PURDUE AERONAUTICS & ASTRONAUTICS

A FRAMEWORK TO DETERMINE NEW SYSTEM REQUIREMENTS UNDER DESIGN PARAMETER AND DEMAND UNCERTAINTIES

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Overview

- Use an optimization-based approach to identify design requirements of new systems
  - Address issue that new systems operate along with existing systems
  - Seek fleet-level performance and capabilities
- Development of a decision-support framework
  - Determine requirements for – and suggest design of – a new system that will optimize fleet-level objectives to support acquisition
  - Fleet-level objectives are functions of new system requirements
  - Account for design parameter and demand uncertainties
- Used the framework to generate tradeoffs between fleet-level productivity and cost
  - Motivated by energy and fuel consumption, reflected via operating cost
  - Route network extracted from Air Mobility Command (AMC) operations
  - New aircraft design change across range of best tradeoff solutions

INTRODUCTION AND MOTIVATION

Motivation

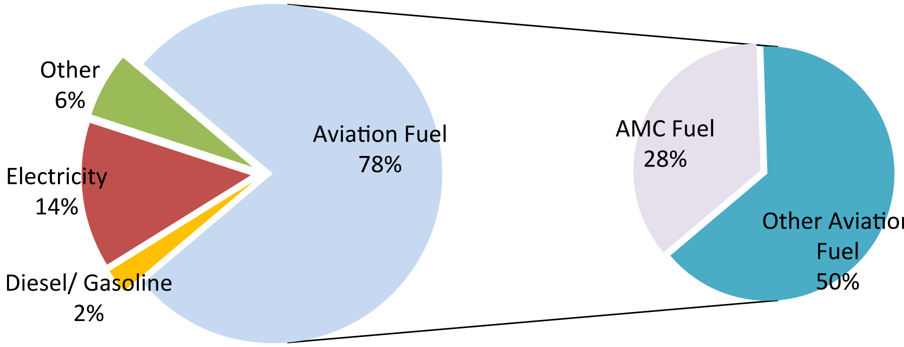
- Fleet-level energy efficiency poses significant risks and operational constraints on military operational flexibility[1]
- Growing emphasis on reducing fuel usage in military systems
  - Streamline operations of existing fleet
  - Acquire efficient platforms and platforms that lead to fleet-level efficiency
- Lack of a framework that captures the effect that fuel-saving measures can have on fleet-level performance metrics[2]
  - Do not accurately explore tradeoff opportunities
- Determining design requirements of ‘yet-to-be-designed’ systems to improve fleet-level metrics is difficult
  - Couples operation decisions with new system design
  - Non-deterministic nature of fleet operations
  - Assumptions in deterministic models leads to sub-optimal performance

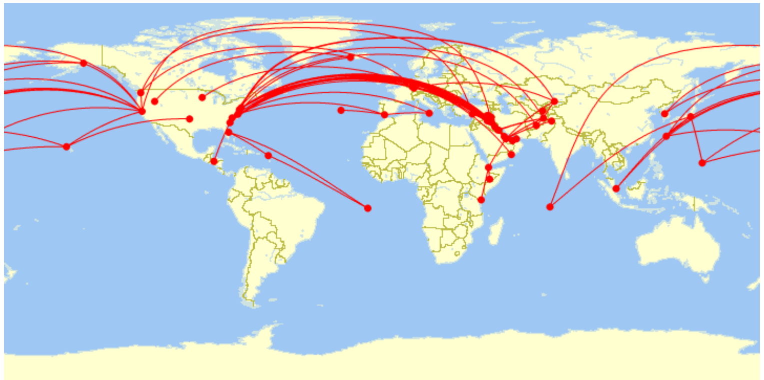
[1] *AMC Vice Commander: Saving fuel secures the future – one gallon at a time. Inside AMC*

[2] *DoD Acquisition and Technology: Energy Efficiency starts with the acquisition process*

Air Mobility Command

- AMC: One of the major command centers of the U.S. Air Force
- AMC is the DoD's single largest aviation fuel consumer (28 % of total aviation fuel use)*.
- Non-deterministic nature of AMC operations
  - Demand is highly asymmetric
  - Demand fluctuation on a day to day basis
  - Routes flown vary based on demand
  - Limited aircraft types: C-5, C-17, C-130, Boeing 747-F, KC-135, etc.
- AMC's mission profile includes
  - Worldwide cargo and passenger transport**
  - Aerial refueling and aeromedical evacuations
- Used Global Air Transportation Execution System (GATES) dataset
  - Large route network (1804 routes)





Sample route network from GATES

**Aviation fuel savings: AMC leading the charge. Air Mobility Command*
***This work only addresses cargo transport*

SCOPE AND METHOD OF APPROACH

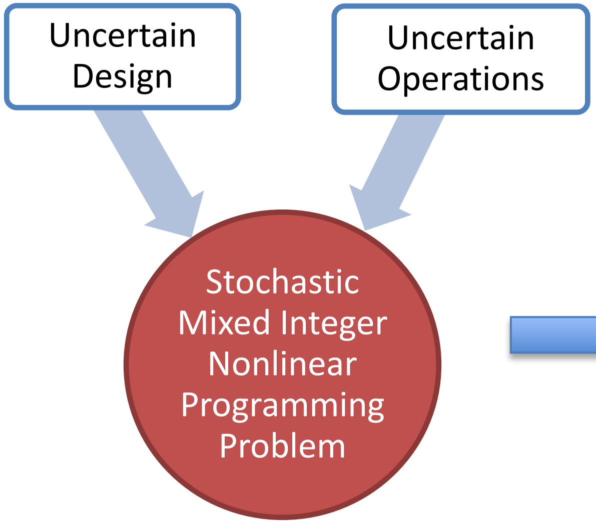
How can our approach help?

