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Multidisciplinary System Design Optimization (MSDO)

Design for Value

Lecture 19

Karen Willcox

Olivier de Weck

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Today's Topics

- An MDO value framework
- Lifecycle cost models
- Value metrics & valuation techniques
- Value-based MDO
- Aircraft example
- Spacecraft Example

Optimal Design

- Traditionally, design has focused on **performance**

  e.g. for aircraft design

  optimal = minimum weight

- Increasingly, **cost** becomes important
- 85% of total lifecycle cost is locked in by the end of preliminary design.
- But *minimum weight* $\neq$ *minimum cost* $\neq$ *maximum value*
- What is an appropriate value metric?

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Design Example

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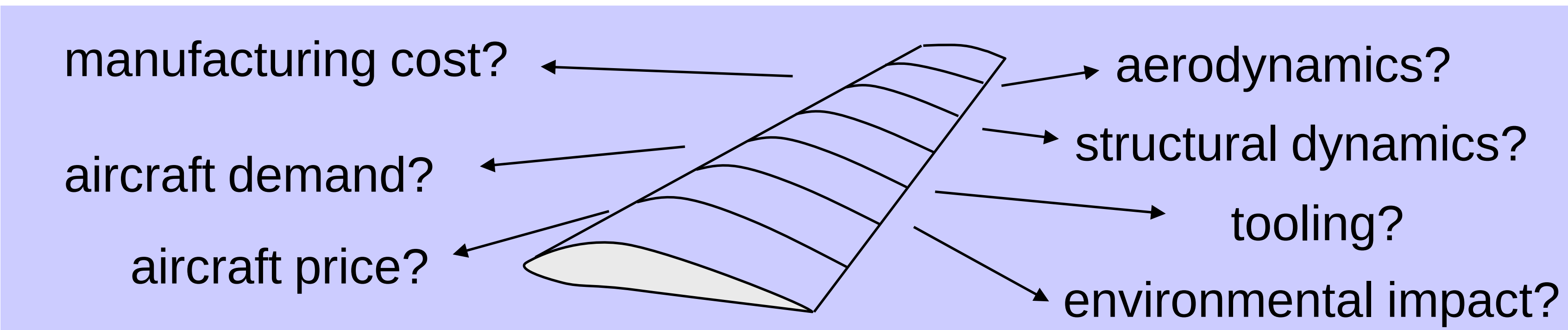
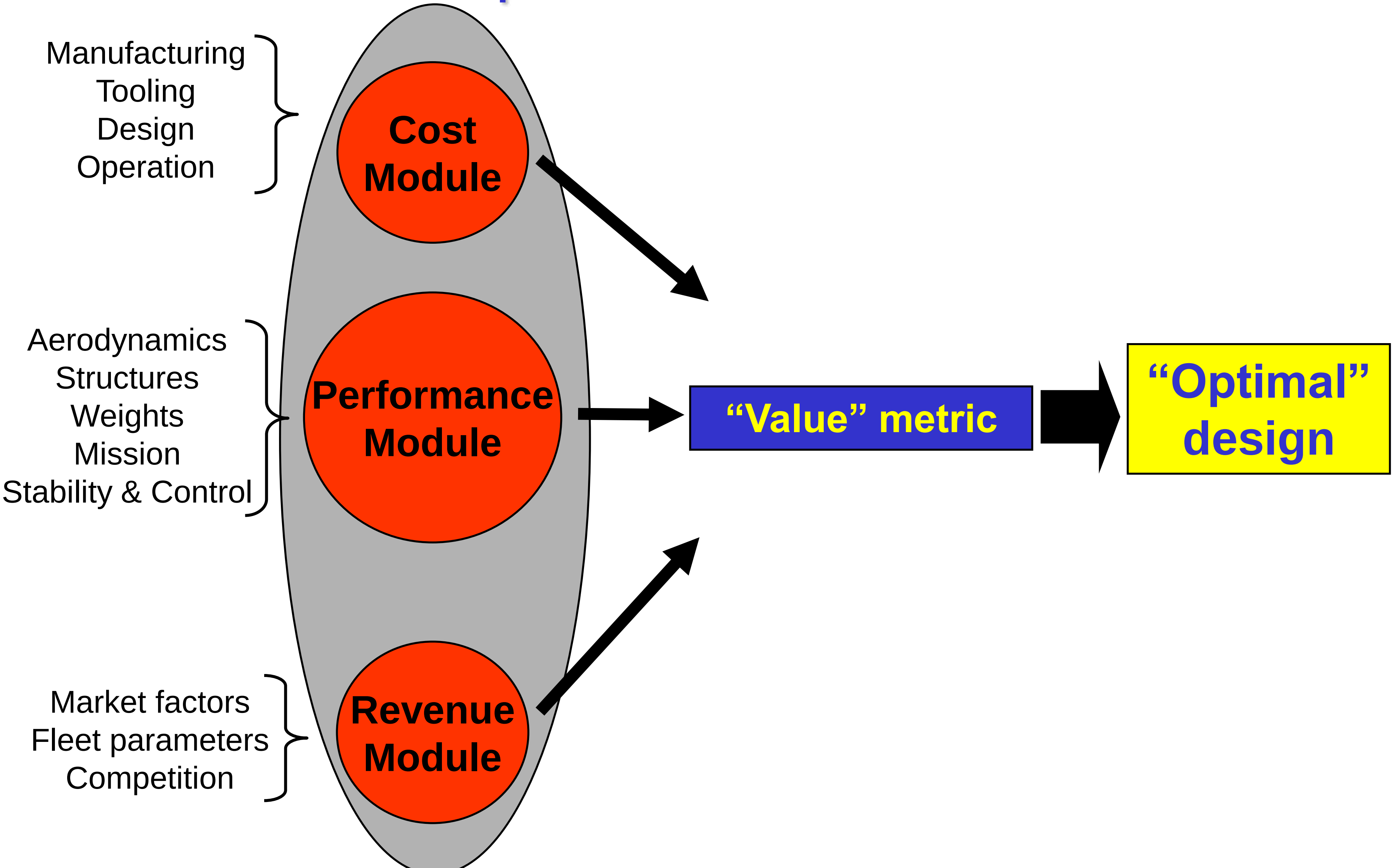
- We need to design a particular portion of the wing
- Traditional approach: balance the aero & structural requirements, minimize weight
- We should consider cost: what about an option that is very cheap to manufacture but performance is worse?



- How do we trade performance and cost?
- How much performance are we willing to give up for $100 saved?
- What is the impact of the low-cost design on price and demand of this aircraft?
- What is the impact of this design decision on the other aircraft I build?
- What about market uncertainty?

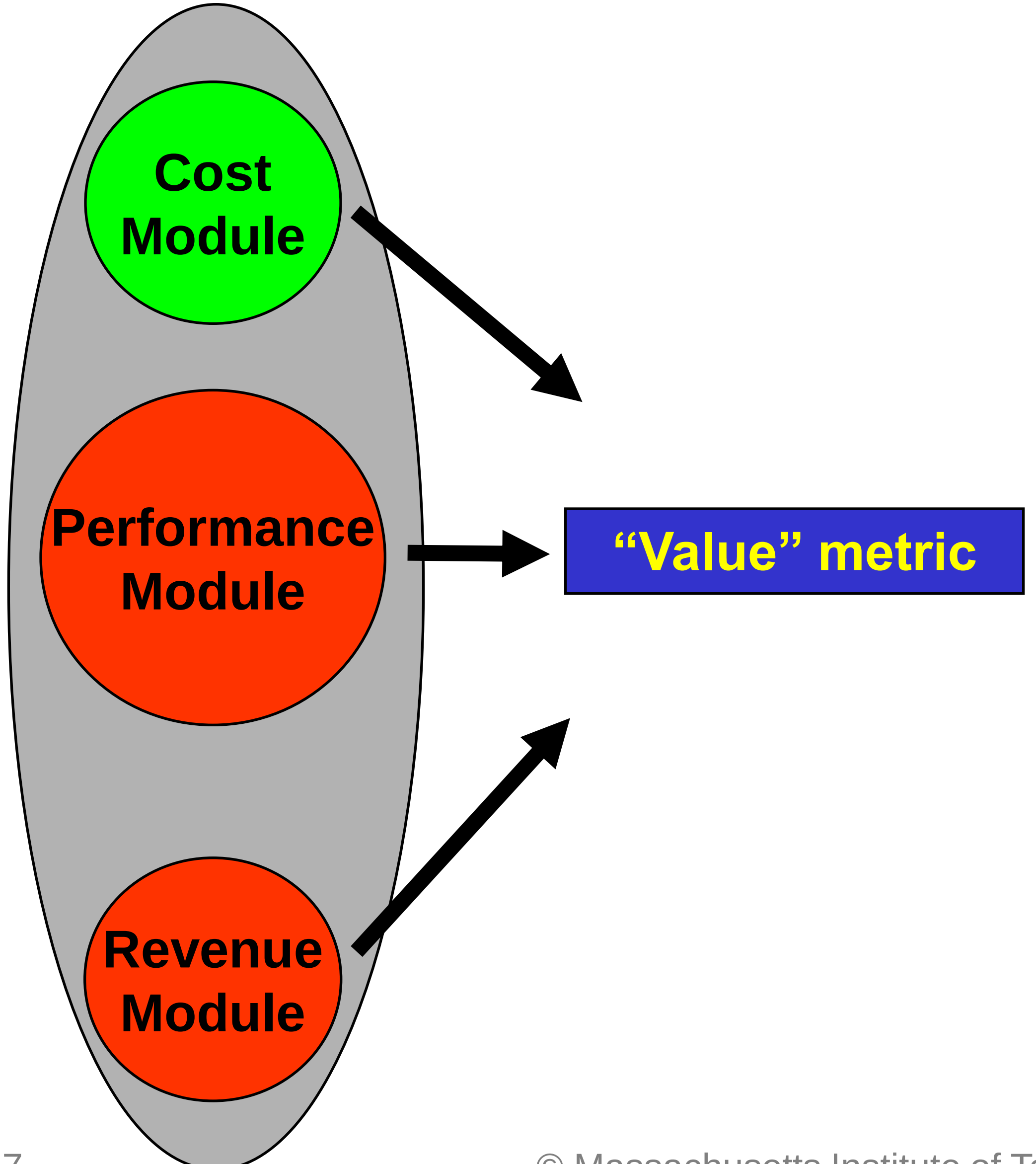
Value Optimization Framework



Challenges

- Cost and revenue are difficult to model
  - often models are based on empirical data
  - how to predict for new designs
- Uncertainty of market
- Long program length
- Time value of money
- Valuing flexibility
- Performance/financial groups even more uncoupled than engineering disciplines

Cost Model



Need to model the lifecycle cost of the system.

Life cycle :

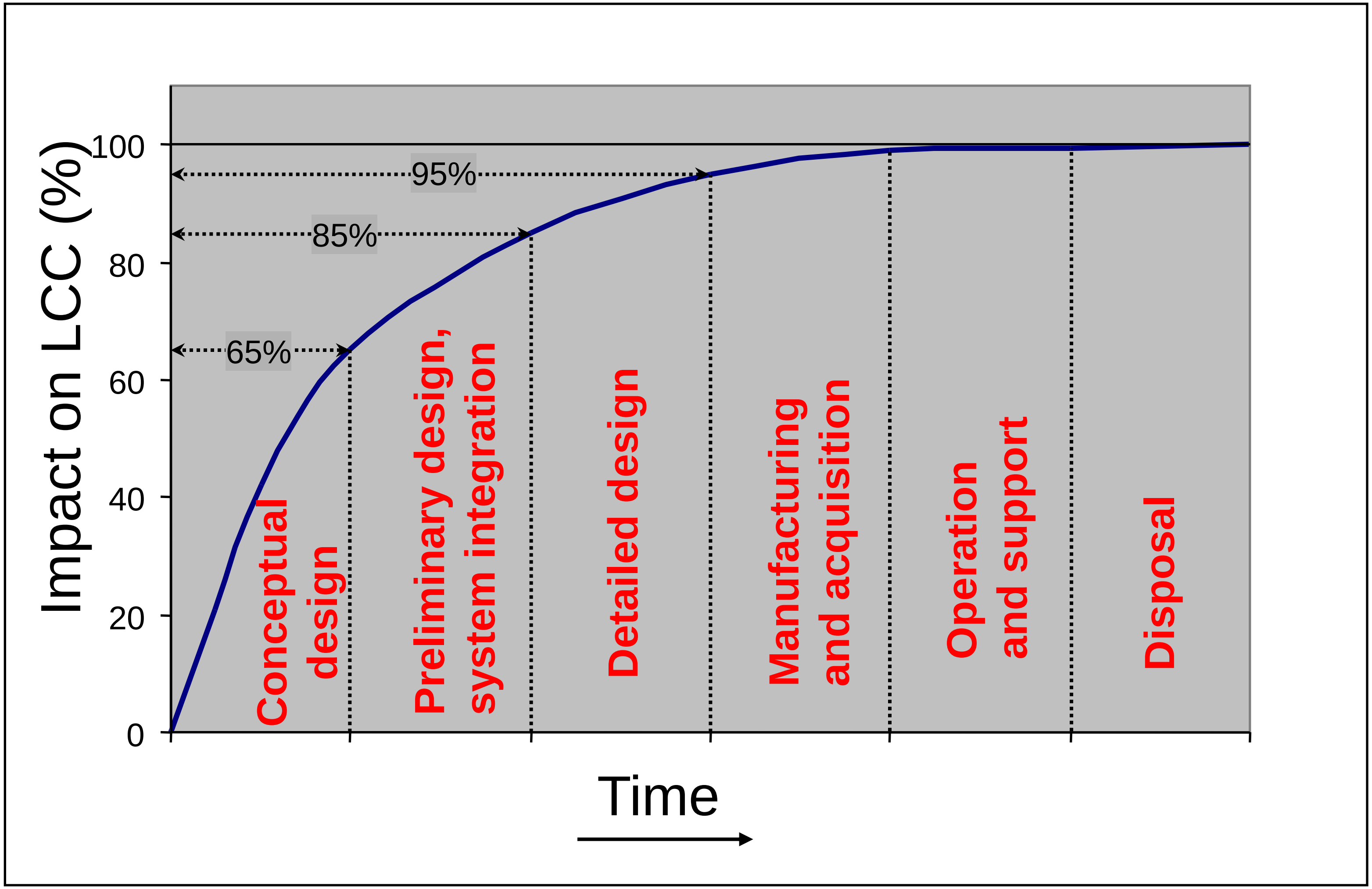
Design - Manufacture - Operation - Disposal

Lifecycle cost :

Total cost of program over life cycle

85% of Total LCC is locked in by the end of preliminary design.

