16.885 Aircraft Systems Engineering

Cost Analysis

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Outline

- Lifecycle cost
- Operating cost
- Development cost
- Manufacturing cost
- Revenue
- Valuation techniques

Lifecycle Cost

Lifecycle :

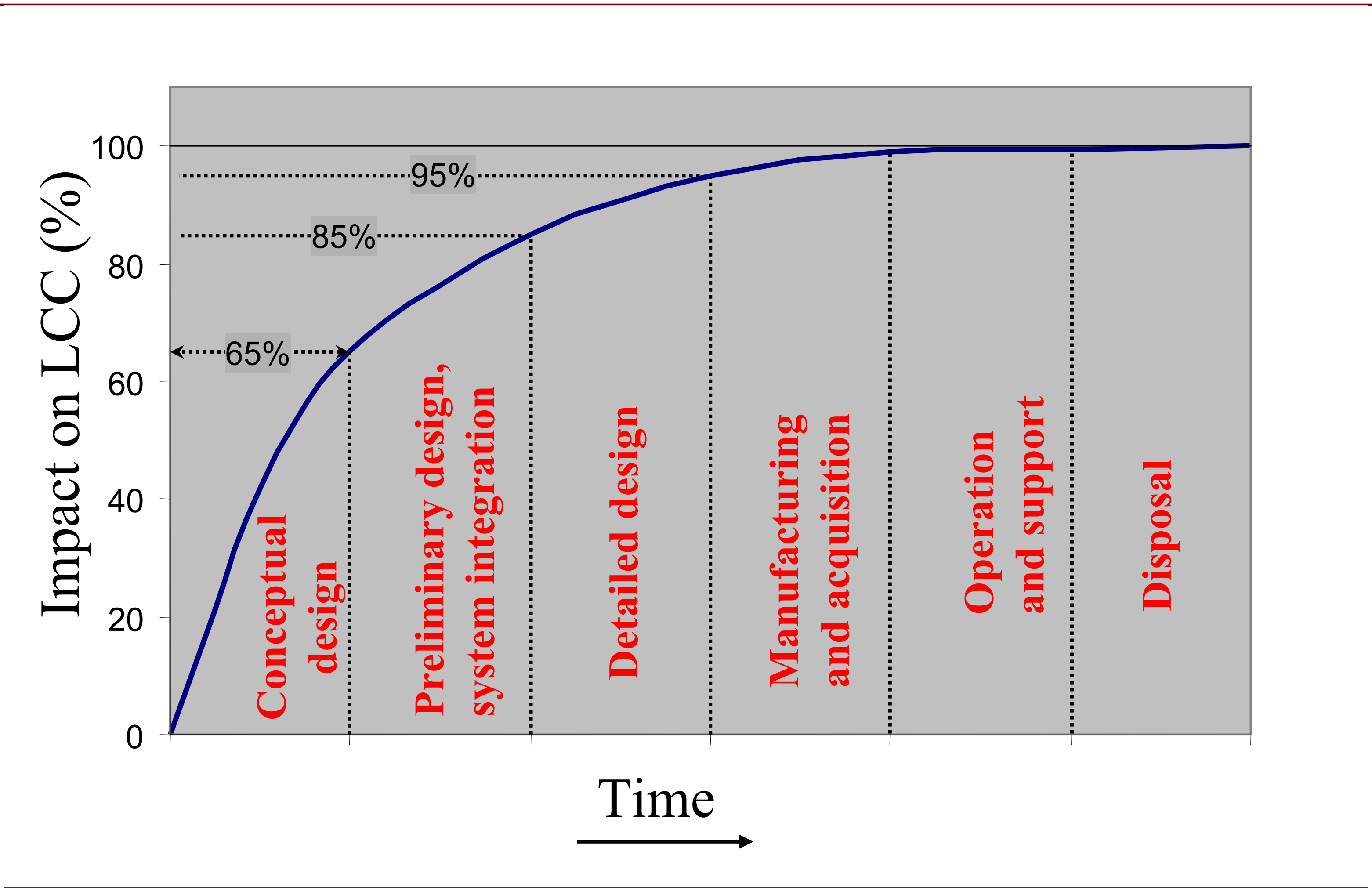
Design - Manufacture - Operation - Disposal

Lifecycle cost :

Total cost of program over lifecycle

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

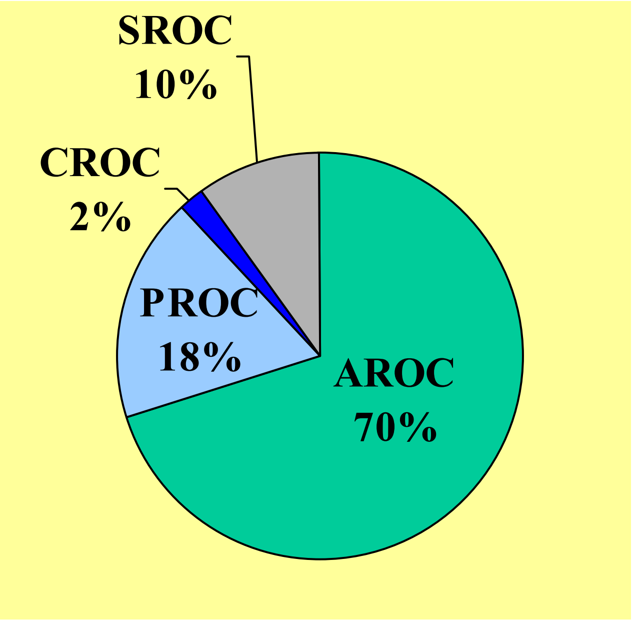
Lifecycle Cost



(From Roskam, Figure 2.3)

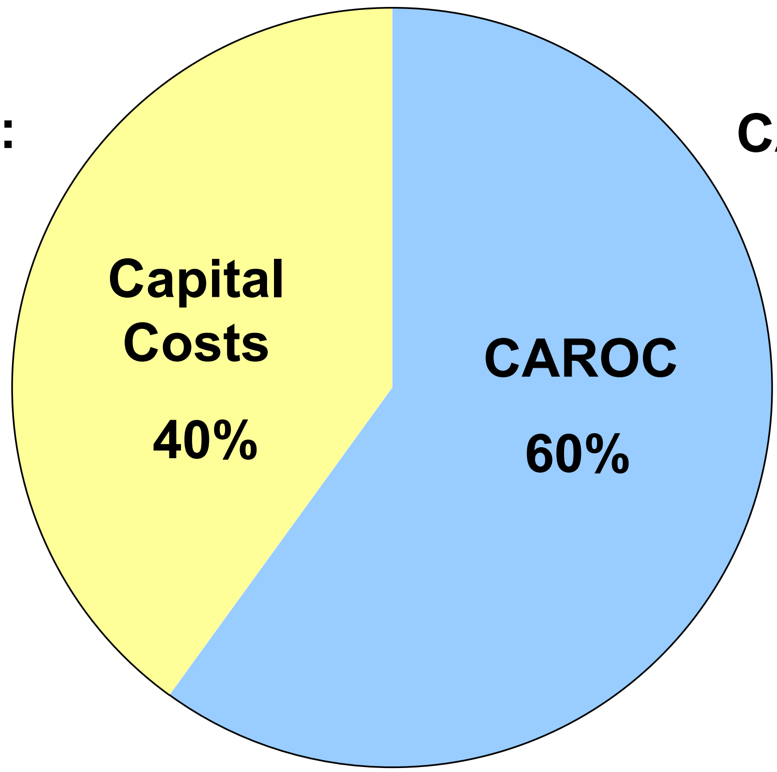
Operating Cost

- Airplane Related Operating Cost (AROC)
- Passenger Related Operating Cost (PROC)
- Cargo Related Operating Cost (CROC)
- Systems Related Operating Cost (SROC)



