Air Vehicle Design

AOE 4065 – 4066

II. Air Vehicle Design Fundamentals

Course Module A6

Cost Considerations

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AOE 4065-4066: Capstone Air Vehicle Design (AVD) Course Modules (CMs)

Overview of AVD Courses

I. Foundational Elements

F1. Design: *An Engineering Discipline*

F2. Systems and Systems Thinking

F3. Basics of Systems Engineering

F4. Decision Making with Ethics and Integrity

II. Air Vehicle Design Fundamentals

A1. Purpose & Process

Conceptual Design

A2. Understand the Problem

A3. Solve the Problem

A4. Initial Sizing: *Takeoff Weight Estimation*

A5. Initial Sizing: *Wing Loading and Thrust Loading Estimation*

A6. Cost Considerations

A7. Concept to Configuration: *Key Considerations*

A7A. Configuration Layout: *Drawings & Loft*

Conceptual & Preliminary Design

A8. Trade Studies

A9. Use of Software Tools

A10. Preliminary Design: *Baseline Design Refinement & Validation*

III. Project Management Topics

P1. Basics of Project Management and Project Planning

P2. Project Organization

P3. Roles & Responsibilities of Team Members

P4. Project Execution: *Teamwork for Success*

P5. Project Risk Management

P6. Delivering Effective Oral Presentations

P7. Writing Effective Design Reports

Disclaimer

Prof. Pradeep Raj, Aerospace and Ocean Engineering, Virginia Tech, collected and compiled the material contained herein from publicly available sources solely for educational purposes.

Although a good-faith attempt is made to cite all sources of material, we regret any inadvertent omissions.

CRUCIALLY IMPORTANT

CMs only introduce key topics and highlight some important concepts and ideas…but without sufficient detail.

We must use lots of Reference Material* to add the necessary details!

(*see Appendix in the Overview CM)

Outline

A6. Cost Considerations

A6.1 Cost Estimating Relationships

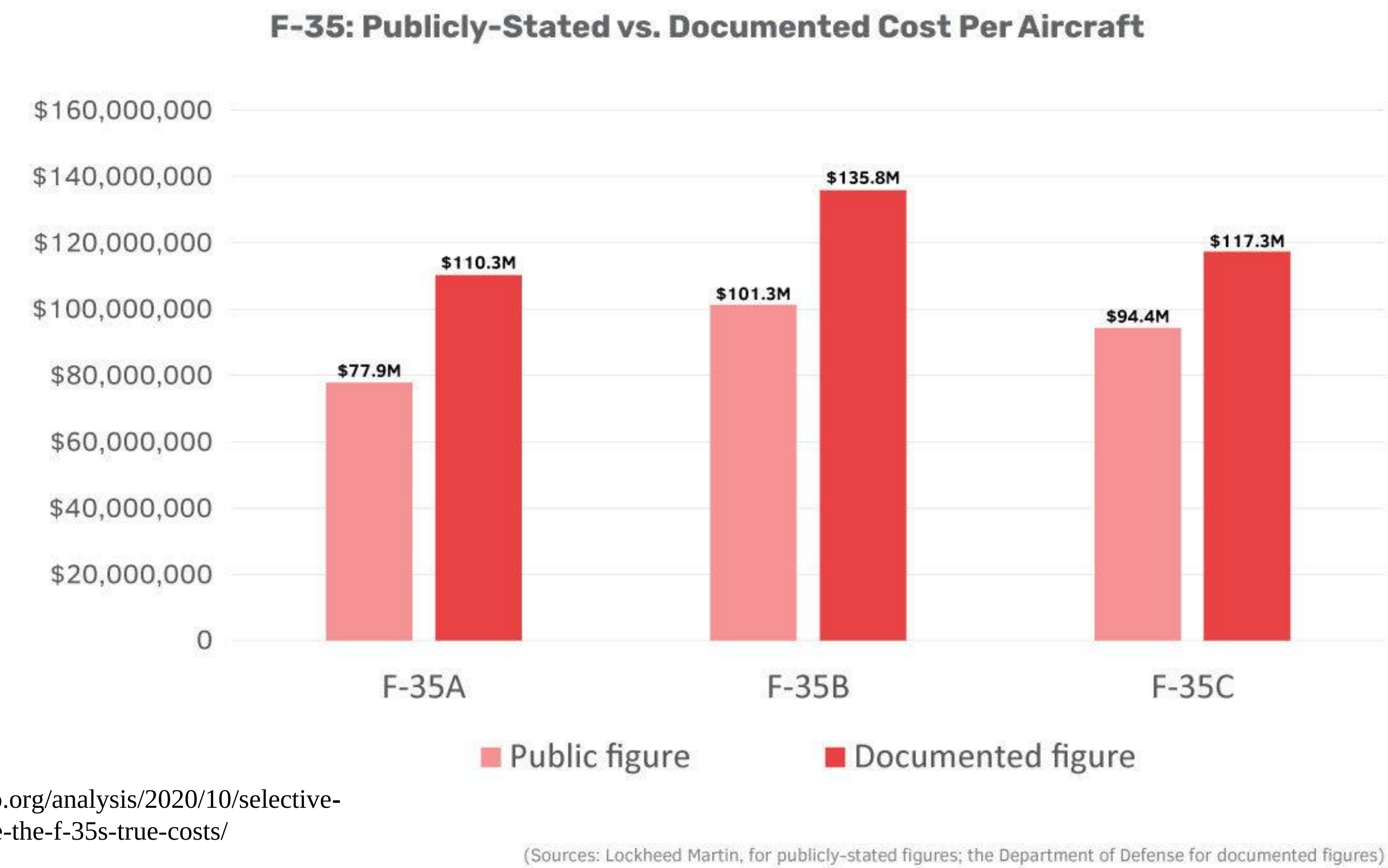
A6.2 O&S Cost Estimation

A6.3 Design for "Best Value"

Early in the Design Process, Developing a Good Understanding of the Factors that Affect Airplane Cost Will Greatly Benefits Design Teams in Making Good Decisions…Decisions That Are Crucial to Generating Quality Affordable Designs.

Cost Estimation: *Not a Science!*

"Aircraft cost estimation occupies the fuzzy gray area between science, art, and politics." -- Raymer

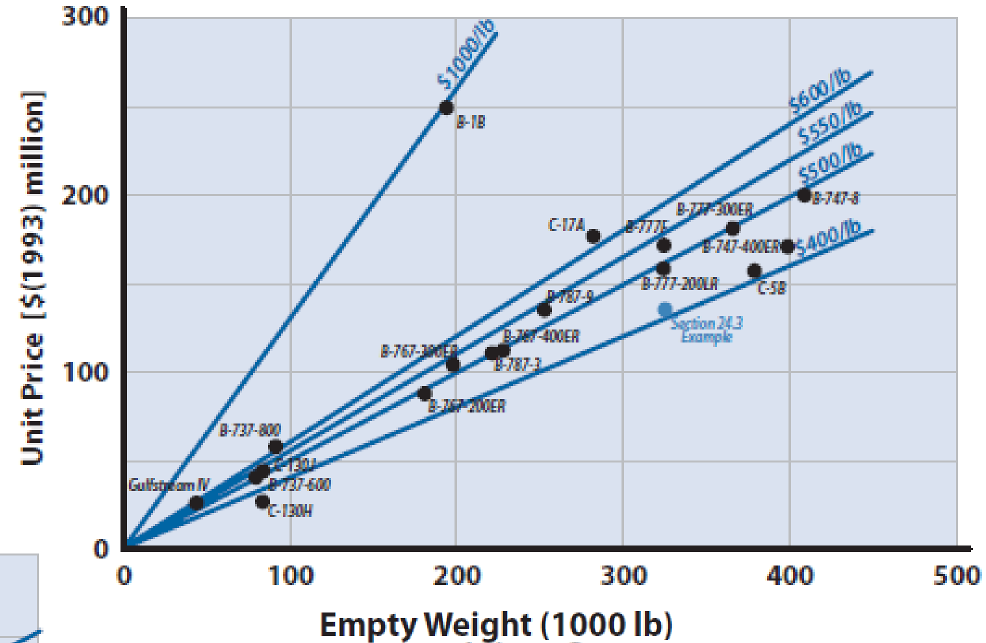


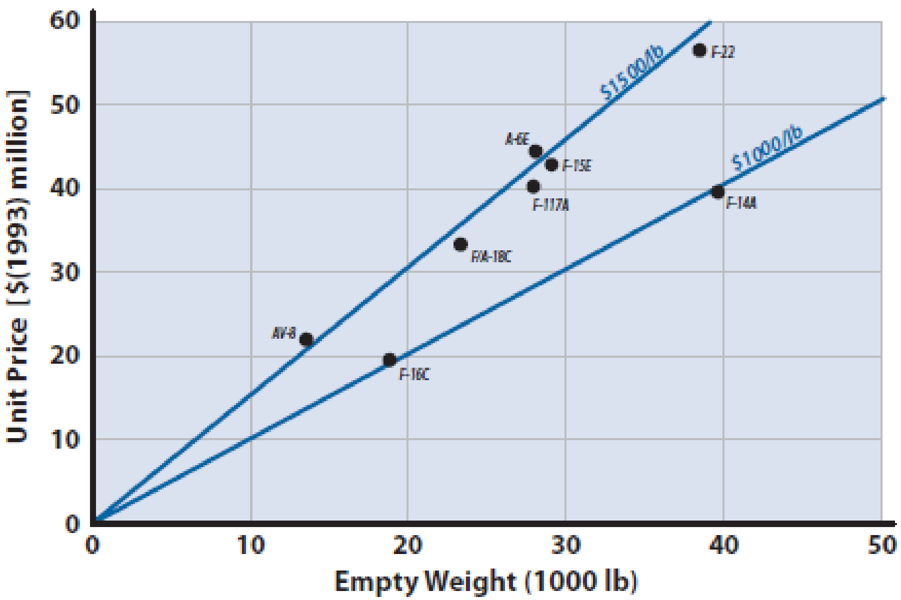
https://www.pogo.org/analysis/2020/10/selective-arithmetic-to-hide-the-f-35s-true-costs/

