European research institutes, universities and small businesses work together to investigate a future air transportation system based on the cruiser-feeder concept.

In Flight Refueling (IFR) operations for passenger aircraft is actually one of the two main concepts addressed by RECREATE.
Payload range efficiency versus range

- The success of staged and IFR flight revolves on the assumption that, flying a mission divided in multiple smaller submissions, yields fuel savings.

- Fuel efficiency between aircraft is compared by the **Payload Range Efficiency**:
  \[ PRE[m] = \frac{WP[kg] \cdot R[m]}{WFB[kg]} \]

\[ X[m] = \frac{V[m/s] \cdot L/D[-]}{SFC[1/s]} \]
Objectives of this work

Although IFR is a time proven concept in military operations, is it possible and convenient to apply as such to passenger air transportation?

Main goal of this research*

*Develop the conceptual design of a passenger aircraft (the cruiser) for IFR operations and compare its fuel consumption to direct and staged flight operation.*

*sub-goal of RECREATE*
Operation concepts and mission profiles

Direct flight

1 Start & Taxi
2 Take-off
3 Climb
4 Descent
5 Landing

Staged flight

IFR operation

1 2 3 4 5

2500nm cruise

2500nm cruise

2500nm cruise

2500nm cruise

Rendezvous with tanker
Change between flight phases

1 2 3 4 5

1 2 3 4 5

1 2 3 4 5
Cruiser Top level requirements

- Use a conventional configuration
- Single stage **range of 2500nm**
- **250 passengers**, single class, twin aisle, LD-3 container capability
- Take-off field length < 2000 m
- Landing field length < 2600 m
- Cruise mach number of 0.82 @ 10500 m
- Specific fuel consumption of 0.525 lb/(lbf·h)
Cruiser-tanker IFR configurations

Is this good if there are passengers here?

A trade-off is performed to assess possible alternatives and finally to select the most convenient procedure for civil refueling operations.
### Cruiser-tanker IFR configurations

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Configuration</th>
<th>Grades (1-9)</th>
<th>Weight</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>c1 Pilot's visibility of approaching aircraft</td>
<td>9</td>
<td>5</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>c2 Component detachment hazard</td>
<td>1</td>
<td>3</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>c3 Ride quality of cruiser</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>c4 Noise to the cruiser</td>
<td>1</td>
<td>2</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>c5 Pump requirement</td>
<td>9</td>
<td>8</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>c6 Fuel pipe fire hazard</td>
<td>5</td>
<td>9</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>c7 Boom related weight</td>
<td>9</td>
<td>8</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>c8 Boom stability</td>
<td>9</td>
<td>9</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>c9 Maturity of boom technology</td>
<td>9</td>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>c10 Formation aerodynamics</td>
<td>6</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>c11 Training cost of approaching aircraft</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>c12 All weather refueling capability</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

**TOTAL** 100 520 536 584 628
Cruiser-tanker IFR configurations

The trade off winning configuration:

The tanker approaches the cruiser from behind and below
Cruiser-tanker IFR configurations

**Advantages**
- No hazard of collision with parts detaching from the tanker
- Cruiser pilots are not required to perform the approach maneuver
- Cruiser’s architecture minimally affected by the presence of the refueling system.
- Only tanker aircraft to be provided with air-to-air radar
- Passengers not subjected to maneuvering acceleration
- No extra thrust requirement for passenger aircraft during refueling

**Disadvantages**
- A forward extending boom (i.e., unstable, subject to divergence) is required.
The Initiator

A software tool under development at the TU Delft for augmented aircraft conceptual design.

It makes use of statistics and semi-empirical design rules, medium fidelity analysis tools, and an optimizer to perform conceptual design of conventional and novel aircraft configurations.
The Initiator

VLM code

Parametric aircraft model

Geometry Model Generator

Weight & CoG analysis

Aerodynamic analysis

Engine & Range analysis

Evaluation

- 3D aircraft model
- Weight
- Center of Gravity
- Lift
- Drag
- Neutral point
- Cruise range
- Controllability
- Stability
- Takeoff
- Landing

KBE fuselage configurator

Challenge the future
Cruiser design

(a) Front view

(b) Side view

(a) Top view

(b) Isometric view
## Cruiser design

<table>
<thead>
<tr>
<th><strong>Fuselage</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>54.0</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>5.64</td>
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</table>

<table>
<thead>
<tr>
<th><strong>Wing</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref Area (m²)</td>
<td>178.2</td>
</tr>
<tr>
<td>Span (m)</td>
<td>42.21</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>10</td>
</tr>
<tr>
<td>Taper Ratio</td>
<td>0.23</td>
</tr>
<tr>
<td>1/4 Chord Sweep (degree)</td>
<td>27.27</td>
</tr>
</tbody>
</table>
Payload range diagram