Airplane Related Operating Costs

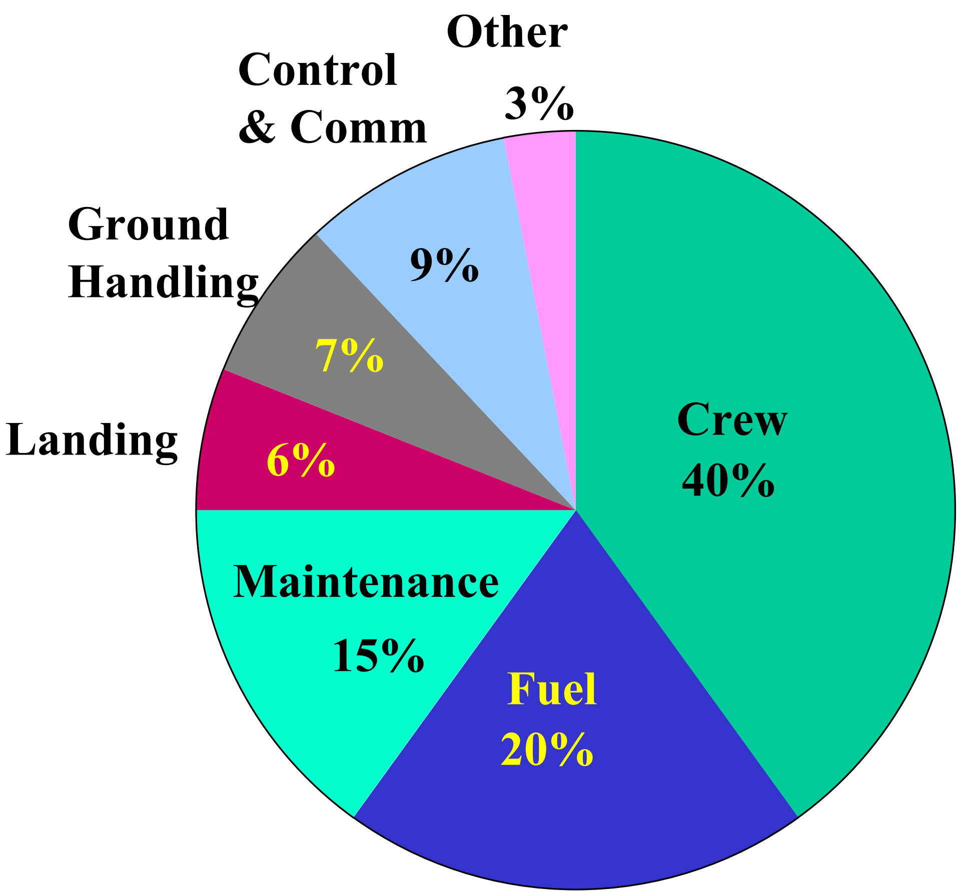
CAPITAL COSTS:
Financing
Insurance
Depreciation



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!

CAROC Breakdown per Trip



Fuel is roughly 20% of 60% of 70% of Total Operating Cost *i.e.* 8%

typical data for a large commercial jet

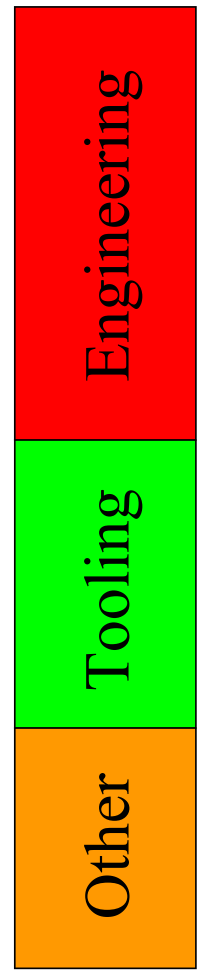
Non-Recurring Cost

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



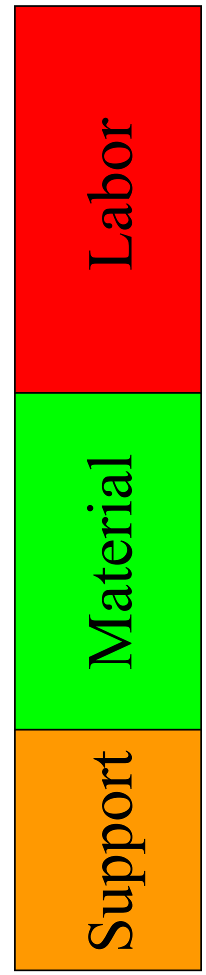
Recurring Cost

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.

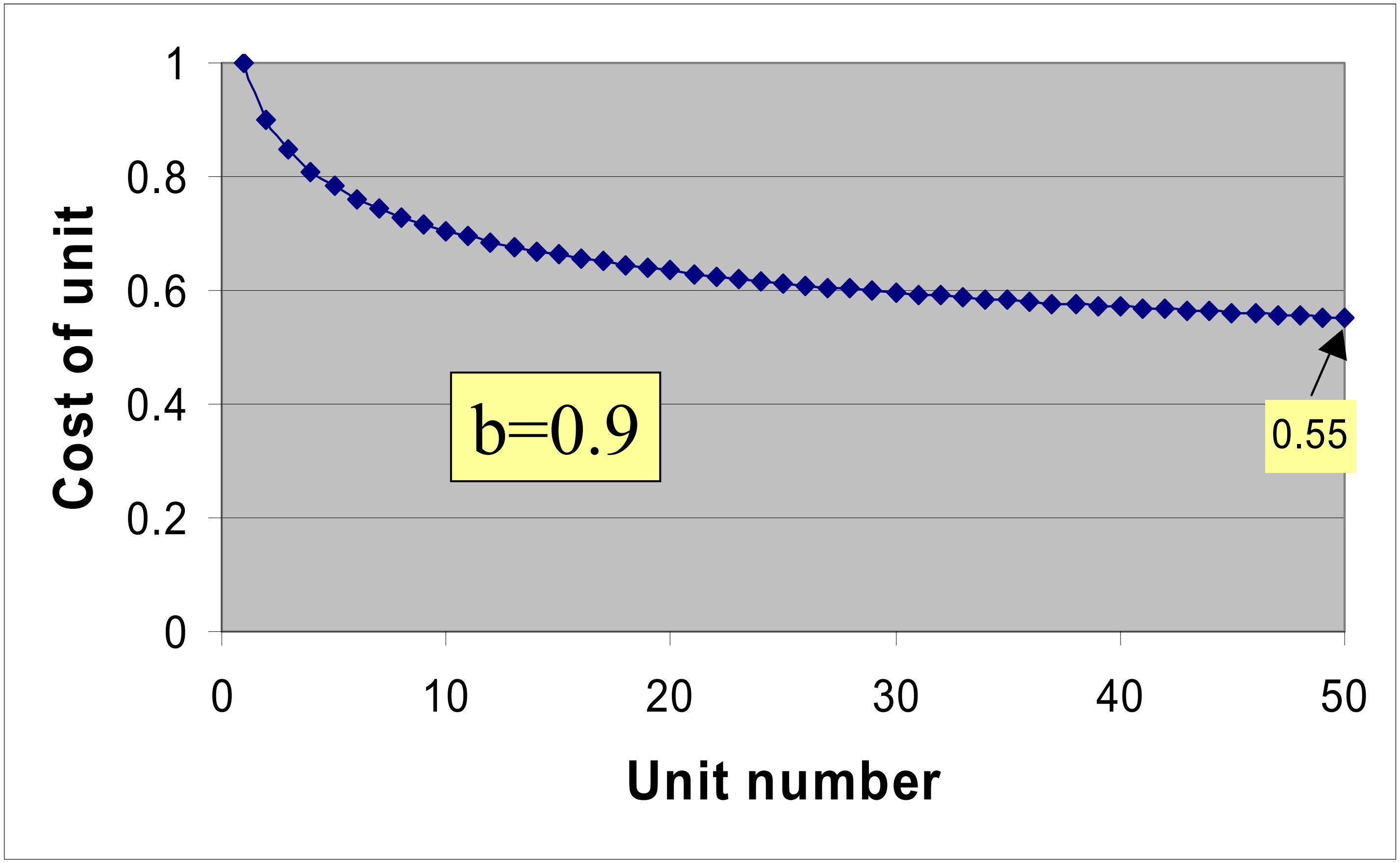
This is the learning curve effect.