Lifecycle Cost



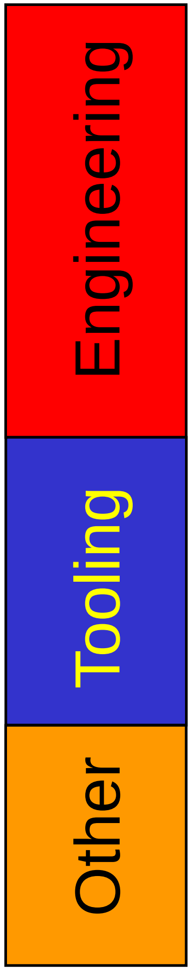
Non-Recurring Cost

Cost incurred one time only:

Engineering
- airframe design/analysis
- configuration control
- systems engineering

Tooling
- design of tools and fixtures
- fabrication of tools and fixtures

Other
- development support
- flight testing



Development Cost Model

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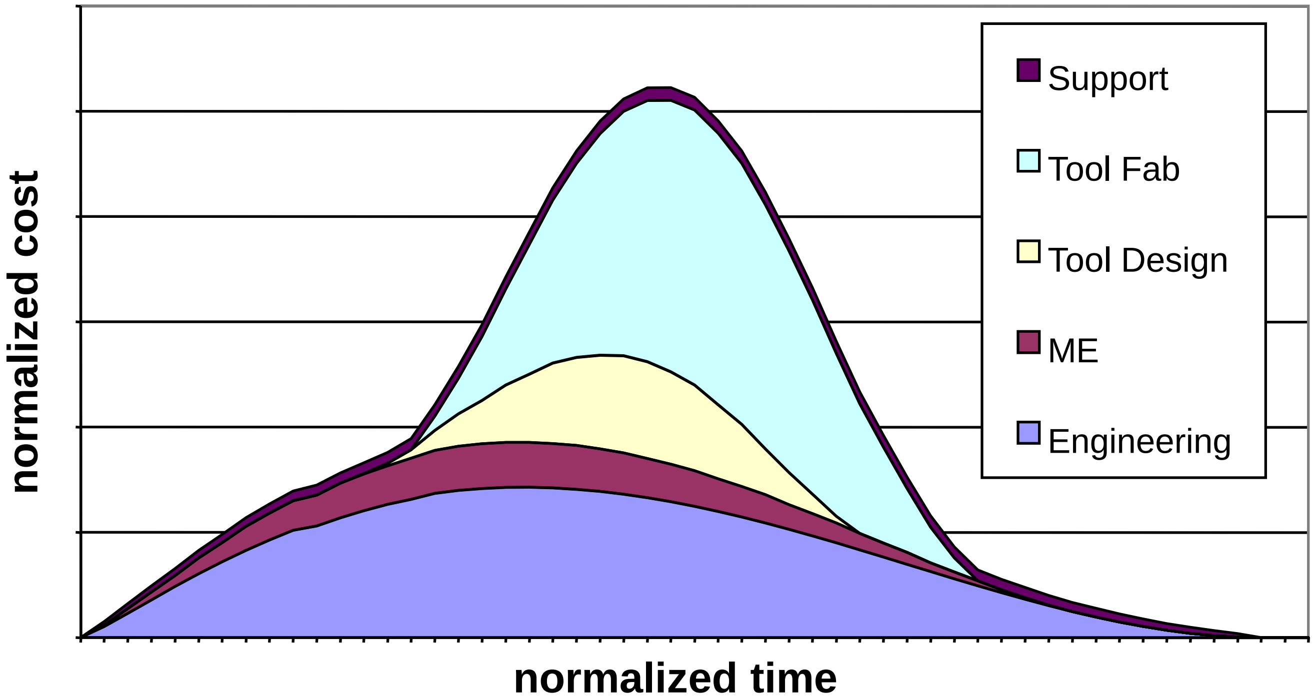
- Cashflow profiles based on beta curve:

$$c(t) = Kt^{\alpha-1}(1-t)^{\beta-1}$$

- Typical development time ~6 years
- Learning effects captured – span, cost

(from Markish)



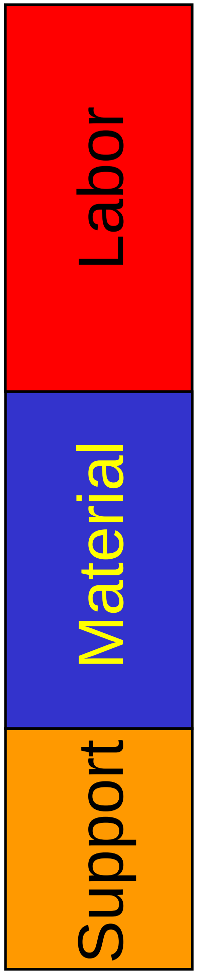
Recurring Cost

Cost incurred per unit:

Labor
- fabrication
- assembly
- integration

Material to manufacture
- raw material
- purchased outside production
- purchased equipment

Production support
- QA
- production tooling support
- engineering support



Learning Curve

As more units are made, the recurring cost per unit decreases.

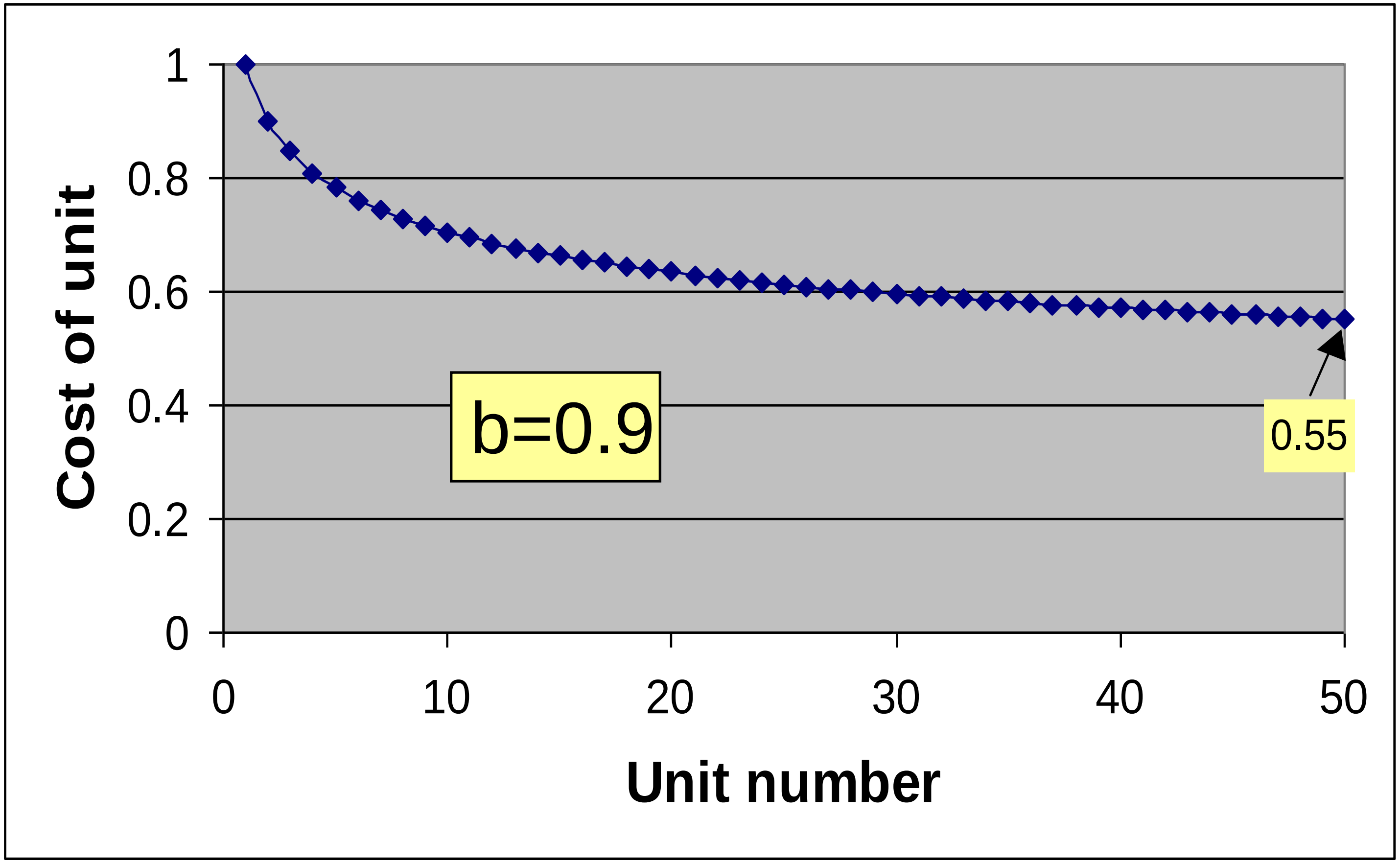
This is the learning curve effect.

e.g. Fabrication is done more quickly, less material is wasted.

$$Y_x = Y_0 x^n$$

Y_x = number of hours to produce unit x
n = log b/log 2
b = learning curve factor (~80-100%)

