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

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Preview

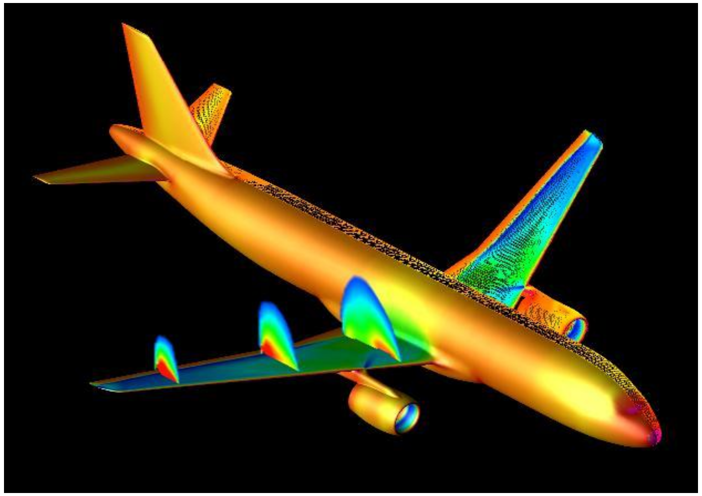
- Research Questions:
  - Can we identify a quantitative approach to determine the “right requirements” for a new system?
  - Can we concurrently optimize multiple systems?
  - Can this approach address multi-domain uncertainties?
- Goals & Objectives:

