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Multi-Objective Optimization Of Fleet-Level Metrics To Determine New System Design Requirements: An Application To Military Air Cargo Fuel Efficiency

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Multi-Objective Optimization Of Fleet-Level Metrics To Determine New System Design Requirements: An Application To Military Air Cargo Fuel Efficiency

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Overview

- Assist decision maker/acquisition practitioner with a decision support framework
  - Determine requirements for – and suggest design of – a new system that will optimize fleet-level objectives
- Motivated by a lack of processes to capture effects of fuel-saving measures on fleet-level performance metrics
- Address combined platform design (here, aircraft) and fleet operations problem
  - Fleet-level objectives are functions of new platform requirements
- Used the approach to generate tradeoffs between fleet productivity and cost
  - Use simple network extracted from Air Mobility Command operations
  - Representation of demand constraint
  - New aircraft design requirements change across range of best tradeoff solutions

MOTIVATION

Motivation

- Current requirements or acquisition processes do not accurately explore tradeoff opportunities for fleet-level fuel (cost) and performance*.
- Lack of a framework that captures the effect that fuel-saving measures can have on fleet-level performance metrics*.
- Fleet-level energy efficiency poses significant risks and operational constraints on military operational flexibility**
- Determining design requirements of 'yet-to-be-designed' systems is difficult
  - Tightly coupled nature of the system design problem with the resource assignment problem
  - Non-deterministic nature of AMC operations
    - Demand is highly asymmetric
    - Demand fluctuation on a day to day basis
    - Routes flown vary based on demand

***Energy Efficiency starts with the acquisition process*

http://www.acq.osd.mil/asda/docs/fact_sheets/energy_efficiency_starts_with_the_acquisition_process.pdf

***Saving fuel secures the future – one gallon at a time. Inside AMC*

http://www.amc.af.mil/news/story.asp?id=123292555

Air Mobility Command

- Air Mobility Command (AMC) - One of the major command centers of the U.S. Air Force
- AMC is the largest consumer of aviation fuel in the Department of Defense
  - AMC Operations
    - Uncertainty in cargo demand
    - Limited aircraft types
- AMC's mission profile includes
  - Worldwide cargo and passenger transport
  - Air refueling
  - Aeromedical evacuations

**Our work only addresses cargo transport*

B747-f chartered from Civil Reserve Air Fleet

Source: *www.amc.af.mil*

How can our approach help?

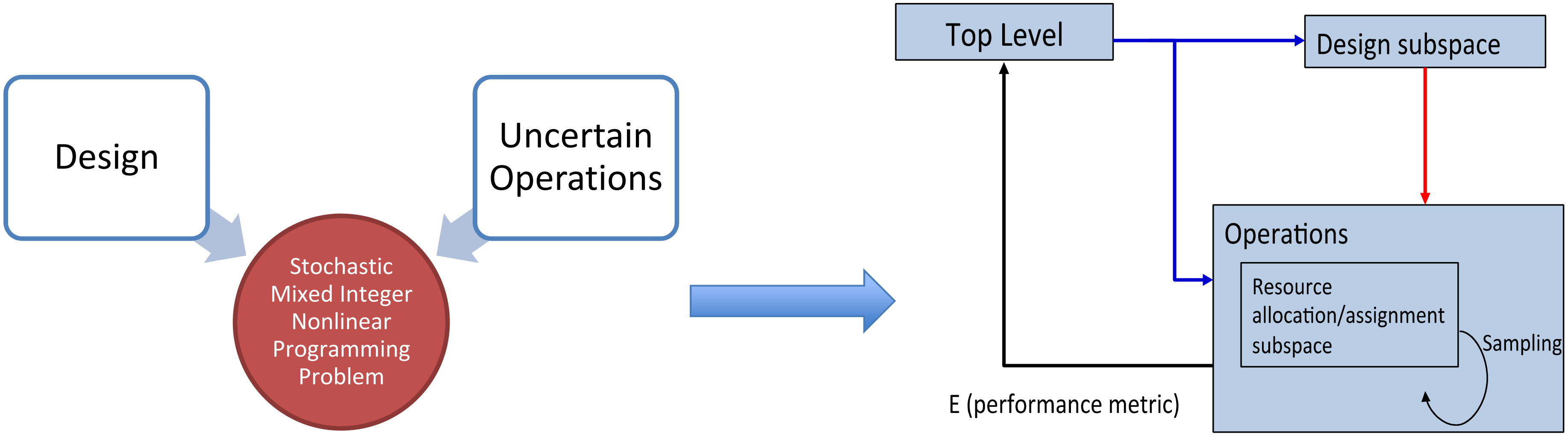
- Our methodology
  - Helps determine the requirements for – and describe the design of – a new aircraft for use in the AMC fleet
  - Optimize fleet-level metrics that address performance and fuel use
- Describe how design requirements of the new aircraft would change for different tradeoff opportunities between productivity and cost