But the Importance of Cost Cannot be Overemphasized! Every Customer Wants Quality Affordable Systems.

Unit Price vs Empty Weight: *Examples*

Unit Price of Medium and Large <u>Transports and Bombers</u>





Unit Prices of <u>Fighter Aircraft</u>

"Aircraft are bought by the pound." -- Raymer!

Source: Figs. from Chapter 24, Ref. AVD 1 (Nicolai & Carichner)

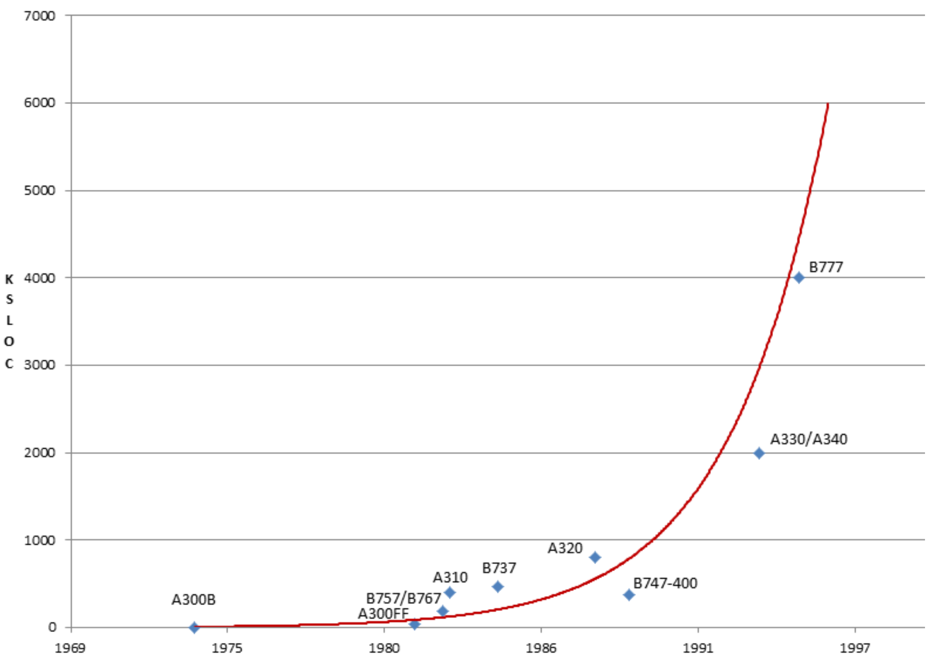
Software:
An Indispensable Element of Modern Aircraft

Civilian Aircraft

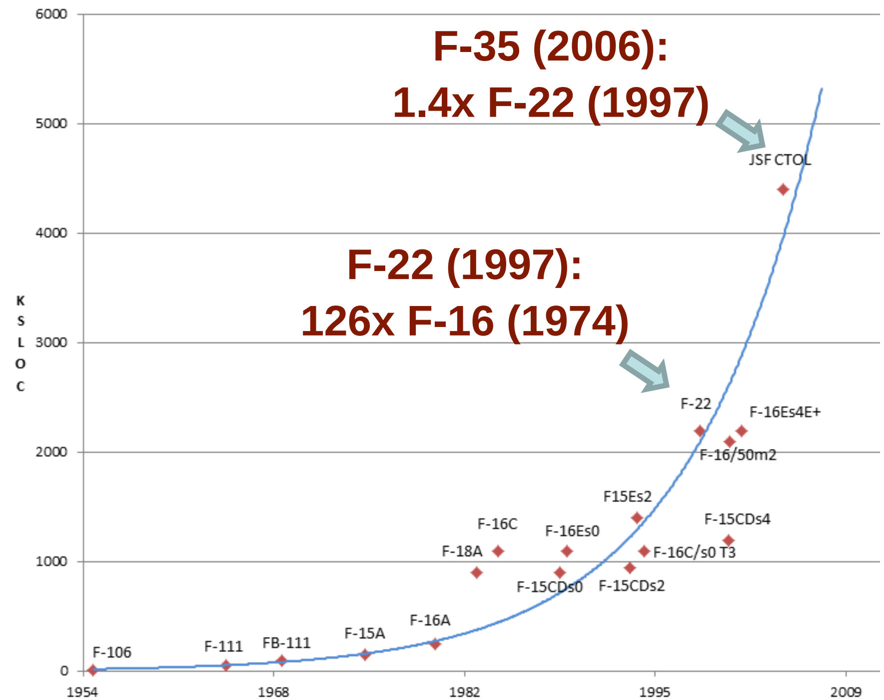
Growth of Onboard SLOCs*

A320 (1988)	**5x A310 (1983)**
A330 (1993)	**12.5x A310 (1983)**
B777 (1993)	**21x B757 (1983)**
B787 (2011)	**42x B757 (1983)**

**Source Lines of Code*



Military Aircraft



SLOCs doubling every 4 yrs.

300x cost increase over 32 yrs.

Do Not Neglect Software Development Costs!

Source: https://savi.avsi.aero/about-savi/savi-motivation/exponential-system-complexity/

Life Cycle Cost (LCC):
A Key Measure of Affordability

- **LCC is *Total "Cradle to Grave" Cost***
  - **LCC = RDT&E cost + Production cost + O&S cost**
- **RDT&E (Research, Development, Test, and Evaluation) Cost (~20%)**
  - **R**esearch includes basic research, exploratory development, technology maturation; *very difficult to estimate* but fixed and ***nonrecurring*** cost
  - **DT&E** includes cost to engineer, develop, fabricate, and flight test a specified number of aircraft (typically 2 to 10) before committing to production; also fixed and ***nonrecurring*** cost
- **Production Cost (~30%)**
  - Includes (i) cumulative cost of labor & material, tooling, facilities, and profit to produce a specified number of aircraft; (ii) initial spares and ground equipment; (iii) training aids (simulators, flight manuals, etc.);
  - Depends on the number of units produced; per unit cost goes down as more aircraft are produced due to *'learning-curve effect';* it is a ***recurring*** cost
- **O&S (Operations & Support) Cost (~50%)**
  - ***Recurring*** cost--depends on types of aircraft mission, military or commercial
  - **MILITARY:** Fuel, crew, and maintenance costs**;**
    COMMERCIAL: Direct Operating Costs (DOC) + Indirect Operating Costs (IOC)

Reduce LCC, Increase Affordability

Source: Chapter 24, Ref. AVD 1 (Nicolai & Carichner)

Outline

A6. Cost Considerations

A6.1 Cost Estimating Relationships

A6.2 O&S Cost Estimation

A6.3 Design for “Best Value”

Cost Estimating Relationships (CERs)

- **In early stages of design, costs are estimated using CERs**
  - Until the design is fully fleshed out, it's too hard to determine actual costs
- **Primary factors driving DT&E and Production costs are:**
  1. W, empty weight of the aircraft in pounds
  2. S, maximum speed of the aircraft in knots
  3. Q, total quantity of aircraft produced (Q_D in DT&E + Q_P in Production)

  This is based on a Rand study for aircraft built between 1945 and 1986

  - The weight, W, that influences the cost is *Total Empty Weight* (W_{empty}) minus the *Total Weight of Procured Items*. Note that W_{empty} may be estimated using *Initial Weight Sizing* procedures. But weights of procured items (engines, landing gear, etc.) are not known in early stages of design. Therefore, in the initial Rand report (R-761-PR, 1971), W is estimated to be 62% of W_{empty}
  - The CER equations in the following slides assume $W = W_{empty}$ since the 62% factor has been absorbed into the coefficients

