Manufacturing Cost Estimating

Techniques for estimating in a manufacturing environment

"Early in the morning factory whistle blows,
Man rises from bed and puts on his clothes,
Man takes his lunch, walks out in the morning light,
It's the working, the working, just the working life."
- "Factory," Bruce Springsteen

Acknowledgments

- ICEAA is indebted to TASC, Inc., for the development and maintenance of the Cost Estimating Body of Knowledge (CEBoK®)
  - ICEAA is also indebted to Technomics, Inc., for the independent review and maintenance of CEBoK®
- ICEAA is also indebted to the following individuals who have made significant contributions to the development, review, and maintenance of CostPROF and CEBoK ®
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Introduction

- Module Objectives
  - Explain the components of the manufacturing process
  - Discuss estimating considerations the cost analyst must be aware of in the manufacturing environment
  - Provide manufacturing cost estimating techniques to address those issues

- Manufacturing cost estimating
  - the complement of techniques used to forecast resources for the manufacturing environment with a process focus

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- Hardware cost estimating is focused on the *end item*

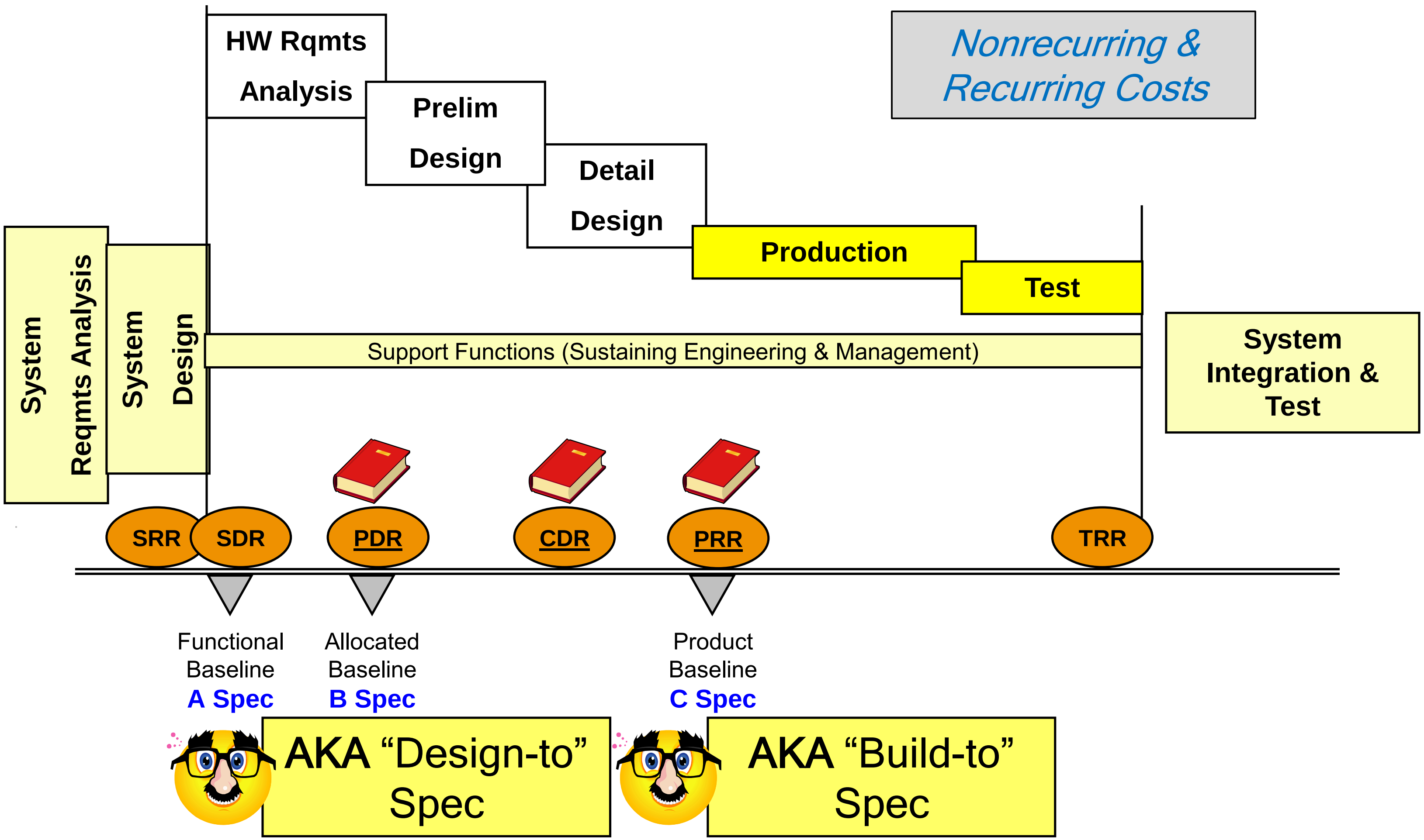
"Hardware Estimating," Galorath Incorporated, http://www.galorath.com/wp/tag/hardware-estimating.