SCOPE AND METHOD OF APPROACH

Scope and Method of Approach

- Consider this as an optimization problem
  - Objectives
    - Fleet Productivity (speed of payload delivery)
    - Fleet Operating cost (strongly driven by fuel use)
  - Variables
    - New aircraft requirements
    - New aircraft design variables
    - Assignment variables
  - Constraints
    - Cargo demand
    - Aircraft performance

Scope and Method of Approach



Design

Uncertain Operations

Stochastic Mixed Integer Nonlinear Programming Problem

Top Level

Design subspace

Operations

Resource allocation/assignment subspace

Sampling

E (performance metric)

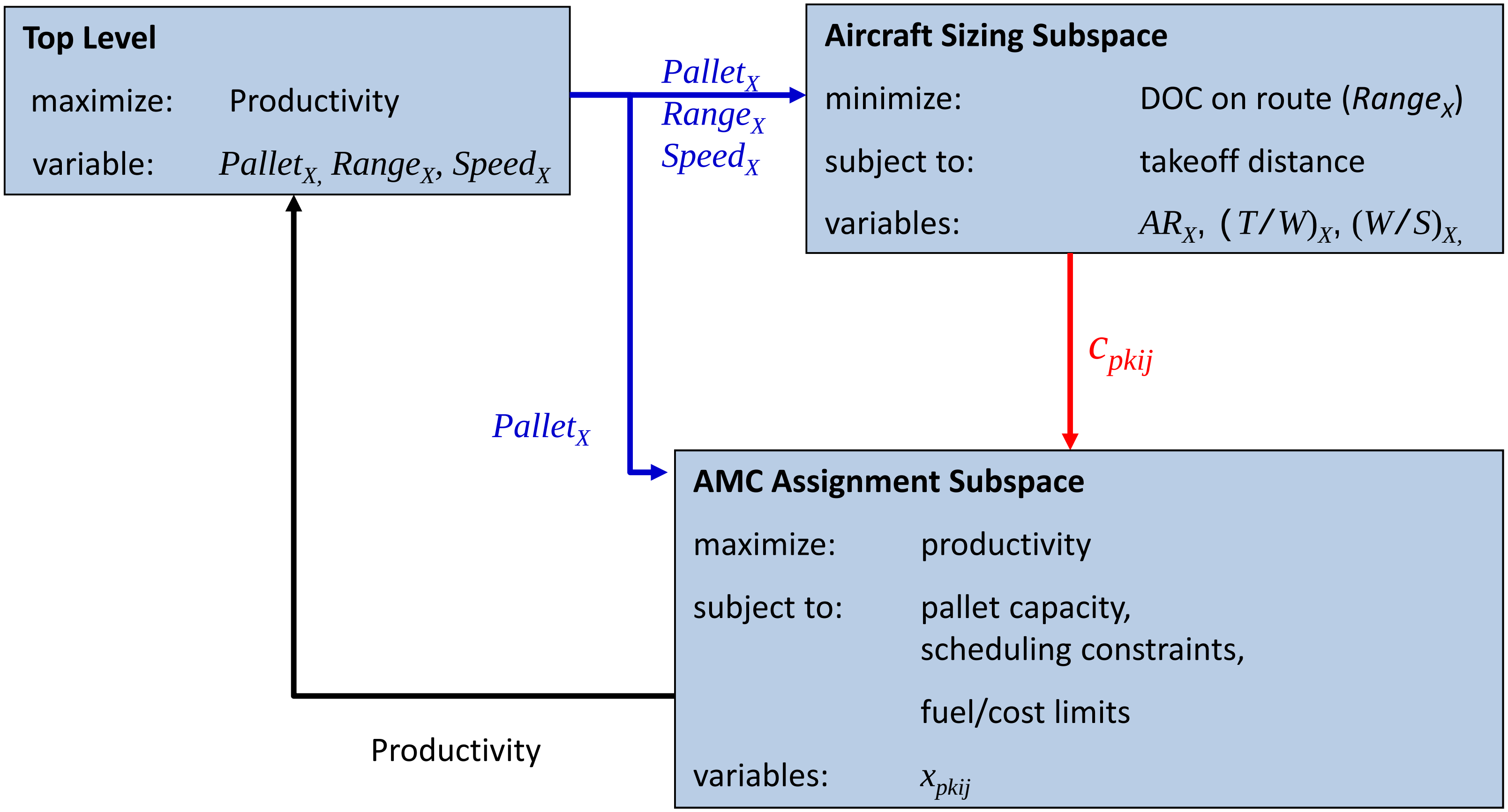
Monolithic Formulation

Subspace Decomposition

Scope and Method of Approach

- Subspace Decomposition approach
  - – Breaks down the computational complexity
  - – Solve a series of smaller sub-problems
    - Controlled by a top level optimization problem
- Addresses the issue of tractability of solving a monolithic, stochastic mixed integer nonlinear programming (MINLP) problem

Subspace Decomposition Approach



Top Level

maximize: Productivity

variable: $Pallet_X, Range_X, Speed_X$

$Pallet_X$
$Range_X$
$Speed_X$

Aircraft Sizing Subspace

minimize: DOC on route ($Range_X$)