- **Total O&S cost estimation requires information about**
  - Estimated period of operation, usually 10 or 20 years
  - Estimated fleet size
  - Estimated number of flying hours per year

Source: Chapter 24, Ref. AVD 1 (Nicolai & Carichner)

Cost Estimating Relationships

DT&E and Production Costs

- **DT&E and Production CERs (RAND DAPCA-IV Model)**

Cumulative <u>Hours</u>

Airframe Engineering: DT&E + Production

$$E = 4.86\ W^{0.777}\ S^{0.894}\ Q^{0.163}$$

Tooling: (DT&E + Production)

$$T = 5.99\ W^{0.777}\ S^{0.696}\ Q^{0.263}$$

Manufacturing Labor: (DT&E + Production)

$$L = 7.37\ W^{0.82}\ S^{0.484}\ Q^{0.641}$$

Quality Control: (DT&E + Production)

$$\text{QC} = 0.076\ L \text{ for cargo and transport aircraft}$$

$$\text{QC} = 0.13\ L \text{ for all other aircraft}$$

Cumulative <u>Costs (1998 $s)</u>

Development Support: DT&E

$$D = 66\ W^{0.63}\ S^{1.3}$$

Flight Test: DT&E

$$F = 1852\ W^{0.325}\ S^{0.822}\ Q_D^{1.21}$$

Manufacturing Material & Equipment: (DT&E + Production)

$$M = 16.39\ W^{0.921}\ S^{0.621}\ Q^{0.799}$$

- W is empty weight in pounds (estimated using *Initial Weight Sizing* procedures); S is maximum speed in knots; and Q is total quantity of aircraft produced (Q_D in DT&E plus Q_P in Production)
- Estimated 1998 $ costs must be adjusted to current-year dollars; using consumer price index (CPI) that is readily available online is one simple option

The CERs above are valid only for the FPS system of units.

Source: Chapter 24, Ref. AVD 1 (Nicolai & Carichner)

Cost Estimating Relationships
Procured Items

- **Use manufacturer's (supplier's) quote for the procured items such as, engine, avionics suite, landing gear, etc., in the later stages of design; *there isn't enough information about them in the early stages, which adds to uncertainties in predictions.***

- **Engine unit cost (1998 $s) may also be estimated using**

$$P = 2306\,[0.043\,T_{SLS} + 243.3\,M_{max} + 0.969\,T_R - 2228]$$

P = production engine unit cost in 1998 dollars
T_{SLS} = sea level maximum thrust in pounds
M_{max} = maximum Mach number
T_R = turbine inlet temperature in degrees absolute (Rankine)

- **Estimated 1998 $ costs must be adjusted by *some* inflation factor to current-year dollars. Inflation factor is <u>not</u> the same for all costs. However, for initial estimates, Consumer Price Index (CPI) can be used, and it's readily available online.**

- **Avionics Cost may be approximated as $4,000 to $8,000 per pound per aircraft in 2012 dollars.**

Source: Chapter 24, Ref. AVD 1 (Nicolai & Carichner) and Chapter 18, Ref. AVD 2 (Raymer)

Cost Estimating Relationships

DT&E + Production Cost

DT&E + Production Cost = $E.R_E + T.R_T + L.R_L + QC.R_{QC} + (D + F) + M + P + (\text{Avionics Cost})$

- **R_E, R_T, R_L, and R_{QC} are current estimates of average hourly labor rate (*shown for the year 2012 in the table*). These rates include worker direct salaries *plus* indirect costs.**

Engineering (R_E)	$115
Tooling (R_T)	$118
Manufacturing (R_L)	$98
Quality Control (R_{QC})	$108

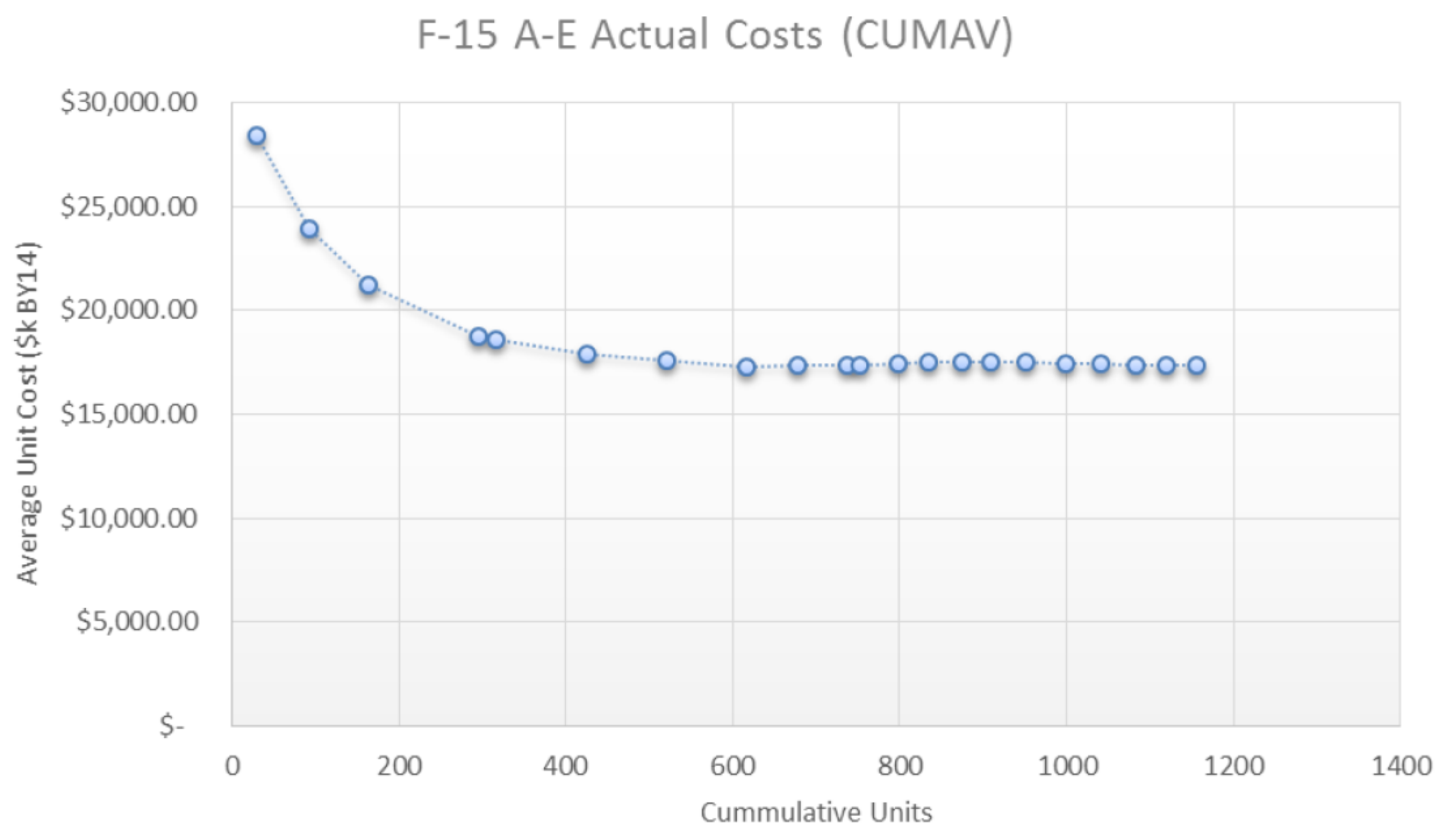
- **DAPCA estimations of hours should be adjusted by multiplying them with a "fudge factor" to account for a more difficult design and fabrication than an aluminum aircraft which is the basis of DAPCA CERs. Recommended "fudge factors" are shown in the table. In addition:**
  - For modern military aircraft designs, increase hours and cost estimates by about 20%
  - For commercial aircraft, apply a 0.9 factor since DAPCA tends to overpredict costs

Aluminum	1.0
Graphite-epoxy	1.1 to 1.8
Fiberglass	1.1 to 1.2
Steel	1.5 to 2
Titanium	1.1 to 1.8

- **Note: Production or Manufacturing Labor Hours, L, follow an industry standard *<u>80% 'Learning Curve</u>'* that is summarized in the next two slides.** (http://www.meyersaircraft.com/DAPCA%20IV/DAPCA%20IV%20Intro%20Page.html)

'Learning-Curve Effect' on Aircraft Unit Cost

- As a worker performs the same task multiple times, the time required to complete that task will decrease at a constant rate due to learning from previous experience and thus becoming more efficient
- F-15 actual cost data in the figure reflects the 'learning-curve effect'