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



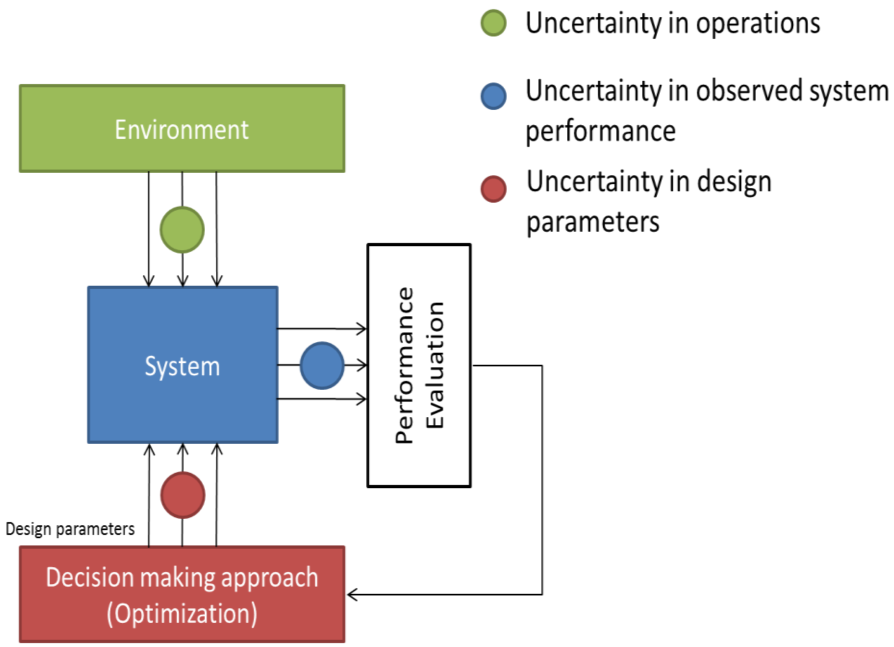
Source: http://adg.stanford.edu/

Source: airliner.net

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

Introduction and Motivation

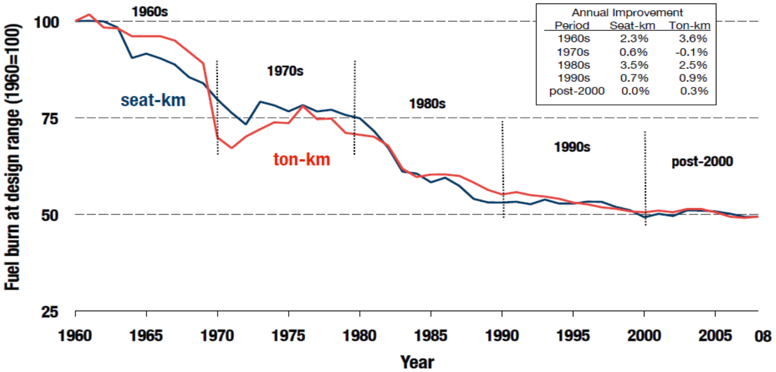
- Further, most complex systems design using deterministic models either chooses to ignore uncertainty or uses *a priori* margins or safety factors to address uncertainty



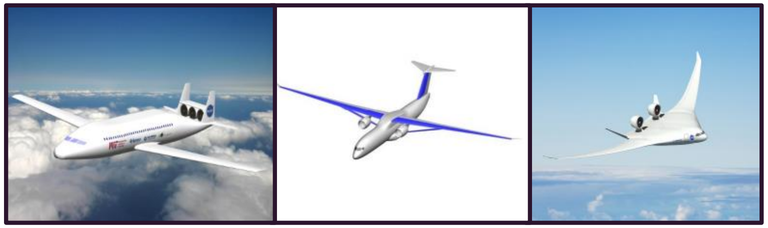
- Uncertainty arises from different domains
- Interacts with sub-systems
- Need to capture this uncertainty propagation within the system

Literature Review

- 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[1]
- Airline Allocation Discipline:
  - One of the first application of linear programming – Airline allocation[2]
  - Led to the foundation of fleet assignment problem (FAP)
  - Forms the back-bone of today's state-of-the-art tools used by airlines[3, 4]



Source: D Rutherford and M Zeinali. Efficiency trends for new commercial jet aircraft 1960 to 2008. Technical report, The International Council on Clean Transportation, 2009



Source: NASA

- Independently, aircraft design and airline allocation are well researched
- Considering any one discipline alone - Not sufficient
- Need to combine both disciplines

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[1] Christopher E. Hughes. An overview of the NASA fundamental aeronautics program subsonic fixed wing project and ultra high bypass partnership research goals. Technical report, NASA, 2013

[2] A. R. Ferguson and G. B. Dantzig. The allocation of aircraft to routes-An example of linear programming under uncertain demand. Management science, 3(1):45–73, 1956

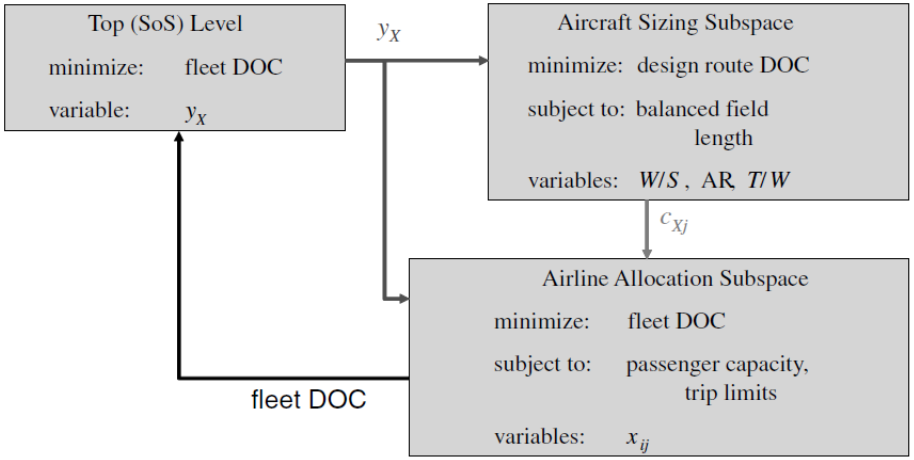
[3] R. Subramanian, R. P. Scheff, J. D. Quillinan, D. S. Wiper, and R. E. Marsten. Coldstart: Fleet assignment at Delta Air Lines

[4] S. Kontogiorgis and S. Acharya. Us Airways automates its weekend fleet assignment