subject to: takeoff distance

variables: $AR_X,\ (T/W)_X,\ (W/S)_X,$

c_{pkij}

$Pallet_X$

AMC Assignment Subspace

maximize: productivity

subject to: pallet capacity,
scheduling constraints,

fuel/cost limits

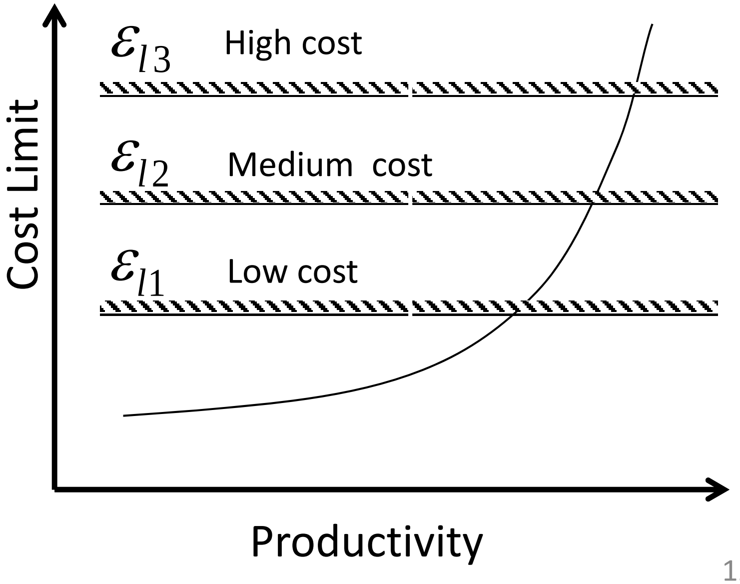
variables: x_{pkij}

Productivity

Multi-Objective Formulation

- Two objectives
  - Maximize fleet-level productivity
  - Minimize fleet-level cost
- Epsilon (Gaming) constraint formulation
  - Converts multi-objective to single objective
  - Identify a primary objective
  - Place limits on other objectives (inequality constraints)

$$
\begin{array}{lll}
\textit{Maximize} & \mathrm{f}_p(x) & \\
\textit{Subject to} & \mathrm{f}_l(x) \le \varepsilon_l & l = 1 \ldots n_{obj} (l \neq p) \\
 & \mathrm{g}_j(x) \le 0 & \\
 & \mathrm{h}_k(x) = 0 &
\end{array}
$$



Top Level Subspace

Maximize Productivity

Subject to $14 \le Pallet_X \le 38$

$2400 \le Range_X \le 3800$

$350 \le Speed_X \le 550$

Productivity = Speed x Capacity

Pallet Capacity Bounds

Range at maximum payload bounds (nm)

Cruise speed bounds (knots)

- Pallet capacity, Range and Speed bounds are set by strategic air lift aircraft description
- Bounds for aircraft design variables similar to current military cargo aircraft