Source: https://scholar.afit.edu/cgi/viewcontent.cgi?article=1155&context=etd

Estimating 'Learning-Curve Effect' on Number of Production Labor Hours

- Learning effect is expressed in terms of percentages, e.g., X%
- An 80% learning curve means, each time the quantity is doubled, the number of hours *for each unit* drops to 80% of the previous value
- Note that lower values of X produce more optimistic cost estimates (when labor hours are converted into cost)

$$2^x = 2\left(\frac{\%\text{learning curve}}{100}\right)$$

$$x = \frac{\ln\left(2 \times \left(\frac{\%\text{learning curve}}{100}\right)\right)}{\ln 2}$$

E.g. for 80% learning curve (typical)

$$x = \frac{\ln\left(2 \times \left(\frac{80}{100}\right)\right)}{\ln 2} = 0.678$$

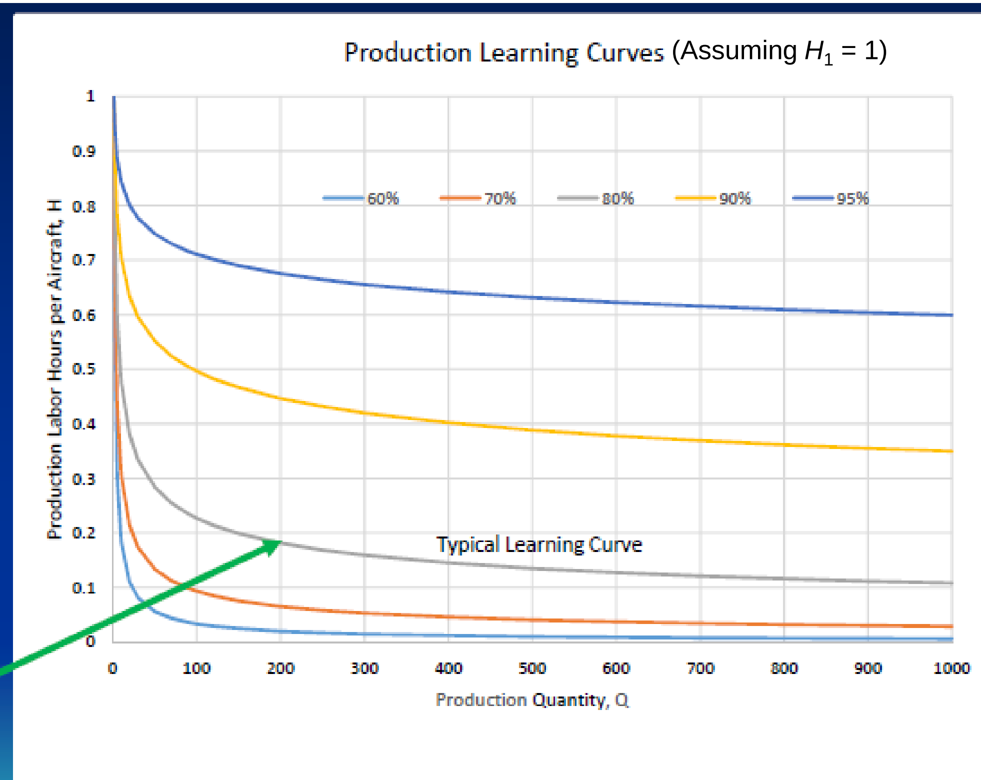
Say it takes 10,000hrs to make first aircraft

For $Q_1 = 1 \quad H_1 = 10{,}000$

$$H = H_1\left(\frac{Q}{Q_1}\right)^{x-1}$$

Number of hours for 200th aircraft $(Q = 200)$

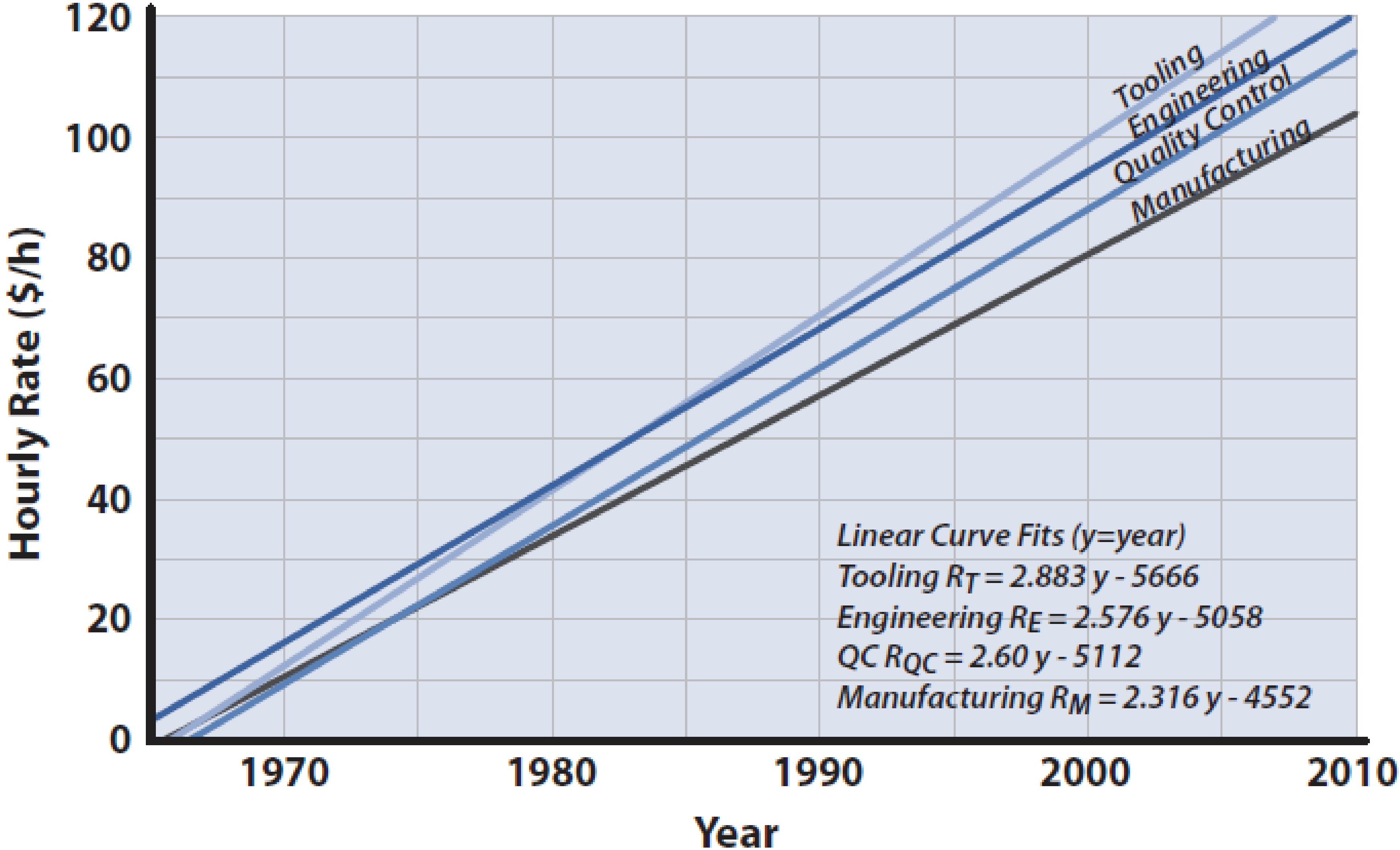
$$H_{200} = 10{,}000 \times (200)^{0.678-1} = 1{,}815 \text{ hrs}$$



Source: Cost Analysis lecture, (AP Hays)

Cost Estimating Relationships (contd.)

Hourly Rates Trends for Updating CER Estimates



Source: Chapter 24, Ref. AVD 1 (Nicolai & Carichner)

Software Development CERs

Development cost depends on the class of project: *Organic, Semi-detached or Embedded*

	Organic	Semi-detached	Embedded
Project size (lines of source code)	2,000 to 50,000	50,000 to 300,000	300,000 and above
Team Size	Small	Medium	Large
Developer Experience	Experienced developers needed	Mix of Newbie and experienced developers	Good experience developers
Environment	- Familiar Environment	- Less familiar environment	- Unfamiliar environment (new) - Coupled with complex hardware
Innovation	Minor	Medium	Major
Deadline	Not tight	Medium	Very tight
Example(s)	Simple Inventory Management system	New Operating system	Air traffic control system

https://medium.com/@warakornjetlohasiri/cocomo-a-regression-model-in-procedural-cost-estimate-model-for-software-projects-65ab5222a1f5

VIRGINIA TECH. COLLEGE OF ENGINEERING KEVIN T. CROFTON DEPARTMENT OF AEROSPACE AND OCEAN ENGINEERING

Software Development CERs (contd.)