Outline

- Manufacturing Estimating
  - Manufacturing Process
  - Labor
  - Rates
  - Material

References: Industrial Engineering Handbook, Rand Studies on Manufacturing, among others

Hardware Development Cycle



Defense Acquisition University.

Manufacturing Flow Diagram

- Receiving
- Tooling
- Machining
- Sub-assembly
- Assembly
- Finishing/Quality Control
- Shipping

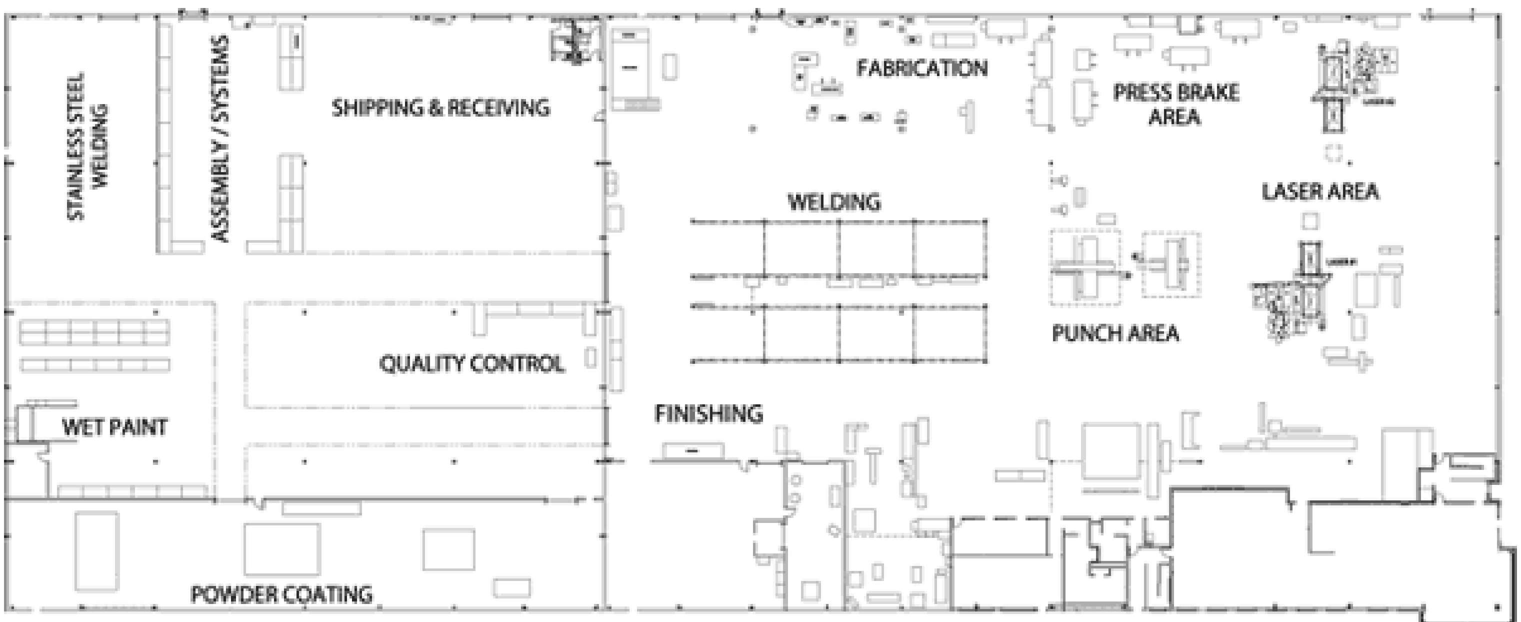


Figure: TruCut Fabricator Plant Layout

Cost Elements in Manufacturing

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- Design & Development
  - Prototyping
- Setup
  - Facilities
  - Tooling and Test Equipment
  - Quality Inspection
- Production Run
  - Labor
    - Touch / Support Labor
    - Labor / Overhead Rates
  - Material
    - Subcontracts / Purchased Parts / Raw Material
    - Material Burdens

DoD Form 1921-1 Functional Cost Hour Report displays costing information by functional cost elements.

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Design and Development

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- Concept Design
- System Design
- Detailed Design / Drawings
- Modeling and Simulation (M&S)
- Prototypes
  - Experimental Development Models (XDMs)
  - Advanced Development Models (ADMs)
  - Engineering Development Models (EDMs)
  - Preproduction Models (PPMs)

http://www.ijee.dit.ie/articles/999975/article.htm

Tip: Prototype costs are a good basis for estimating Recurring Production unit costs. EDMs are most common.