- 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

Method of Approach (1)

- Consider this as an optimization problem
  - Objectives
    - Fleet Productivity (speed of payload delivery)
    - Fleet Direct Operating Cost (strongly driven by fuel use)
  - Variables
    - New aircraft requirements (pallet capacity, range, speed)
    - New aircraft design variables (AR, W/S , T/W)
    - Assignment variables (flight on a particular route)
  - Constraints
    - Cargo demand
    - Aircraft performance (takeoff distance)
    - Fleet Operations (maximum operational hours)

Method of Approach (2)

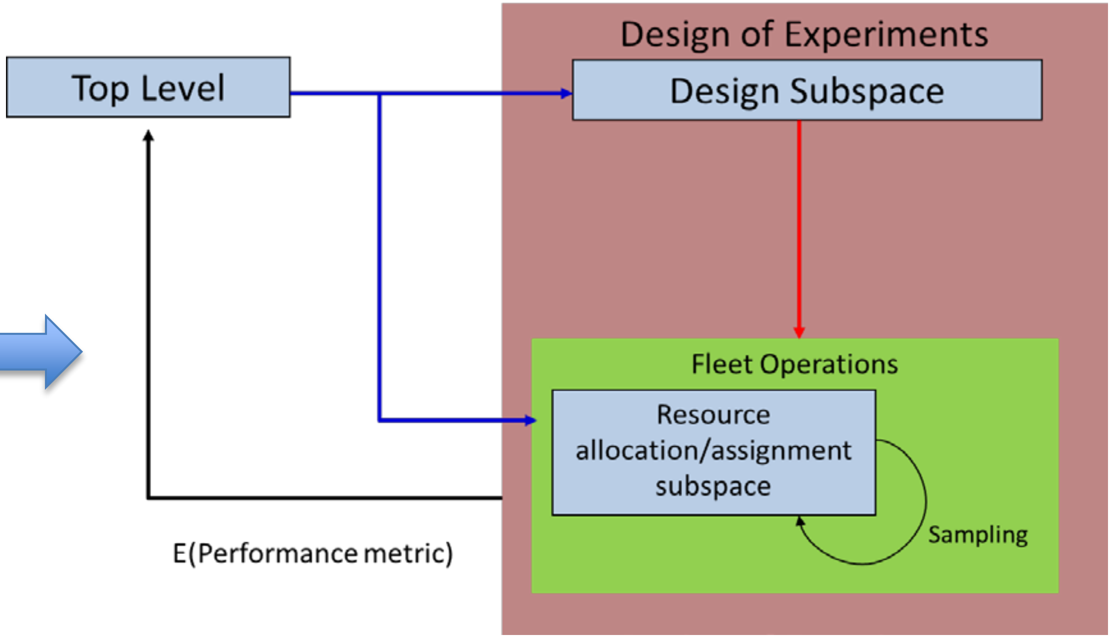


Uncertain Design