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

$$\boxed{Y_x \qquad Y_0 x^n}$$

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

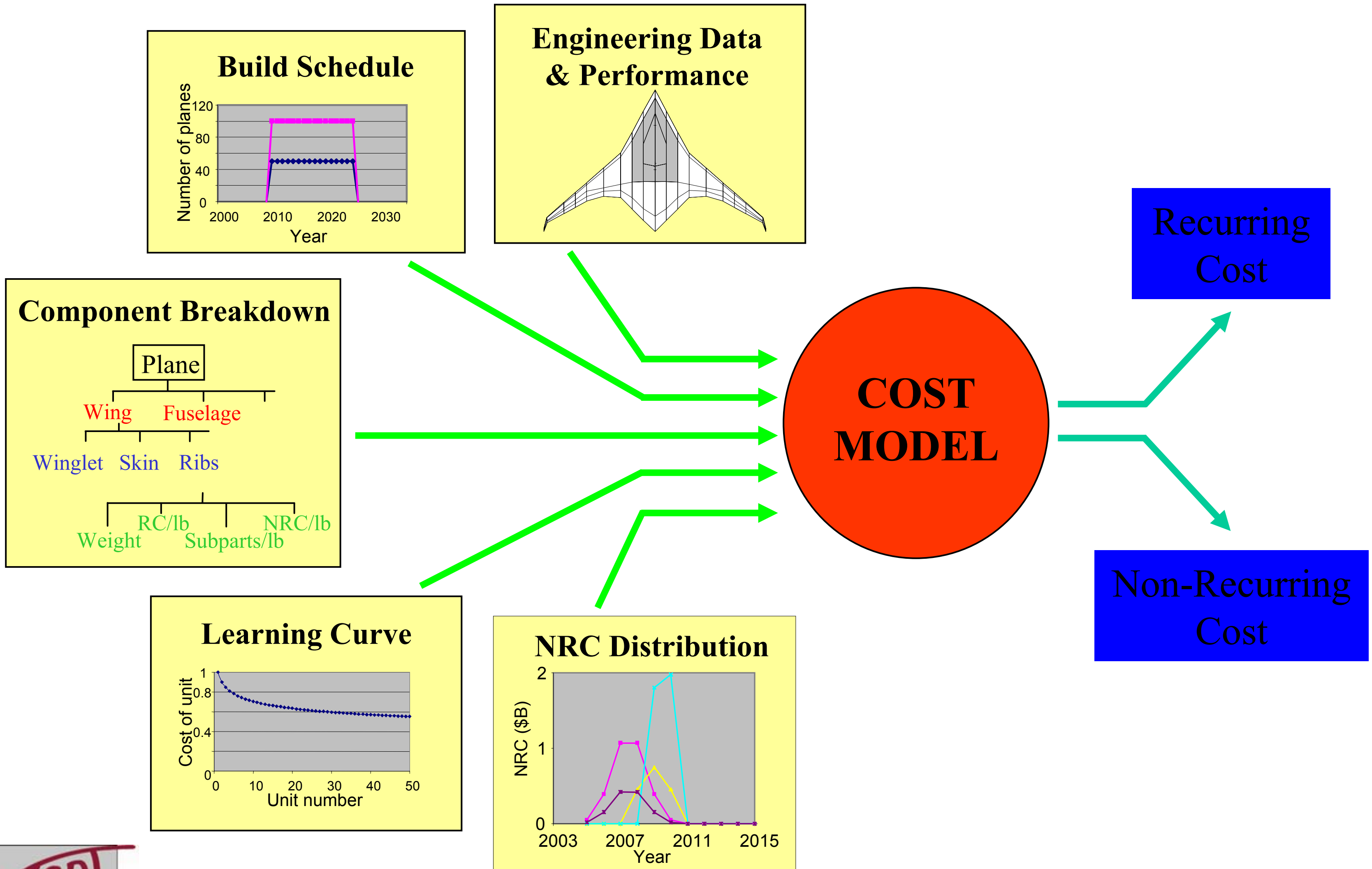
Learning Curve



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

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

Elements of a Cost Model



Typical Cost Modeling

1. Take empirical data from past programs.

2. Perform regression to get variation with selected parameters, *e.g.* cost vs. weight.

3. Apply "judgment factors" for your case. e.g. configuration factors, complexity factors, composite factors.

There is widespread belief that aircraft manufacturers do not know what it actually costs to turn out their current products.

Cost Modeling

- Aircraft is broken down into modules
  - Inner wing, outer wing, …
  - Modules are classified by type
    - Wing, Empennage, Fuselage, …
- ***Cost per pound*** specified for each module type
  - Calibrated from existing cost models
  - Modified by other factors
    - Learning effects
    - Commonality effects
- Assembly & Integration: a separate "module"
- 2 cost categories: development & manufacturing

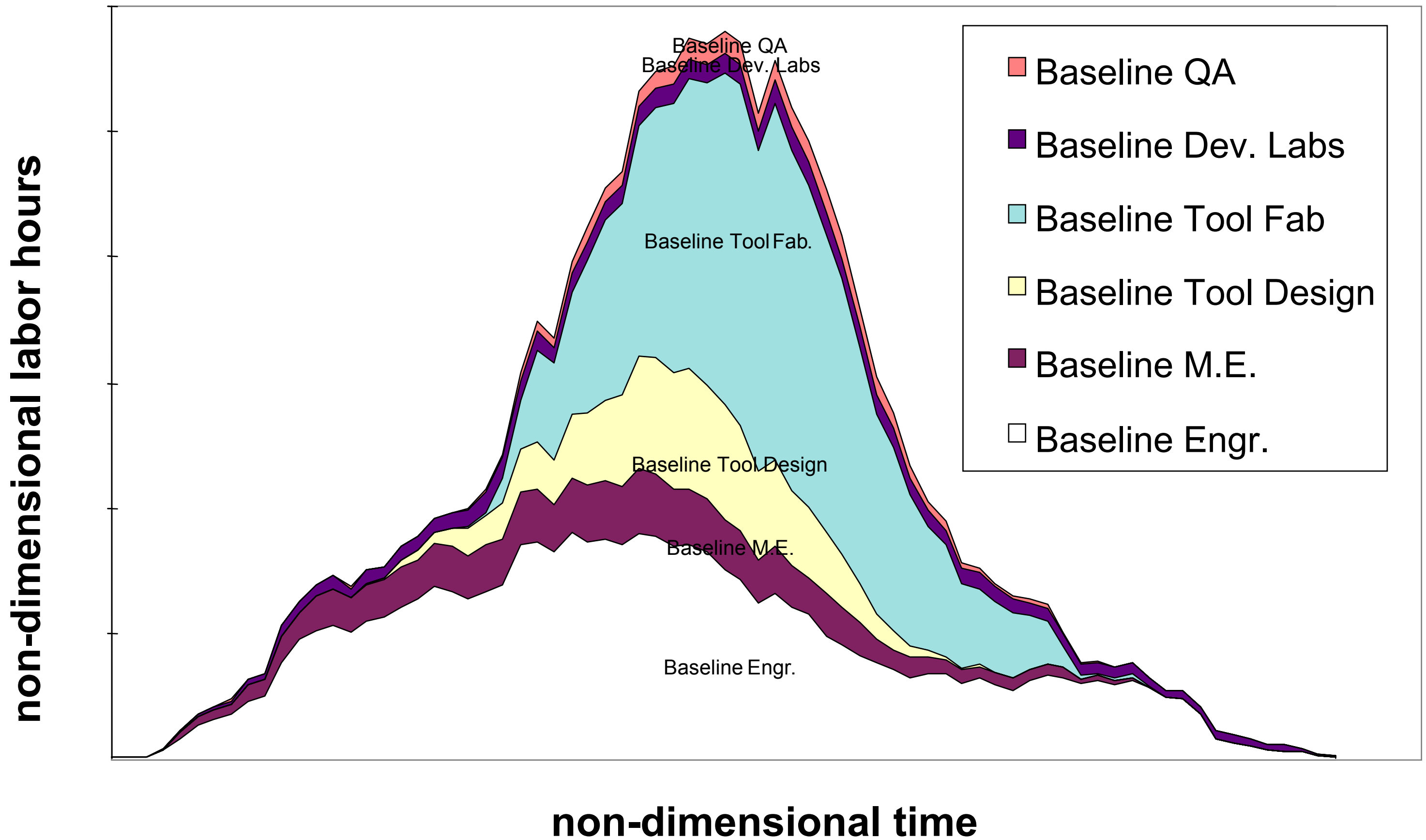
Production run: a collection of modules

Cost Modeling

- **Plane**
  - Centerbody
  - Wing
    - Winglet
    - Outer Wing
    - Inner Wing
      - Identifier
      - Weight
      - Area
      - **RC per pound**
        - Labor
        - Material & Equipment
        - Support
      - Subparts per pound
      - **NRC per pound**
        - Tooling
        - Engineering
        - Other
      - NRC time distribution
    - …
  - Landing Gear
  - Propulsion
  - Systems
  - Payloads
  - Final Assembly

At this level, the degree of detail can range from e.g. "wing" to "rivet".

Development Cost Data



Boeing data for large commercial jet

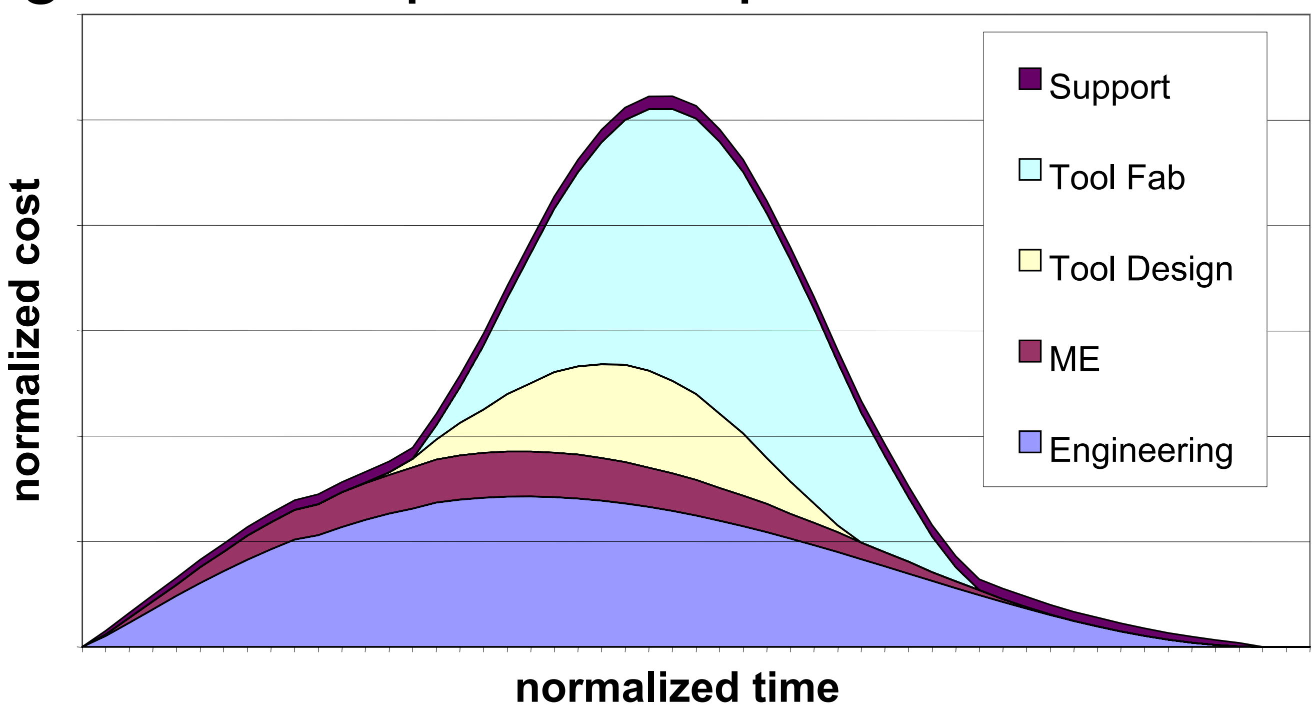
Development Cost Model

- Cashflow profiles based on beta curve:

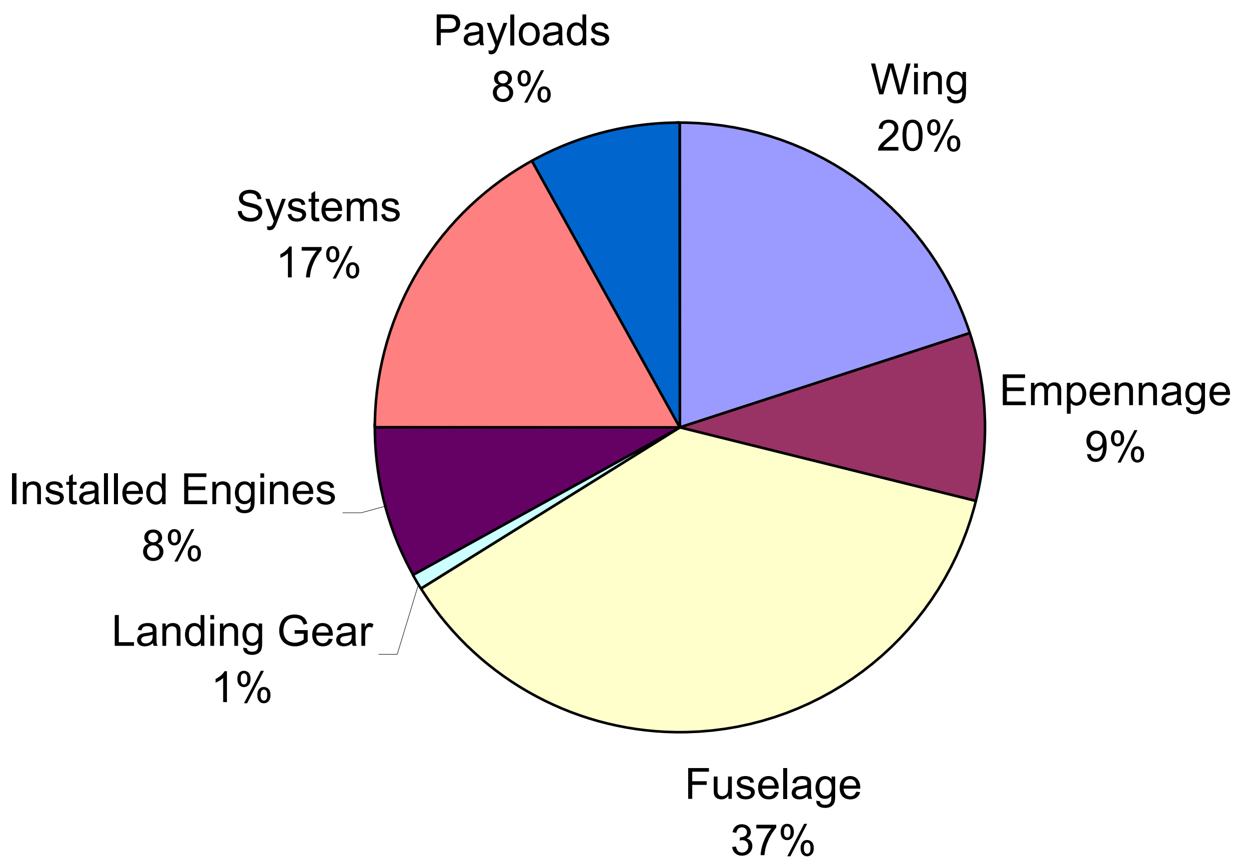
$$c(t) \quad Kt^{\alpha-1}(1-t)^{\beta-1}$$

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

(from Markish)



Development Cost Model



Representative non-recurring cost breakdown by parts for large commercial jet (from Markish).

Development Cost Data

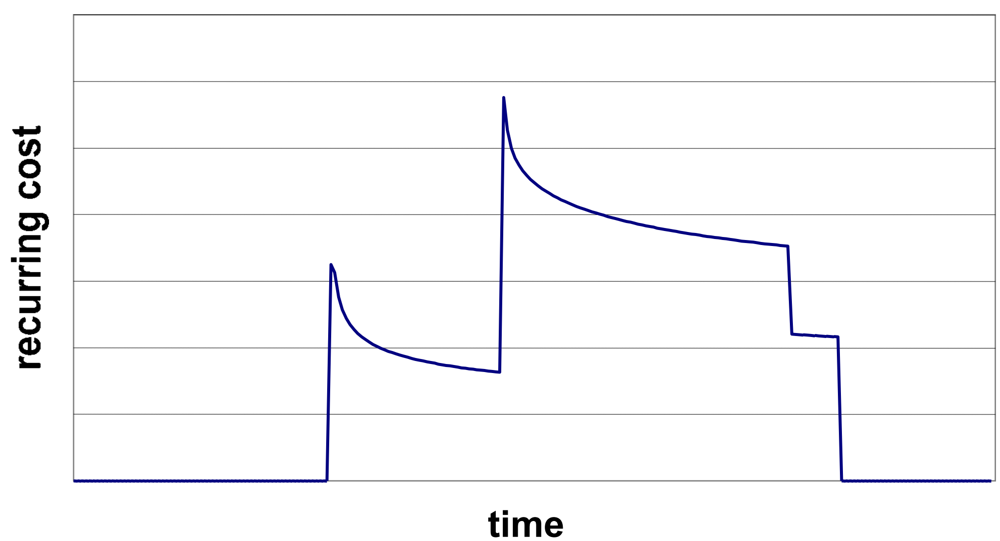
For your reference: $/lb assembled from public domain weight and total cost estimates plus representative NRC breakdown by aircraft part (see Markish).

	Engineering	ME	Tool Design	Tool Fab	Support	Totals
	40.0%	10.0%	10.5%	34.8%	4.7%	100.0%
Wing	$7,093	$1,773	$1,862	$6,171	$833	$17,731
Empennage	$20,862	$5,216	$5,476	$18,150	$2,451	$52,156
Fuselage	$12,837	$3,209	$3,370	$11,169	$1,508	$32,093
Landing Gear	$999	$250	$262	$869	$117	$2,499
Installed Engines	$3,477	$869	$913	$3,025	$408	$8,691
Systems	$13,723	$3,431	$3,602	$11,939	$1,612	$34,307
Payloads	$4,305	$1,076	$1,130	$3,746	$506	$10,763