Step Down

"Analyses of the Relationship Between Development and Production Costs and Comparisons with Other Related Step-up/Step-down Studies," Paul L. Hardin, Daniel A. Nussbaum, NCCA, 7 January 1994

Integrated Product and Process Development (IPPD)

- Integrated Product Team (IPT) theory
  - Product orientation instead of functional orientation

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- Need cost estimating and analysis representation on IPT
  - Essential to provide input to Engineering Change Board (ECB) decisions, design trades

Affordability, Value Engineering, CAIV, DTC, DFMA and CBAs

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  - Keeping up can become a challenge
- Budget allocation by IPT (see Example)

Production Setup

- The “non-recurring” process of setting up prior to performing a production run of a component

Set-up for facility, line, lot or processing

- Production Setup includes:
  - Process Engineering – define / refine manufacturing procedures
  - Facility Layout – establish manufacturing flow
  - Tooling and Test Equipment – develop layout and procedures

Facilities

- Capital Investments/Improvements
  - Production house often works single program
  - Development house often has several programs
  - Costs spread more for development
- Facilities Capital Cost Of Money (FCCOM)
- Facility Maintenance

AKA Cost Of Facilities Capital (COFC)

Tip: Facilities can be a Direct or Indirect expense, but needs to be accounted for.

Annual facility maintenance costs increase over time as facilities age, and recapitalization becomes more economical.

Tooling and Test Equipment

- Tooling
  1
  - Required to produce (e.g., lathe) and support (e.g., jigs and fixtures) components during production and test
  - Soft Tooling / Rate Tooling
  - Requires maintenance and recapitalization
- Test Equipment
  - Required to qualify design and verify manufacturing process yielded acceptable component
  - Can be segregated into mechanical / electrical
    - Mechanical ground support equipment (MGSE) + electrical ground support equipment (EGSE) = aerospace ground equipment (AGE)
  - Requires maintenance and recapitalization

Production Setup Considerations

- Manufacturing Environment
  - Prototype vs. Full-Rate or Limited-Rate Production

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- Degree of Automation
  - Computer-Aided Design (CAD)
    - Used for design and particularly drafting (technical drawing and engineering drawing) of a part or product
  - Computer-Aided Manufacturing (CAM)
    - Used to manufacture physical models

i.e. NC machining, 1- or 2-sided with multiple spindles

  - Computer-Aided Engineering (CAE)
    - Used to supports engineers in tasks such as analysis, simulation, design, manufacture, planning, diagnosis, and repair
- Availability and Flexibility of Tooling / Test Equipment

Integrated Software tools are often referred to collectively as **CAD / CAM / CAE** and can be used in conjunction with three-dimensional (3D) modeling.

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Estimating Setup Costs

- When developing estimates for production setup
  - Consider commodity type
  - Account for production rate
  - Consider automation
    - Consider applying a percent reduction factor from a *different* analogy program
- Commonly estimated by analogy to similar programs or by parametric CER
  - Scale by T1 cost (or labor hours)
  - Scale by Weight (or other sizing parameter)

Double Analogy

Is cost history representative of costs being estimated?

Tip: Be sure estimating methods account for the considerations listed earlier

Production Run Characteristics

- Recurring Cost Elements
  - Labor
    - Touch / Support Labor
    - Labor / Overhead Rates
  - Material
    - Subcontracts / Purchased Parts / Raw Material
    - Material Burdens
- Considerations
  - Learning Curve / Production Breaks
  - Process "Improvements"
    - Integrated Product Teams (IPTs)
    - Lean Manufacturing
    - Six Sigma
    - Agile Production

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Estimating Labor Costs

- Manufacturing / Production Labor can be estimated by the following methods:
  - Build-up from detailed labor standards
  - Analogy to actual labor hours from similar project
  - Parametric CER of actual labor hours from similar "in-family" projects

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Build-up is the most common method used in Manufacturing Cost Estimating

DAU course "CLB029 Rates" introduces the basics of wrap rate development as it relates to cost estimating

Manufacturing Analogy Estimate

- The Space and Technology Company that manufactures satellites is creating an estimate for a new satellite
- The antenna subsystem that will be used on the new satellite is very similar to that of an existing satellite the company also manufactures

Attribute	Analogy Satellite	New Satellite
Antenna Subsystem Weight	500 lbs	300 lbs
T1$K:	$21,000	?

Q: What is the 1st unit cost of the new satellite antenna subsystem?

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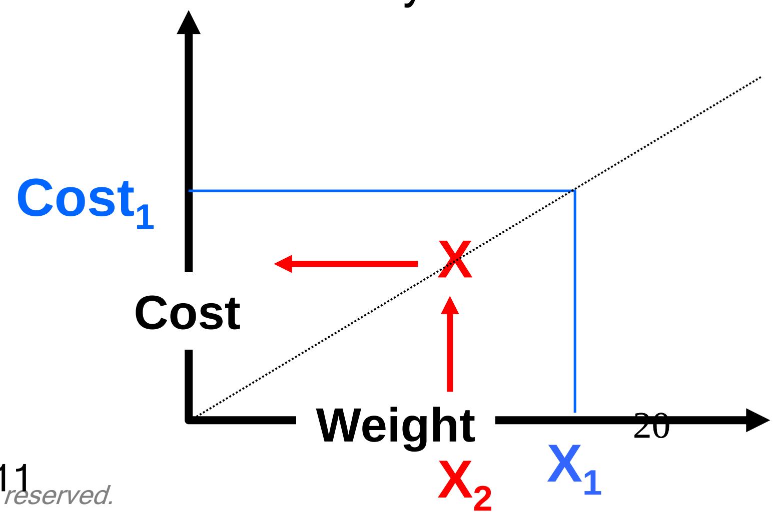
A: $21,000 * (300 / 500) = $12,600K

Warning: Making a smaller antenna is different than making an antenna smaller!