Uncertain Operations

Stochastic Mixed Integer Nonlinear Programming Problem

Monolithic Formulation



Top Level

Design of Experiments

Design Subspace

Fleet Operations

Resource allocation/assignment subspace

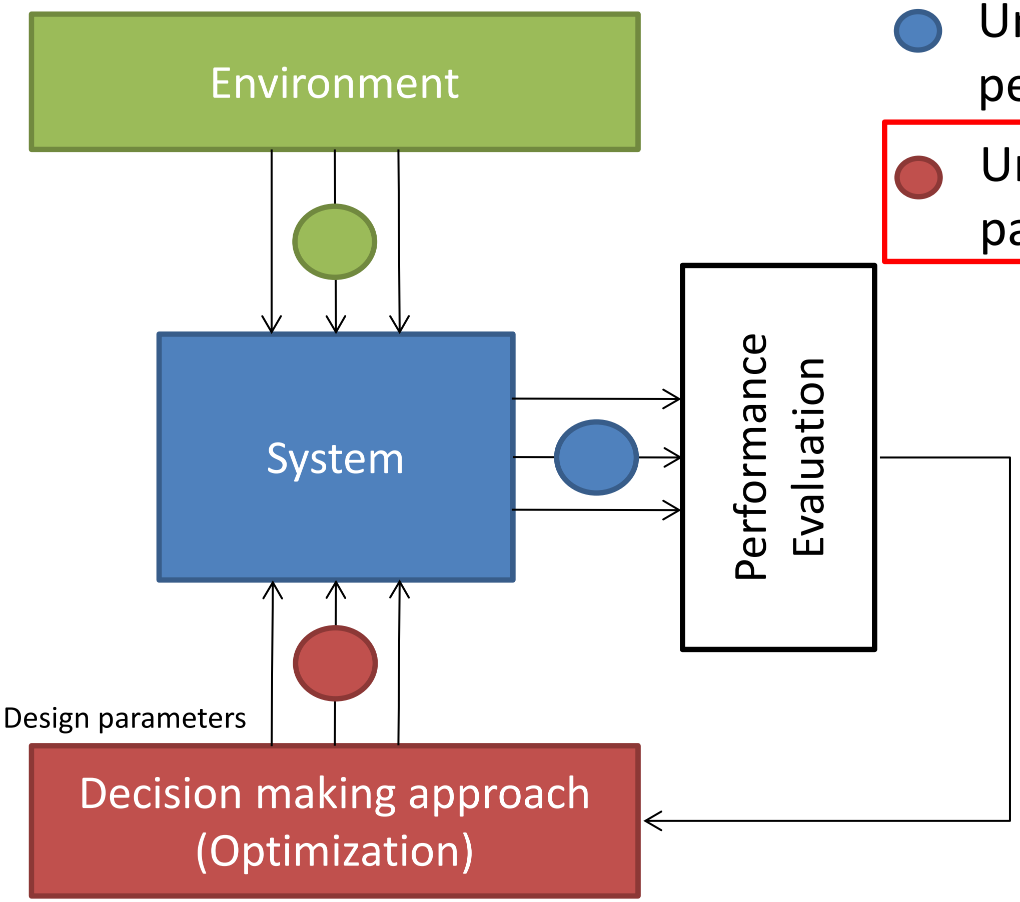
Sampling

E(Performance metric)

Subspace Decomposition

Classes of Uncertainties

- 🟢 Uncertainty in operations
- 🔵 Uncertainty in observed system performance
- 🔴 Uncertainty in design parameters



Environment

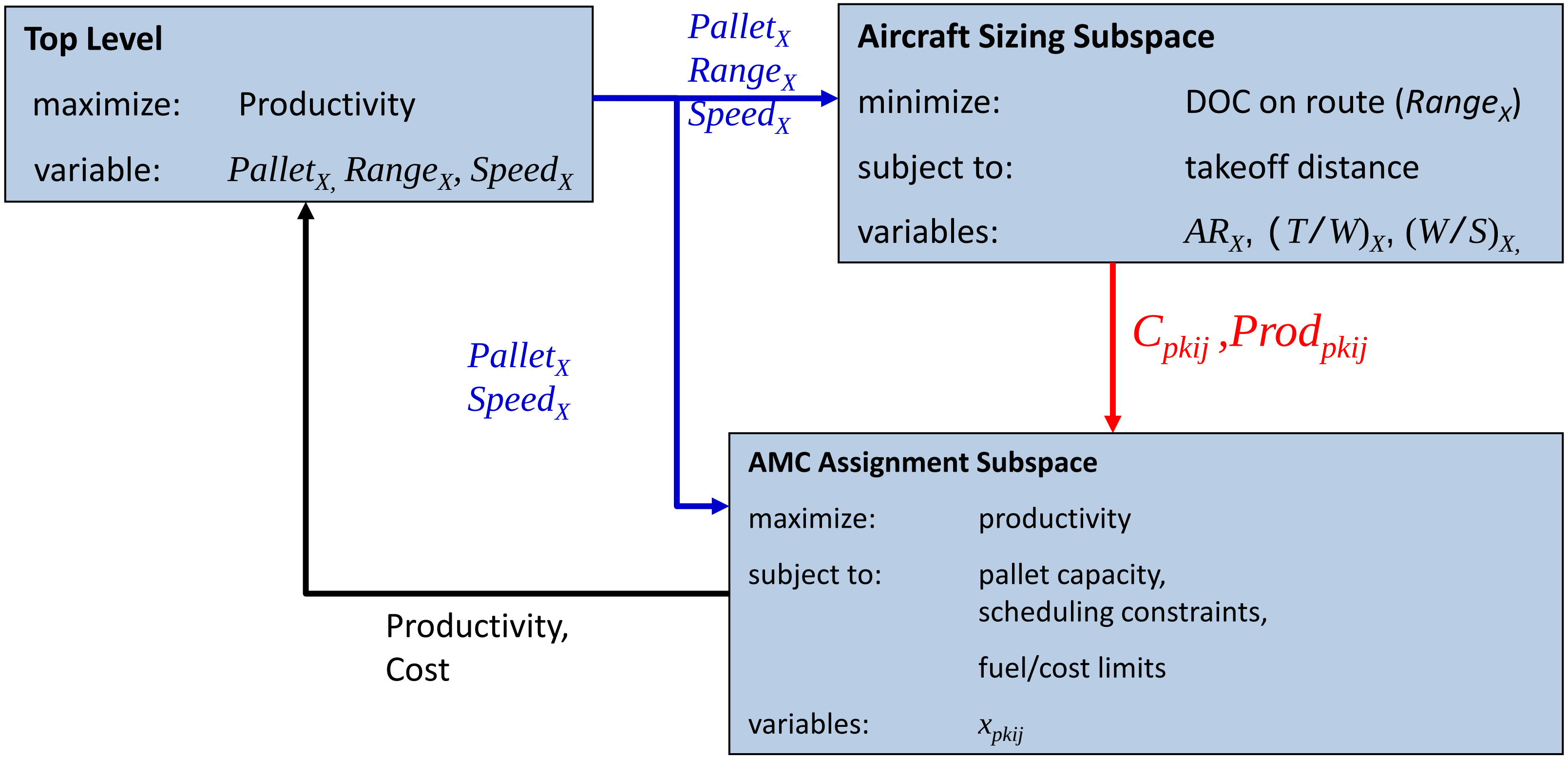
System

Performance Evaluation

Design parameters

Decision making approach (Optimization)

Subspace Decomposition Approach (Deterministic)