Learning Curve



Every time production doubles, cost is reduced by a factor of 0.9

Typical LC slopes: Fab 90%, Assembly 75%, Material 98%

Airplane Related Operating Costs

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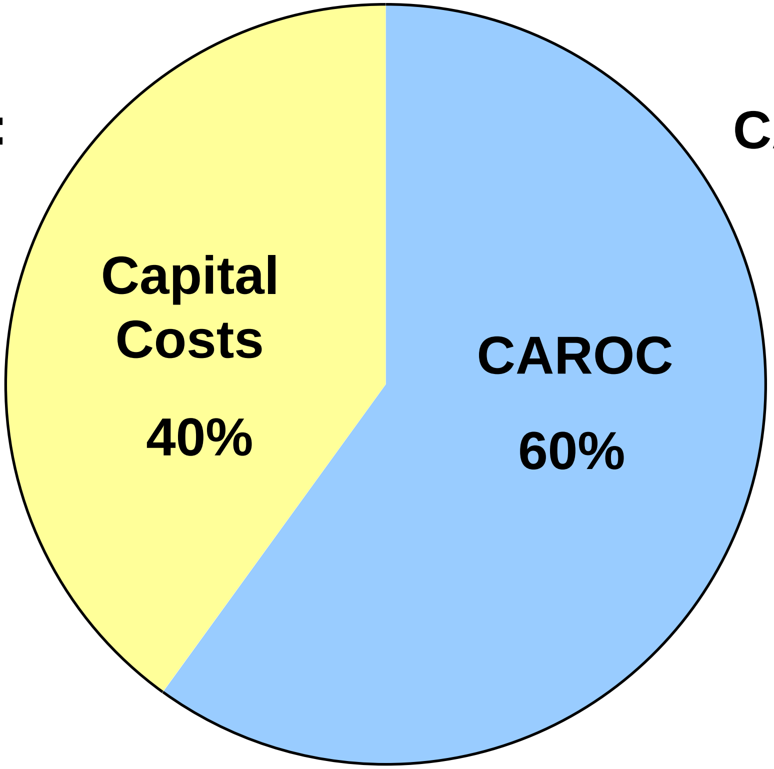
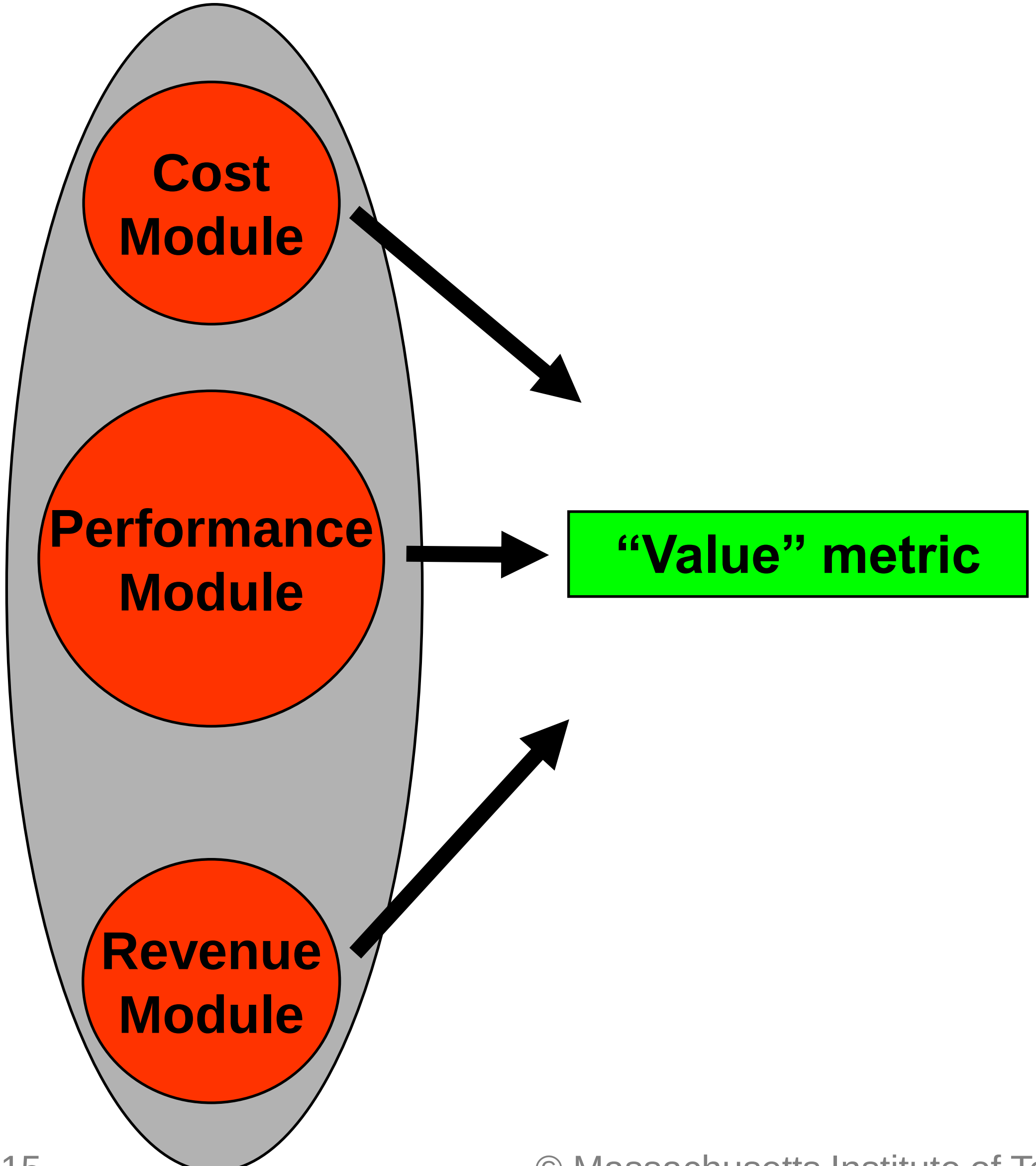
CAPITAL COSTS:
Financing
Insurance
Depreciation



CASH AIRPLANE RELATED OPERATING COSTS:
Crew
Fuel
Maintenance
Landing
Ground Handling
GPE Depreciation
GPE Maintenance
Control & Communications

CAROC is only 60% - ownership costs are significant!

Value Metric



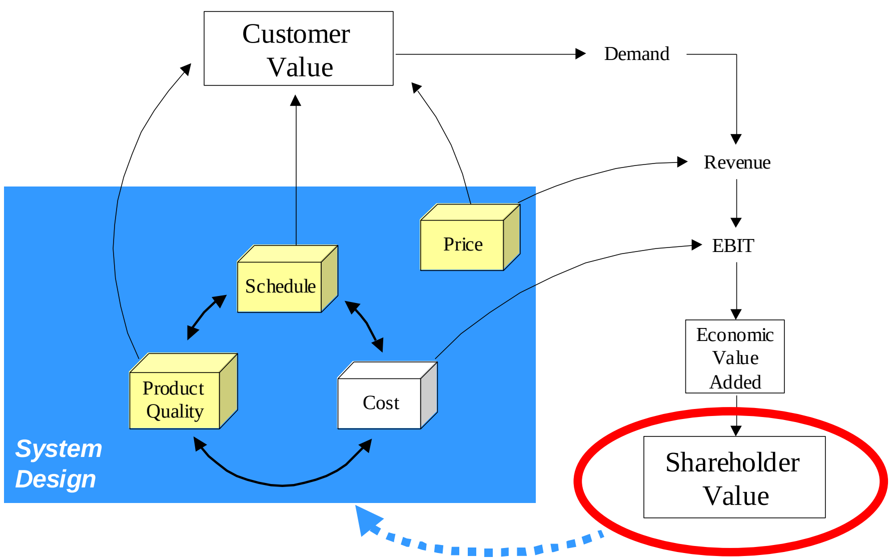
Need to provide a quantitative metric that incorporates cost, performance and revenue information.

In optimization, need to be especially carefully about what metric we choose...

What is Value?

- Objective function could be different for each stakeholder *e.g.* manufacturer vs. airline vs. flying public
- Program related parameters vs. technical parameters

  cost, price, production quantity, timing
- Traditionally program-related design uncoupled from technical design



Customer value *derived from quality, timeliness, price.*

Shareholder value *derived from cost and revenue, which is directly related to customer satisfaction.*

From Markish, Fig. 1, pg 20

Value Metrics

Traditional Metrics	Augmented Metrics
performance weight speed	cost revenue profit quietness emissions commonality ...

The definition of value will vary depending on your system and your role as a stakeholder, but we must define a quantifiable metric.

Valuation Techniques

Investor questions:

- How much will I need to invest?
- How much will I get back?
- When will I get my money back?
- How much is this going to cost me?
- How are you handling risk & uncertainty?

Investment Criteria

- Net present value
- Payback
- Discounted payback
- Internal rate of return
- Return on investment

Net Present Value (NPV)

- Measure of present value of various cash flows in different periods in the future
- Cash flow in any given period discounted by the value of a dollar today at that point in the future
  - "Time is money"
  - A dollar tomorrow is worth less today since if properly invested, a dollar today would be worth more tomorrow
- Rate at which future cash flows are discounted is determined by the "discount rate" or "hurdle rate"
  - Discount rate is equal to the amount of interest the investor could earn in a single time period (usually a year) if s/he were to invest in a "safer" investment

Discounted Cash Flow (DCF)

- Forecast the cash flows, C_0, C_1, ..., C_T of the project over its economic life
  - Treat investments as negative cash flow
- Determine the appropriate opportunity cost of capital (i.e. determine the discount rate r)
- Use opportunity cost of capital to discount the future cash flow of the project
- Sum the discounted cash flows to get the net present value (NPV)

$$NPV = C_0 + \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + \cdots + \frac{C_T}{(1+r)^T}$$

DCF example

Period	Discount Factor	Cash Flow	Present Value
0	1	-150,000	-150,000
1	0.935	-100,000	-93,500
2	0.873	+300000	+261,000

Discount rate = 7%

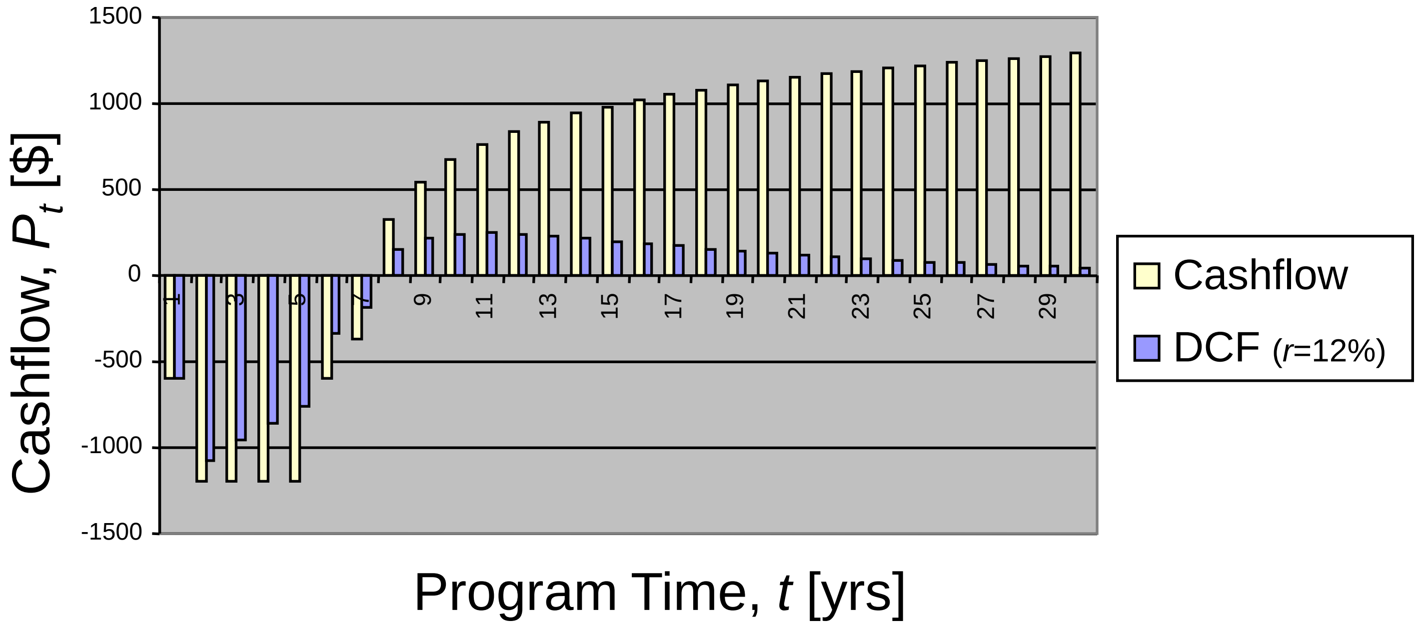
NPV = $18,400

Risk-Adjusted Discount Rate

- DCF analysis assumes a fixed schedule of cash flows
- What about uncertainty?
- Common approach: use a risk-adjusted discount rate
- The discount rate is often used to reflect the risk associated with a project: the riskier the project, use a higher discount rate
- Typical discount rates for commercial aircraft programs: 12-20%
- Issues with this approach?

Net Present Value (NPV)

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



Payback Period

- How long it takes before entire initial investment is recovered through revenue
- Insensitive to time value of money, i.e. no discounting
- Gives equal weight to cash flows before cut-off date & no weight to cash flows after cut-off date
- Cannot distinguish between projects with different NPV
- Difficult to decide on appropriate cut-off date

Discounted payback

- Payback criterion modified to account for the time value of money
  - Cash flows before cut-off date are discounted
- Overcomes objection that equal weight is given to all flows before cut-off date
- Cash flows after cut-off date still not given any weight

Internal rate of return (IRR)

- Investment criterion is "rate of return must be greater than the opportunity cost of capital"
- Internal rate of return is equal to the discount rate for which the NPV is equal to zero

$$NPV = C_0 + \frac{C_1}{1+IRR} + \frac{C_2}{(1+IRR)^2} + \cdots + \frac{C_T}{(1+IRR)^T} = 0$$

- IRR solution is not unique
  - Multiple rates of return for same project
- IRR doesn't always correlate with NPV
  - NPV does not always decrease as discount rate increases

Return on Investment (ROI)

- Return of an action divided by the cost of that action

$$ROI = \frac{\text{revenue} - \text{cost}}{\text{cost}}$$

- Need to decide whether to use actual or discounted cashflows

Decision Tree Analysis (DTA)

- NPV analysis with different future scenarios
- Weighted by probability of event occurring

Real Options Valuation Approach

- In reality:
  - Cashflows are uncertain
  - Ability to make decisions as future unfolds
- View an aircraft program as a series of investment decisions
- Spending money on development today gives the option to build and sell aircraft at a later date
- Better valuation metric: ***expected NPV*** from dynamic programming algorithm (Markish, 2002)

Dynamic Programming: Problem Formulation

- The firm:
  - Portfolio of designs
  - Sequential development phases
  - Decision making
- The market:
  - Sale price is steady
  - Quantity demanded is unpredictable
  - Units built = units demanded
- Problem objective:
  - Which aircraft to design?
  - Which aircraft to produce?
  - When?