ICEAA CEBoK

Manufacturing Parametric Estimate

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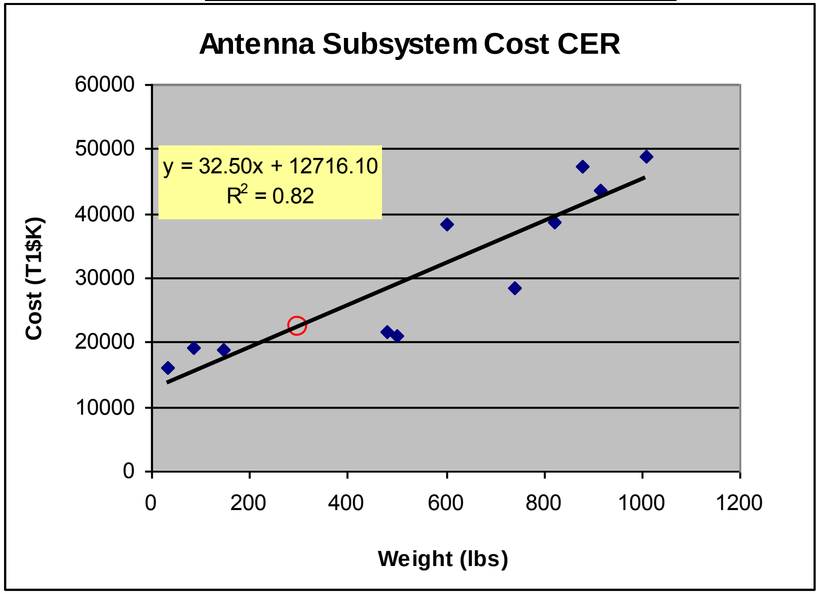
Using the satellite manufacturing example from the previous slide, suppose that the Space and Technology Company had several analogous satellite antenna to use as historical data points.

Cost (T1$K)	Weight (lbs)
15950	32
19175	86
18725	145
21500	480
21000	500
38300	600
28550	740
38575	820
47300	880
43650	914
48875	1010

Attribute	New System
Satellite Antenna Subsystem:	300 lbs
Cost:	?

Q: What is the 1st unit cost of the new satellite antenna subsytem?

A: 32.5 * 300 + 12,716 = $22,466K



Note: This estimate for the same new system is much higher than the analogy estimate on the previous slide. This illustrates the perils of factors, and arises due to the y intercept.

Manufacturing Build-Up Estimate
Labor and Time Standards

- Standards are a direct result of time studies and work measurement
- Time standard is the amount of time allowed to complete a given task
- In addition to estimating, the following operational areas require accurate time and cost data in a manufacturing environment
  - Production control
  - Plant layout
  - Purchasing
  - Cost accounting and control
  - Process and product design

Time Studies

- A time (and motion) study is a method for establishing an allowed time standard for performing a specific task
  - Method to determine a "fair day's work"
- Time study analysts can employ many different techniques to establish a time standard
  - Stopwatch time studies
  - Computerized data collection
  - Standard data
  - Formulas
  - Work sampling studies
  - Predetermined time systems

Tip: Time studies should be based on *your* data, whenever possible!

Development of Time Standards

- Many factors should be taken into consideration during the development of a time standard:
  - The amount of work
  - The type of work
  - The prescribed work method
  - Fatigue
  - Delays (personal and unavoidable)
  - Unit at which standards are derived

AKA Standard Time

- Standard Time = $\frac{\text{Measured Time * Pace}}{\text{1-PF\&D}}$
  - Personal Fatigue and Delay (PF&D)
    - PF&D factors can run as high as 25%
  - Pace is a measure of relative rate
    - Pace may be related to position on the learning curve (unit number), maturity of work, and worker experience
    - As an area of considerable variation, it should be used with great care

Use of Time Standards

- Predict direct labor costs
  - Direct Labor Costs = Std Time * Realization Factor * Wage Rate
- Measure labor efficiency
  - Efficiency = Earned Hours of Production / Actual Labor Hours

Earned hours of production is calculated from the time standards of the work produced

- Determine employee wages and incentives
  - Provides a yardstick to measure individual performance
- Compare work methods
- Determine plant capacity
- Improve production control
- Size workforce and new equipment purchases
- Coverage of standards is often more complete in earlier phases of work on a unit than in later
  - Simple repeatable actions are easiest for standards (e.g., time to weld 1 meter of ½" steel, time to install 1 meter of ½" pipe, etc.)