- **Basic COCOMO Model provides Software Development CERs**

Effort applied to the project: $E = a_b(KLOC)^{b_b}$ (in Person-month)

Development time: $D = c_b(E)^{d_b}$ (in month)

Manpower required: $P = \frac{E}{D}$ (in Person)

Where a_b, b_b, c_b, d_b are constants for each category of software product **and KLOC is thousands of lines of code**

SW project	a_b	b_b	c_b	d_b
Organic	2.4	1.05	2.5	0.38
Semi detached	3.0	1.12	2.5	0.35
Embedded	3.6	1.20	2.5	0.32

- **Intermediate COCOMO Model improves the Basic model by incorporating other project attributes—rather than relying solely on KLOC—through subjective assessment of 15 "cost drivers"**

https://medium.com/@warakornjetlohasiri/cocomo-a-regression-model-in-procedural-cost-estimate-model-for-software-projects-65ab5222a1f5

Outline

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A6.2 O&S Cost Estimation

A6.3 Design for “Best Value”

COLLEGE OF ENGINEERING
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VIRGINIA TECH.

O&S Cost Estimation

- **Operations & Support Costs include**
  - **MILITARY:** Fuel, crew, and maintenance
  - **COMMERCIAL: Direct Operating Costs (DOC)** + **Indirect Operating Costs (IOC)**
    - DOC includes fuel, oil, crew, maintenance, depreciation, and insurance—usually expressed as "cost per seat-mile (CSM)"; typically about 6 to 8 cents
    - IOC includes costs of depreciation of ground facilities and equipment, sales & customer service, administrative and overhead
    - "Cost per available seat-mile (CASM)" is based on DOC + IOC; typically 15 cents
- **O&S costs are based upon**
  - A period of operation, usually 10 or 20 years
  - Estimated fleet size
  - Estimated number of flying hours per year
- **In early stages of design, not enough information is available for good estimations**
  - *A Good Alternative:* *Research existing aircraft to choose 'targets' for your new design*
  - Typical military aircraft O&S cost: about 15% fuel, 35% crew, 50% maintenance
  - Typical commercial aircraft O&S cost: about 38% fuel, 24% crew, 25% maintenance, 12% depreciation, and remaining 1% insurance. Beware that *actual values vary widely*. Check Airline Transport Association website (www.airlines.org)

Source: Chapter 24, Ref. AVD 1 (Nicolai & Carichner)

Military Aircraft O&S Costs Estimation

- **Annual Crew Cost**
  - Total annual crew cost = # of aircraft x # of flight-crew members (kept on active duty) per aircraft* x crew ratio x average annual cost per crew member
  - Use typical Crew Ratio estimates based on historical data

Aircraft Type	Annual Flight Hours per Aircraft	Crew Ratio
Transport	< 1200	1.5
	1200 to 2400	2.5
	2400 to 3600	3.5
Bomber	500	1.5
Fighter	500	1.1

  - Average cost per crew member may be estimated as 2080 hr. x engineering hourly wrap rate (as suggested by Raymer for initial trade studies and student design projects) unless better data can be obtained from the military
- **Annual Fuel Cost**
  - Total annual fuel cost = # of aircraft x average fuel (gallons) per flight hour x # of annual flight hours per aircraft x average fuel cost per gallon
  - Oil costs are less than 0.5% of fuel costs and may be neglected

Source: Ch. 18, Ref. AVD 2 (Raymer); Ch. 24, Ref. AVD 1 (Nicolai & Carichner)

Military Aircraft O&S Costs Estimation (contd.)

- **Annual Maintenance Costs may be estimated using Maintenance-Man-Hours per Flying Hour (MMH/FH) *from historical data***
  - Strong dependence on type of aircraft, mission or sortie length, utilization rate, and years in service
  - Tables show data for typical sortie length and years of service
  - Use labor wrap rate from airlines or military to estimate maintenance cost; if not available use manufacturing labor wrap rate
  - Materials, parts, supplies costs for MMHr. equal labor costs for military aircraft (see Ch. 18, Raymer, for commercial aircraft)

Aircraft	Average Annual FH per Aircraft	MMH/FH	Year
DC-10-10	2450	11	1981
B727-100	2670	8	1974
B727-200	2800	6.5	1974
B737-200	2200	6.6	1974
B747	3525	14.5	1981
B757	3010	9.1	1998
B767	3010	11.4	1998
B777	3010	10.2	1998
SR-71	260	~400	1981

Source: Ch. 18, Ref. AVD 2 (Raymer)

Aircraft	Average Annual FH per Aircraft	MMH/FH	Year
Cessna 150/172		0.3	1974
Cessna Skywagon		0.5	1974
Beech Kingair		1.0	1974
Citation II		3.0	1988
T-37		7.8	1981
T-38	400	10	1981
T-39	600	9.8	1974
T-43	700	10	1974
F-5E	410	17	1981
A-7D	300	25	1974
A-10A	300	13	1984
F-14	314	48	1988
F-15C	302	22	1998
F-16C	346	19	1998
F-18C	360	18	1988
F-4E	302	33	1981
F-105G	316	58	1974
F-111D	280	40	1974
F-117A	—	113	1983 (IOC)
F-117A	—	45	2003
F-22A	316	10.5	2009
B-2A	—	124	1997 (IOC)
B-2A	—	51	2002
B-2A	—	32	2004
C-17	780	24	2005
C-17	780	20	2007
C-17	780	16	2008
C-5B	716	58	2005
C-5B	716	41	2007
C-5B	716	33	2008
C-130E	720	20	1974
C-141B	1080	21	1981
B-52D	424	37	1981
B-52G	516	49	1981
B-58A	430	54	1974
KC-135	377	27	1974
L1011	1870	14.1	1981

Source: Ch. 24, Ref. AVD 1 (Nicolai & Carichner)

Commercial Aircraft: A Simple DOC Model

- **DOC = Route Dependent (*Variable*) Costs + Route Independent (*Fixed*) Costs**
- ***Variable Costs*: Fuel, Flight Deck and Cabin Crew, Airframe and Engine Maintenance Labor and Material**
- ***Fixed Costs*: Depreciation, Interest, Insurance**
- **Fuel Cost**

$$\text{Fuel cost} = \frac{W_f}{\rho_f} \times C_f$$

W_f – Mission block fuel weight (excluding reserves) in lb_f

ρ_f – Fuel density (lb_f/gal); may use 6.7 lb_f/gal

C_f – Fuel cost

- **Flight Deck Crew Cost**

$$\text{Flight deck crew cost} = T_{block} \times N_{fc} \times \left(C_{fc} + 0.532 \times \frac{W_{to}}{1000}\right) \times F_i$$

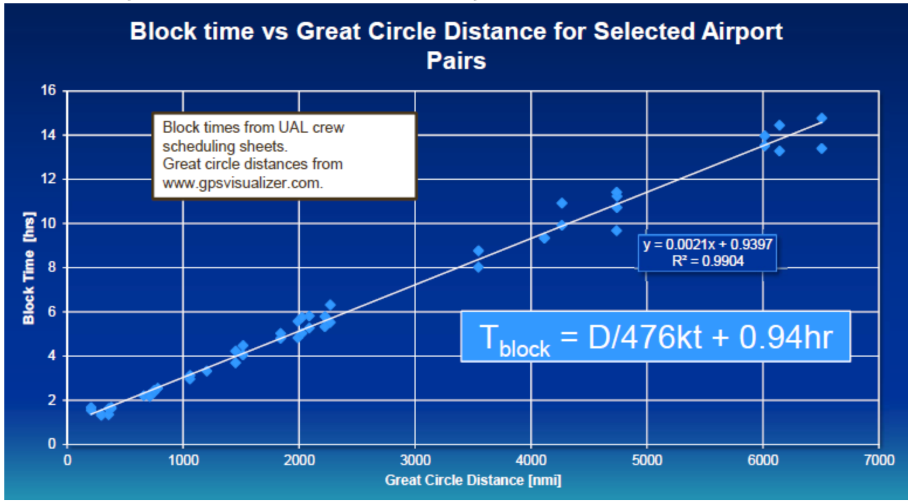
T_{block} – Estimated Block Time equals mission flight time + 15 min for ground maneuver + 6 min for air maneuver

N_{fc} – Number of crew (usually 2, transpacific 4)

C_{fc} – Base flight crew cost (~ $440/hr.)

W_{to} – Maximum takeoff gross weight

F_i – Salary premium (1.1 for international)



Note: Block hours per year = (Block hours per flight hour) x total flight hours per aircraft (typically 2500 – 4500)

Source: Lecture notes (AP Hayes)

A Simple DOC Model (contd.)

- **Cabin Crew Cost**

$$Cabin\ crew\ cost = T_{block} \times N_{cc} \times C_{cc}$$

N_{cc} – Number of cabin crew

For > 100 seats: 2 + [(No. of passenger seats) – 100]/2

For < 100 seats: see FAR 121.391(a)

C_{cc} – Base cabin crew cost (~ $60/hr. domestic, $78/hr. international)

- **Airframe Maintenance Labor Cost**

$$\text{Airframe maintenance labor cost} = \left(\left(1.26 + 1.774 \times \left(\frac{W_{airframe}}{10^5} \right) - 0.1071 \times \left(\frac{W_{airframe}}{10^5} \right)^2 \right) \times T_{block} + \left(1.614 + 0.7227 \times \left(\frac{W_{airframe}}{10^5} \right) + 0.1204 \times \left(\frac{W_{airframe}}{10^5} \right)^2 \right) \right) \times C_{ml}$$

$W_{airframe} = W_{empty}$ – [Dry weight of all engines] (in lb_f)

C_{ml} – Direct maintenance labor cost (~ $25/hr.)