Aircraft Sizing Subspace

Minimize	$f = \left(DOC_{pallet,range,speed} \right)_X$	Direct Operating Cost
Subject to	$6.0 \le \left(AR \right)_X \le 9.5$	Wing aspect ratio bounds
	$65 \le \left(W/S \right)_X \le 161$	Wing loading bounds (lb/ft^2)
	$0.18 \le \left(T/W \right)_X \le 0.35$	Thrust-to-weight ratio bounds
	$S_{TO}\left(Pallet_X, \left(AR \right)_X, \left(W/S \right)_X, \left(T/W \right)_X \right) \le D$	Aircraft takeoff distance

- Bounds for aircraft design variables similar to current military cargo aircraft

Fleet Assignment Subspace

Maximize

$$E\left[\sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{p,k,i,j}\cdot\left(Speed_{p,k,i,j}\cdot Pallet_{p,k,i,j}\right)\right]$$

Productivity = Speed x Capacity

Subject to

$$\sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{p,k,i,j}\cdot C_{p,k,i,j} \le M$$

Fleet-level DOC or fuel limits

$$\sum_{i=1}^{N} x_{p,k,i,j} \ge \sum_{i=1}^{N} x_{p,k+1,i,j} \quad \forall k = 1,2,3\ldots K, \quad \forall p = 1,2,3\ldots P, \quad \forall j = 1,2,3\ldots N$$

Node balance constraints

$$\sum_{p=1}^{P}\sum_{k=1}^{K} Cap_{p,k,i,j}\cdot x_{p,k,i,j} \ge dem_{i,j} \quad \forall i = 1,2,3\ldots N, \forall j = 1,2,3\ldots N$$

Demand constraints

$$\sum_{i=1}^{N} x_{p,1,i,j} \ge O_{p,i} \quad \forall p = 1,2,3\ldots P, \forall i = 1,2,3\ldots N$$

Starting location of aircraft constraints

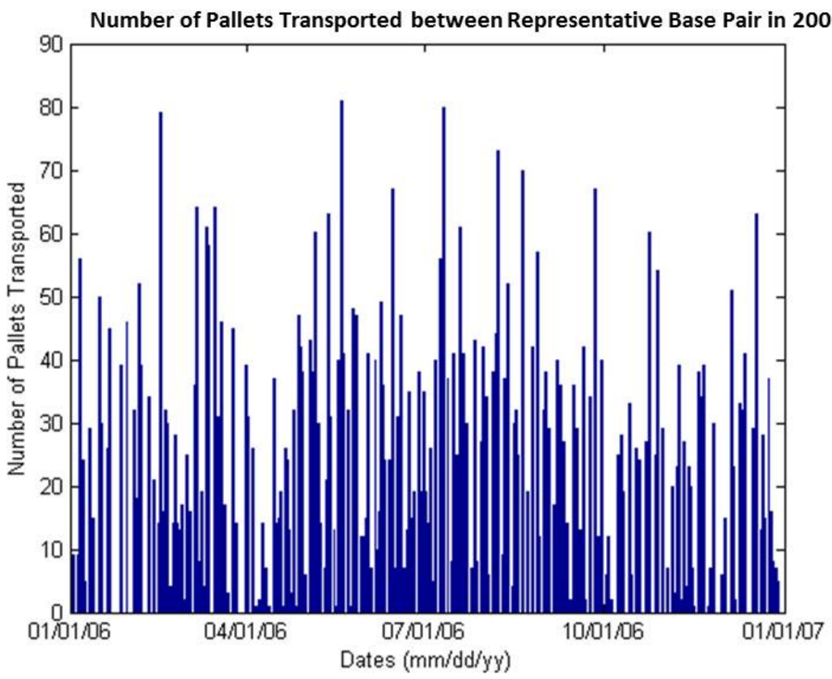
$$\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{p,k,i,j}\cdot BH_{p,k,i,j} \le B_P \quad \forall p = 1,2,3\ldots P$$