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)



Top (SoS) Level
minimize: fleet DOC
variable: y_X

Aircraft Sizing Subspace
minimize: design route DOC
subject to: balanced field length
variables: W/S, AR, T/W

Airline Allocation Subspace
minimize: fleet DOC
subject to: passenger capacity, trip limits
variables: x_{ij}

Source: Ref. [1]

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[1] Muharrem Mane, William A Crossley, and Antonius Nusawardhana. System-of Systems inspired aircraft sizing and airline resource allocation via decomposition. Journal of Aircraft, 44(4):1222–1235, July 2007

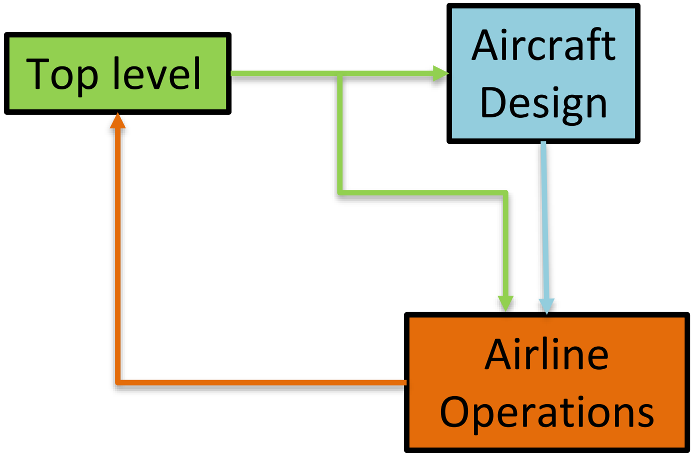
[2] Daniel A. DeLaurentis, William A. Crossley, and Muharrem Mane. Taxonomy to guide systems-of-systems decision-making in air transportation problems. Journal of Aircraft, 48(3):760–770, May 2011

[3] Muharram Mane and William A Crossley. Allocation and design of aircraft for on-demand air transportation with uncertain operations. Journal of aircraft, 49(1):141–150, 2012

[4] Nusawardhana. Dynamic Programming Methods for Concurrent Design and Dynamic Allocation of Vehicles Embedded in a System-of-systems. Purdue University, West Lafayette, IN, 2007

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)
    - ○ Aspect ratio, taper ratio, wing sweep, engine thrust etc.
  - — Allocation variables (MIP: Mixed integer programming)
    - ○ 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.)



