A JOINT PERFORMANCE AND FINANCIAL APPROACH TO AIRCRAFT DESIGN OPTIMIZATION

16.888 Project Presentation

Ryan Peoples
Todd Schuman
May 9, 2003

Agenda

- Motivation
- Objectives & problem setup
- Simulation model
  - Cost, revenue, and value
  - Sizing and performance
- Optimization framework
- Design of experiment
- Single-objective optimization
  - Gradient-based
  - Genetic algorithm
- Multi-objective optimization
- Conclusions & future work

Motivation

- Traditional aircraft design objective: minimum GTOW
  - Improved performance
  - Reduced operating cost
- Does not guarantee financial viability of program
- Better aircraft program design methodology would take into account:
  - Performance
  - Development and manufacturing cost
  - Demand
  - Operating cost
  - Market uncertainty
- Better design objective: program value (Markish)

Objectives & Problem Setup

- Objectives:
  - Create an optimization framework to consider performance and finance in aircraft program design
  - Solve for financially optimal designs
    - Program value as objective
    - Deterministic solutions
- Problem setup:
  - Design vector
    - Number of passengers
    - Aircraft range
  - Objective vector: program Net Present Value (NPV)

Net Present Value

- Metric for estimating future value of fiscal activity in current terms
  - Based upon risk-adjusted discount rate (typically 12-20%)
  - Future expected cash flows discounted to reflect opportunity cost of capital and perceived risk of venture
  - NPV is the sum of discounted cash flows:

$$NPV = \sum_{t=0}^{\infty} \frac{P_t}{(1+r)^t}$$

  - Positive NPV indicates a profitable investment
- Requires cost, revenue, and demand estimates to calculate future income and expenses

Financial Models

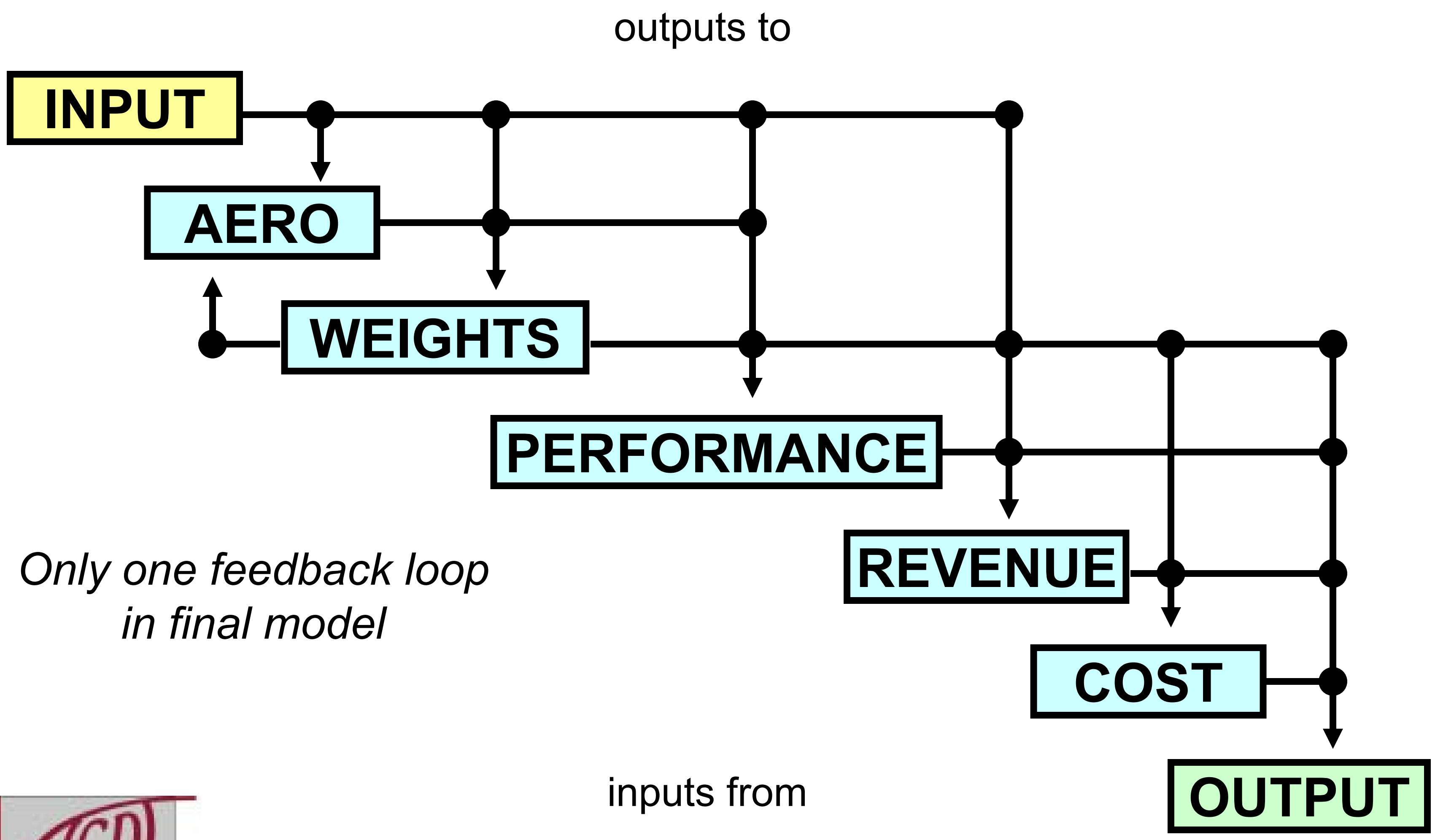
- Cost(Weight)
  - Nonrecurring, recurring costs estimated by process type from breakdown of weights
  - Learning curve effects captured
- Price(# Seats, Range, Operating Cost)
  - $Price = [k_1 \times (\frac{N\_seats}{N\_seats\_ref})^{\alpha} + k_2 \times (\frac{Range}{Range\_ref})] \times Price\_ref - \Delta LC$
  - ΔLC accounts for differences in operating cost based on fuel burn as a percentage of overall CAROC
- Demand(# Seats, Range)
  - Baseline demand & growth from empirical data by aircraft “class”