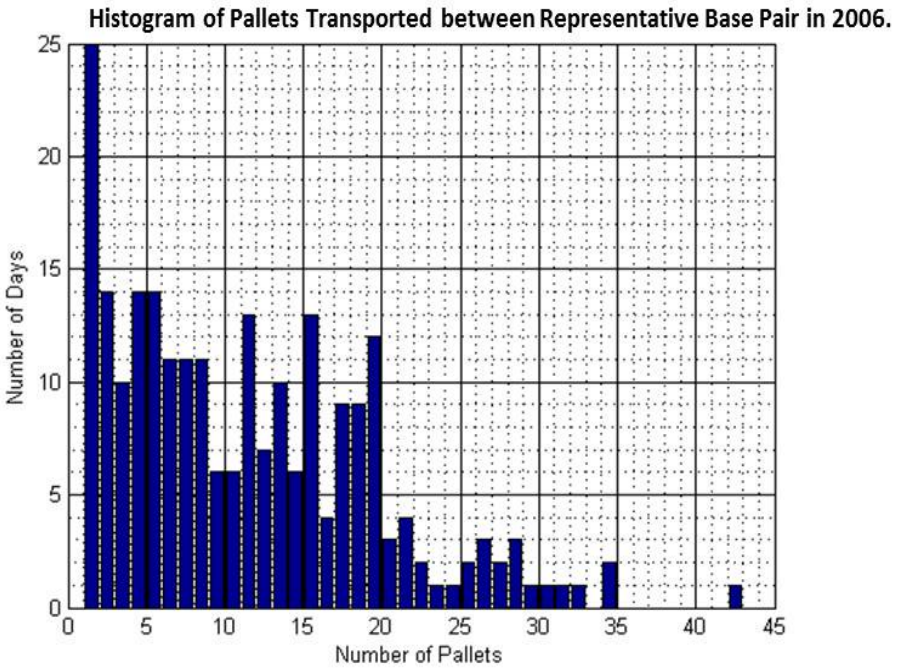
Trip constraints

$$x_{p,k,i,j} \in \{0,1\}$$

Binary Variable

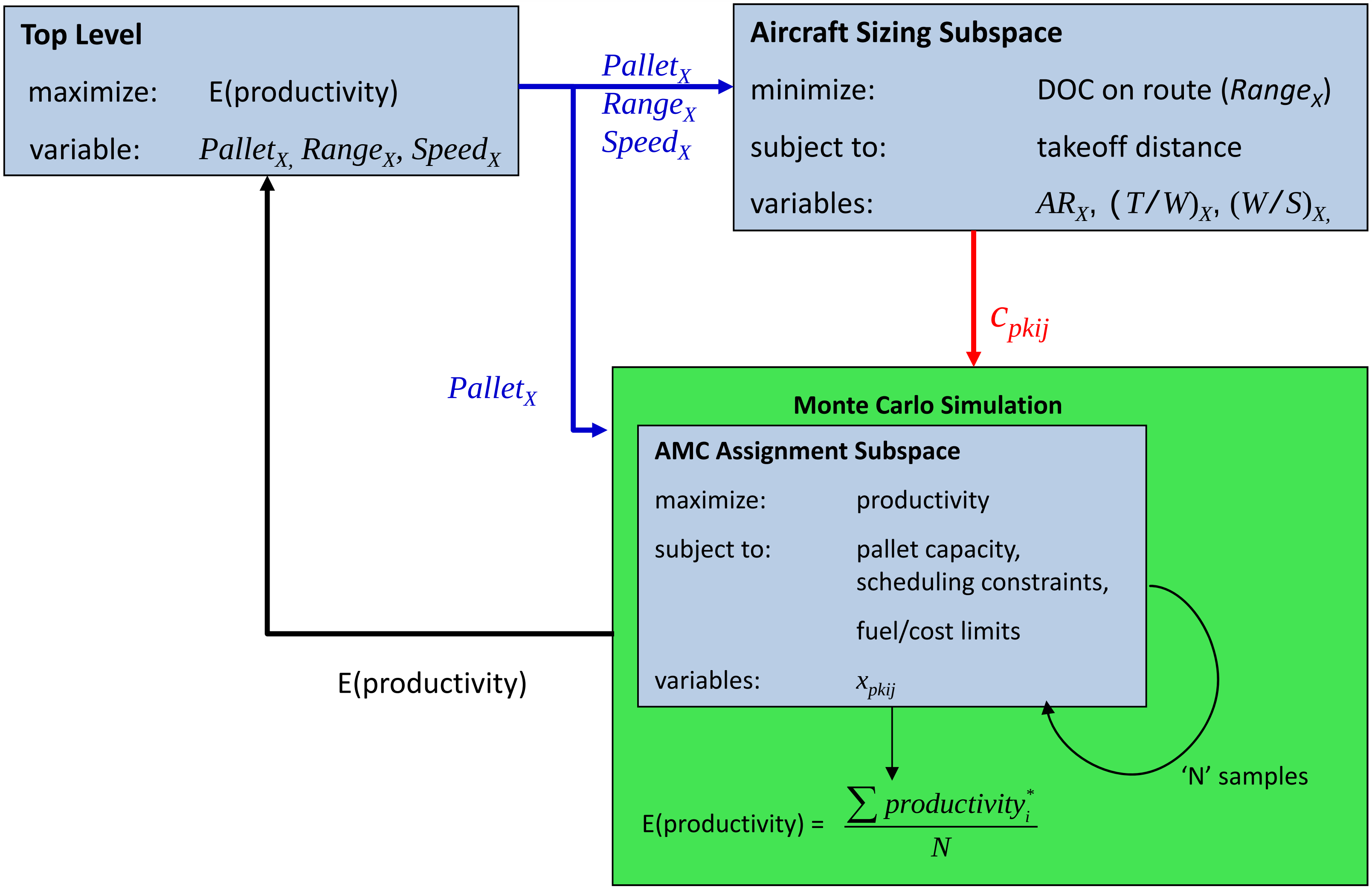
Pallet Cargo Demand


Number of Pallets Transported between Representative Base Pair in 2006.


Histogram of Pallets Transported between Representative Base Pair in 2006.

- High levels of uncertainty in cargo demand
- Addressed using Monte Carlo sampling methods
  - Repeated deterministic calculations for statistical distribution of input parameters

Subspace Decomposition Approach



Top Level

maximize: E(productivity)

variable: $Pallet_{X}, Range_{X}, Speed_{X}$

$Pallet_X$
$Range_X$
$Speed_X$

Aircraft Sizing Subspace

minimize: DOC on route ($Range_X$)

subject to: takeoff distance

variables: $AR_X,\ (T/W)_X,\ (W/S)_{X,}$

C_{pkij}