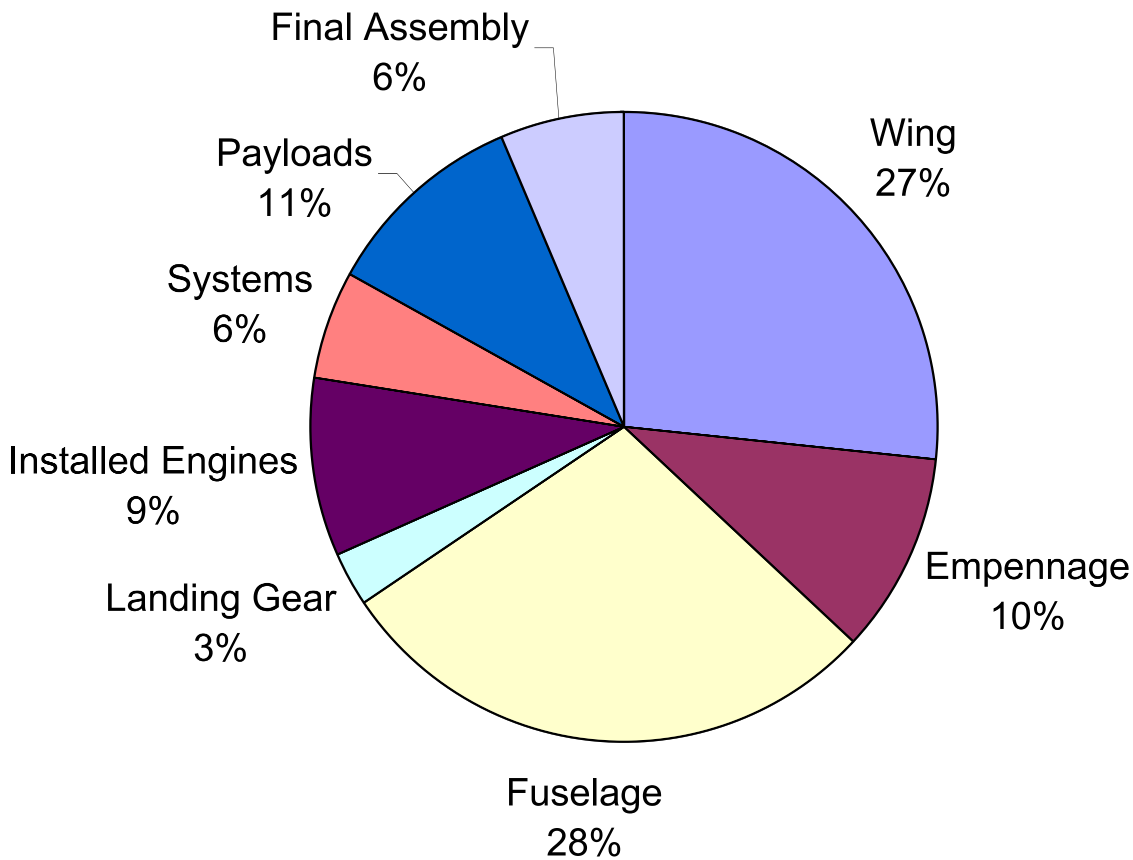
Manufacturing Cost Model

- Aircraft built → modules required
- Modules database
  - Records quantities, marginal costs
  - Apply learning curve effect *by module, not by aircraft*

Labor	Materials	Support
85%	95%	95%



Manufacturing Cost Model



Representative recurring cost breakdown by parts for large commercial jet (from Markish).

Manufacturing Cost Data

For your reference: $/lb values assembled from public domain weight and total cost estimates plus representative RC breakdown by aircraft part (see Markish).

	Labor	Materials	Other	Total
Wing	$609	$204	$88	$900
Empennage	$1,614	$484	$233	$2,331
Fuselage	$679	$190	$98	$967
Landing Gear	$107	$98	$16	$221
Installed Engines	$248	$91	$36	$374
Systems	$315	$91	$46	$452
Payloads	$405	$100	$59	$564
Final Assembly	$58	$4	$3	$65

NASA Cost Models

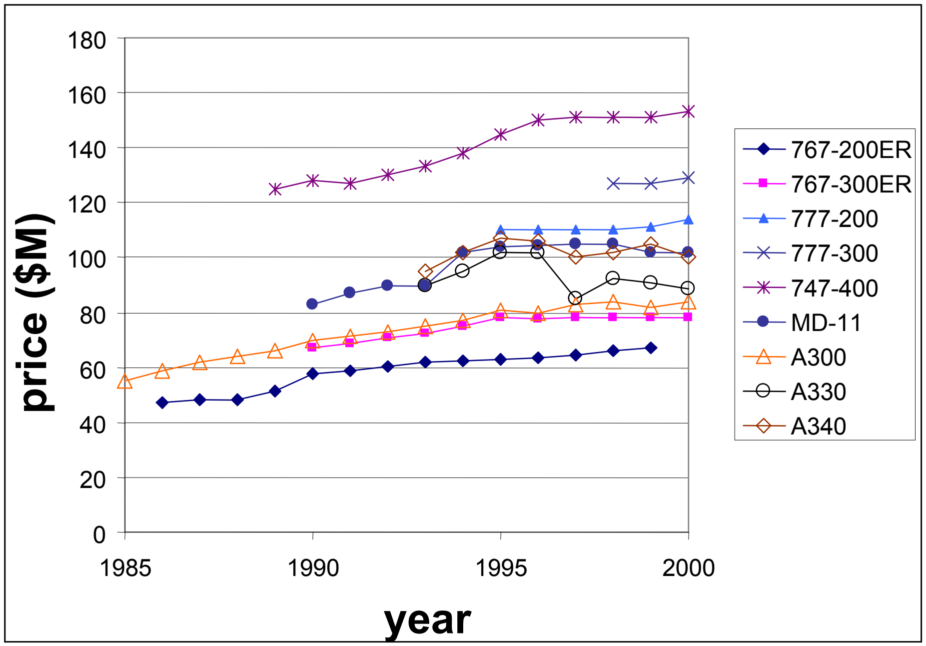
Online cost models available at
http://www.jsc.nasa.gov/bu2/airframe.html

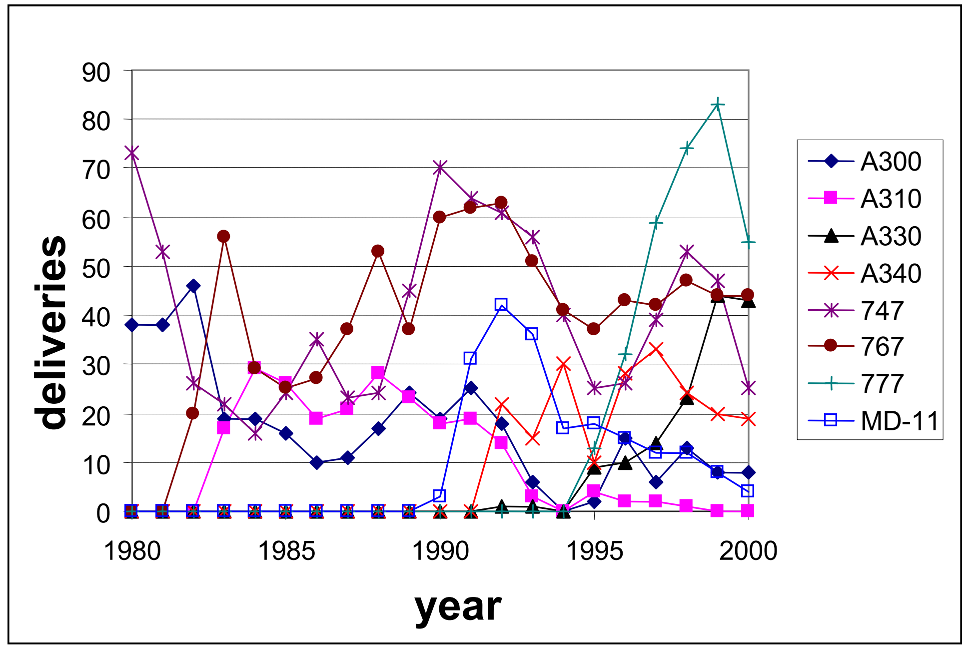
e.g. Airframe Cost Model

- simple model for estimating the development and production costs of aircraft airframes
- based on military jet data
- correlation with empty weight, max. speed, number of flight test vehicles, and production quantity

Revenue Model

Revenue model must predict market price and demand quantity.





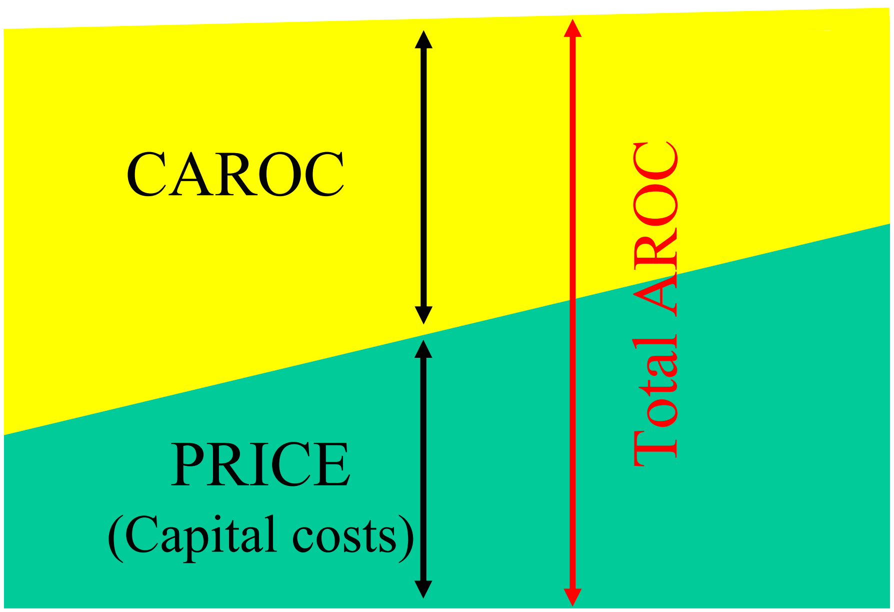
Historical wide body data from Markish. No correlation found between price and quantity.

Aircraft Pricing

Cost-Based Pricing	Market-Based Pricing
Cost + Profit = Price	Performance Operating Cost Competition Passenger Appeal } Market Value
Personal aircraft Business jets? → Military aircraft	Commercial transport

Source: Schaufele

Commercial Aircraft Pricing



- Total Airplane Related Operating Costs are fairly constant.
- Aircraft price must balance CAROC.