Sequential Decomposition Approach

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

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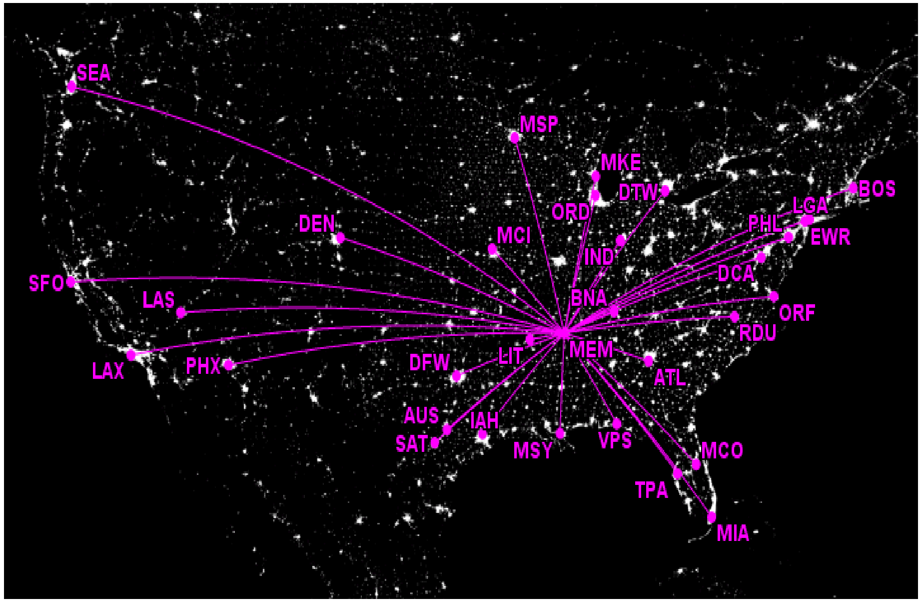
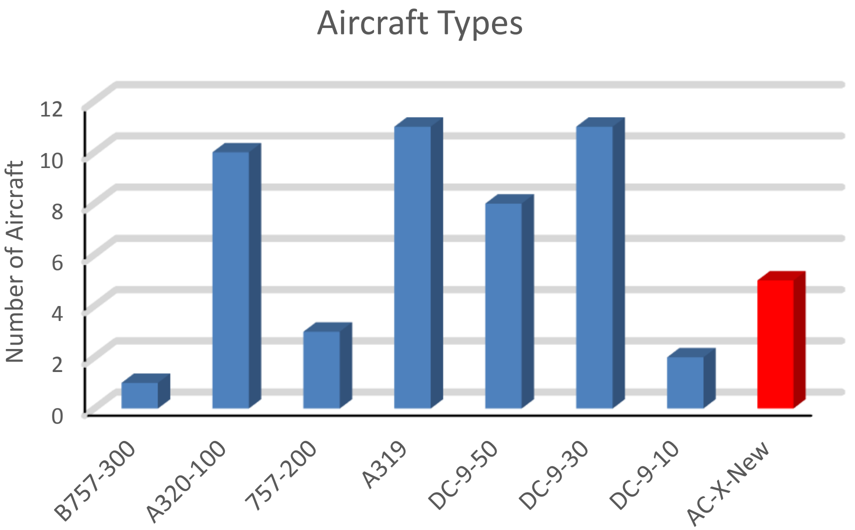
*Work by Parithi Govindaraju, Graduate Student, School of Aeronautics and Astronautics, Purdue University

Case-Study

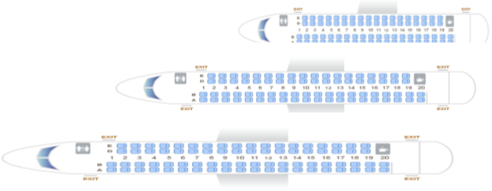
- A notional 31-route network airline with hub at Memphis



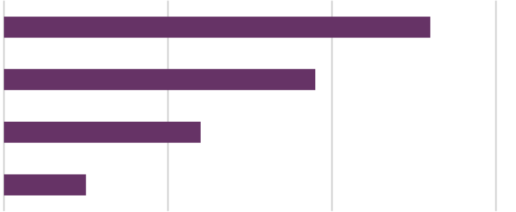
- Airline has 7 different aircraft types currently in its fleet (blue bars)
- User-determined 5 new aircraft to be acquired (red bar)



Design variables at top level problem for enumeration



Seat Capacity	Design Range [nmi]
75	2600
150	1900
250	1200
	500

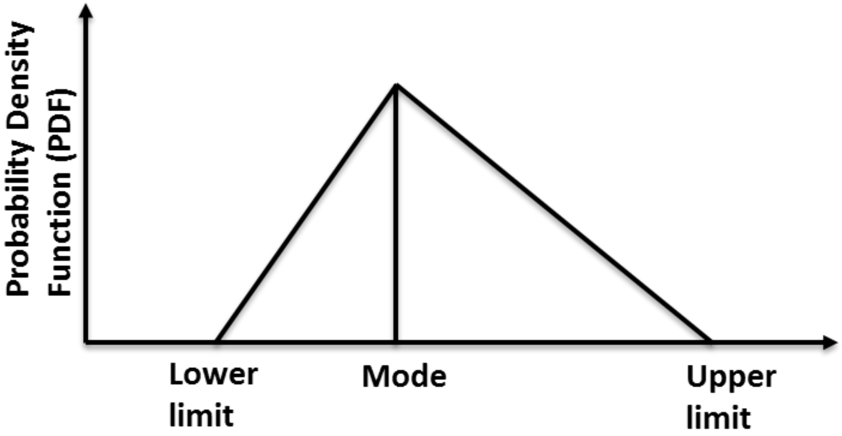


Aircraft Design (Sizing) Uncertainty*

- Uncertain parameters characterized via scaling factors with triangular distributions