$Pallet_X$

Monte Carlo Simulation

AMC Assignment Subspace

maximize: productivity

subject to: pallet capacity,
scheduling constraints,
fuel/cost limits

variables: x_{pkij}

'N' samples

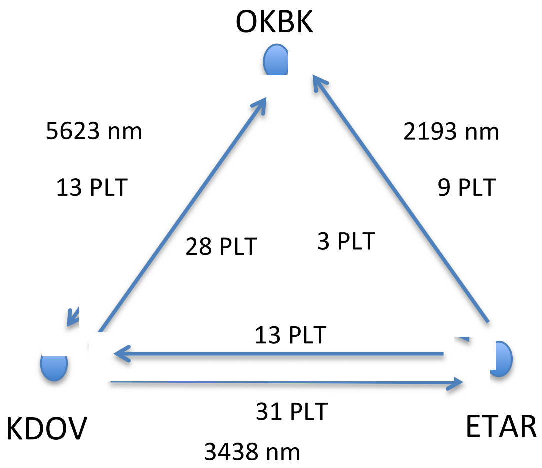
E(productivity)

E(productivity) = $\dfrac{\sum productivity_i^*}{N}$

SCENARIOS & STUDIES

Three-base Problem

- Filtered route network from GATES dataset
  - Demand for subset served by C-5, C-17 and 747-F (~75% of total demand)
- Simple three-base problem consisting of 6 directional routes
  - Extracted from the GATES dataset
  - Most flown routes in March 2006
- Existing fleet for AMC
  - Three C-5: 36 pallet capacity
  - Three C-17: 18 pallet capacity
  - Three B747-F: 29 pallet capacity
- 3 new aircraft X are introduced to the existing baseline fleet