Performance Models

- Performance models based on aircraft sizing routine developed by Prof. Liebeck
- Combination of many different techniques
  - Aerodynamic first principles
  - Empirical data
  - Rules of thumb
- Calculates all necessary aircraft specifications
  - GTOW, fuselage dimensions, fuel fraction, etc.
- Physical model based on DC-10 class aircraft vs. financial model based on 777

➡ Physical model re-calibrated to account for this discrepancy

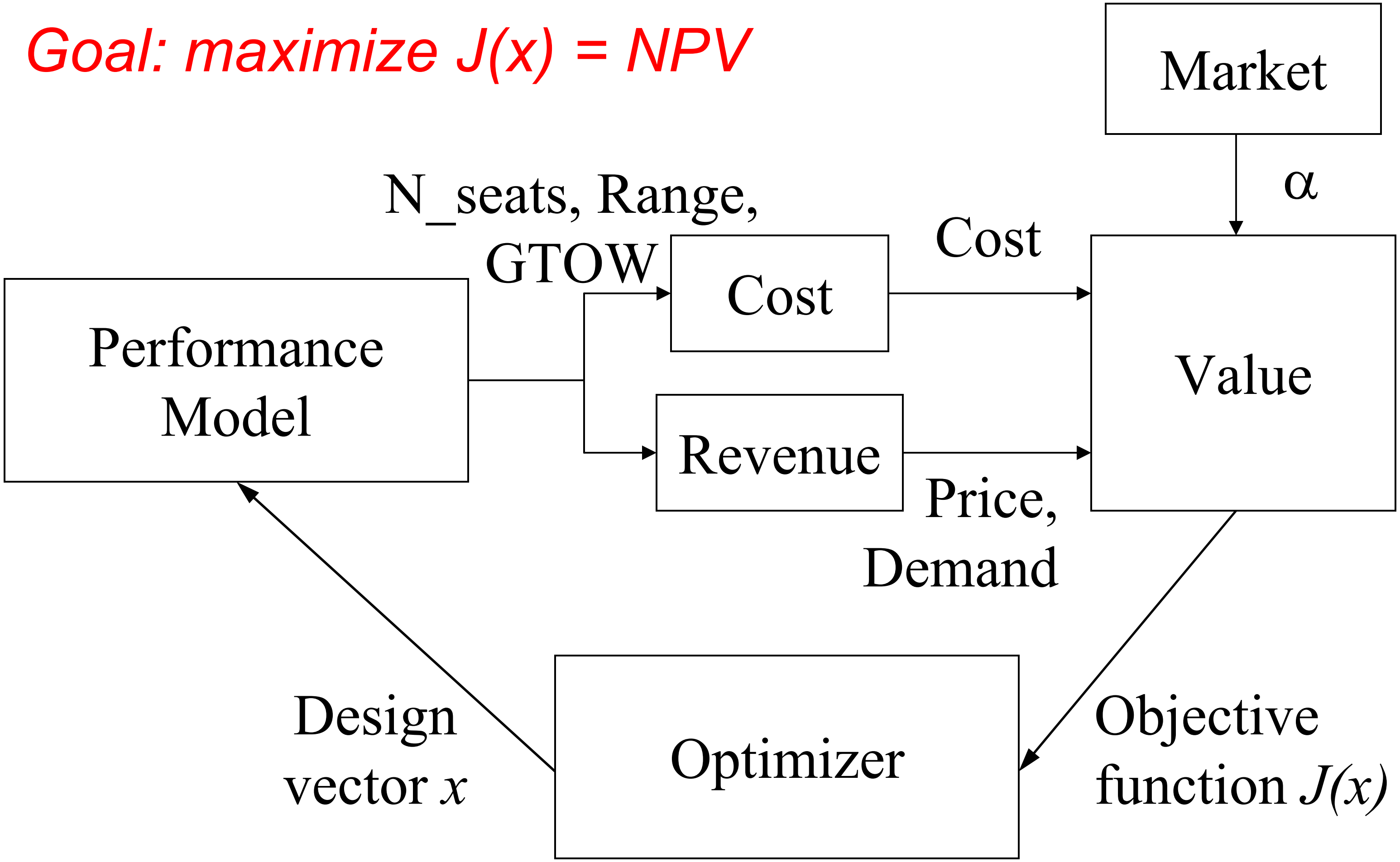
N^2 Diagram



Only one feedback loop in final model

Optimization Framework

Goal: maximize J(x) = NPV



Market

α

N_seats, Range, GTOW

Cost

Cost

Performance Model

Value

Revenue

Price, Demand

Design vector *x*

Optimizer

Objective function *J(x)*

Design of Experiment

- DOE used several times during project to validate model behavior
  - Identified model flaws early in optimization process
- Used “one-at-a-time” setup due to low number of design variables
- Chose initial design vector directly from DOE results
- Example DOE:

	Variables		**Objectives**	
Experiment #	**# Passengers**	**Range (nm)**	**NPV ($B)**	**GTOW (lbs.)**
1	250	5500	17.8	352,000
2	300	5500	18.8	413,000
3	350	5500	10.1	475,000
4	400	5500	4.7	537,000
5	450	5500	5.4	600,000
6	300	6000	20.9	425,000
7	300	6500	23.1	436,000
8	300	7000	25.6	445,000
9	300	7500	28.3	452,000