**Performance**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L/D</td>
<td>17.9</td>
</tr>
<tr>
<td>X</td>
<td>16116 [nm]</td>
</tr>
<tr>
<td>Max. wing loading (kg/m²)</td>
<td>648</td>
</tr>
<tr>
<td>Thrust/Weight Ratio</td>
<td>0.32</td>
</tr>
<tr>
<td>PRE values (nm) @ pts.</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>3341</td>
</tr>
<tr>
<td>B</td>
<td>2992</td>
</tr>
<tr>
<td>D</td>
<td>3166</td>
</tr>
</tbody>
</table>

**Weights and Weight Ratios**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MTOW (kg)</td>
<td>115396</td>
</tr>
<tr>
<td>OEW (kg)</td>
<td>62774</td>
</tr>
<tr>
<td>WFB (kg) @ pts.</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>16252</td>
</tr>
<tr>
<td>B</td>
<td>23578</td>
</tr>
<tr>
<td>D</td>
<td>20928</td>
</tr>
<tr>
<td>WP (kg) @ pts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>31176</td>
</tr>
<tr>
<td></td>
<td>23850</td>
</tr>
<tr>
<td></td>
<td>26500</td>
</tr>
<tr>
<td>WFR = 4.5 % of MTOW (kg)</td>
<td>5192.8</td>
</tr>
<tr>
<td>Max. fuel/MTOW (Point B)</td>
<td>0.25</td>
</tr>
<tr>
<td>Max. landing/MTOW</td>
<td>0.83</td>
</tr>
</tbody>
</table>
Payload range efficiency (PRE)
Non-stop versus IFR operations

AER

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>WFB$_1$ [kg]</th>
<th>WFB$_2$ [kg]</th>
<th>WFB$_T$ [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruiser</td>
<td>18955</td>
<td>18182</td>
<td>37137</td>
</tr>
<tr>
<td>5000nm non-stop</td>
<td>-</td>
<td>-</td>
<td>46652</td>
</tr>
</tbody>
</table>

5000nm, IFR vs. Non-stop

- Fuel received by tanker [kg]: 16259
- Fuel saved by cruiser w.r.t non-stop (tanker fuel not accounted!) [kg]: 9515
- Fuel$_{saved}$/Fuel$_{received}$: 0.58

**IF** the fuel burnt by tanker to deliver the fuel required by cruiser (16259 Kg) < 9515 Kg, **THEN** IFR operation yields fuel saving!
**Staged-flight versus IFR operations**

- In term of flight duration (comfort) and fatigue life, IFR is obviously better than staged-flight
- IFR with small tankers can be more fuel efficient than staged-flight operations

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>WFB₁ [kg]</th>
<th>WFB₂ [kg]</th>
<th>WFB₇ [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-flight refueling</td>
<td>18955</td>
<td>18182</td>
<td>37137</td>
</tr>
<tr>
<td>Staged flight</td>
<td>20928</td>
<td>20928</td>
<td>41856</td>
</tr>
</tbody>
</table>

**5000nm, IFR vs. Non-stop**

- received fuel for AAR operation [kg] 16259
- saved fuel by AAR operation [kg] 4719
- Fuel_saved/Fuel_received 0.29
2 families of tankers designed for 10 specific missions (radius & no ref. ops.)

Tanker coding:

T-250-3: Conventional tanker
Design refueling radius: 250nm
Refueling num. of cruisers: 3

TF-500-5: Flying-wing tanker
Design refueling radius: 500nm
Refueling num. of cruisers: 5

Challenge the future
Tankers family

Aircraft to scale for size comparison
**IFR benefit – Flying Wing VS Conventional tankers**

![Graph showing benefits of IFR (Instrument Flight Rules) with Flying Wing versus Conventional tankers.](image)

- **IFR benefit comparison**:
  - Benefit margin (AAR vs. single route)
  - Benefit margin (AAR vs. Intermediate stop)

- **Graph Details**:
  - OEW/MTOW vs. Design Refueling Times
  - Fuel Consumed / Fuel Delivered vs. Design Refueling Times

- **Legend**:
  - Conventional 250nm
  - Conventional 500nm
  - Flying-wing 250nm
  - Flying-wing 500nm
The RECREATE design agenda

In Flight refueling

Conventional approach

Cruiser tanker boom

Simulation

Innovative approach (cruiser ahead and above of tanker)

Cruiser tanker boom

Simulation ???

Passengers and freight exchange by in flight docking

See next presentation:
*Feasibility study of a nuclear propelled blended wing body aircraft for the cruiser/feeder concept*
The research leading to the results presented in this paper was carried within the project RECREATE (REsearch on a CRuiser Enabled Air Transport Environment) and has received funding from the European Union Seventh Framework Programme under grant agreement no. 284741.