Realization Factor and Efficiency

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- <u>Realization Factor (F_R)</u> and <u>Efficiency Factor (F_E)</u> both compare actual labor hour to a previously determined standard effort
  - F_R = Actuals / Standard <1 good, >1 bad
  - F_E = Standard / Actuals >1 good, <1 bad
  - $F_R = 1/ F_E$, $F_E = 1/ F_R$

F_R **AKA** Variance Factor
F_E **AKA** Performance to Standards (PTS)

- As already noted, F_R (F_E) is likely to change with unit, because this is implicit in the theory of learning
- It is speculated that F_R (F_E) and Pace are intimately connected

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Standard Time is used to set a benchmark that the operator should meet.

Realization factors are metrics to determine how close operators performed to the standard time.

Manufacturing Build-Up Estimate Using Labor Standards

- **An estimator is trying to estimate the number of man-hours required to fit, weld and grind an assembly at a shipyard**
- **The work on new assembly will be performed in an uncovered work area that has a Personal Fatigue & Delay (PF&D) factor of 25% associated with it**
- **The assembly work would normally be performed in a covered shop area with a 10% PF&D factor**

Operation	Standard (mhr / lf)	Normal PF&D
Fit	2.5	10%
Weld	1.7	10%
Grind	0.8	10%

Q: The new assembly has 750 linear ft that must be fit, welded, and ground. How many manhours should be estimated for each operation of the new assembly?

A: Fit mhrs = 2250, Weld mhrs = 1530,
Grind mhrs = 720

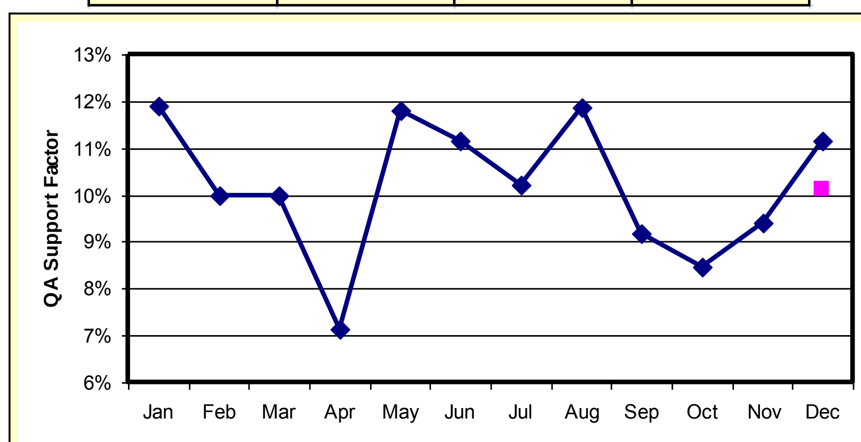
$$\text{Standard Time} = \frac{\text{Measured Time} * \text{Pace}}{1-\text{PF\&D}}$$

Unit IV - Module 11

Support Labor

- Support Labor = Non-"touch" labor that supports the manufacturing process
  - Manufacturing Engineers
  - Industrial Engineers
  - Quality Control
  - Parts, Materials, & Processes
- Typical estimates
  - Factor of Touch Labor
  - LOE (FTEs per time)

747 Center Bulk Head Machining			
Month	Machining Standard Hours	Quality Assurance Hours	Average Monthly Ratio
January	42.0	50.0	11.90%
February	48.0	48.0	10.00%
March	47.0	47.0	10.00%
April	56.0	40.0	7.14%
May	50.0	59.0	11.80%
June	52.0	58.0	11.15%
July	49.0	50.0	10.20%
August	48.0	57.0	11.88%
September	49.0	45.0	9.18%
October	52.0	44.0	8.46%
November	50.0	47.0	9.40%
December	43.0	48.0	11.16%



"Non-Standard" Labor Element Example - Quality Assurance (QA)

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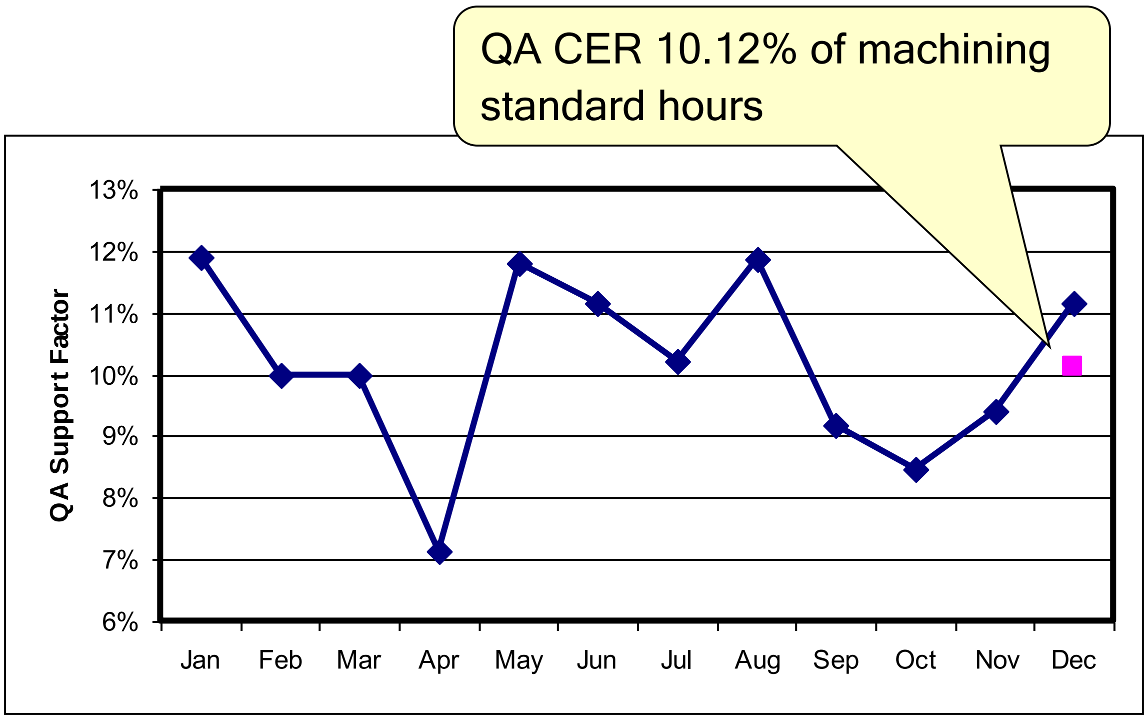
- Non-Standard CER Development
  - Projected future cost of QA for next January will be 10.12% of machining standard hours