Source: Lecture notes (AP Hayes)

A Simple DOC Model (contd.)

- **Airframe Maintenance Material Cost**

Airframe maintenance material cost

$$= \left(\left(12.39 + 29.8 \times \left(\frac{W_{airframe}}{10^5} \right) + 0.1806 \times \left(\frac{W_{airframe}}{10^5} \right)^2 \right) \times T_{block} + \left(15.2 + 97.33 \times \left(\frac{W_{airframe}}{10^5} \right) - 2.862 \times \left(\frac{W_{airframe}}{10^5} \right)^2 \right) \right) \times 1.47$$

- **Engine Maintenance Labor Cost**

$$\text{Engine maintenance labor cost} = \left(0.645 + \left(\frac{0.05 \times F_n}{N_e \times 10^4} \right) \times \left(0.566 + \frac{0.434}{T_{block}} \right) \right) \times T_{block} \times N_e \times C_{ml}$$

F_n – Total net SLS thrust of all engines (in lb_f)

N_e – Number of engines

- **Engine Maintenance Material Cost**

$$\text{Engine maintenance material cost} = \left(25 + \left(\frac{0.05 \times F_n}{N_e \times 10^4} \right) \times \left(0.62 + \frac{0.38}{T_{block}} \right) \right) \times T_{block} \times N_e \times 1.47$$

Source: Lecture notes (AP Hayes)

A Simple DOC Model (contd.)

- **Landing Fees**

$$\text{Domestic Landing fee} = C_{land} \times \left(\frac{W_{ml}}{1000}\right)$$

$$\text{International landing fee} = C_{land} \times \left(\frac{W_{to}}{1000}\right)$$

C_{land} – Landing fee coefficient (~$2.20 domestic; $6.25 international)

W_{ml} – Maximum landing weight

- **Navigation Fees**

$$\text{Navigation fee} = C_{nav} \times 500\ \text{nm} \times \sqrt{\frac{W_{to}}{1000}}$$

International flights only

C_{nav} – Navigation fee coefficient (~ $0.20)

- **Depreciation Per Year**

$$\text{Depreciation per year} = (1 - R) \times \left(\left(\frac{C_{af}}{P_{af}}\right) + S_{af} \times \left(\frac{C_{af}}{P_{af}}\right)\right) + \left(\frac{C_e}{P_e}\right) + S_e \times \left(\frac{C_e}{P_e}\right)$$

R – Residual fraction for airframe and spares (~10% of price)

C_{af} – Airframe cost*

P_{af} – Airframe life

S_{af} – Airframe spares

C_e – Engine cost in $ x No. of engines

P_e – Engine life

S_e – Engine spares (~ 0.23 x engine cost)

*RAND DAPCA IV model (see slide 28)

Source: Lecture notes (AP Hayes)

A Simple DOC Model (contd.)

- **Depreciation Per Trip**

$$\text{Depreciation per trip} = \frac{\text{Depreciation per year}}{\text{Trips per year}}$$

Short-range (~500 nm) aircraft – 2100 trips/year

Medium-range (~ 500 to 3000 nm) aircraft – 625 trips/year

Long-range (~ 3000 to 4000 nm) aircraft – 480 trips/year

- **Interest Cost**

$$\text{Annual Interest} = \text{Interest rate} \times \text{Loan amount}$$

$$\text{Interest per trip} = \frac{\text{Annual Interest Cost}}{\text{Trips per year}}$$

- **Insurance Cost**

$$\text{Annual Insurance} = 0.0035 \times (\text{Airframe Cost} + \text{Engine Cost})$$

$$\text{Insurance per trip} = \frac{\text{Annual Insurance}}{\text{Trips per year}}$$

Source: Lecture notes (AP Hayes)

Outline

A6. Cost Considerations

A6.1 Cost Estimating Relationships

A6.2 O&S Cost Estimation

A6.3 Design for "Best Value"

Commercial Aircraft Programs

"Figure 2 illustrates the cash flow during the life cycle of a typical commercial aircraft development program. Before it can begin manufacturing and selling a new aircraft, the manufacturer must invest in the development of the aircraft, including research, engineering, testing, and tooling. This investment puts the manufacturer in the red. The manufacturer must then sell a critical number of aircraft in order to get his initial investment back. Aircraft sold beyond that number then earn the manufacturer a profit. As illustrated in Fig. 2, the demand for any new aircraft will eventually diminish and ultimately end as other manufacturers develop competing aircraft, new technologies make older aircraft obsolete, or government regulations or economic conditions change.

Additional development costs, suggested by the dashed lines in Fig. 2, will directly reduce profits by pulling the curves down; if these costs get large enough, they may even make the whole project unprofitable."

Typical Profit Profile

Notional: Not to scale

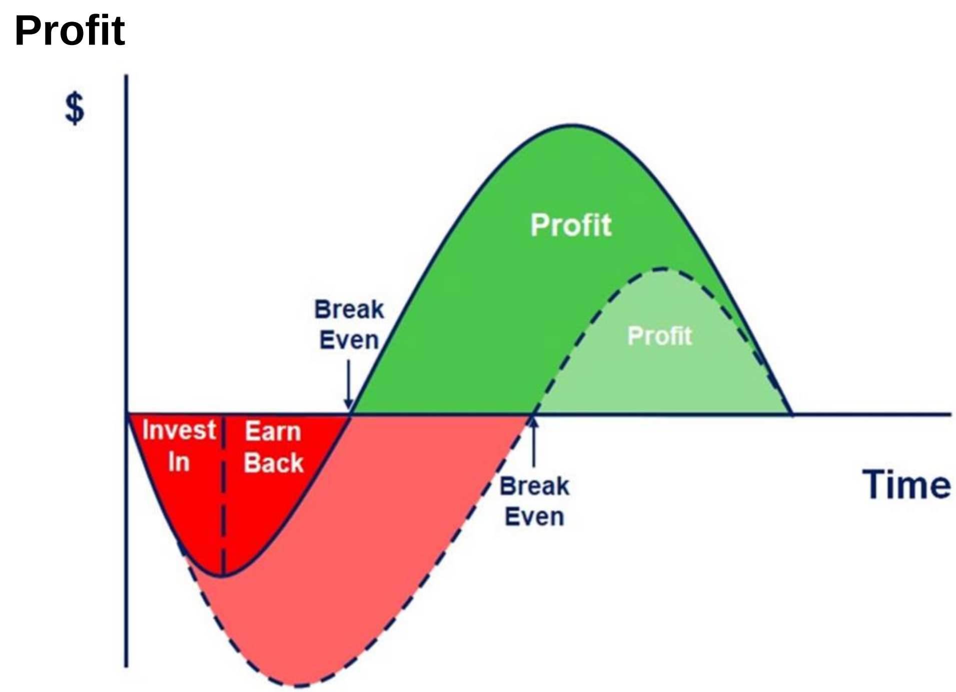


Fig. 2 Funding profile for commercial aircraft programs.

Source: Bevilaqua, P.M., "Design of Aircraft for Best Value," AIAA Journal of Aircraft, Vol. 58, No. 4, Jul-Aug 2021, pp 793-802

Military Aircraft Programs

"…military programs are funded differently, as shown in Fig. 3. Because the military is the sole customer, the manufacturer is reimbursed for the cost of development and earns a profit on those costs. Since any additional development costs are also reimbursed, the manufacturer may feel encouraged to optimize the design of an aircraft in order to increase its performance and their profits. In fact, manufacturers may convince themselves that a better aircraft will sell in greater numbers and earn even greater profits."