⇨ **COST/WEIGHT TRADE-OFF**

Business Jet Empirical Data

Figure A7 in Roskam:

$$AMP_{1989} = \log^{-1}\{0.6570 + 1.4133 \log W_{TO}\}$$

AMP_{1989} is predicted airplane market price in 1989 dollars
Take-off weight: 10,000 lb < W_{TO} < 60,000 lb

BUT Gulfstream GIV and 737 BJ versions do not fit the linear trend.

Commercial Jet Empirical Data

Figure A9 in Roskam:

$$\mathbf{AMP_{1989} = \log^{-1}\{3.3191 + 0.8043 \log W_{TO}\}}$$

AMP_{1989} is predicted airplane market price in 1989 dollars

Take-off weight: 60,000 lb < W_{TO} < 1,000,000 lb

Military Aircraft Empirical Data

Figure A10 in Roskam:

$$AMP_{1989} = \log^{-1}\{2.3341 + 1.0586 \log W_{TO}\}$$

AMP_{1989} is predicted airplane market price in 1989 dollars

Take-off weight: 2,500 lb < W_{TO} < 1,000,000 lb

Revenue Model: Price

- Assumption: market price based on
  1. Range
  2. Payload
  3. Cash Airplane-Related Operating Cost (CAROC)

- Regression model:

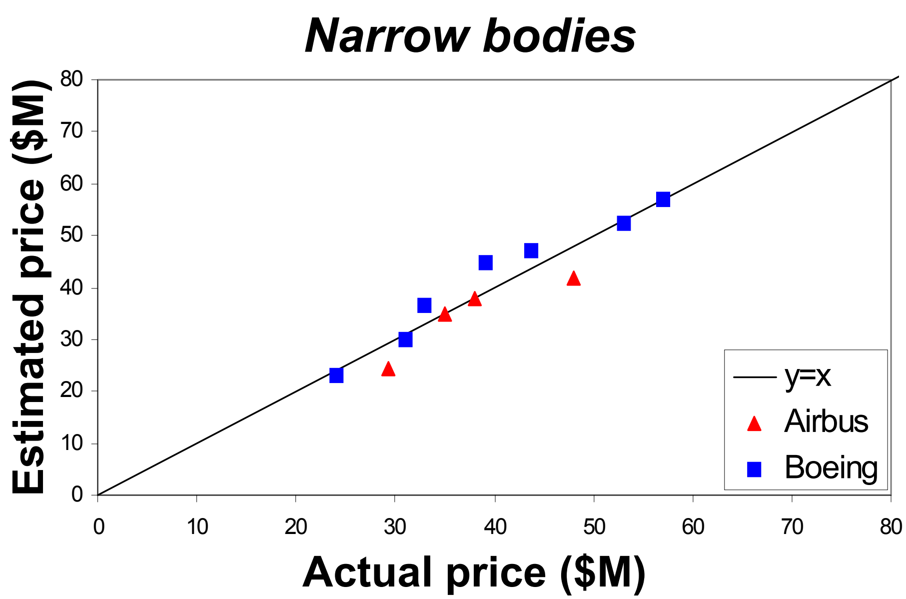
$$P = k_1(Seats)^{\alpha} + k_2(Range) - f(CAROC)$$

- Note that speed does not appear. No significant statistical relationship between price and speed was found in available data.

Revenue Model: Price

Narrow bodies:

$$P = 0.735(Seats)^{1.91} + 0.427(Range) - f(CAROC)$$

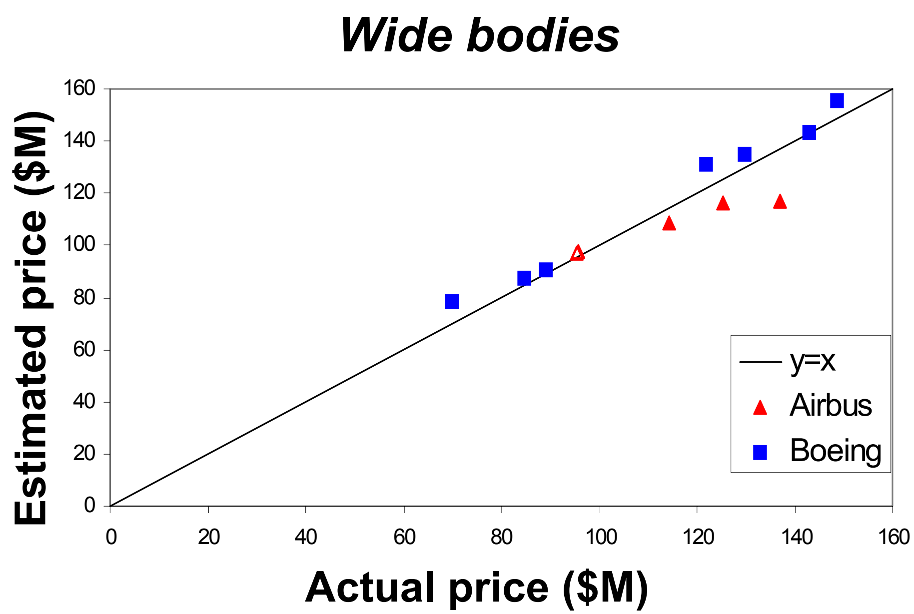


Model from Markish, price data from Aircraft Value News, The Airline Monitor, 2001.

Revenue Model: Price

Wide bodies:

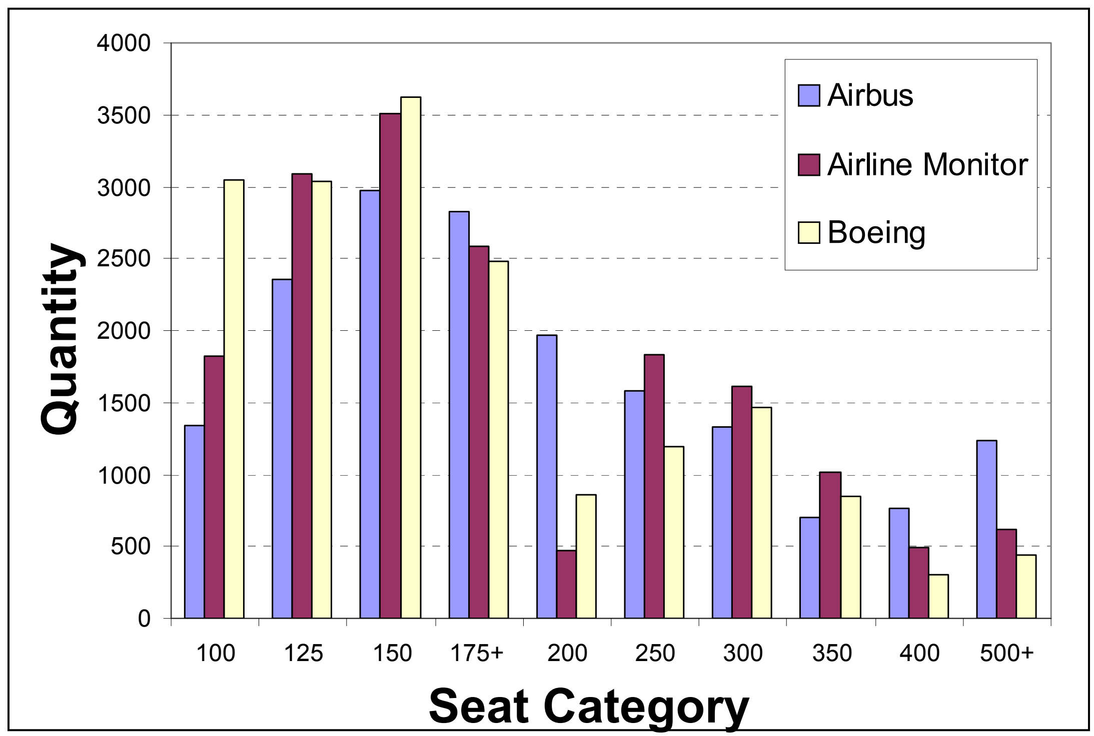
$$P = 0.508(Seats)^{2.76} + 0.697(Range) - f(CAROC)$$



Model from Markish, price data from Aircraft Value News, The Airline Monitor, 2001.