Gradient-Based Optimization

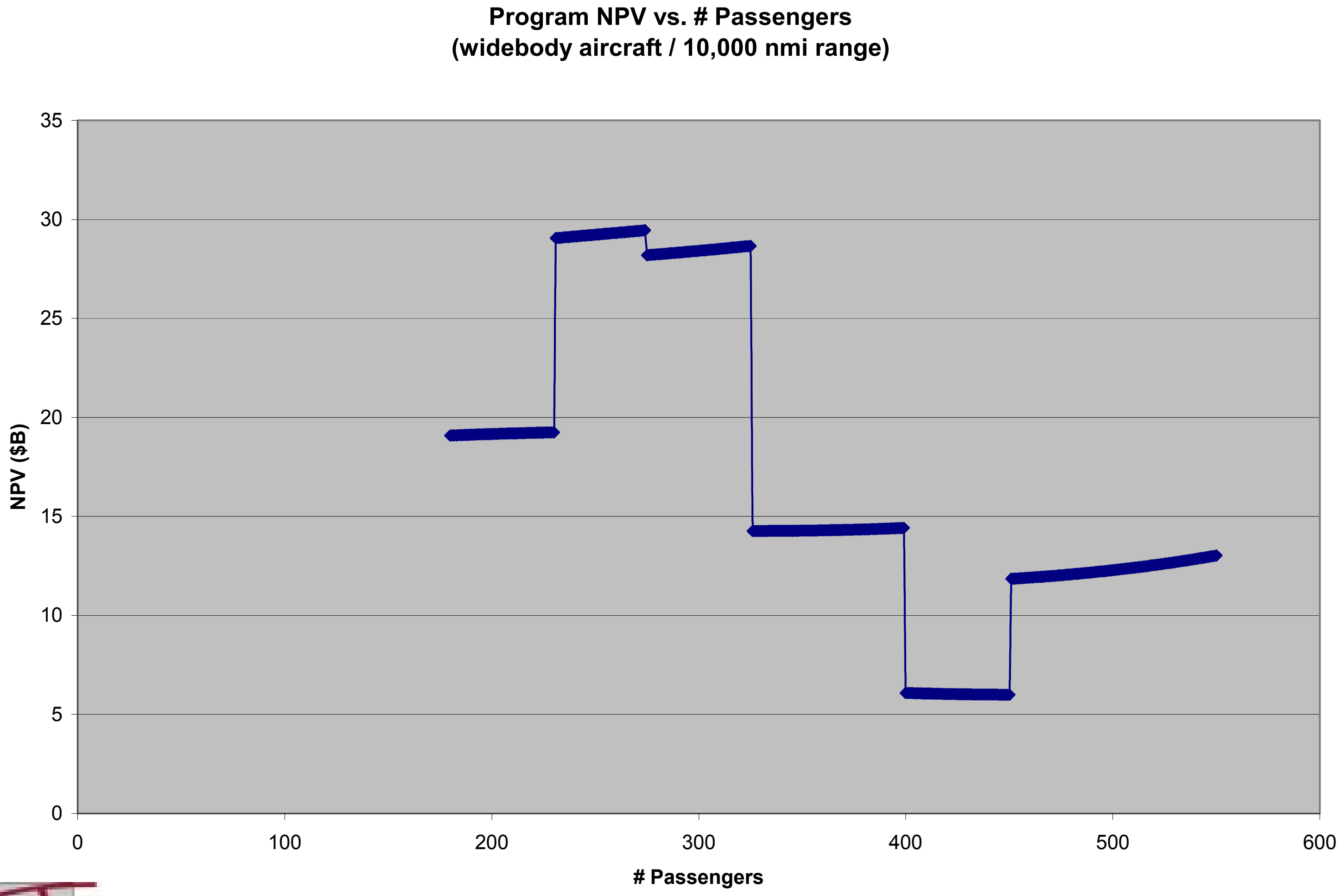
- NPV chosen for single-objective optimization
  - Allowed full functionality test, as NPV depends on physical and financial models
- Used combination of sequential quadratic programming + mixed-integer optimization in iSIGHT
  - Low number of inputs, outputs, and constraints
  - # of passengers is a discrete variable
- Single-objective results:

x_0		x^*		Objectives	
NPass	**Range**	**NPass**	**Range**	**NPV**	**GTOW**
300	7500	325	10,000	47.5	479,000
350	7500	550	10,000	29	787,000
250	7500	550	10,000	29	787,000

Gradient-Based Optimization (2)

- Sensitivity Analysis
  - Little change in NPV within individual demand bucket, large change between buckets
  - Steady change in NPV due to range variation
- Scaling
  - Unable to scale Hessian for # passengers below O(100)
  - Tradeoff: integer solution desirable but not well conditioned
- Conclusions:
  - Sensitivity to range => max range at optimal solution
  - Design space highly sensitive to discretized demand based on # passengers
  - Gradient search unreliable, possibly inherently poorly-scaled problem

Design Space



Heuristic Optimization

- Genetic algorithms are very well suited for this problem
  - Avoids local minimums caused by discretized demand function
  - More reliable convergence on global maximum (coupled with MOST)
- GA results:

Sub-population size	# of generations	Mutation rate	x*		J*	
			NPass	Range (nmi)	NPV ($B)	GTOW (lbs)
10	10	1%	273	10000	29.43	512,000
10	12	1%	266	10000	29.37	500,000
12	10	1%	273	9978	29.39	511,000
10	**10**	**10%**	**274**	**10000**	**29.45**	**514,000**
5	10	1%	271	9992	29.4	508,000
10	5	1%	251	9979	29.18	474,000

