Identifying the Requirements and Design Variables for New Aircraft Considering Fleet-Level Objectives Under Uncertainties

By
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4th Annual SERC Doctoral Students Forum
November 16, 2016
20 F Street NW Conference Center
20 F Street, NW
Washington, DC

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• Research Questions:
  — Can we identify a quantitative approach to determine the “right requirements” for a new system?
  — Can we concurrently optimize multiple systems?
  — Can this approach address multi-domain uncertainties?

• Goals & Objectives:
  Develop decision support framework that:
  - Assists decision-maker or acquisition practitioner to identify new system requirements that improve (maximize) system-level objective
  - Allows new system to operate along with the existing system
  - Optimizes new system with respect to the system level objective (in this presentation, airline profit)
  - Addresses uncertainties arising from various factors and uncertainty propagation
Introduction and Motivation

- Aircraft designed for a particular design range and payload

- In reality, aircraft flies to different operating routes together with other existing aircraft of the airline

- Leads to a sub-optimal aircraft design with respect to the fleet-level objective

Aircraft that the airlines would like to buy is the one that is optimized with respect to its fleet level objective

Source: airliner.net

Source: http://adg.stanford.edu/
• Further, most complex systems design using deterministic models either chooses to ignore uncertainty or uses *a priori* margins or safety factors to address uncertainty

- Uncertainty arises from different domains
- Interacts with sub-systems
- Need to capture this uncertainty propagation within the system
• Aircraft Design Discipline:
  — Typically, design commercial aircraft for minimum fuel burn or operating cost
  — Reduction in fuel burn started to plateau in the last decade
  — NASA’s Subsonic Fixed Wing (SFW) project investigating novel aircraft configurations

• Airline Allocation Discipline:
  — One of the first application of linear programming – Airline allocation
  — Led to the foundation of fleet assignment problem (FAP)
  — Forms the back-bone of today’s state-of-the-art tools used by airlines


Source: NASA
Literature Review: MDO Motivated Decomposition

- Among the fewer works that combine the two disciplines – MDO motivated decomposition approach within the context of System of systems\(^1,\,^2,\,^3,\,^4\) – Starting step

- Approach decomposes the large MINLP into three subspaces
  - Top level space: A small Mixed Discrete Non-Linear Programming (MDNLP)
  - Aircraft design subspace: A Non-Linear Programming (NLP)
  - Airline allocation sub-space: A Mixed Integer Linear Programming (MILP)

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Optimization-based Approach: Uses Sequential Decomposition Strategy

• **Objective**
  — Maximize fleet level expected profit

• **Variables**
  — New aircraft requirements (design range, seat capacity)
  — New aircraft design variables (NLP: Nonlinear Programming)
    o Aspect ratio, taper ratio, wing sweep, engine thrust etc.
  — Allocation variables (MIP: Mixed integer programming)
    o Trips, passengers carried on a particular route

• **Constraints**
  — Passenger demand
  — Aircraft performance (takeoff distance, landing distance etc.)
  — Fleet operations (maximum operational hours, number of each aircraft types etc.)
Approach: Handling Uncertainty*

- Reliability-based design optimization (RBDO) formulation to handle uncertainty in new system design
- Descriptive sampling approach to handle uncertainty in passenger demand
- Propagation of uncertainty from aircraft sizing subspace
  - Performance of new aircraft is uncertain
  - Coefficients in allocation problem have distributions
- Used a ‘Robust Optimization’ approach
  - Interval Robust Counterpart (IRC) formulation: Optimize considering the nominal and worst-case values of uncertain parameters within a pre-defined tolerance limit

*Work by Parithi Govindaraju, Graduate Student, School of Aeronautics and Astronautics, Purdue University
Case-Study

- A notional 31-route network airline with hub at Memphis
- Airline has 7 different aircraft types currently in its fleet (blue bars)
- User-determined 5 new aircraft to be acquired (red bar)

Design variables at top level problem for enumeration

<table>
<thead>
<tr>
<th>Seat Capacity</th>
<th>Design Range [nmi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>2600</td>
</tr>
<tr>
<td>150</td>
<td>1900</td>
</tr>
<tr>
<td>250</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>500</td>
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</tbody>
</table>