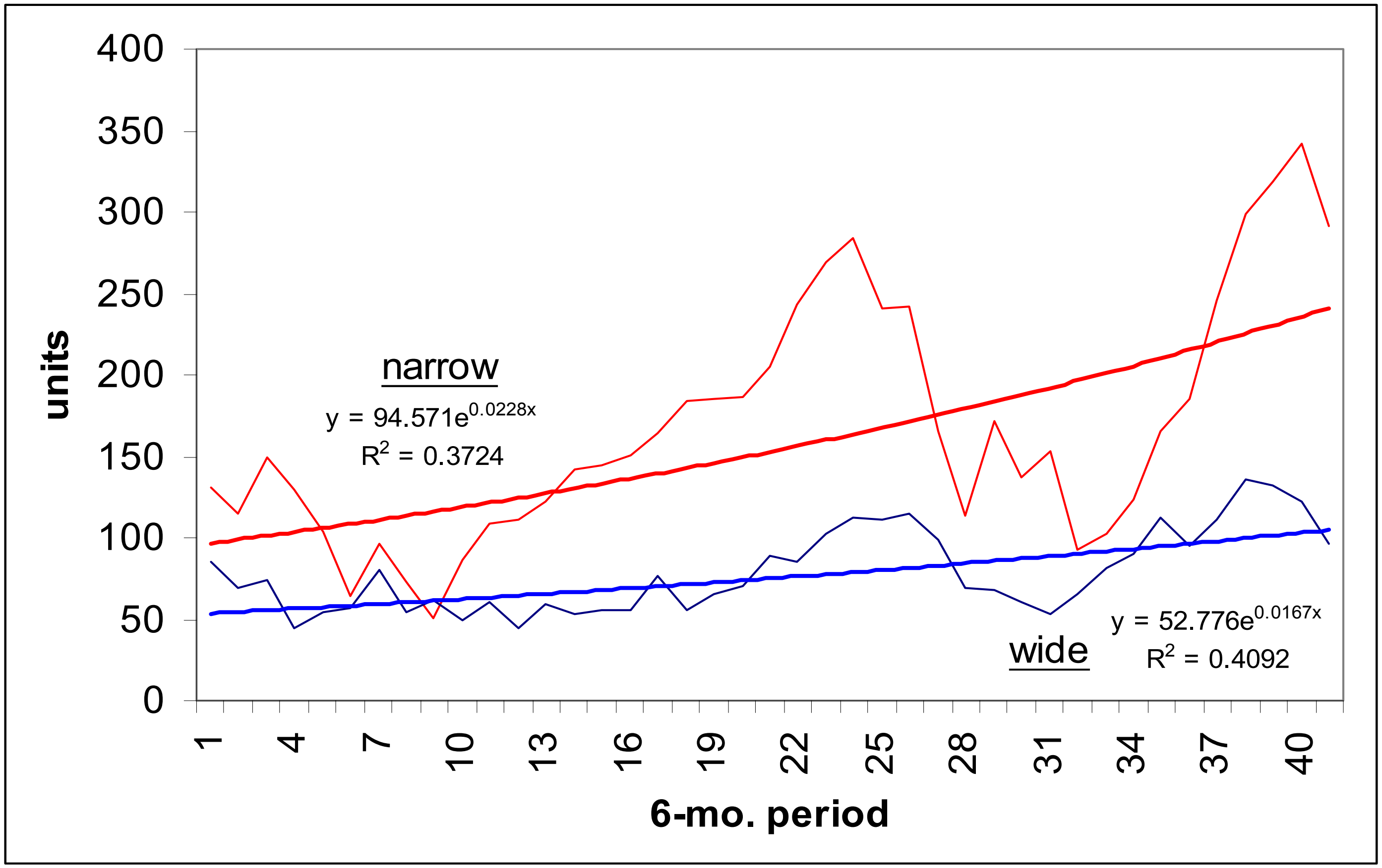
Revenue Model: Quantity

- Demand forecasts
  - 3 sources: Airbus; Boeing; Airline Monitor
  - Expected deliveries over 20 years
  - Arranged by airplane seat category
- Given a new aircraft design:
  - Assign to a seat category
  - Assume a market share
  - Demand forecast → 20-year production potential



Revenue Model: Dynamics

- Expected aircraft deliveries: forecasted
- Actual deliveries: unpredictable
- Observe historical trends: growth rate, volatility



Valuation Techniques

The top 5 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

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

Calculating NPV

- Forecast the cash flows 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)

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

NPV 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

Discount Rate

- One of the problems with NPV: what discount rate should we use?
- 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%
- The higher the discount rate, the more it does not matter what you do in the future...

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
- Surmounts 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

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

- 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

Decision Tree Analysis

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

Dynamic Programming

- A way of including **uncertainty** and **flexibility** in the program valuation
- Key features:
  - Certain aspects of the system may be uncertain, e.g. the demand quantity for a given aircraft = UNCERTAINTY
  - In reality, the decision-maker (aircraft manufacturer) has the ability to make decisions in real-time according to how the uncertainty evolves = FLEXIBILITY

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?

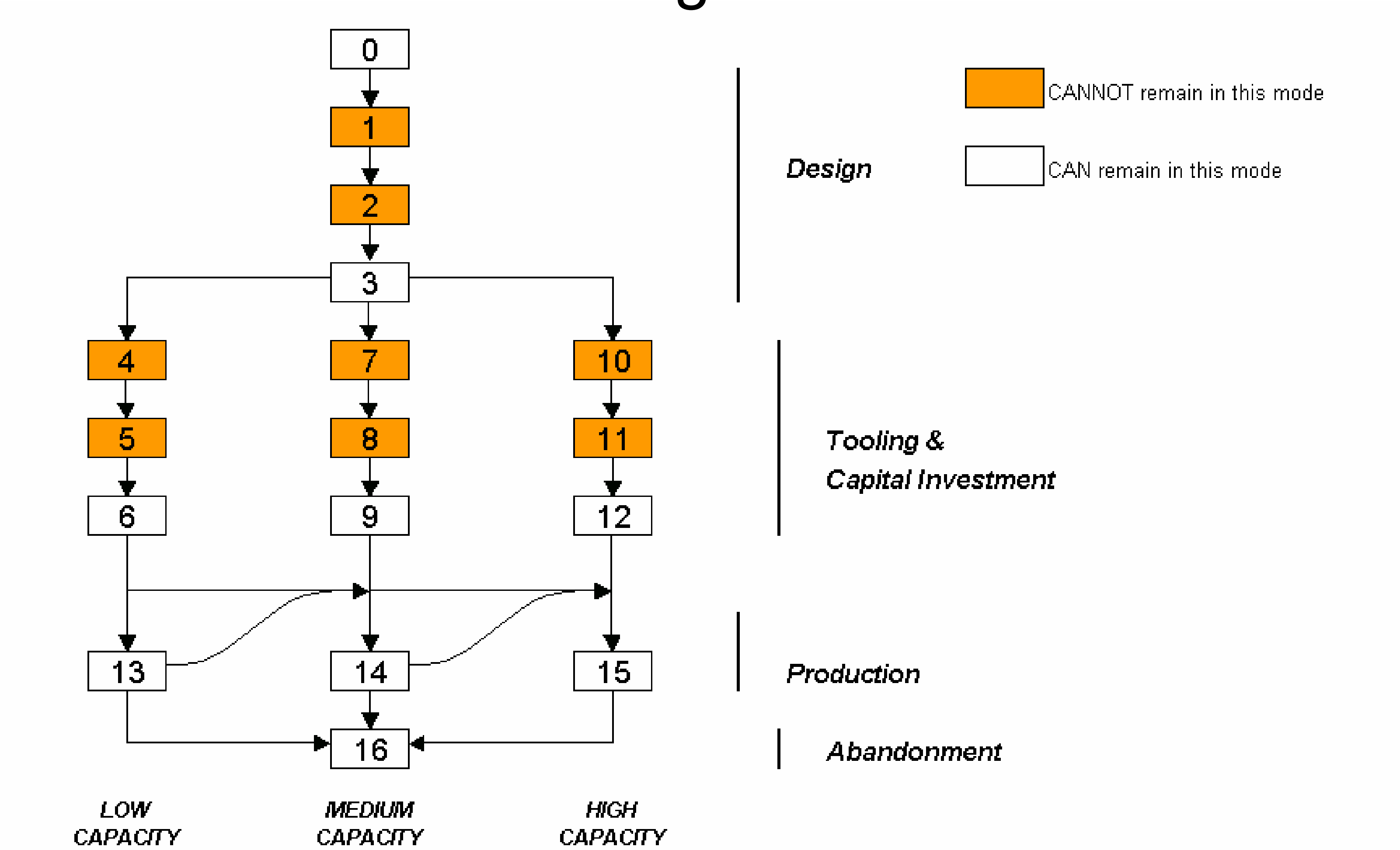
Dynamic Programming: Problem Elements

1. State variables s_t
2. Control variables 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 iteratively.

Dynamic Programming: Operating Modes

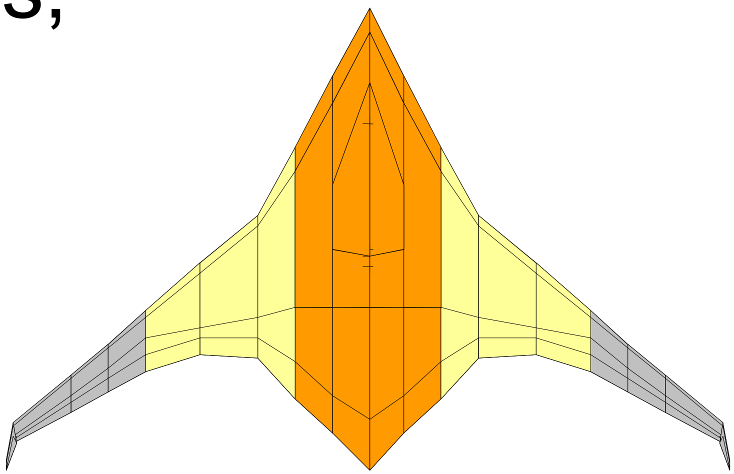
How to model decision making?