- Aircraft performance predictions follow distributions

$$C_{D_0} = k_{C_D} \times (C_{D_0 \ predicted})$$



Uncertain Parameters (ξ)	Lower Bound	Default	Upper Bound
C_{D0} Multiplier [non-dim]	0.95	1	1.05
Oswald Efficiency Factor [non-dim]	0.95	1	1.05
Thrust Specific Fuel Consumption Multiplier [non-dim]	0.95	1	1.05
Passenger Weight [lbs]	90	165	220

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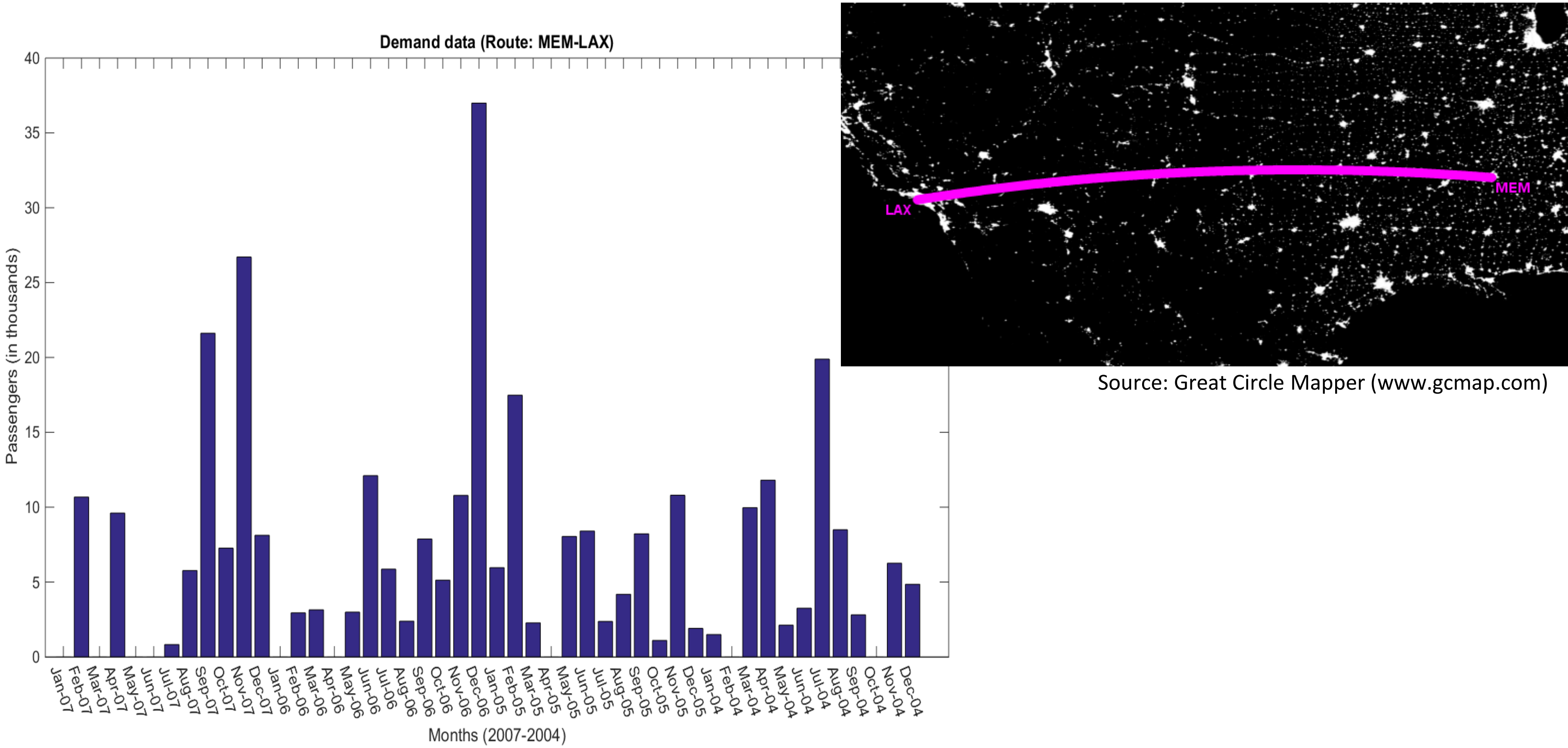
*Work by Parithi Govindaraju, Graduate Student, School of Aeronautics and Astronautics, Purdue University