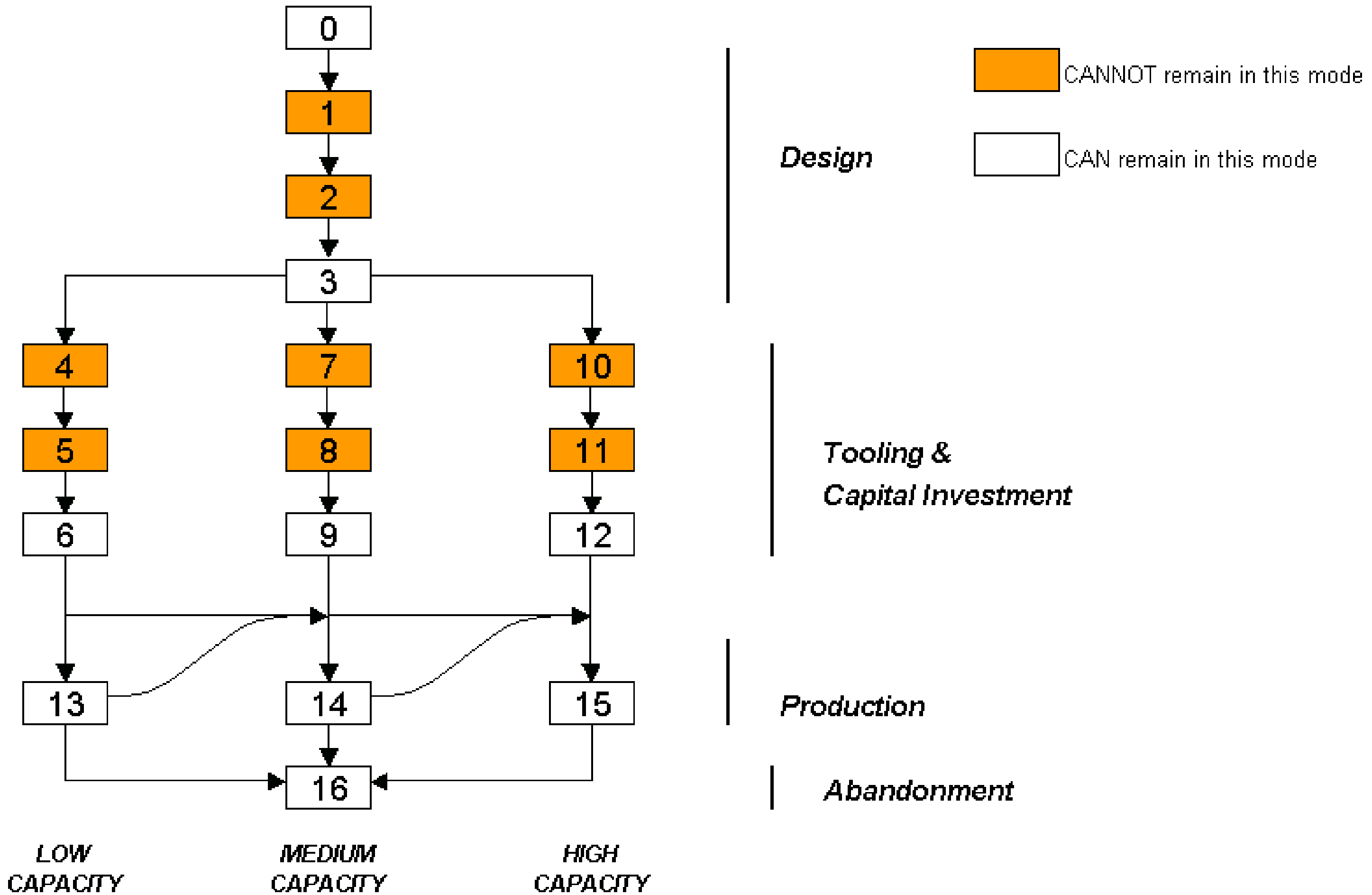
Dynamic Programming: Problem Elements

1. State variables $\boldsymbol{s_t}$
2. Control variables $\boldsymbol{u_t}$
3. Randomness
4. Profit function
5. Dynamics

- Solution: $$F_t(s_t) = \max_{u_t}\left\{\pi_t(s_t, u_t) + \frac{1}{1+r}E_t\left[F_{t+1}(s_{t+1})\right]\right\}$$
- Solve recursively

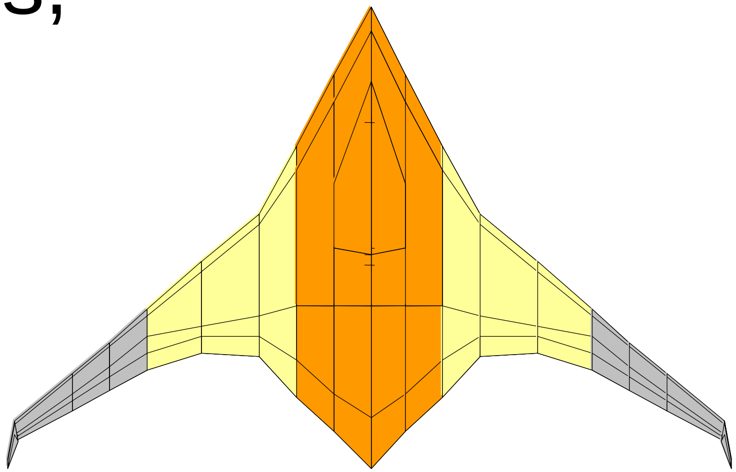
Dynamic Programming: Operating Modes

How to model decision making?

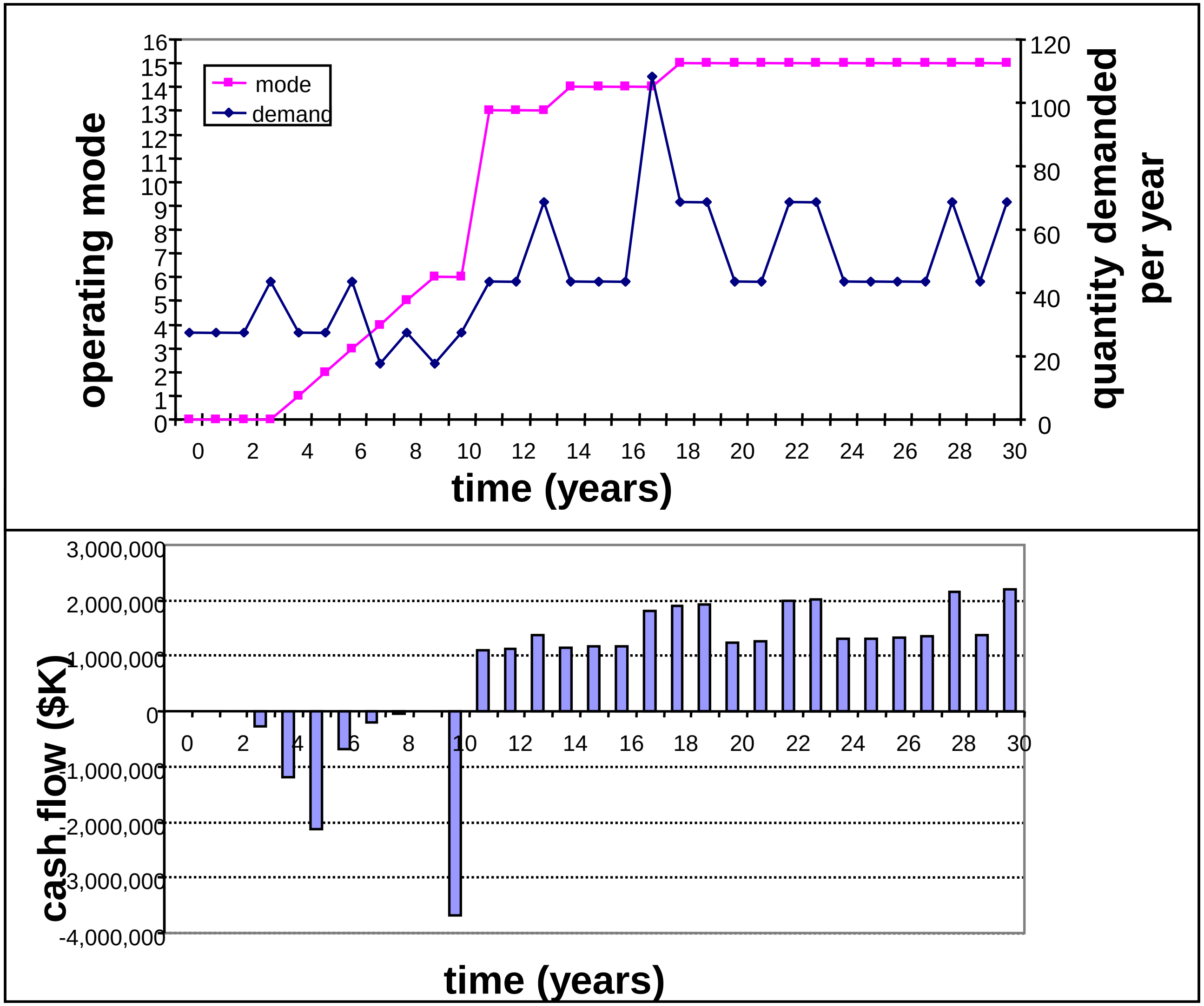


Example: BWB

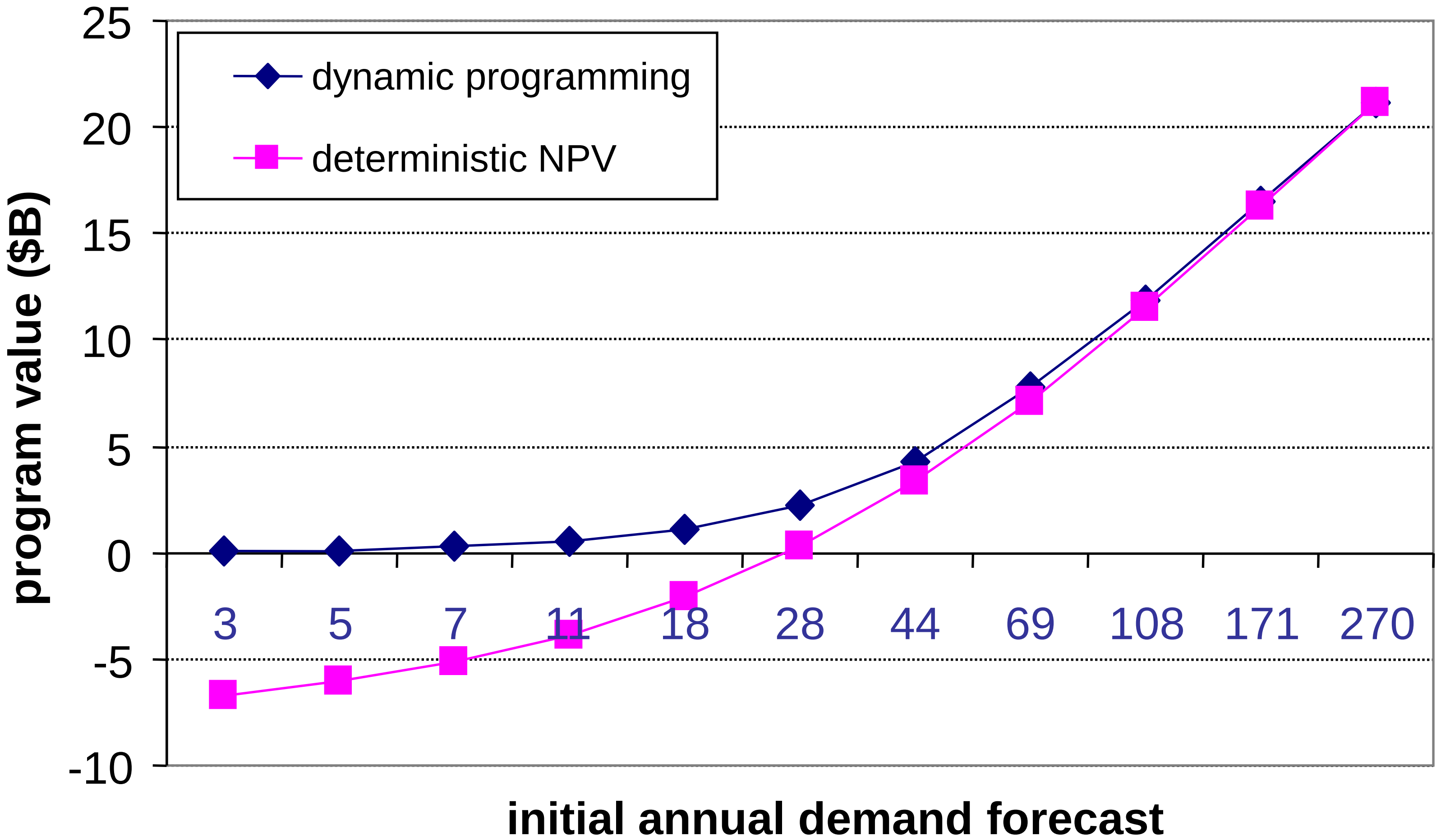
- Blended-Wing-Body (BWB):
  - Proposed new jet transport concept
- 250-seat, long range
- Part of a larger family sharing common centerbody bays, wings, ...