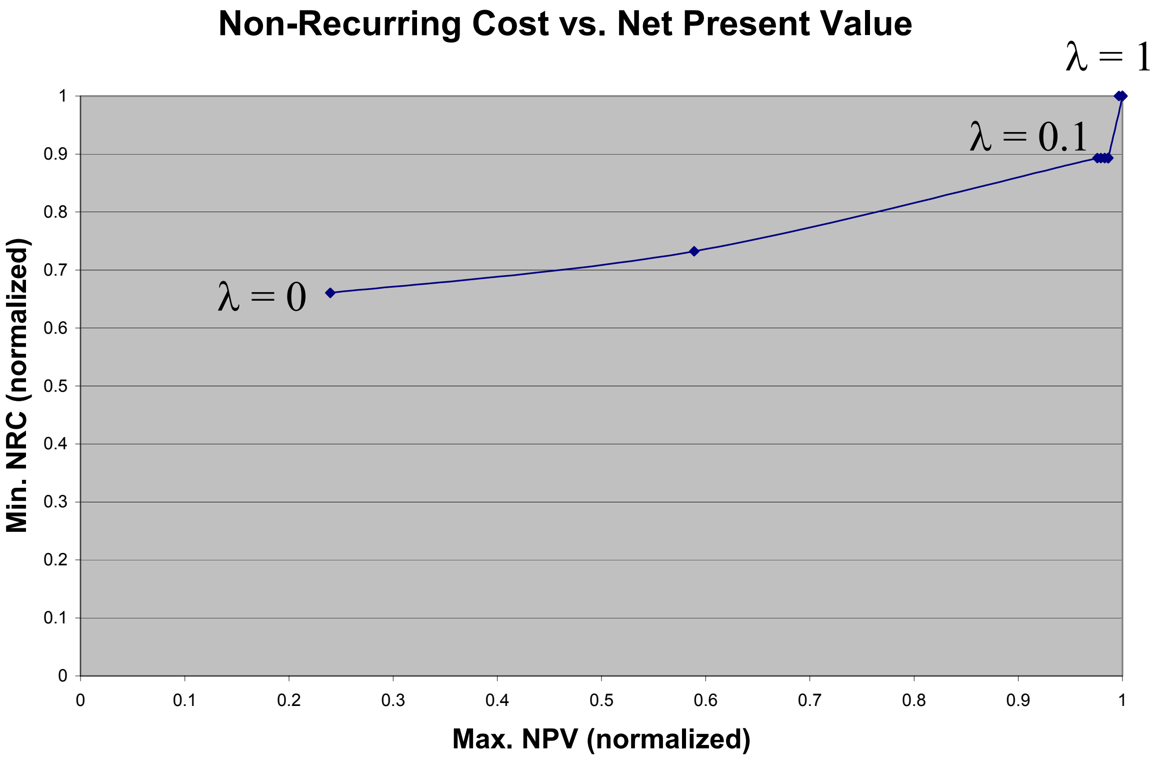
- Improvements made to physical model after gradient-based optimization makes comparing the two methods difficult
- Trends are still similar

Multi-objective Optimization

- Second objective: minimize non-recurring cost (NRC)
  - Ideal for manufacturer to reduce initial investment
  - Correlated to weight in model, but not same as min. GTOW
- New objective vector:
  - $$J = \begin{Bmatrix} J_1 \\ J_2 \end{Bmatrix} = \begin{Bmatrix} \max NPV \\ \min NRC \end{Bmatrix}$$
  - Weighted sum approach: $J = \lambda * J_1 + (1-\lambda) * J_2$
- Results
  - Individual objectives mutually opposed
    - $\lambda = 1$ => max range
    - $\lambda = 0$ => min range, min # passengers
  - Discrete jumps in objective *J* due to design space

Pareto Front

- Minimized NRC vs. maximized NPV
- Extremely sensitive to weighting
- Discrete "jumps" dictated by design space (# seats)
- Objectives strongly opposed



Conclusions & Future Work

- Conclusions
  - Successful implementation of optimization for value
  - # passengers most greatly affects design solution
  - Benefit of longer range aircraft outweighs costs of increased weight
  - Heuristic algorithms better suited to this problem

- Future work
  - Refinement of performance and financial models
  - Stochastic demand model to account for market uncertainty
  - Dynamic programming approach to allow for flexibility in the design process