Operational Uncertainty in Passenger Demands

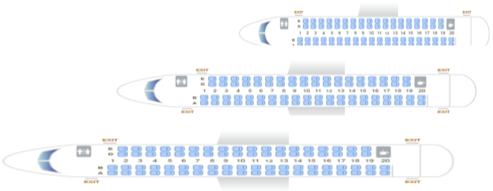


Source: Great Circle Mapper (www.gcmap.com)

- 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

Preliminary Expected Fleet Profit Results

Design variables at top level problem for enumeration



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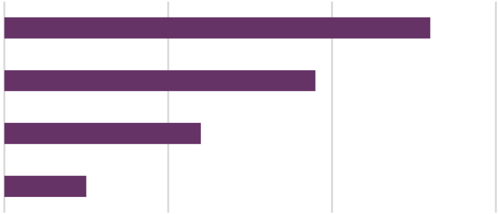
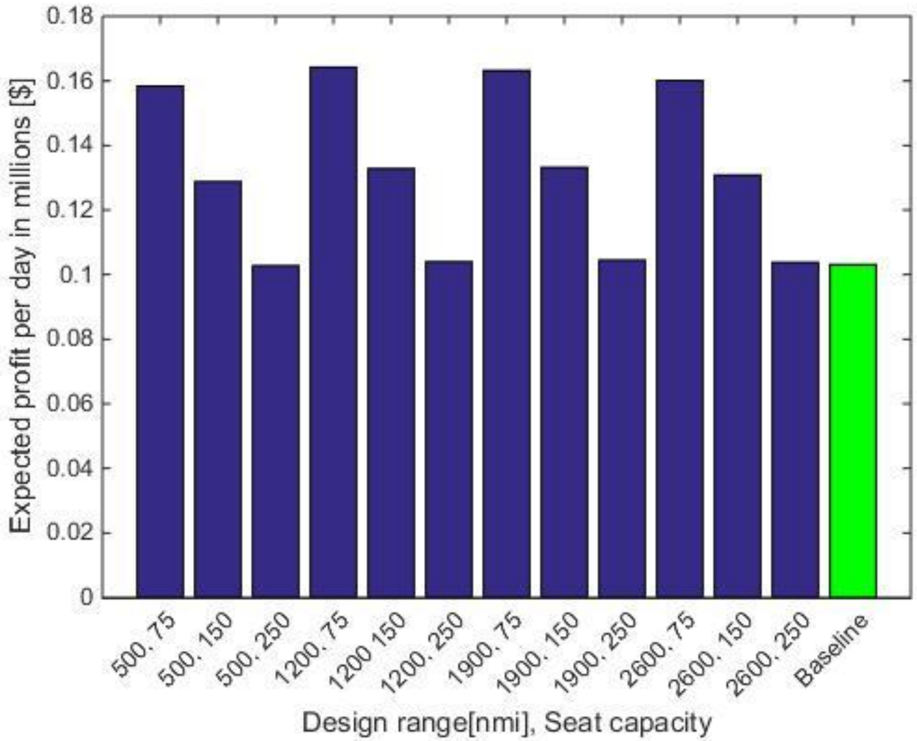