BWB Example: Simulation Run



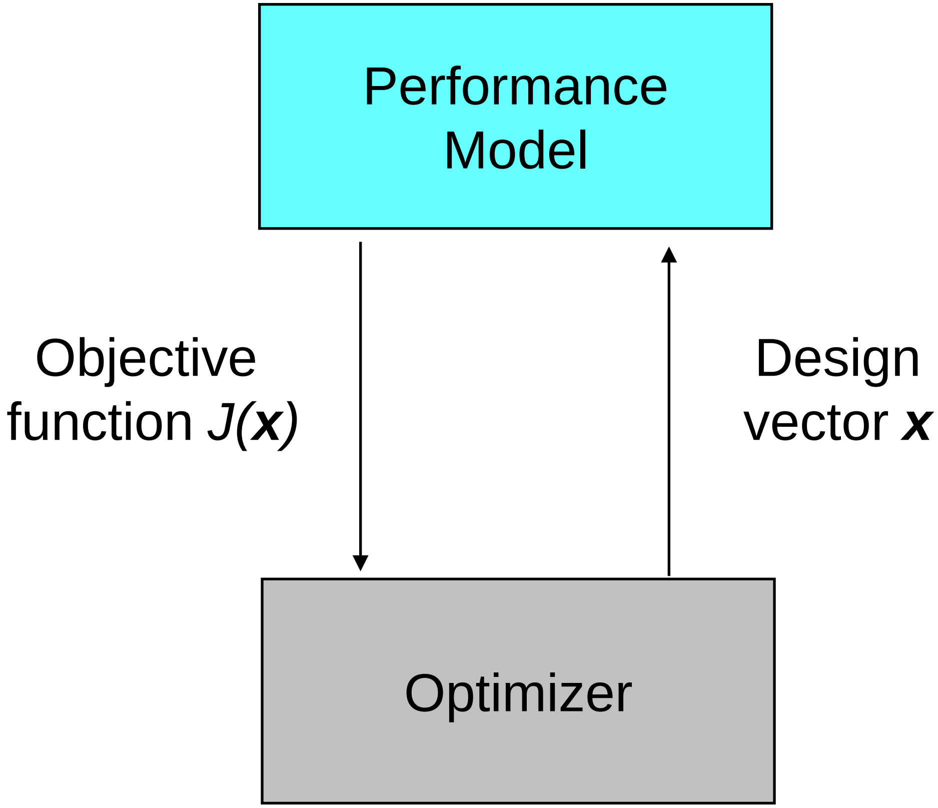
BWB Example: Importance of Flexibility



At baseline of 28 aircraft, DP value is $2.26B versus deterministic value of $325M

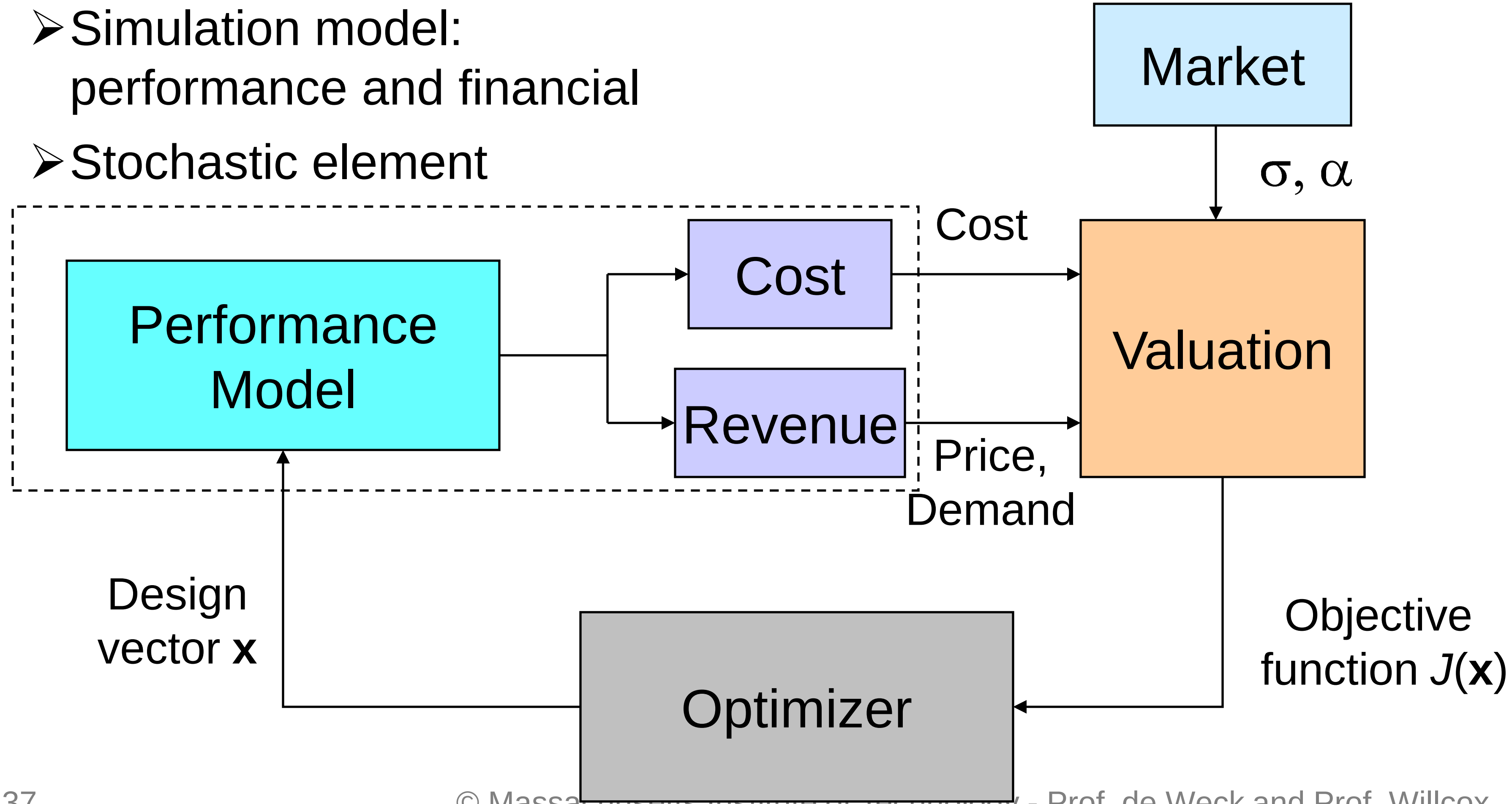
Traditional Design Optimization

- Objective function: usually minimum weight
- Design vector: attributes of design, e.g. planform geometry
- Performance model: contains several engineering disciplines



Coupled MDO Framework

- Objective function: value metric, e.g. NPV
- Simulation model: performance and financial
- Stochastic element



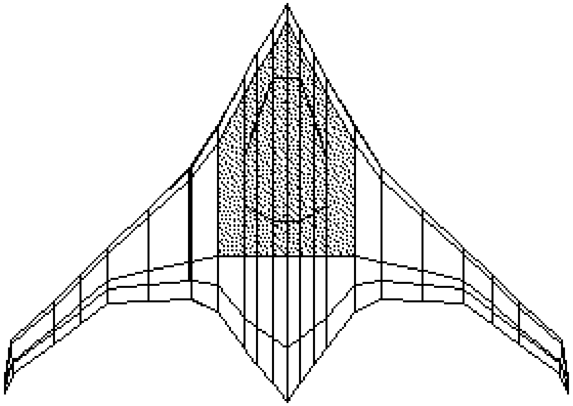
Value-Based Optimization Results

- Boeing BWB case study
  - 475 passengers, 7800 nmi range
  - Baseline: optimized for minimum GTOW
- Outcomes
  - Comparison of min GTOW and max E[NPV] designs
  - Traditional NPV vs. stochastic E[NPV]
  - Effect of range requirement on program value
  - Effect of speed requirement on program value

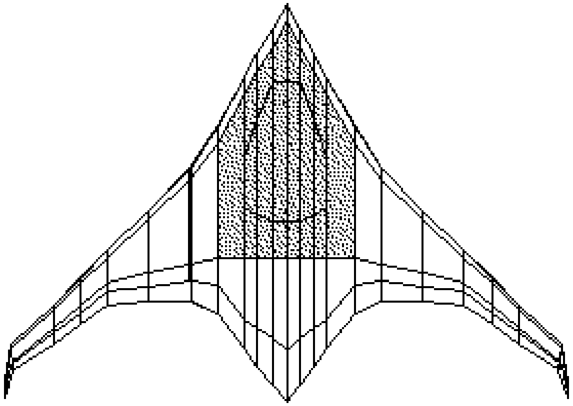
Different Objectives, Different Designs

- New objective results in tradeoff:
  - Lower structural weight, lower cost
  - Higher fuel burn, lower price
- Net result

  2.3% improvement in value
- Overall design very similar
  - Constrained to satisfy design requirements
  - Unable to move dramatically in design space



Minimum-GTOW planform

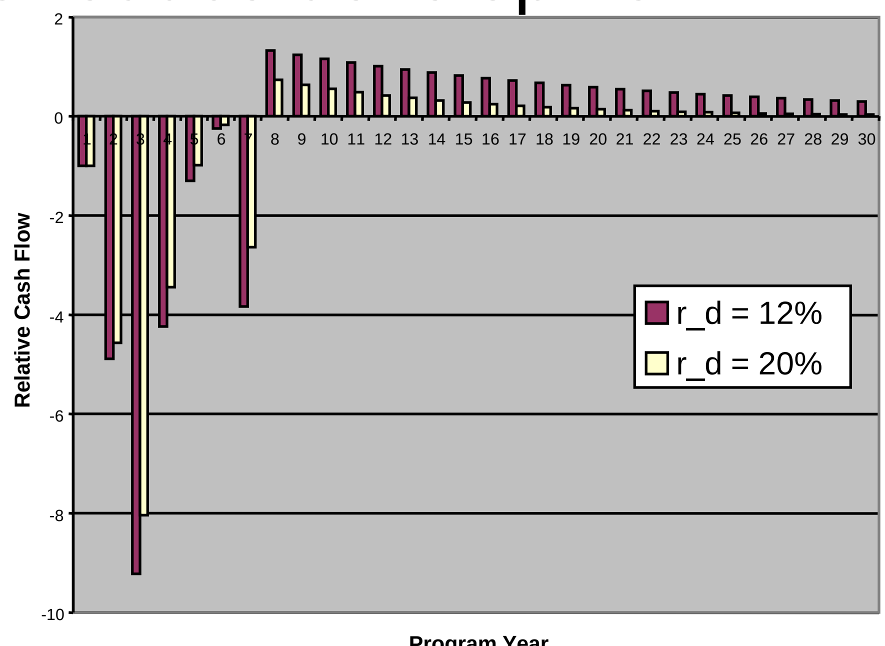


Maximum-value planform

Deterministic vs. Stochastic Valuation

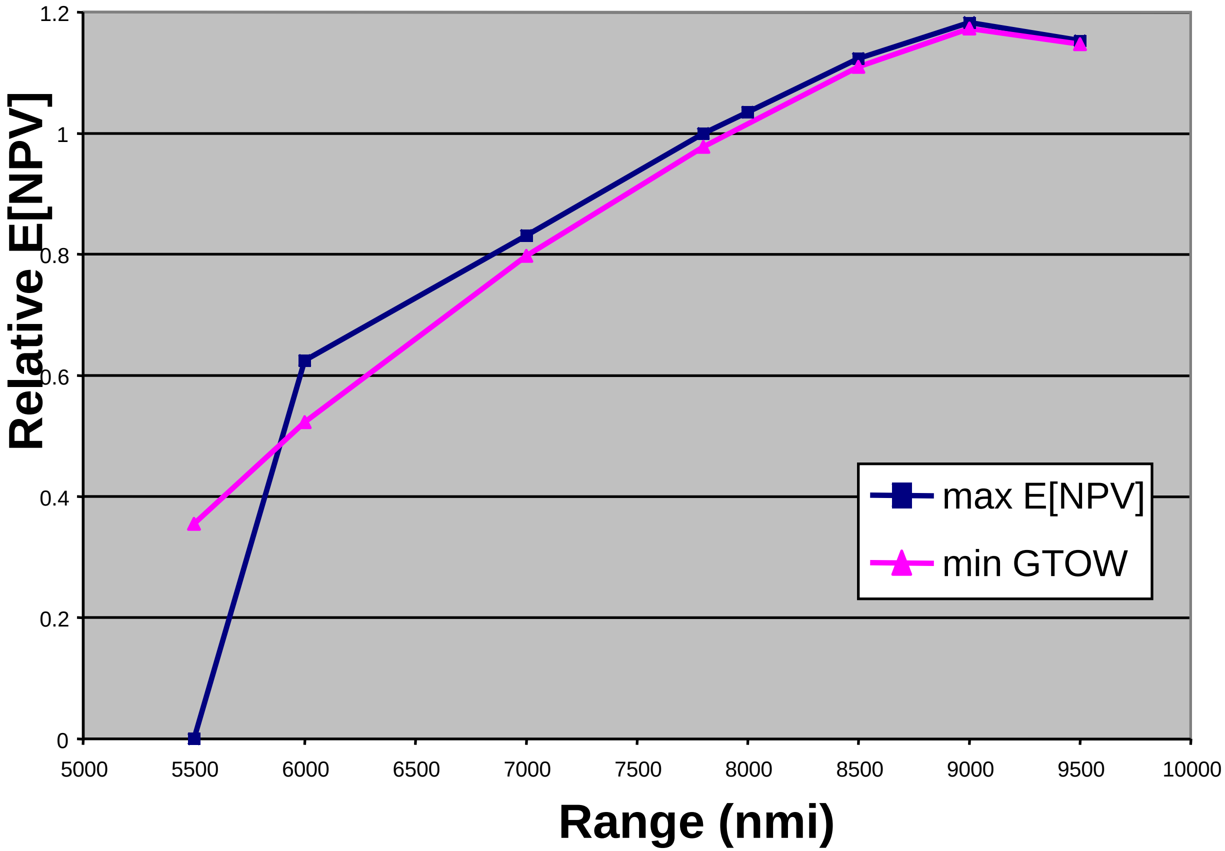
- Discount rates: 12% and 20%
  - Computational expense reduced, but NPV results are negative
  - E[NPV] for 12% design = 0.58% decrease
  - E[NPV] for 20% design = 3.7% decrease