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} ,$Prod_{pkij}$

$Pallet_X$
$Speed_X$

AMC Assignment Subspace

maximize: productivity

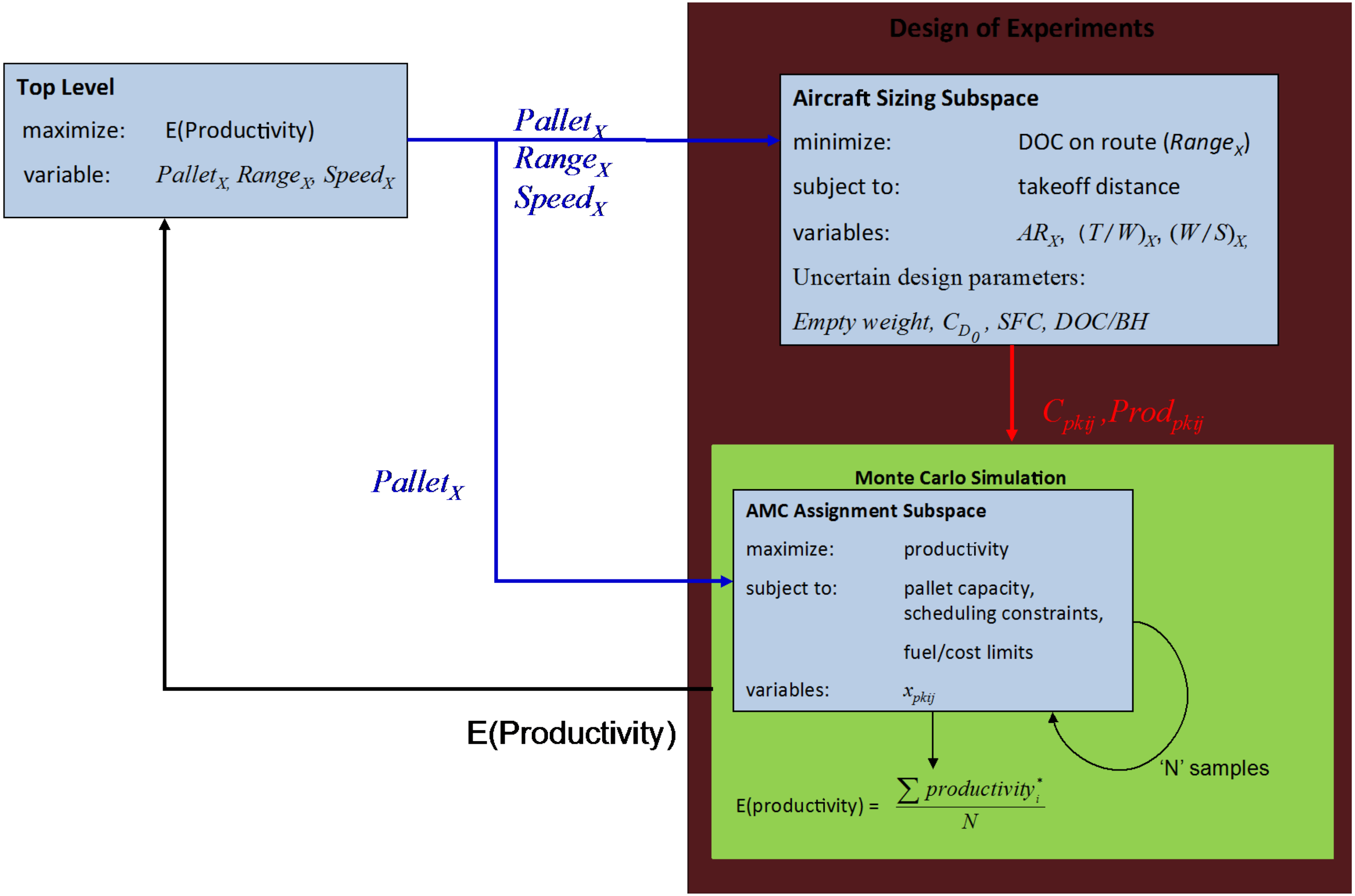
subject to: pallet capacity,
scheduling constraints,

fuel/cost limits

variables: x_{pkij}

Productivity,
Cost

Subspace Decomposition Approach



Top Level

maximize: E(Productivity)

variable: $Pallet_X, Range_X, Speed_X$

$Pallet_X$

$Range_X$

$Speed_X$

Design of Experiments

Aircraft Sizing Subspace

minimize: DOC on route ($Range_x$)

subject to: takeoff distance

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

Uncertain design parameters:

Empty weight, C_{D_0}, *SFC, DOC/BH*

$C_{pkij}, Prod_{pkij}$

$Pallet_X$

Monte Carlo Simulation

AMC Assignment Subspace

maximize: productivity

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

variables: x_{pkij}

‘N’ samples

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

E(Productivity)

Top Level Subspace

Maximize Fleet-level Productivity

Productivity = Speed x Capacity

Subject to

$$14 \le Pallet_X \le 38$$

Pallet Capacity Bounds

$$350 \le Speed_X \le 550$$

Cruise speed bounds (knots)

$$2400 \le Range_X \le 3800$$

Range at maximum payload bounds (nm)

$$Speed_X\,,\ Range_X \in R^+$$

$$Pallet_X \in Z^+$$

Design variables

- Pallet capacity, Range and Speed bounds are set by strategic air lift aircraft description