Typical Profit Profile

Notional: Not to scale

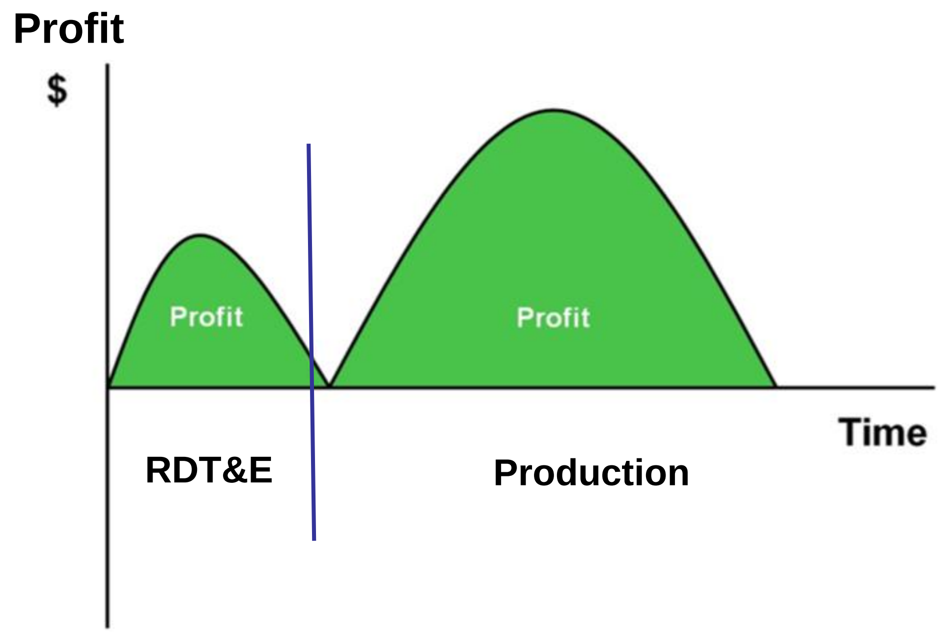


Fig. 3 Funding profile for military aircraft programs.

"However, examination of some recent aircraft programs reveals that when costs increase the opposite occurs: fewer aircraft are sold."

Source: Bevilaqua, P.M., "Design of Aircraft for Best Value," AIAA Journal of Aircraft, Vol. 58, No. 4, Jul-Aug 2021, pp 793-802

Military Aircraft Programs
*Cost Share Considerations**

WHY COST SHARE?

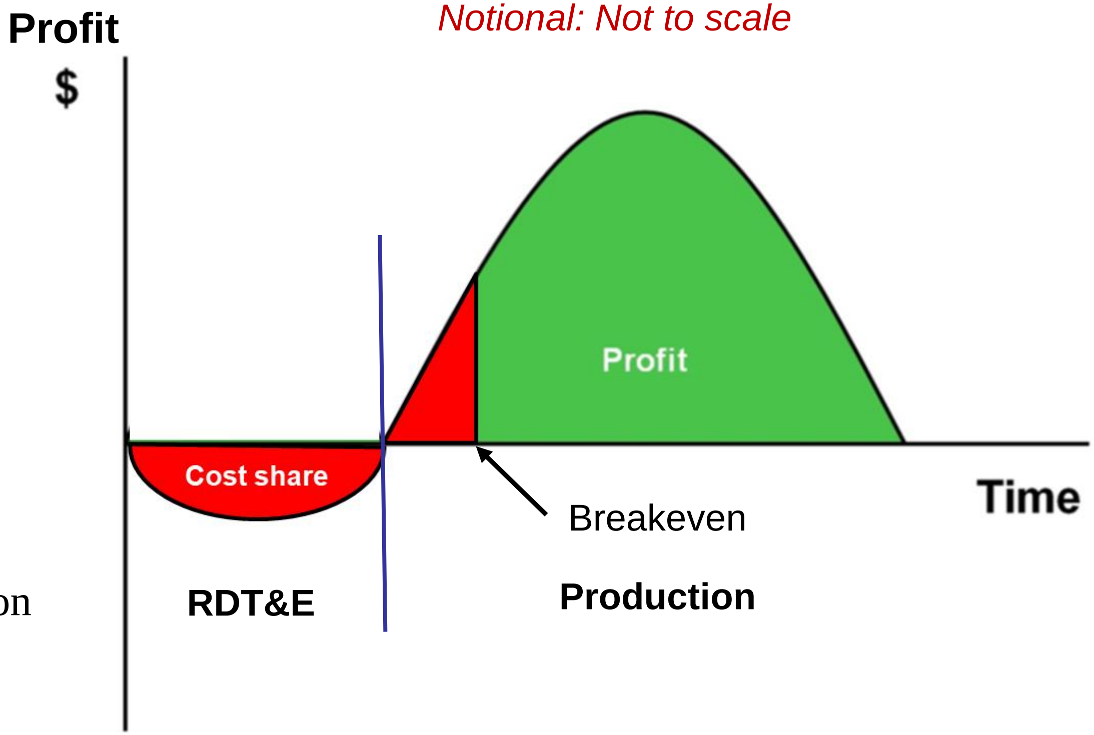
- Customer: reduced investment in aircraft development
- Contractor: may incentivize contractor to focus on successful development by bearing some of the financial risk – "skin in the game"

ASSUMPTIONS

- Contractor offers to cost share a certain percentage (say, *x %*) of total RDT&E cost as shown by red region marked as "Cost share" in the figure
- Customer funds the other (1-*x*)% of the total RDT&E cost on a "cost reimbursement" basis, i.e., no profit
- Contractor uses profits from the initial production lots to cover their cost-share investment for RDT&E
- Past the Breakeven point, the customer books profit on the remaining production lots. *The Breakeven point is obviously determined by the selected value of x!*

Typical Profit Profile

Notional: Not to scale



CHALLENGE: The main challenge for the customer is to select *x* that strikes the right balance between competitiveness and long-term profitability

*Personal communication: Paul M. Bevilaqua, March 2024

Design for Low Production Costs: *Key Considerations*

1. Minimize the part count; this in turn reduces the tooling, fabrication, and assembly time, which reduces touch labor.
2. Standardize left and right tooling; this is another way to keep the part count down. Examples would be interchangeable right and left ailerons, main landing gears, and horizontal tails.
3. Require structural parts to perform multiple functions. An example would be the main landing gear mounted to the wing carry-through structure.
4. Use large unitary pieces of structure rather then build up the structure from many smaller pieces. This reduces touch labor and is often the rationale for using composites (large co-cured pieces) rather than metal built-up parts.
5. Minimize complex checkout.
6. Combine engineering and quality testing.
7. Use simple curvature shapes; the use of compound curvature surfaces greatly increases the tooling and fabrication time.
8. Use simple and common parts; use parts that are common to other aircraft such as landing gears, crew furnishings, and equipment.
9. Use state-of-the-art materials and structures design; this means the use of technology demonstrators during the research phase to fully develop and validate materials and structural concepts before committing them to the aircraft.
10. Use proven engines and inlet–nozzle configurations.

Overall Design Rule is: "Keep It Simple."

Source: Ch. 24, Ref. AVD 1 (Nicolai & Carichner)

Design for Low O&S Costs: *Key Considerations*

- **Design for quick and easy access to everything!**
  - A slightly larger and roomier fuselage, although weighing more and giving lower performance, may pay for itself in reduced MMH/FH
- **MMH/FH is a direct function of**
  - Accessibility (getting to the faulty or suspicious item)
  - Complexity of the system
  - Ease of component removal
- **Designer should recognize that**
  - Avionics equipment is always going to need attention
  - Hydraulic systems are going to leak
  - Fasteners are going to “unfasten”
  - Mechanisms are going to wear out and/or need adjusting
- **Note: The location of most of the components and the roominess of the equipment bays are locked-in during the conceptual and early preliminary design phases**

A good design rule: only package equipment “one deep”

Source: Ch. 24, Ref. AVD 1 (Nicolai & Carichner)

Baseline Average Unit Cost Estimation Example

Table 2 Baseline financial profile for a representative aircraft program

					Development and Manufacturing Costs					
Cost Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Development Engineering	$958,226,808	$958,226,808								
Annual Sustaining Engineering			$163,179,558	$326,359,115	$489,538,673	$652,718,231	$652,718,231	$489,538,673	$326,359,115	$163,179,558
Annual Fixed Expenses	$19,164,536	$19,164,536	$3,263,591	$6,527,182	$9,790,773	$13,054,365	$13,054,365	$9,790,773	$6,527,182	$3,263,591
Total Operating Expense	$977,391,345	$977,391,345	$166,443,149	$332,886,298	$499,329,447	$665,772,595	$665,772,595	$499,329,447	$332,886,298	$166,443,149
Annual Number of Aircaft Sold			50	100	150	200	200	150	100	50
Cummulative Sales			50	150	300	500	700	850	950	1,000
Unit Manufacturing Cost			$31,903,038	$21,014,255	$17,235,169	$15,017,889	$13,629,344	$12,822,210	$12,375,688	$12,143,647
Annual Manufacturing Cost			$1,595,151,881	$2,101,425,486	$2,585,275,307	$3,003,577,753	$2,725,868,836	$1,923,331,494	$1,237,568,757	$607,182,375
Annual Total Costs	$977,391,345	$977,391,345	$1,761,595,030	$2,434,311,784	$3,084,604,754	$3,669,350,348	$3,391,641,431	$2,422,660,940	$1,570,455,055	$773,625,523
					Annual Sales and Profits					
Annual Total Sales	$ 1,124,000,046	$ 1,124,000,046	$ 2,025,834,284	$ 2,799,458,552	$ 3,547,295,467	$ 4,219,752,900	$ 3,900,387,646	$ 2,786,060,082	$ 1,806,023,313	$ 889,669,352
Average Sales Price			$40,516,686	$27,994,586	$23,648,636	$21,098,765	$19,501,938	$18,573,734	$18,060,233	$17,793,387
Annual Gross Margin (Dollars)	$ 165,773,238	$ 165,773,238	$ 430,682,403	$ 698,033,065	$ 962,020,160	$ 1,216,175,148	$ 1,174,518,810	$ 862,728,588	$ 568,454,556	$ 282,486,977
Annual Gross Margin (percent)	14.7	14.7	21.3	24.9	27.1	28.8	30.1	31.0	31.5	31.8
Annual Profit Before Tax	$ 146,608,702	$ 146,608,702	$ 264,239,254	$ 365,146,768	$ 462,690,713	$ 550,402,552	$ 508,746,215	$ 363,399,141	$ 235,568,258	$ 116,043,829
Cumulative Profit	$ 146,608,702	$ 293,217,403	$ 557,456,658	$ 922,603,425	$ 1,385,294,138	$ 1,935,696,691	$ 2,444,442,905	$ 2,807,842,046	$ 3,043,410,305	$ 3,159,454,133
Annual Percent Profit on Sales	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
Average Unit Cost	$ 24,222,482									