  } relative to max-E[NPV] design
- High-r_d drives design to reduce development costs
- *Traditional NPV not appropriate*
  - *As valuation metric*
  - *As optimization objective*



Range Specification

- Comparison of min-GTOW and max-E[NPV] design solutions
- E[NPV] for varying ranges relative to max-E[NPV] design



Design decisions based on understanding of E[NPV] impact

Speed Specification

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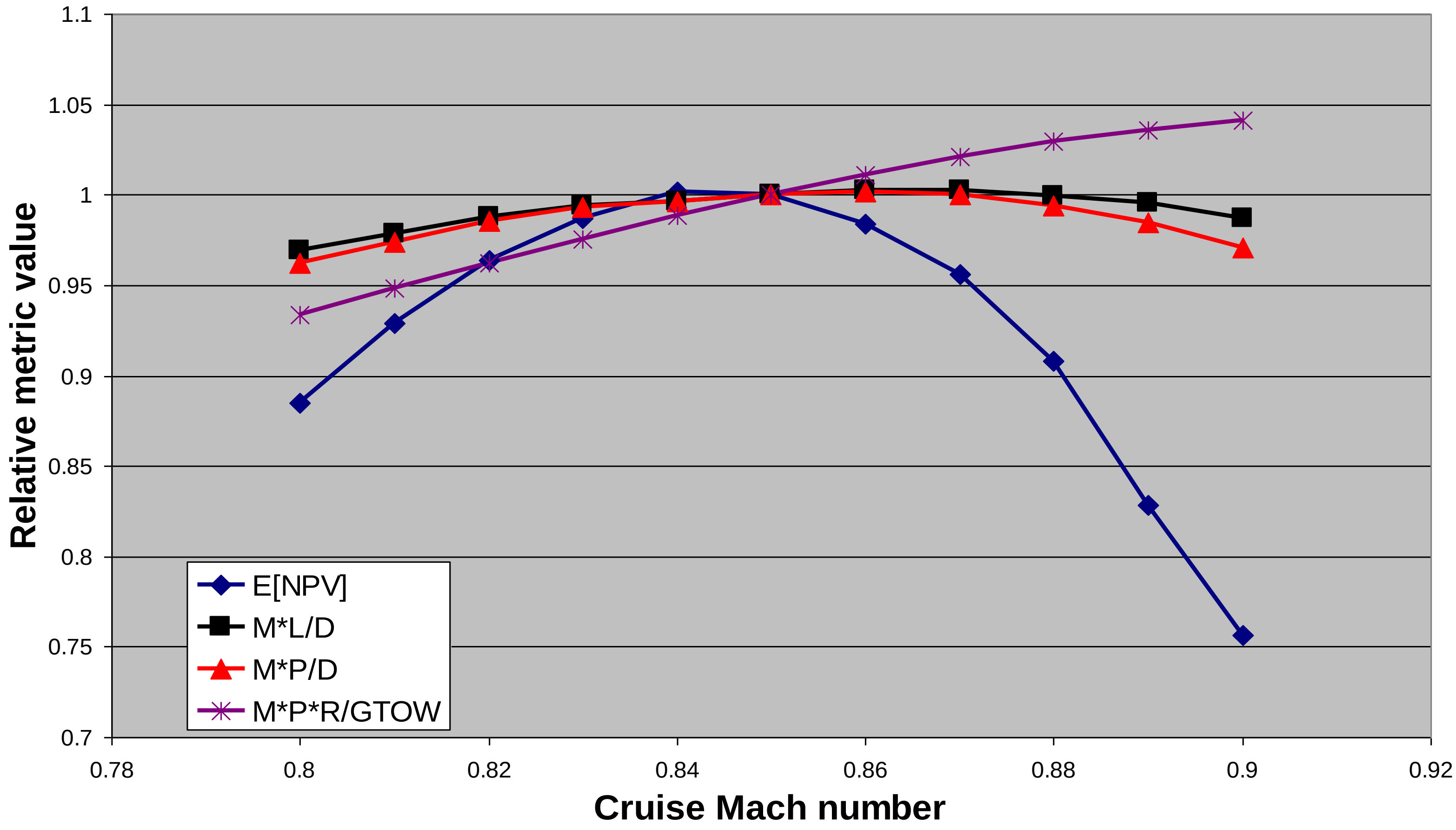
- Comparison of E[NPV] and other metrics for varying speeds



Lecture Summary

- Designing for value is crucial: for a program to be successful, we cannot focus exclusively on performance
- The definition of value is flexible, and will vary depending on the application and on your interest as a stakeholder
- Financial metrics can be used to quantifying value, but use caution in your choice of value objective function
- Cost and revenue are difficult to model – often use empirical data
- It is important that uncertainty and risk are handled appropriately
- There is much work to be done on this issue

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Schaufele, R., *The Elements of Aircraft Preliminary Design*, 2000.

System Cost Modeling

This section will:

- present a process for obtaining system cost estimates, particularly for space systems
- provide cost-estimating relationships
- describe how to assess uncertainty in cost estimates
- provide a specific example: optical systems cost

dWo, 5-6-2002

Cost Breakdown Structure (CBS)

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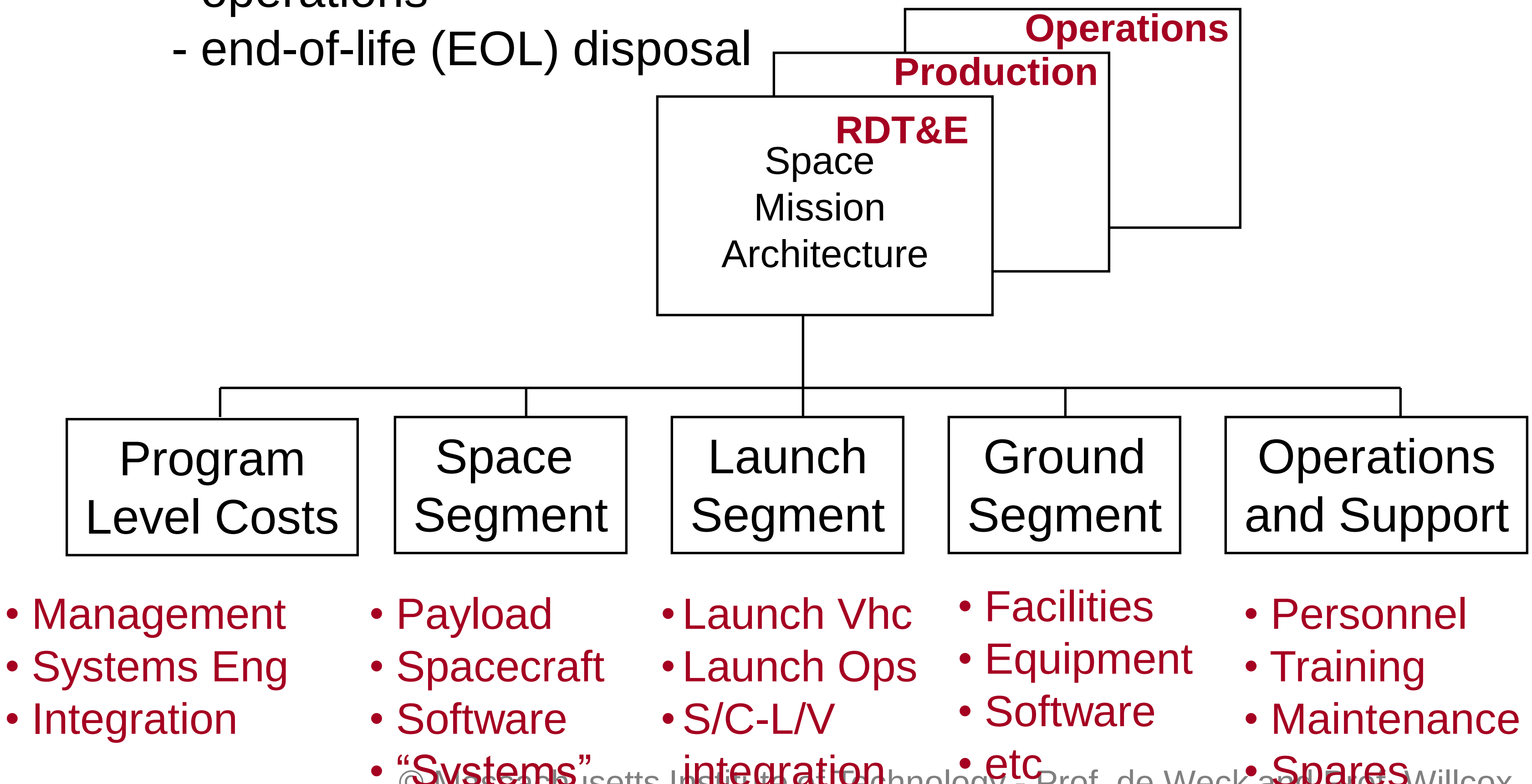
Organizational Table that collects costs, covers:

- research, development, test and evaluation (RDT&E)
- production, including learning curve effects
- launch and deployment
- operations
- end-of-life (EOL) disposal



Cost Estimating Methods

Basic techniques to develop Cost Models:

(1) Detailed bottom-up estimating
- identify and specify lower level elements
- estimated cost of system is Σ of these
- time consuming, not appropriate early, accurate

(2) Analogous Estimating
- look at similar item/system as a baseline
- adjust to account for different size and complexity
- can be applied at different levels

(3) Parametric Estimating
- uses Cost Estimation Relationships (CER's)
- needed to find theoretical first unit (TFU) cost

Parametric Cost Models

Are most appropriate for trade studies:

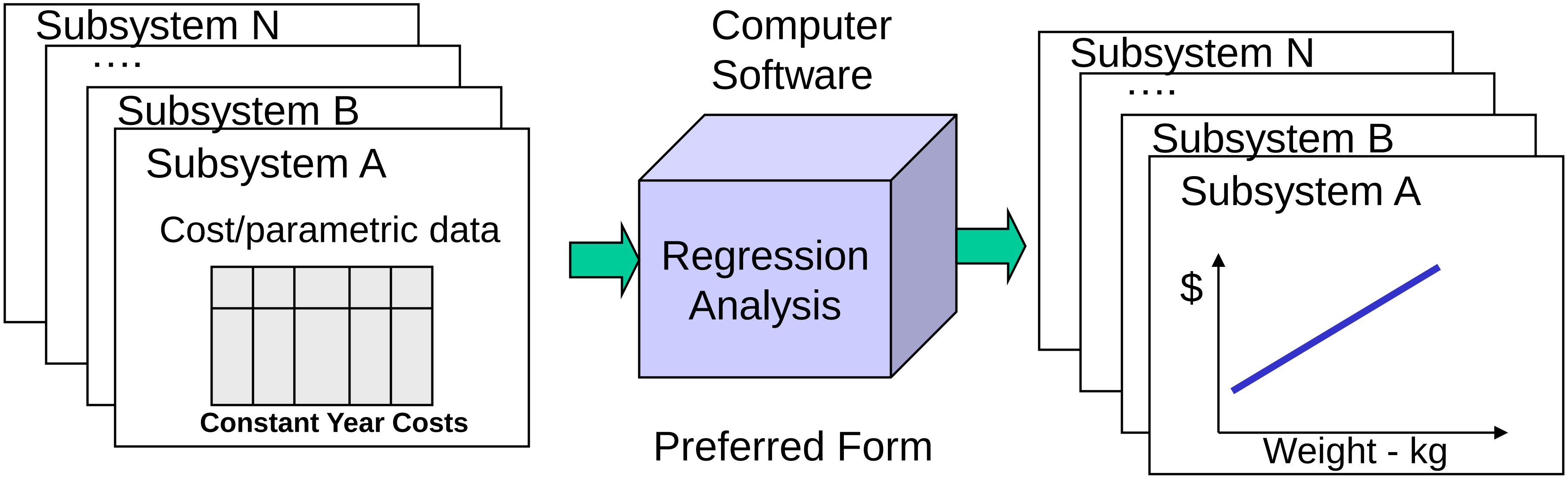
Advantages:

- less time consuming than traditional bottom-up estimates
- more effective in performing cost trades
- more consistent estimates
- traceable to specific class of (space) systems

Major Limitations:

- applicable only to parametric range of historical data
- lacking new technology factors, adjust CER to account for new technology
- composed of different mix of “things” in element to be costed
- usually not accurate enough for a proposal bid

Process for developing CER's



Preferred Form

$$\$ = AW^b$$

Key statistics: R^2, ρ
Standard Error: RMS, σ

Step 1
Develop Database File

Step 2
Apply Regression Analysis

Step 3
Obtain CER's and Error Statistics

(Cost Model Assumption)

Adjustment to constant-year dollars

It is critical that cost estimated be based on a constant-year dollar bases. Reason: INFLATION