OKBK

5623 nm

13 PLT

2193 nm

9 PLT

28 PLT

3 PLT

13 PLT

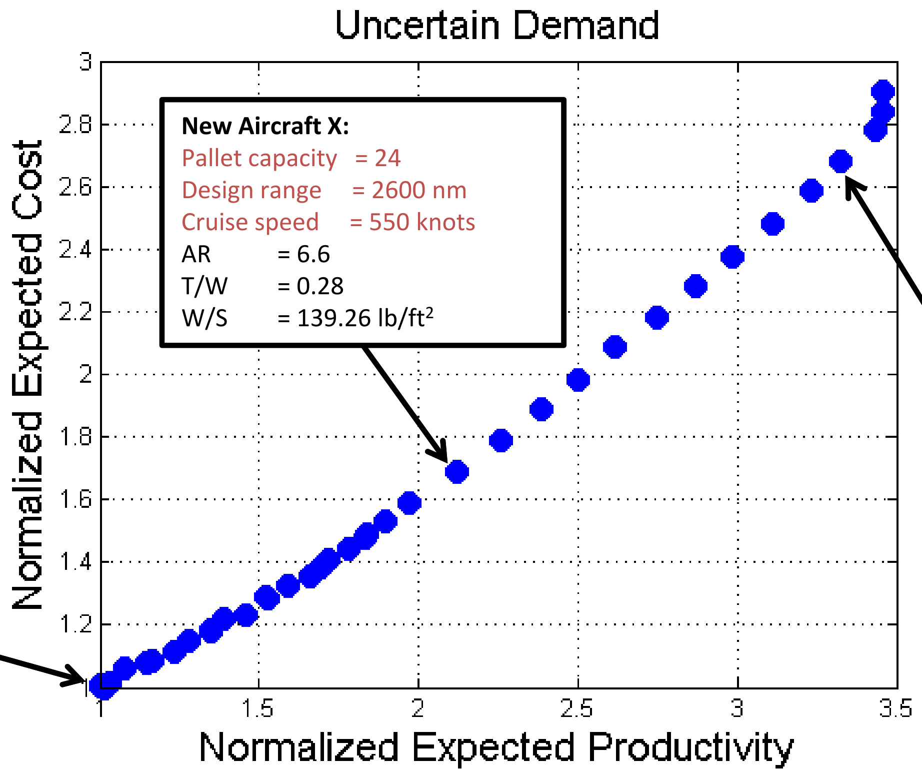
31 PLT

KDOV

ETAR

3438 nm

Results

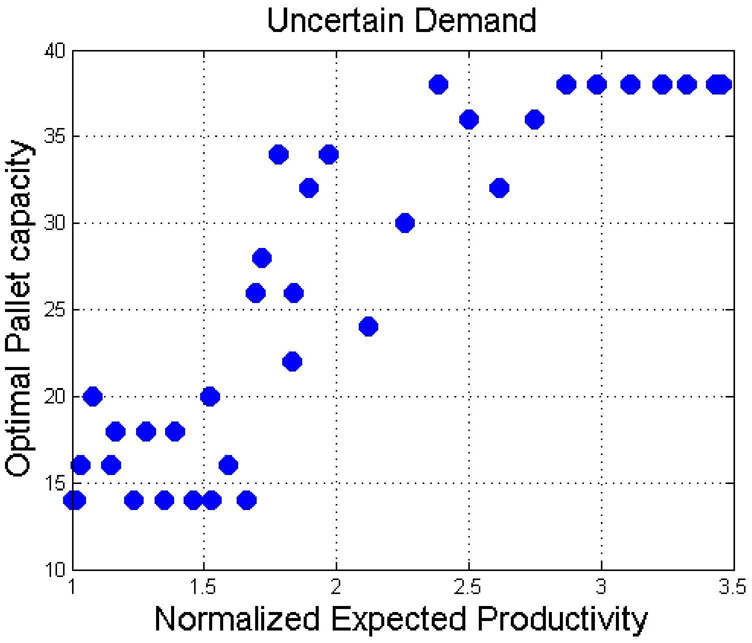


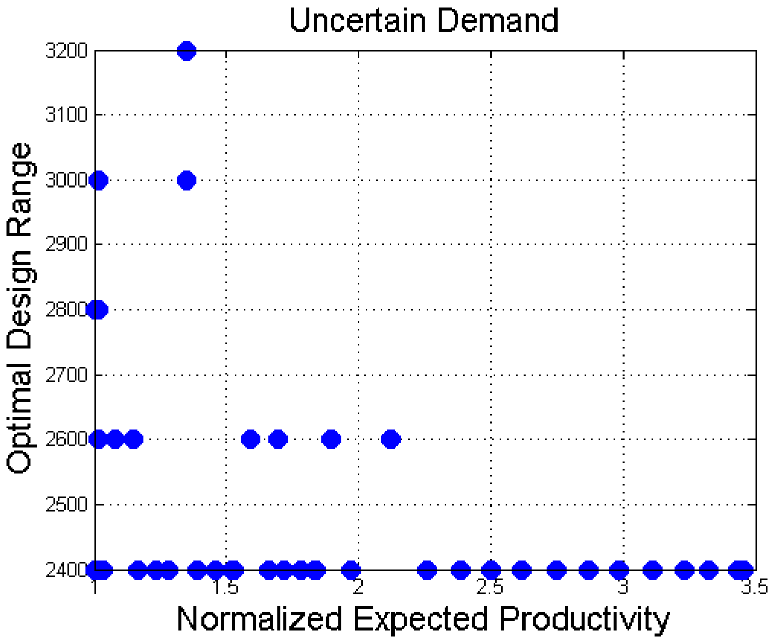
New Aircraft X:
Pallet capacity = 24
Design range = 2600 nm
Cruise speed = 550 knots
AR = 6.6
T/W = 0.28
W/S = 139.26 lb/ft^2