747 Bulkhead Machining			
Month	Machining Std MH	QA Hours	Factor
Jan	420	50	11.9%
Feb	480	48	10.0%
Mar	470	47	10.0%
Apr	560	40	7.1%
May	500	59	11.8%
Jun	520	58	11.2%
Jan-Jun	491.7	50.3	10.24%
Jul	490	50	10.2%
Aug	480	57	11.9%
Sep	490	45	9.2%
Oct	520	44	8.5%
Nov	500	47	9.4%
Dec	430	48	11.2%
Jul-Dec	485	48.5	10.00%
Jan-Dec	488.3	49.4	10.12%
Avg Factor			10.19%



QA Non-Standard CER Example

- Note that a statistical examination of this problem produces a *similar* result with a *very different* approach:
  - There is no significant function linking QA to Machining hours
  - There is no significant difference in regression of the full year vs. the halves
  - The CV of the monthly ratios is small at 14.6%
  - So, we resort to a year-long ratio of 10.12%

747 Bulkhead Machining			
Month	Machining Std MH	QA Hours	Factor
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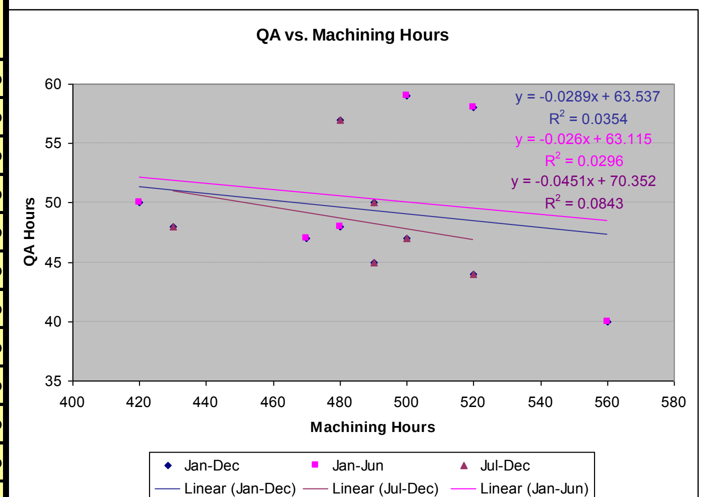
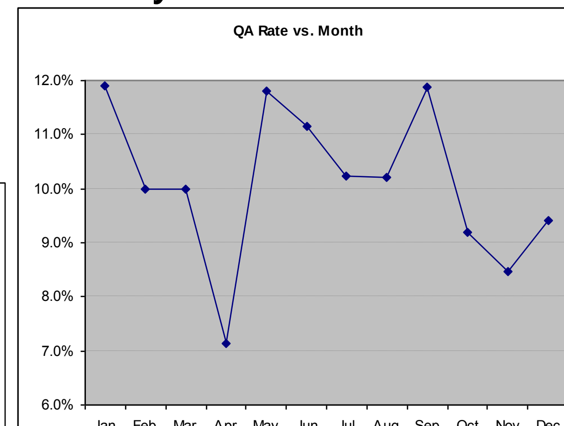
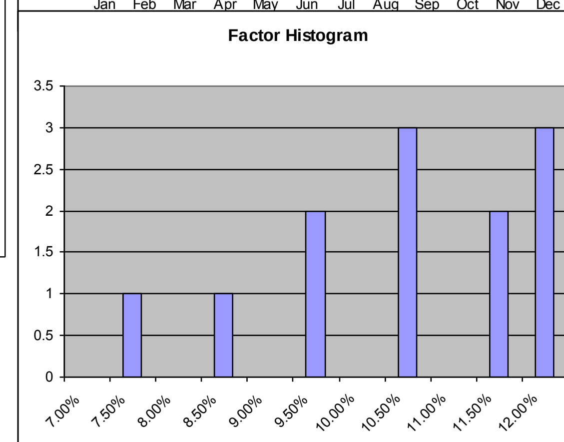
Jul	490	50	10.2%
Aug	480	57	11.9%
Sep	490	45	9.2%
Oct	520	44	8.5%
Nov	500	47	9.4%
Dec	430	48	11.2%
Jan-Dec	488.3	49.4	10.12%
Avg Factor			10.19%
Std Dev			1.48%
CV			14.6%