Aircraft Sizing Subspace

Minimize	$(DOC_{Pallet,Range,Speed})_X$	Direct Operating Cost
Subject to	$6.0 \le (AR)_X \le 9.5$	Wing aspect ratio bounds
	$65 \le (W/S)_X \le 161$	Wing loading bounds (lb/ft^2)
	$0.18 \le (T/W)_X \le 0.35$	Thrust-to-weight ratio bounds
	$S_{TO}\left(Pallet_X, (AR)_X, (W/S)_X, (T/W)_X\right) \le D_{takeoff}$	Aircraft takeoff distance
	$(AR)_X, (W/S)_X, (T/W)_X \in R^+$	Design variables

- Bounds for aircraft design variables based on current military cargo aircraft

Uncertainty in Aircraft Design Parameters

Uncertain design parameter	Range of values
ΔW_E (lbs) – empty weight	±10%
ΔC_{D_0} – drag coefficient	±10%
ΔDOC/BH ($/hr) – direct operating cost / block hour	±10%
ΔSFC (1/hr) – specific fuel consumption	±10% (Baseline value: 0.5)

- Four-factor, three-level full factorial design of experiments (DOE)
  - Levels: 90%, 100% ,and 110% of baseline or empirically-predicted value
  - 81 experiments = 81 sizing + allocation under uncertainty
- Best aircraft design based on mean from DOE trials
  - Our approach to account for uncertainty with low computational cost

Fleet Assignment Subspace

Maximize

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

Productivity = Speed × 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 limits

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

$$\forall p = 1, 2, 3 \dots P, \quad \forall j = 1, 2, 3 \dots N$$

Node balance constraints

Fleet Assignment Subspace

Subject to

$$\sum_{p=1}^{P}\sum_{k=1}^{K} Cap_{p,k,i,j} \cdot x_{p,k,i,j} \geq dem_{i,j}$$

$$\forall i = 1, 2, 3 \ldots N, \forall j = 1, 2, 3 \ldots N$$

Demand constraints

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

Starting location of aircraft constraints

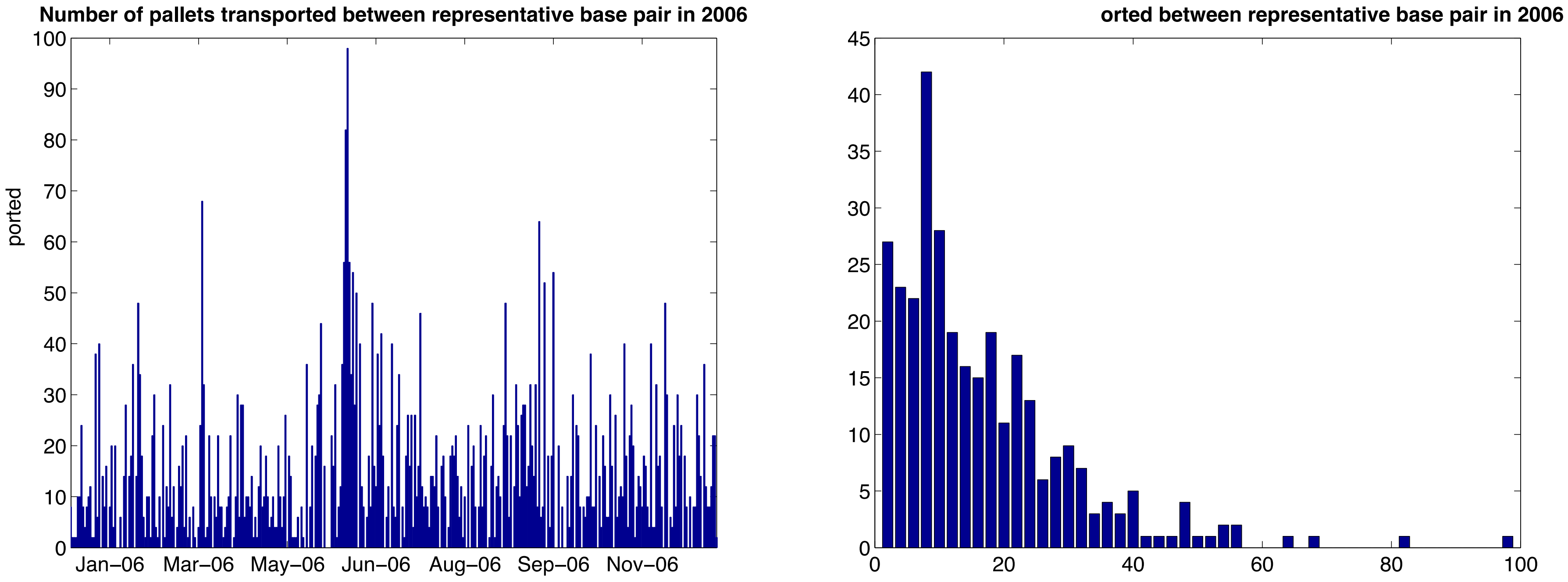
$$\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{p,k,i,j} \cdot BH_{p,k,i,j} \leq B_P \quad \forall p = 1, 2, 3 \ldots P$$