New Aircraft X:
Pallet capacity = 14
Design range = 3000 nm
Cruise speed = 550 knots
AR = 7.04
T/W = 0.3
W/S = 150 lb/ft^2

New Aircraft X:
Pallet capacity = 38
Design range = 2400 nm
Cruise speed = 550 knots
AR = 6.3
T/W = 0.26
W/S = 130.72 lb/ft^2

Results


Uncertain Demand


Uncertain Demand

- Optimum pallet capacity varies based on fleet-level productivity /DOC values
  - Pallet capacity increases with fleet-level productivity
- Optimum design range varies between 2400 nm to 3200 nm
  - Design range increases when sampled demand instances are higher than average

CONCLUSIONS

Summary/Conclusions

- Developed a framework that identifies the tradeoffs between fleet-level cost and productivity
  - Each tradeoff solution describes the design requirements, and design variables for the new aircraft
  - Uncertainty in demand addressed using Monte Carlo sampling techniques
- Demonstrates the viability and applicability of the subspace decomposition framework
  - Assist acquisition practitioners

Future Work

- Demonstrate the decomposition framework for a larger, i.e. realistic network
- Aircraft sizing accounts for outsized/oversized cargo
- Reduce computational cost associated with sampling demand uncertainty
- Generalize to other systems

Questions?

BACKUP SLIDES

Asymmetric Demand

- Prior work assumed symmetric demand*
- Developed metric calculates the asymmetry in demand between bases

$$\text{Demand asymmetry} = \sum_{O=1}^{N}\sum_{D=1}^{N}\frac{\left|Demand_{O,D} - Demand_{D,O}\right|}{\max(Demand_{O,D}, Demand_{D,O})}\times 100$$

- Calculates demand asymmetry between origin-destination pairs
- The AMC network reconstructed from the 2006 GATES dataset shows 65.15% demand asymmetry
- Symmetric demand assumption is not suited for AMC operations

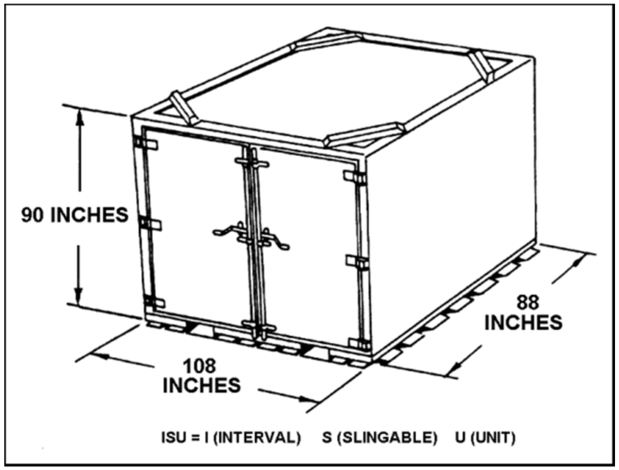
*Choi, J., Govindaraju, P., Davendralingam, N., & Crossley, W. (2013). Platform Design for Fleet-Level Efficiency: Application for Air Mobility Command (AMC). In *10th Annual Acquisition Research Symposium*.

Air Mobility Command

- Used Global Air Transportation Execution System (GATES) dataset

- Filtered route network from GATES dataset
  - Demand for subset served by C-5, C-17 and 747-F (~75% of total demand)
  - Fixed density and dimension of pallet (463 L)

- Our aircraft fleet consists of only the C-5, C-17 and 747-F.



Source: *www.amc.af.mil*