Considerations in Manufacturing

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- Learning Curve
- Production Breaks

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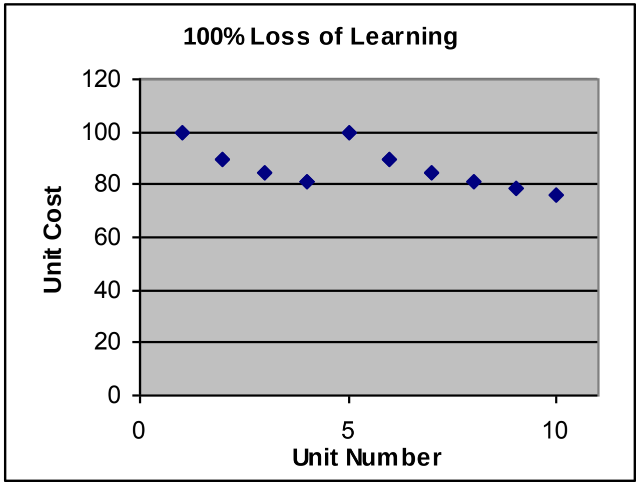
- - Schedule Delays
  - Engineering Changes
  - Rework and Retrofitting
  - Shut-down Breaks
- Green Labor
- Process Improvements
- Make or Buy



Learning Curve Example

- Using the example of satellite antenna subsystems previously discussed, calculate the total cost of the satellite antenna subsystems for the first 4 satellites from our previous example assuming a 90% Cumulative Average LCS

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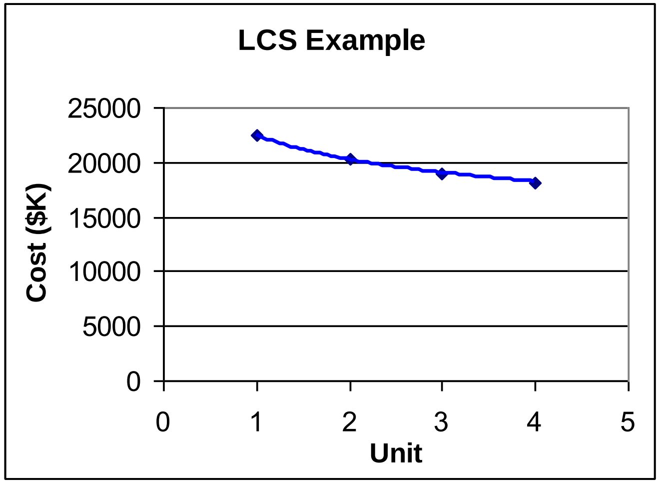
  - Lot Size → 4
  - Learning Curve Theory → CumAv
  - Learning Curve %, T1 → 90%, $22,466K



$$b = \log_2 0.90 \approx -0.152$$

  - Answer
    - Total Cost = aX $^{b+1}$ =$22,466 * 4 ^ 0.848
      - » $72,790K

$$Total = aX^{b+1}$$

Production Break Example

- Stress fractures in vertical tail of an aircraft
  - Design change required to reinforce vertical tail implemented at 85th unit
  - Design change and retooling cause a break in production
  - Break in production increases costs and reduces efficiency
- Break analysis
  - Units 1 through 84 should be treated as a dataset
  - Cost of Unit 85 is determined using break analysis and a new learning curve is run from there to predict the cost of future units

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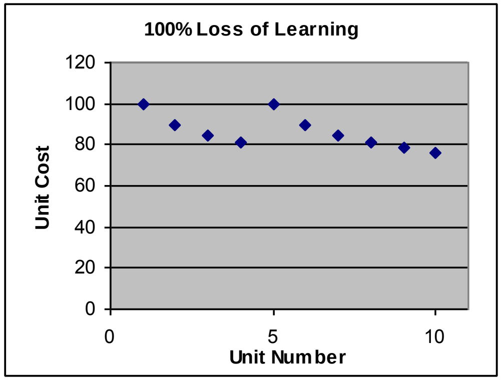
Andelohr analysis of learning loss



Lean Manufacturing Techniques

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- **Just-in-Time (JIT) Production**
  - Inventory strategy to improve the return on investment by reducing in-process inventory and its associated carrying/holding costs
- **Kanban System**
  - Related to JIT Production and is a signaling pull system that determines what to produce by the actual customer demand.
- **Value Stream Mapping**
  - Analyzes the flow of materials and information currently required to bring a product or service to a customer
- **Poka-yoke**
  - "Mistake-proofing" methodology for production
- **5S**
  - Philosophy and way of organizing and managing the workspace (normally a shared workspace) and work flow with the intent to improve efficiency by eliminating waste, improving flow, and reducing process unreasonableness