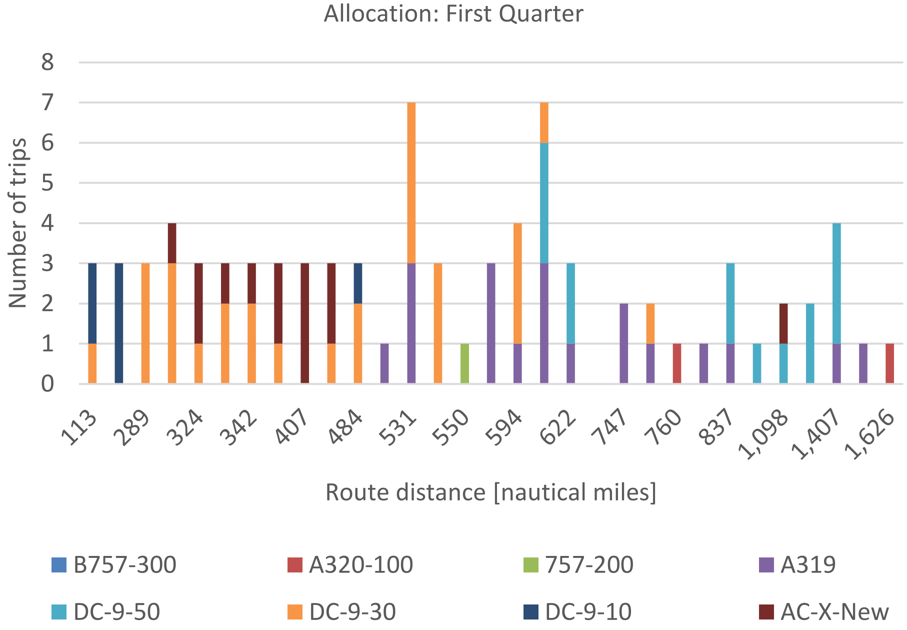
- Green bar denotes baseline fleet with no new aircraft type-X in use
- 75 seats has higher expected profit
- 75 seats with 1200nmi design range leads to highest fleet expected profit

Result: Design-Allocation subspace

Optimal Design Variables

Top Level (aircraft requirements)	
Design Range [nautical miles]	1200
Seat Capacity	75
Aircraft Design Subspace	
Aspect ratio	12.0
Taper ratio	0.3
Thickness to chord ratio	0.095
Wing area [sq. ft]	664.76
Wing sweep (LE) [deg]	13.22
Thrust per engine [lbs]	9351

Source: Delta Cargo



- 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

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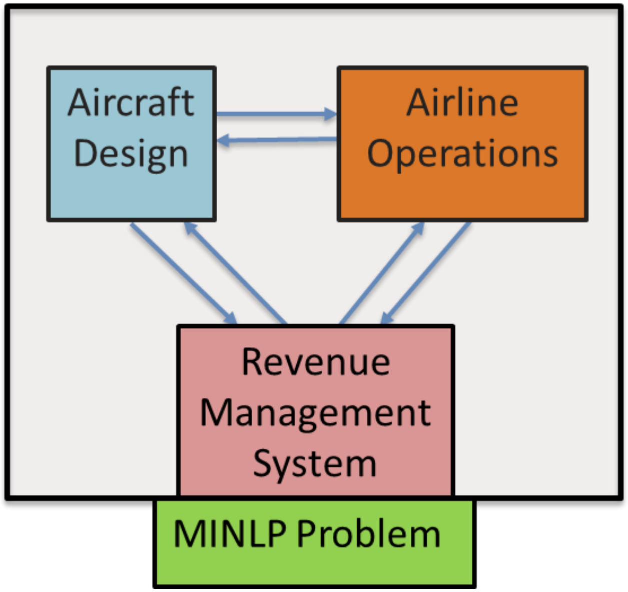
*Limited by the fidelity of the sizing tool used in this study

Conclusion

- 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

Future Research

- 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** **M**ixed **I**nteger **E**fficient **G**lobal **O**ptimization) - 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

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