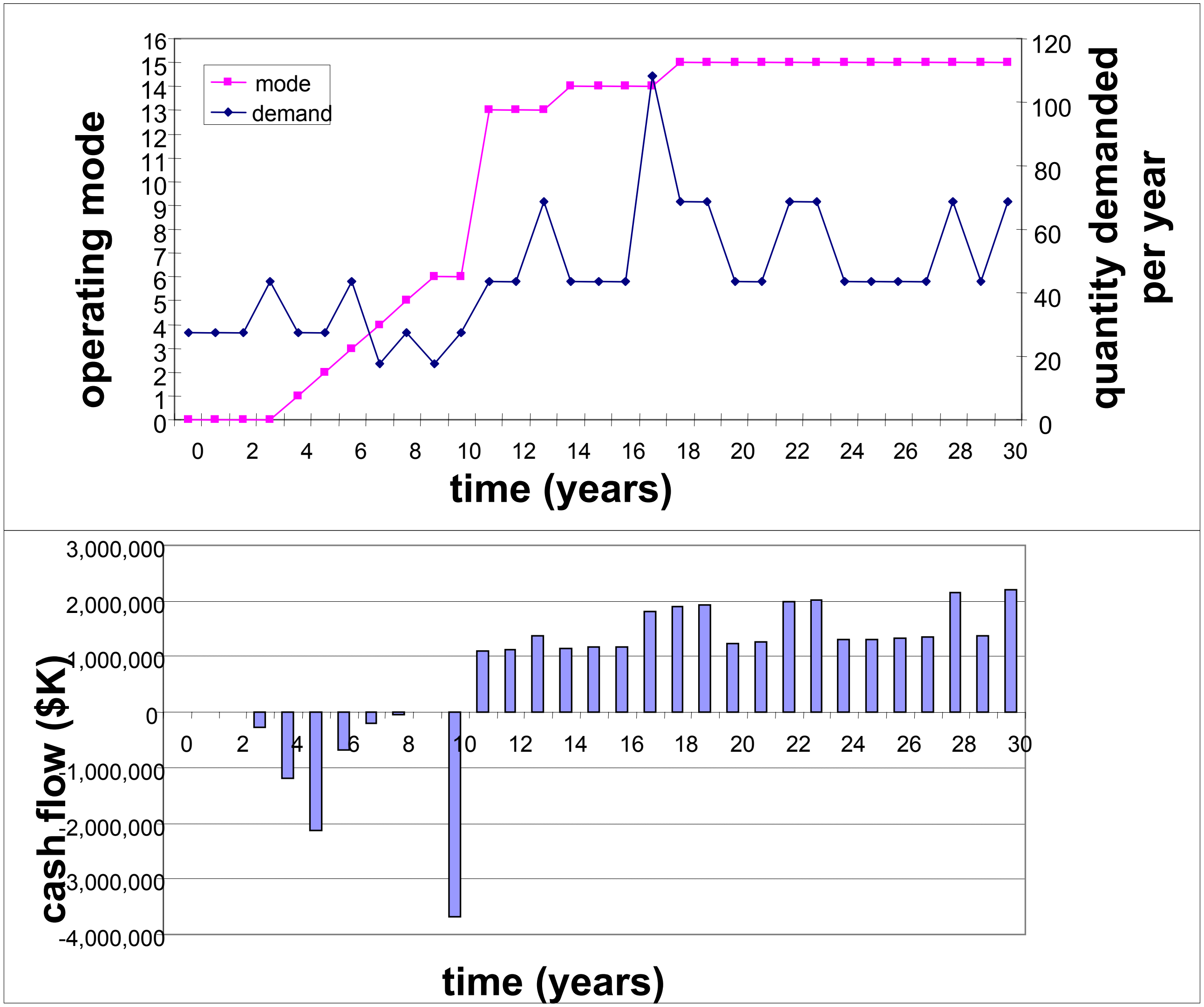
Example: BWB

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

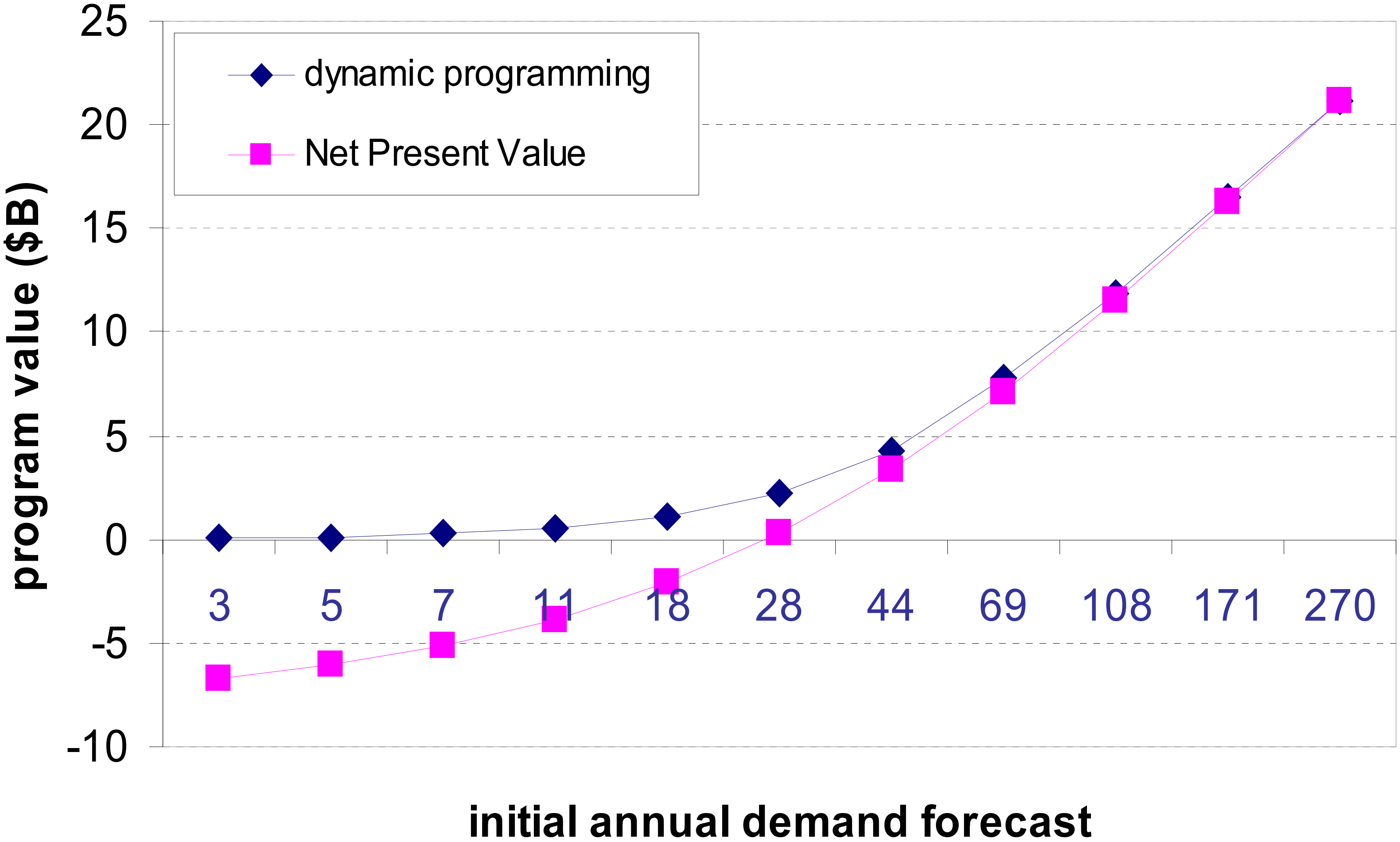
Image taken from NASA's web site: http://www.nasa.gov.



Example: BWB Simulation Run



Example: BWB Importance of Flexibility



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

References

Airbus Global Market Forecast, 2000-2019. Appendix G, Detailed passenger fleet results, p. 74.

Aircraft Value News Aviation Newsletter www.aviationtoday.com/catalog.htm

The Airline Monitor, ESG Aviation Services.

Boeing Current Market Outlook, 2000. Appendix B, p. 42.

Jane's All the World's Aircraft. London : Sampson Low, Marston & Co., 2001.

Markish, J. *Valuation Techniques for Commercial Aircraft Program Design*, S.M. Thesis, MIT, June 2002.

Markish, J. and Willcox, K. "Valuation Techniques for Commercial Aircraft Program Design," AIAA Paper 2002-5612, presented at 9th Multidisciplinary Analysis and Optimization Symposium, Atlanta, GA, September 2002.

Markish, J. and Willcox, K., "A Value-Based Approach for Commercial Aircraft Conceptual Design," in Proceedings of the ICAS2002 Congress, Toronto, September 2002.

NASA Cost Estimating website, http://www.jsc.nasa.gov/bu2/airframe.html

Roskam, J., *Airplane Design Part VIII*, 1990.

Raymer, D., *Aircraft Design: A Conceptual Approach,* 3rd edition, 1999.

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