Aircraft Types

Number of Aircraft

Route Network with Memphis Hub

Seat Capacity and Design Range Chart
• Uncertain parameters characterized via scaling factors with triangular distributions

• Aircraft performance predictions follow distributions

\[ C_{D_0} = k_{C_D} \times (C_{D_0}^{predicted}) \]

<table>
<thead>
<tr>
<th>Uncertain Parameters (ξ)</th>
<th>Lower Bound</th>
<th>Default</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{D_0} ) Multiplier [non-dim]</td>
<td>0.95</td>
<td>1</td>
<td>1.05</td>
</tr>
<tr>
<td>Oswald Efficiency Factor [non-dim]</td>
<td>0.95</td>
<td>1</td>
<td>1.05</td>
</tr>
<tr>
<td>Thrust Specific Fuel Consumption Multiplier [non-dim]</td>
<td>0.95</td>
<td>1</td>
<td>1.05</td>
</tr>
<tr>
<td>Passenger Weight [lbs]</td>
<td>90</td>
<td>165</td>
<td>220</td>
</tr>
</tbody>
</table>

*Work by Parithi Govindaraju, Graduate Student, School of Aeronautics and Astronautics, Purdue University*
• Uses BTS data to sample passenger demand for the Monte-Carlo simulation

• From this, treat future daily passenger demand as uncertain

• Perform quarterly allocation to capture seasonal variation in passenger demand
Design variables at top level problem for enumeration

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- Green bar denotes baseline fleet with no new aircraft type-X in use
- 75 seats has higher expected profit
- 75 seats with 1200nmi design range leads to highest fleet expected profit
Result: Design-Allocation subspace

Optimal Design Variables

<table>
<thead>
<tr>
<th>Top Level (aircraft requirements)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Range [nautical miles]</td>
<td>1200</td>
</tr>
<tr>
<td>Seat Capacity</td>
<td>75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aircraft Design Subspace</th>
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</tr>
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<tbody>
<tr>
<td>Aspect ratio</td>
<td>12.0</td>
</tr>
<tr>
<td>Taper ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Thickness to chord ratio</td>
<td>0.095</td>
</tr>
<tr>
<td>Wing area [sq. ft]</td>
<td>664.76</td>
</tr>
<tr>
<td>Wing sweep (LE) [deg]</td>
<td>13.22</td>
</tr>
<tr>
<td>Thrust per engine [lbs]</td>
<td>9351</td>
</tr>
</tbody>
</table>

- Result resembles a Embraer 175 type aircraft*
- Optimized with respect to this airline network

- Acquisition practitioner seeks customized aircraft tailored towards their operational behavior
- Aircraft manufacturer wants to sell aircraft to multiple customers – Changing to a multi-objective approach at the top level would facilitate this

*Limited by the fidelity of the sizing tool used in this study
• Decision support framework to assist decision-maker or acquisition practitioner to identify the “right requirements” for the new system

• Addressed multi-domain uncertainty and uncertainty propagation

• Approach identified new system requirements that improved (maximized) fleet-level objective
• Alternate approach to address multi-domain problems as Mixed-Integer Non-Linear Programming (MINLP) problem
  — Requires a new MINLP solving approach to address complex tightly coupled systems
  — **AMIEGO (A Mixed Integer Efficient Global Optimization)** - A MINLP solver to address Aircraft design and Airline allocation as MINLP problem (under development)

• Solving all the sub-spaces as MINLP problem
  — Would enable to integrate other complex systems
  — For example, an integrated Revenue Management System will enable to decide the ticket prices under uncertain demand (under development)
Acknowledgments

• Work has been partially supported by
  — Acquisition Research Program, Naval Post Graduate School through the grant number N00244-15-1-0063
  — NASA through grant number NNX14AC73A as a part of the LEARN project: “Scalable Multi-fidelity Design Optimization: Next Generation Aircraft and their Impact on the Air Transportation System”

Thanks to

• Dr. William A. Crossley, Professor (Advisor)
• Dr. Navin Davendralingam, Research Scientist
• Parithi Govindaraju, Graduate Student

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