Trip constraints

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

Binary decision variable

Uncertainty in Pallet Cargo Demand



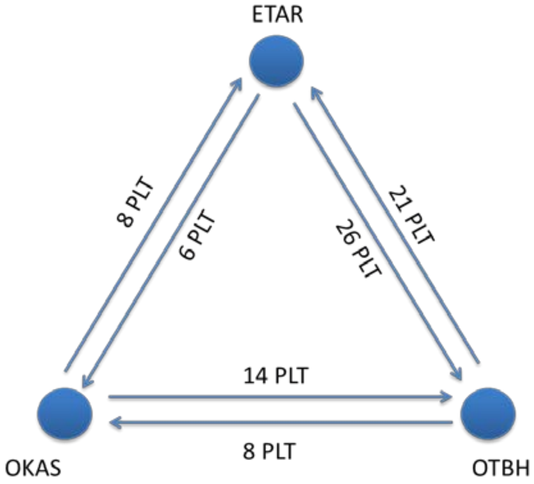
- Highly uncertain cargo demand
- Monte Carlo sampling (MCS) methods
  - Repeated deterministic calculations for statistical distribution of input random parameters

Palletized and Oversized Cargo Transport for Military Airlift Operations

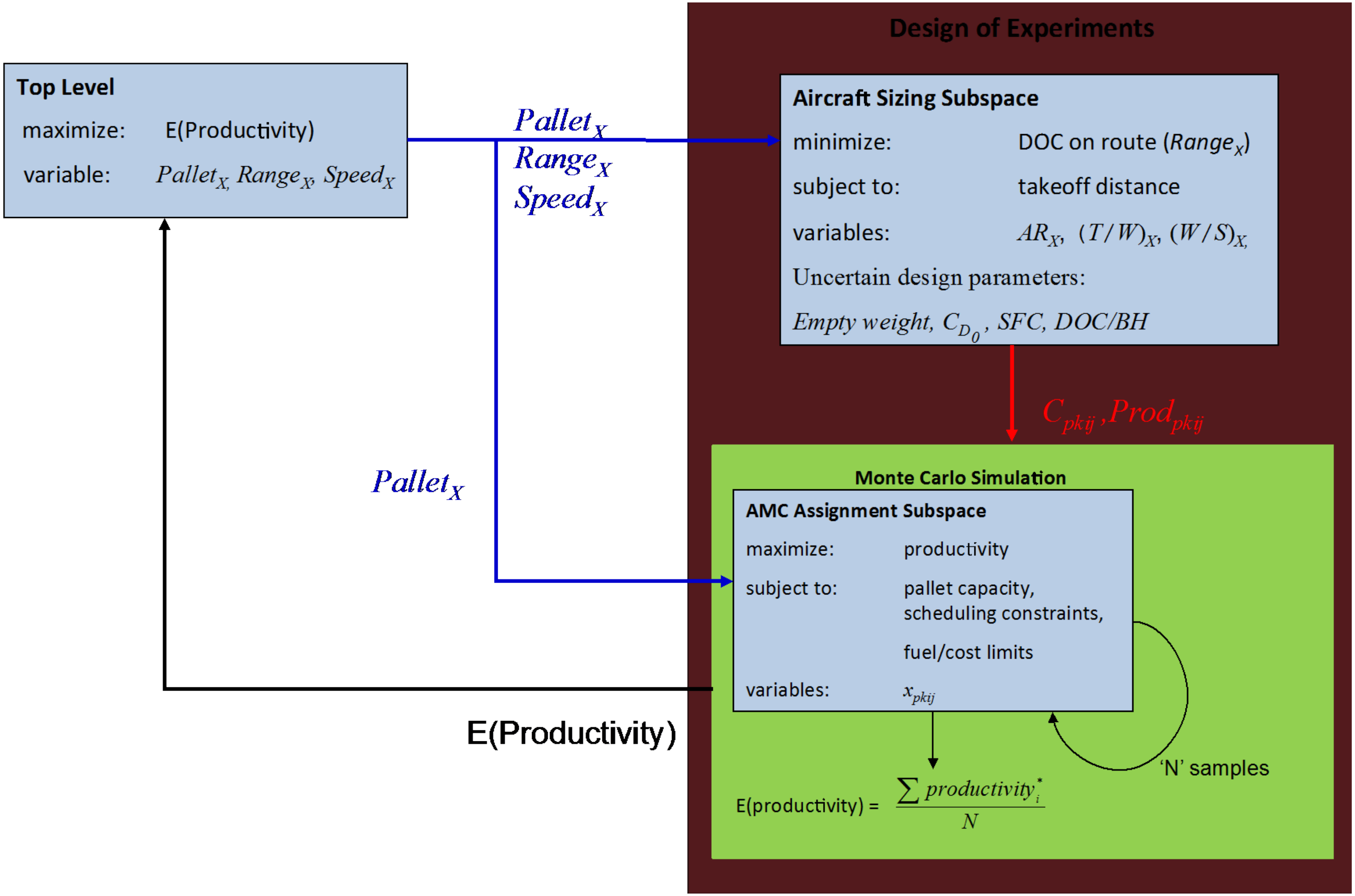
SCENARIOS & STUDIES

Three-base Problem

- Simple three-base problem consisting of 6 directional routes
  - Extracted from the GATES dataset
  - Most flown routes in May 2006
- Existing fleet for AMC
  - Three C-5: 36 pallet capacity
  - Three C-17: 18 pallet capacity
  - Three B747-F: 29 pallet capacity
- 1 new aircraft of type X is introduced