Source: Bevilaqua, P.M., "Design of Aircraft for Best Value," AIAA Journal of Aircraft, Vol. 58, No. 4, Jul-Aug 2021, pp 793-802

Effect of Increased Development Cost on Average Unit Cost

Table 3 Effect of increasing the aircraft development costs

Cost Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
					Development and Manufacturing Costs					
Development Engineering	$958,226,808	$1,058,226,808								
Annual Sustaining Engineering			$163,179,558	$326,359,115	$489,538,673	$652,718,231	$652,718,231	$489,538,673	$326,359,115	$163,179,558
Annual Fixed Expenses	$19,164,536	$21,164,536	$3,263,591	$6,527,182	$9,790,773	$13,054,365	$13,054,365	$9,790,773	$6,527,182	$3,263,591
Total Operating Expense	$977,391,345	$1,079,391,345	$166,443,149	$332,886,298	$499,329,447	$665,772,595	$665,772,595	$499,329,447	$332,886,298	$166,443,149
Annual Number of Aircaft Sold			50	100	150	200	200	150	100	50
Cummulative Sales			50	150	300	500	700	850	950	1000
					$31,903,038					
Unit Manufacturing Cost			$ 31,903,038	$ 21,014,255	$ 17,235,169	$ 15,017,889	$ 13,629,344	$ 12,822,210	$ 12,375,688	$ 12,143,647
Annual Manufacturing Cost			$ 1,595,151,881	$ 2,101,425,486	$ 2,585,275,307	$ 3,003,577,753	$ 2,725,868,836	$ 1,923,331,494	$ 1,237,568,757	$ 607,182,375
Annual Total Costs	$ 977,391,345	$ 1,079,391,345	$ 1,761,595,030	$ 2,434,311,784	$ 3,084,604,754	$ 3,669,350,348	$ 3,391,641,431	$ 2,422,660,940	$ 1,570,455,055	$ 773,625,523
					Annual Sales and Profits					
Annual Total Sales	$ 1,124,000,046	$ 1,241,300,046	$ 2,025,834,284	$ 2,799,458,552	$ 3,547,295,467	$ 4,219,752,900	$ 3,900,387,646	$ 2,786,060,082	$ 1,806,023,313	$ 889,669,352
Average Sales Price			40,516,686	27,994,586	23,648,636	21,098,765	19,501,938	Chart Area 734	18,060,233	$ 17,793,387.04
Annual Gross Margin (Dollars)	$ 165,773,238	$ 183,073,238	$ 267,502,846	$ 371,673,950	$ 472,481,486	$ 563,456,917	$ 521,800,579	$ 373,189,915	$ 242,095,441	$ 119,307,420
Annual Gross Margin (percent)	14.7	14.7	13.2	13.3	13.3	13.4	13.4	13.4	13.4	13.4
Annual Profit Before Tax	$ 146,608,702	$ 161,908,702	$ 264,239,254	$ 365,146,768	$ 462,690,713	$ 550,402,552	$ 508,746,215	$ 363,399,141	$ 235,568,258	$ 116,043,829
Cumulative Profit	$ 146,608,702	$ 308,517,403	$ 572,756,658	$ 937,903,425	$ 1,400,594,138	$ 1,950,996,691	$ 2,459,742,905	$ 2,823,142,046	$ 3,058,710,305	$ 3,174,754,133
Annual Percent Profit on Sales	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
Average Unit Cost	$ 24,339,782									

Source: Bevilaqua, P.M., "Design of Aircraft for Best Value," AIAA Journal of Aircraft, Vol. 58, No. 4, Jul-Aug 2021, pp 793-802

Effect of Increased Development Time on Average Unit Cost

Table 4 Effect of extending the time for engineering development by one year

				Development and Manufacturing Costs						
Item	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Development Engineering	$ 958,226,808	$ 958,226,808	$ 958,226,808							
Annual Sustaining Engineering				$ 192,619,421	$ 385,238,843	$ 577,858,264	$ 770,477,686	$ 577,858,264	$ 385,238,843	$ 192,619,421
Annual Fixed Expenses	$ 19,164,536	$ 19,164,536	$ 19,164,536	$ 3,852,388	$ 7,704,777	$ 11,557,165	$ 15,409,554	$ 11,557,165	$ 7,704,777	$ 3,852,388
Total Operating Expense	$ 977,391,345	$ 977,391,345	$ 977,391,344	$ 196,471,810	$ 392,943,620	$ 589,415,430	$ 785,887,240	$ 589,415,430	$ 392,943,620	$ 196,471,810
Annual Number of Aircraft Sold				50	100	150	200	150	100	50
Cummulative Sales				50	150	300	500	650	750	800
Unit Manufacturing Cost				$ 31,903,038	$ 21,014,255	$ 17,235,169	$ 15,017,889	$ 13,759,066	$ 13,129,880	$ 12,817,030
Annual Manufacturing Cost				$ 1,595,151,881	$ 2,101,425,486	$ 2,585,275,307	$ 3,003,577,753	$ 2,063,859,872	$ 1,312,987,971	$ 640,851,483
Annual Total Costs	$ 977,391,345	$ 977,391,345	$ 977,391,344	$ 1,791,623,691	$ 2,494,369,106	$ 3,174,690,737	$ 3,789,464,992	$ 2,653,275,302	$ 1,705,931,591	$ 837,323,293
					Annual Sales and Profits					
Annual Total Sales @ 15%	$ 1,124,000,046	$ 1,124,000,046	$ 1,124,000,046	$ 2,060,367,244	$ 2,868,524,472	$ 3,650,894,347	$ 4,357,884,741	$ 3,051,266,598	$ 1,961,821,329	$ 962,921,787
Average Sales Price				$ 41,207,345	$ 28,685,245	$ 24,339,296	$ 21,789,424	$ 20,341,777	$ 19,618,213	$ 19,258,436
Annual Gross Margin (Dollars)	$ 165,773,238	$ 165,773,238	$ 165,773,238	$ 272,595,942	$ 381,860,143	$ 487,760,776	$ 583,829,303	$ 409,548,461	$ 263,594,515	$ 129,450,882
Annual Gross Margin (percent)	14.7	14.7	14.7	13.2	13.3	13.4	13.4	13.4	13.4	13.4
			$ 146,608,702							
Annual Profit Before Tax	$ 146,608,702	$ 146,608,702	$ 146,608,702	$ 268,743,554	$ 374,155,366	$ 476,203,611	$ 568,419,749	$ 397,991,295	$ 255,889,739	$ 125,598,494
Cumulative Profit	$ 146,608,702	$ 293,217,403	$ 439,826,105	$ 708,569,659	$ 1,082,725,025	$ 1,558,928,635	$ 2,127,348,384	$ 2,525,339,679	$ 2,781,229,418	$ 2,906,827,912
Annual Percent Profit on Sales	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
Average Unit Price	$ 27,857,101									

Source: Bevilaqua, P.M., "Design of Aircraft for Best Value," AIAA Journal of Aircraft, Vol. 58, No. 4, Jul-Aug 2021, pp 793-802

Recommended Reading

Ref. No.	Chapter	Author(s)	Title
AVD 1	**Chapters 24**	Nicolai, L.M. and Carichner, G.E.	***Fundamentals of Aircraft and Airship Design*, *Volume I—Aircraft Design*,** AIAA Education Series, AIAA, Reston, VA, 2010.
AVD 2	**Chapter 18**	Raymer, D.P.	***Aircraft Design* : *A Conceptual Approach*,** AIAA Education Series, AIAA, Reston, VA, 2012.

NOTE: See Appendix in Overview CM