E.g. All costs are adjusted to FY92 (“Fiscal Year 1992”)

$$C_Y = R \cdot C_{Y-N}$$

Past Years

Use actual inflation numbers

$$R = \underbrace{1.040}_{FY92} \underbrace{1.037}_{FY93} \underbrace{1.034}_{FY94} = 1.115$$

Convert Oct-1991 cost to Oct-1994 costs

Future Years

$$R = \left(1 + i_{RATE}\right)^N$$

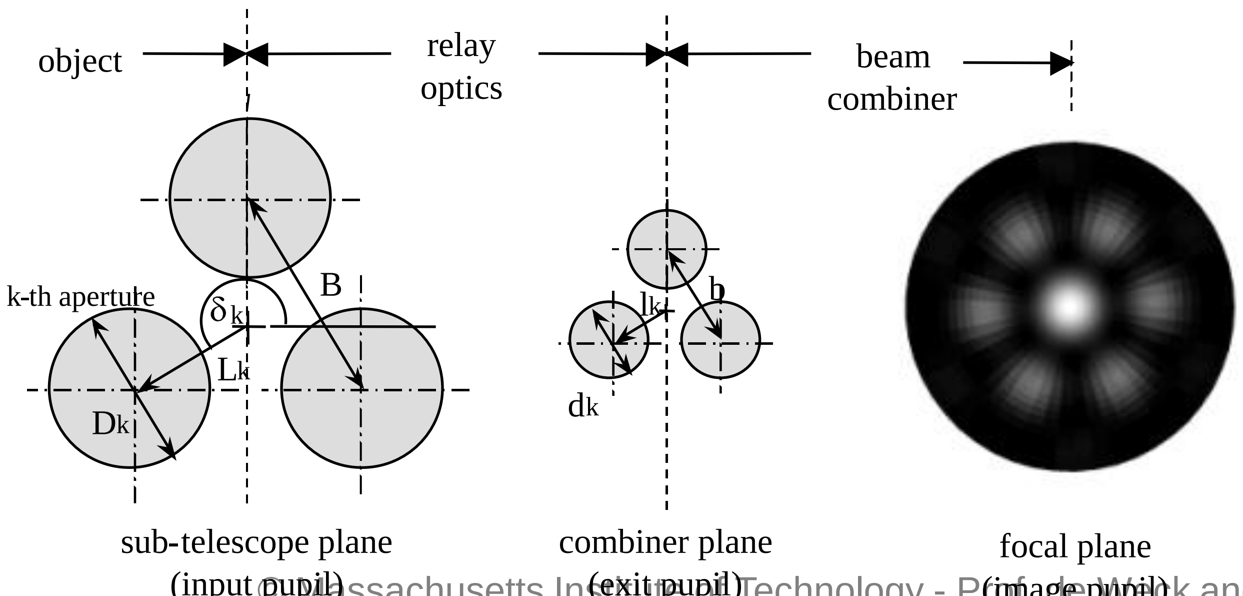
Use forecasted inflation numbers e.g. 3.1% yearly inflation in U.S.

$ 1M in FY 1980 corresponds to $ 2.948M in FY 2005 (projected)

See Table 20-1 on handout

Case: Modular Optics Cost Modeling

- Investigate economical viability of modular optics given performance constraints
- Focus on monolithic Cassegrain telescopes versus Golay-3 design
- Use real data and experience from ARGOS



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Literature Search

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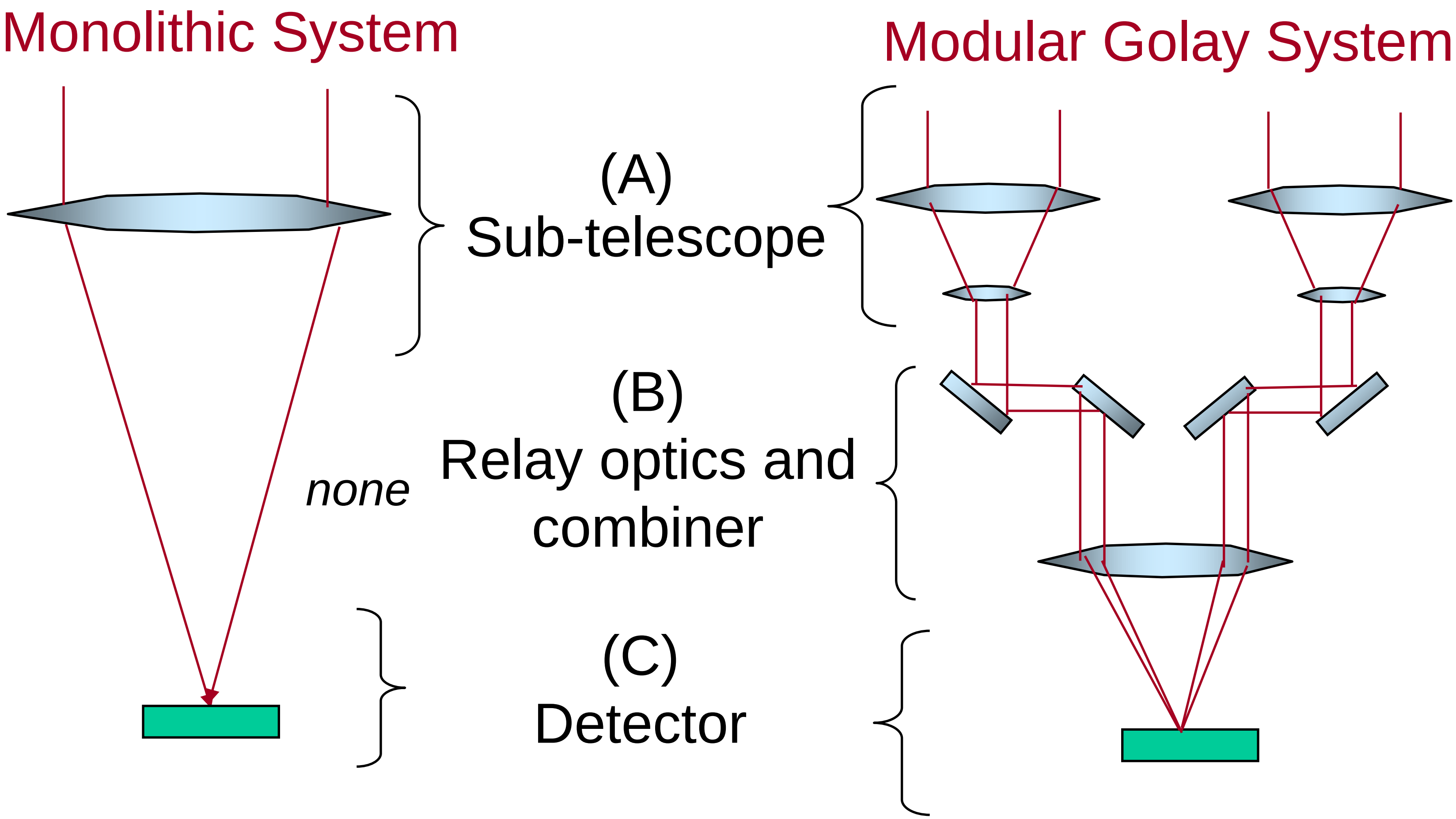
Kahan, Targrove, “Cost modeling of large spaceborne optical systems”, SPIE, Kona, 1998

Humphries, Reddish, Walshaw,”Cost scaling laws and their origin: design strategy for an optical array telescope”, IAU, 1984

Meinel, “Cost-scaling laws applicable to very large optical telescopes”, SPIE, 1979

Meinel’s law: $$S = 0.37 \cdot D^{2.58} \quad [\text{M\$}]\ (1980)$$

Cost Modeling Approach



Total Cost: $\Sigma_{total} = C_A + C_B + C_C$

Does not include development cost

Cost Estimation Relationships

(A) Optical Telescope Assy: $C_A = L_A \cdot D^{\alpha}$

Modular array telescope: $C_A = \underbrace{\left[L_A \cdot D^{\alpha} \right]}_{\text{TFU}} \cdot N^{B}$

(includes learning curve)

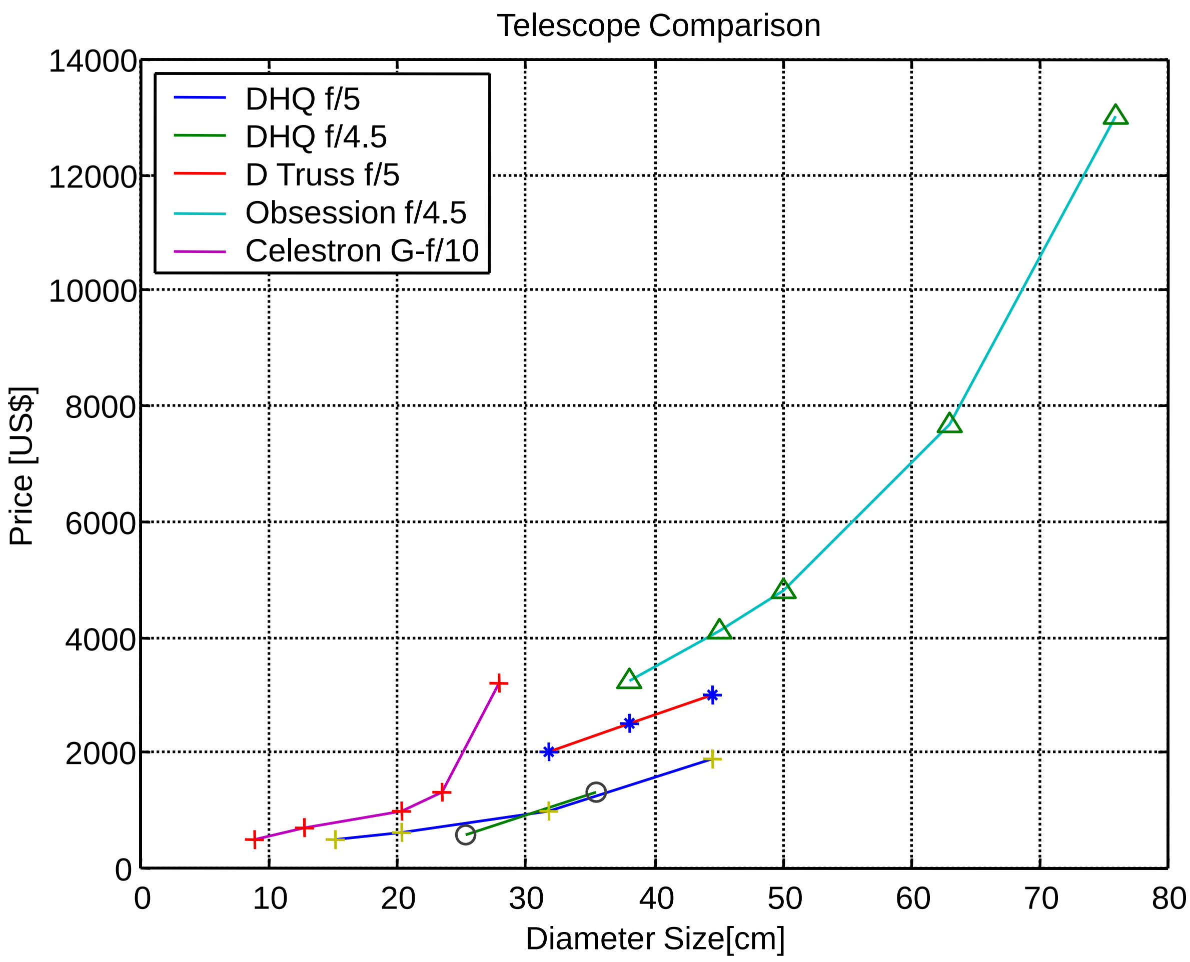
$$B = 1 - \left[\log \ 100\% / S \ \ / \log 2 \right]$$

(B) Relay & Combining Optics: Use ARGOS cost database

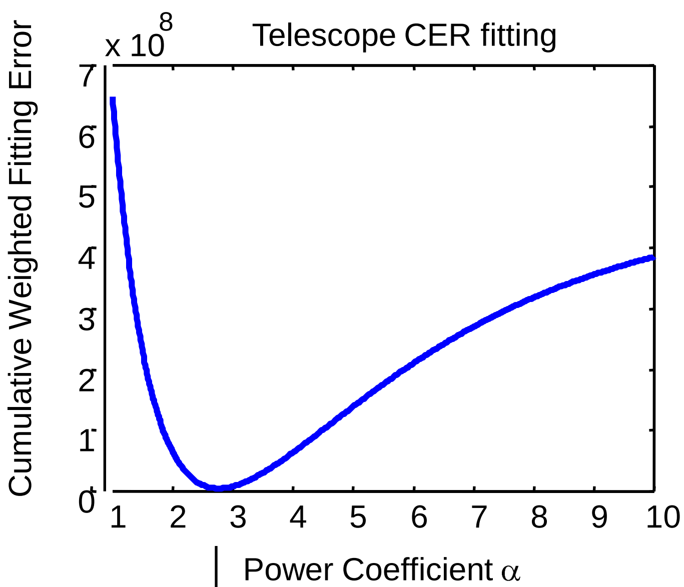
(C) Detector: CCD: $C_c = L_c \cdot \sqrt{n_{pix}}^{\alpha}$