Subspace Decomposition Approach



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Monte Carlo Simulation

AMC Assignment Subspace

maximize: productivity

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

variables: x_{pkij}

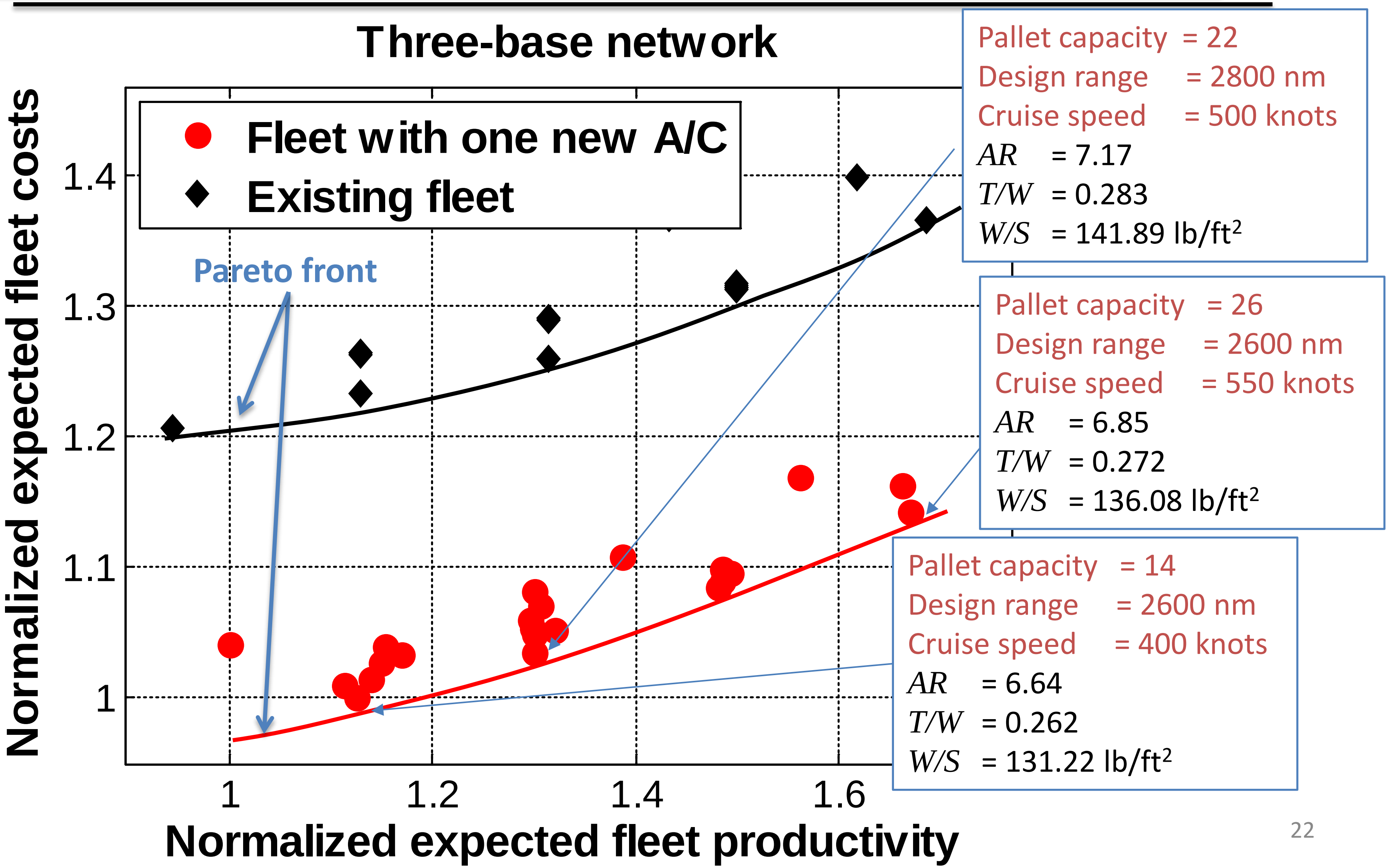
$Pallet_X$

'N' samples

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

E(Productivity)

Three-base Results

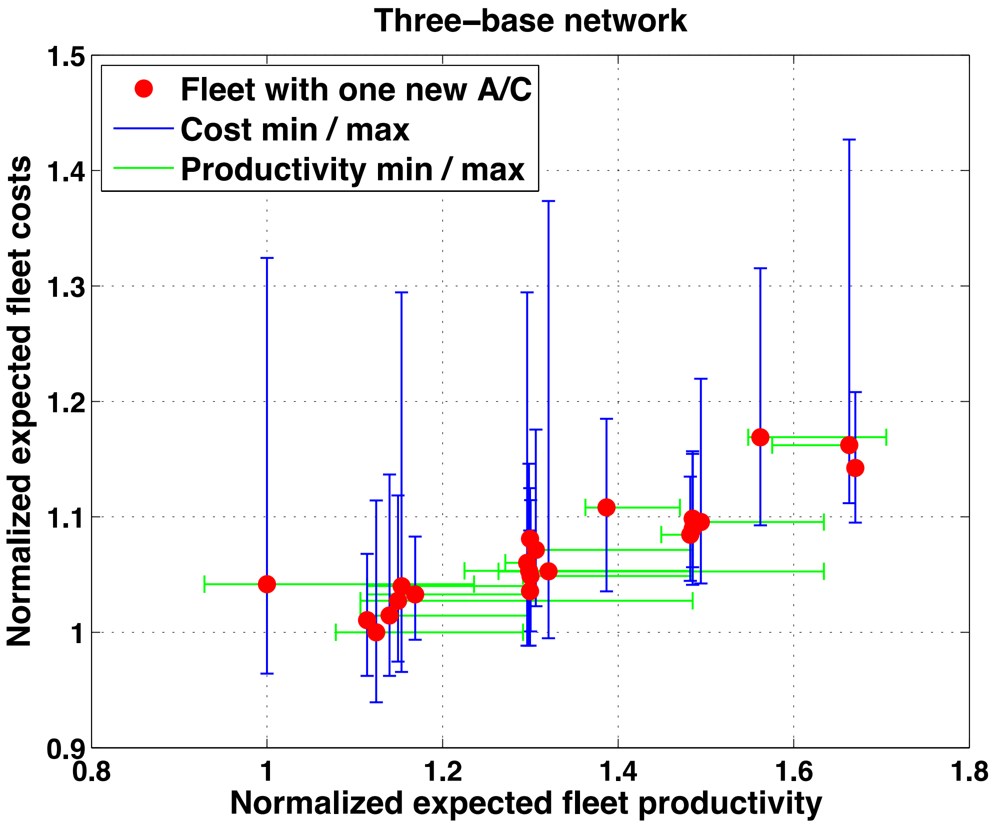


Pallet capacity = 22
Design range = 2800 nm
Cruise speed = 500 knots
AR = 7.17
T/W = 0.283
W/S = 141.89 lb/ft^2

Pallet capacity = 26
Design range = 2600 nm
Cruise speed = 550 knots
AR = 6.85
T/W = 0.272
W/S = 136.08 lb/ft^2

Pallet capacity = 14
Design range = 2600 nm
Cruise speed = 400 knots
AR = 6.64
T/W = 0.262
W/S = 131.22 lb/ft^2

Three-base Results



Error bars show min-max variation in fleet-level metrics due to uncertainties in demand and in the new aircraft design

- Degree of dispersion for some results are smaller than for others
- For the same productivity, some maximum fleet costs values on this plot still lower than costs of using existing fleet

CONCLUDING STATEMENTS AND FUTURE WORK

Concluding Statements

- We felt there was a need for an efficient decision-support tool to determine design requirements for new, to-be-acquired systems
- We developed a framework that identifies the tradeoffs between fleet-level metrics
  - Each tradeoff solution describes the design requirements, and optimal design of the new aircraft
  - MCS techniques to address uncertainty in demand
  - DOE to explore uncertainty in system design
  - Framework appears domain agnostic, should apply to many different applications, vehicles, etc.

Future Work

- Robust/Reliability-based problem formulations
- Reduce computational expense
  - Metamodeling or response surfaces
  - Improved sampling techniques

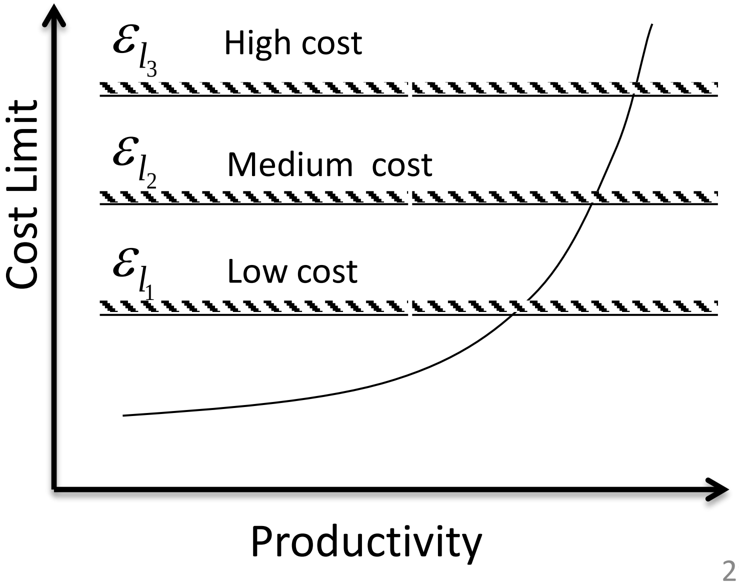
Thank You

BACKUP SLIDES

Multi-Objective Formulation

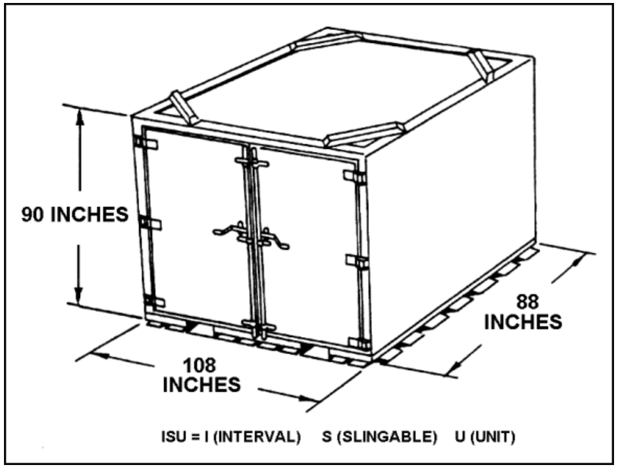
- Two objectives
  - Maximize fleet-level productivity
  - Minimize fleet-level cost
- Epsilon (Gaming) constraint formulation
  - Converts multi-objective to single objective
  - Identify a primary objective
  - Place limits on other objectives (inequality constraints)

$$
\begin{aligned}
&\mathit{Maximize} && f_p(x) \\
&\mathit{Subject\ to} && f_l(x) \le \varepsilon_l \qquad l = 1 \ldots n_{obj} (l \ne p) \\
& && g_j(x) \le 0 \\
& && h_k(x) = 0
\end{aligned}
$$



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*