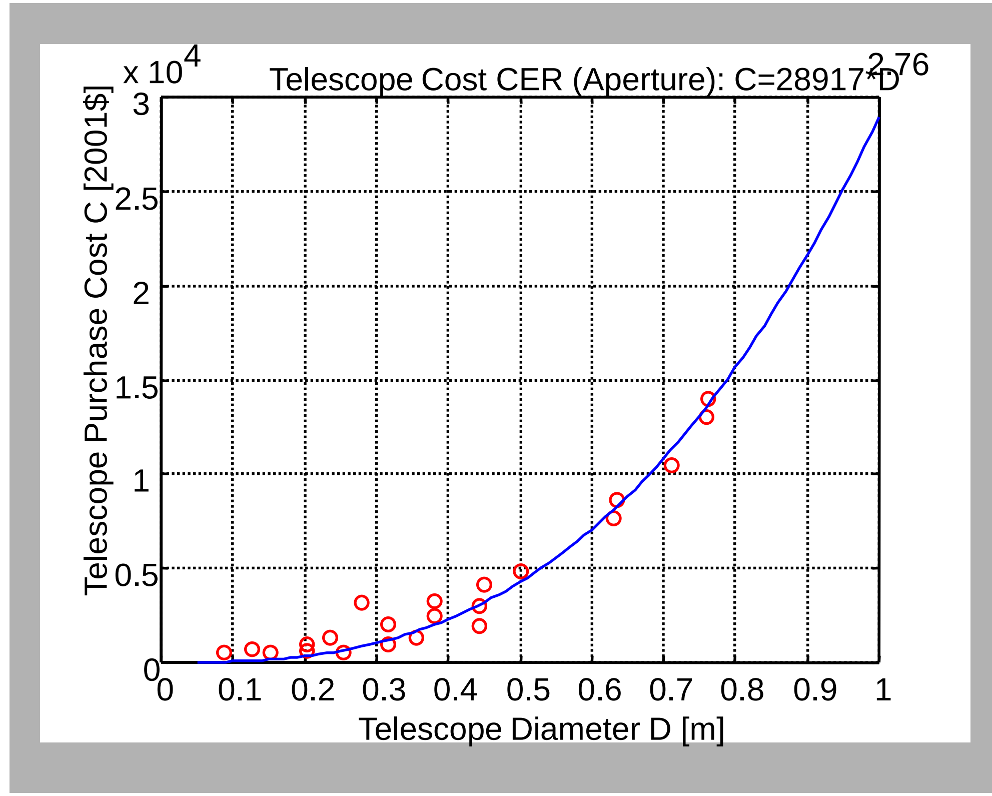
Next Step: Need to determine coefficients based on available commercial pricing data

Small Amateur Telescopes (I)



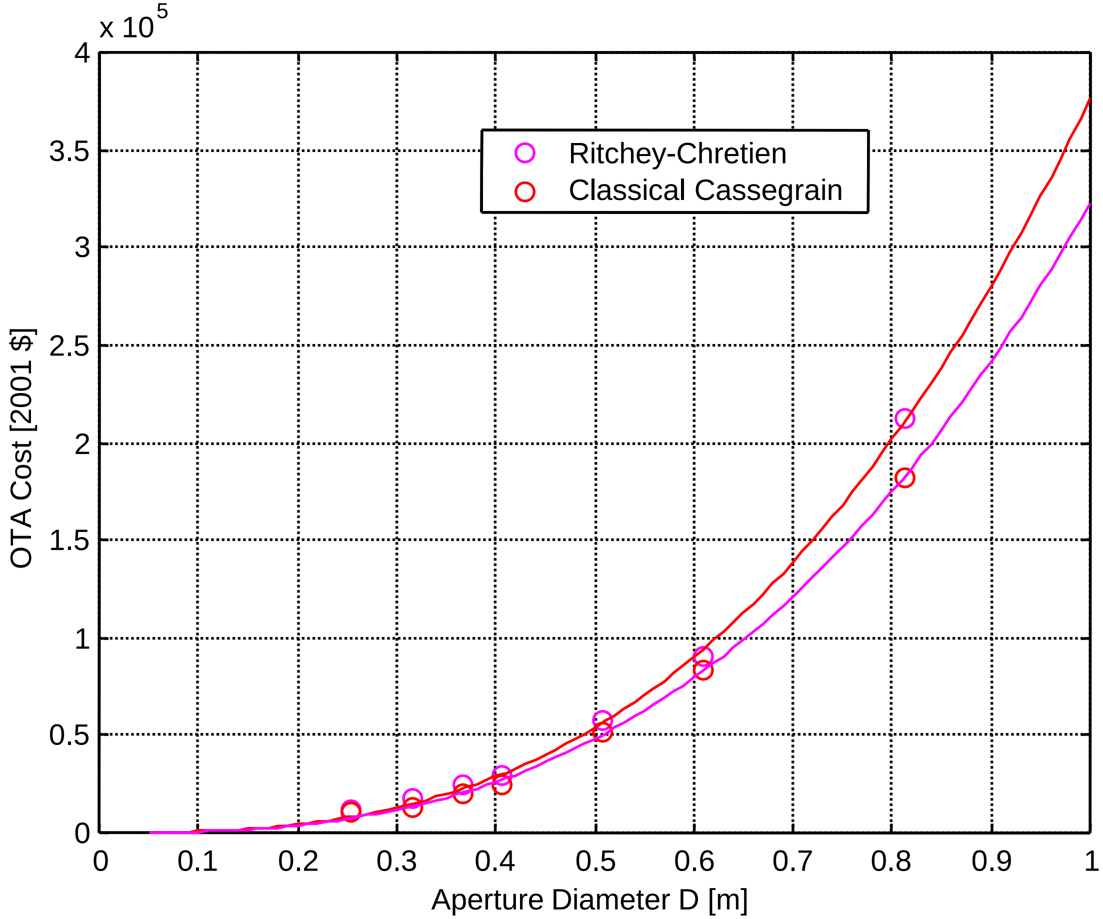
Small Amateur Telescopes (II)





Minimum yields best CER fit exponent α=2.76

Professional Telescope OTA cost



CERs for

Ritchey-Chretien

$$C_{RC} = 376000 \cdot D^{2.80}$$

Classical Cassegrain

$$C_{CC} = 322840 \cdot D^{2.75}$$

Remarkable Result: virtually identical power law across completely different product lines.

Company: Optical Guidance Systems (http:www.opticalguidancesystems.com)

Relay and Combining Optics

Cost of relay optics depends on:

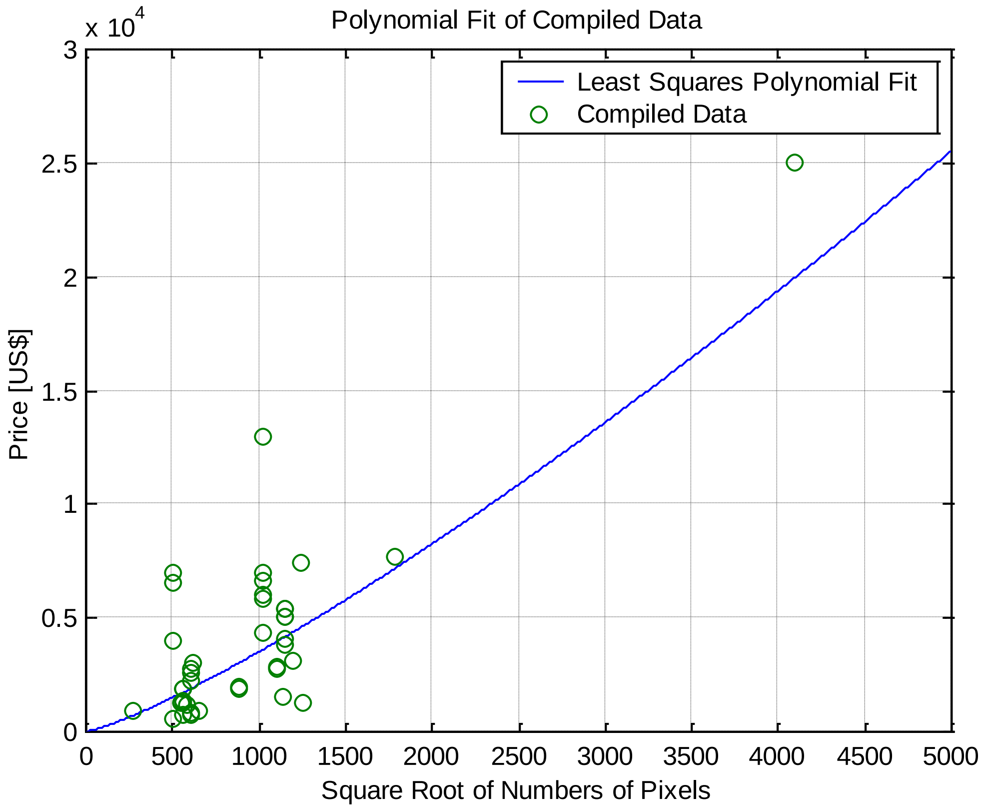
- number and type of actuators: ODL, FSM, active translation stages, active pyramid mirrors
- sensing elements (CCD, quad cells etc)
- aperture magnification m_a
- Quality requirements (RMS WFE)

As interim solution use ARGOS cost database:

Passive Optics: Collimators, Combiner, etc	$ 32,874.-
Active Optics: FSM, Fold Mirrors etc...	$ 18,859.-
About:	$ 50,000.-

$m_a = 10$

CCD Cost Models

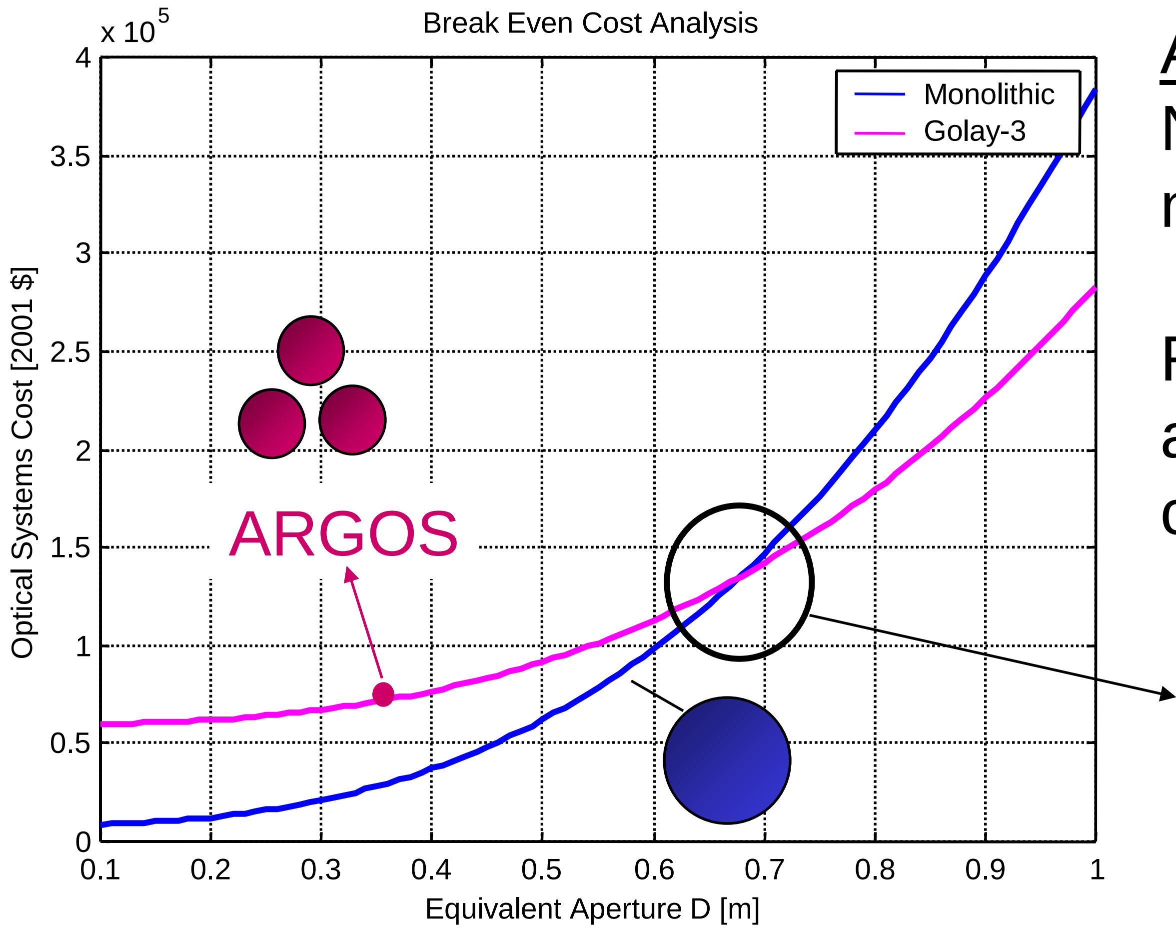


AP-9 (KAF-6303E)

$$C_{CCD} = 0.68 \cdot \sqrt{n_{pix}}^{1.23}$$

It appears that CCD cost also depends on factors other than raw pixel count. Need to investigate.

Break-Even Analysis



Assumptions:
N=3
n_{pix} = 2048

Relay optics and combiner costs fixed

Preliminary Analysis suggest crossover around 0.7 m

ESD.77 / 16.888 Multidisciplinary System Design Optimization
Spring 2010