Quality Assurance (QA)

- Quality Assurance (QA) Inspection and Reporting Methods
  - Non-Destructive Inspection (NDI) vs. sampling inspection
  - Statistical Process Control (SPC)
  - Computerized Inspection Equipment

AKA Quality Control (QC)

Cost Benefit Analyses to justify tech insertions that reduce QA costs can be challenging

Make or Buy

- Product manufacture and delivery responsibility of IPT Lead leads to creative use of resources
- 13 IPT Lead may incorporate "Make or Buy" process
- Might be more cost effective (or faster) to buy a part from an outside vendor instead of making the part in-house

AKA Backdooring

Rates Estimating

- Direct Rates
- Indirect Rates

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Direct Labor Cost ($) =
Direct Labor Rate ($/hr) x Labor Hours

Total Labor Cost ($) =
(1 + Overhead Rate) x Direct Labor Cost ($)

Warning: Overhead rates are usually additive, but like many such numbers, may be stated as either additive (100% more) or multiplicative (200%). Be sure of which you are using.

Tip: Correct application of labor and overhead rates is extremely important for pricing

Labor Elements and Burdening

- Direct Labor
  - Direct Salary
    - Gross Pay
  - Fringe Benefits
    - Paid Time Off (PTO) – vacation, sick, holiday
    - Health Plan
    - 401K, Pension
- Indirect Functions
  - Supervisor and Management Salaries
  - Operating Expenses
    - Lease, utilities, etc.
  - Subcontract and Material burdens
  - General and Administrative (G&A) expenses
    - Payroll, Marketing, Corporate Expenditures
  - Facilities Capital Cost Of Money (FCCOM)

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Tip: Don't forget Fee! 14

Rates Example

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	Company A		Company B	
Manufacturing Labor Standard	100 Hours		150 Hours	
ENGR Support Labor Factor		45%		25%
ENGR Support Labor		45		37.5
MFG Direct Labor Rate	$	25.00	$	20.00
ENGR Labor Rate	$	40.00	$	35.00
Fringe Rate		50%		50%
MFG OH		100%		100%
ENGR OH		80%		80%
Material Cost	$	2,500.00	$	2,500.00
Material Burden		10%		10%
G&A Burden (non value added)		20%		20%
Cost Through G&A	$	15,132.00	$	15,352.50
What is the Fully Burdened WRAP Rate?	$	104.36	$	81.88

Accounts for Fringe benefits that are the Company contribution to health plan, 401K, etc.

Total dollars divided by total hours: $15,132 / 145

Labor Rate Challenges

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- Use of Correct Labor Rates
  - Skill mix required for estimating
  - Labor category determines labor rate
- Forward Pricing Rate Agreements (FPRAs)
  - Include business base assumptions
  - Account for cost of living adjustments (COLA)
- Organized Labor issues
- Regulatory Issues
  - Labor laws
  - Premium Pay

Federal Acquisition Regulation (FAR) 15.801

Composite Rate = Σ (Direct Rate * Hours) / Σ Hours

Skill Mix Example	Direct Rate	Hours
Engineer 1	$ 25.00	1,000
Engineer 2	$ 30.00	500
Engineer 3	$ 40.00	250
Engineer 4	$ 50.00	250
Composite Rate	**$ 31.25**	

Material Cost Estimating

- Material Costs and Types of Materials
- Material Concerns
  - Tolerances
  - Quality
  - Scrap Rates
  - CAD/CAM
- Material Manufacturability

Material Costs

- Raw Material
  - Material to be transformed by manufacturer into a product
  - Example: Steel Plate transformed to Hull Structure by Welding and Shipfitting Processes
- Purchased Parts
  - Materials to be installed by manufacturer to make a final product
  - Example: Prefabricated Doors and Hatches installed on a Ship
- Subcontractor Costs
  - Costs associated with an outside company that produces a product or performs a service
  - Determined by make/buy analysis
  - May include Long-Lead Material
  - Examples: Power Plant subcontract, Armament subcontract
  - Often labeled as "Material" by the contractor, even though it may be part or all labor
    - Examples: Consultants, Engineering Services

Types of Raw Materials

- Metal
  - Ferrous
  - Nonferrous
- Non-Metal
  - Organic
  - Inorganic
- Composites
- Bonding Material and Laminates
- Exotic Materials
  - Radar-Absorbing Material (RAM)
  - Composite Tubing
  - Coating Materials

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Aluminum machining costs less than stainless steel with same strength properties after anodizing

Methods exist to enable the costing of various types of materials

Material Concerns

- <u>Tolerances</u>
  - Performance
  - Reliability
  - Manufacturability

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- Quality
  - Defects
  - Performance Properties

9

  - Vendor Self-Inspection
  - In-process Inspection
- <u>Scrap Rates</u>
  - Rework
  - Percentage of end item material
  - Negotiated <u>Material Usage Allowance (MUA)</u>
- CAD/CAM
  - Material Take-off List (MTOL)

Quality Assurance costs reduced with the implementation of vendor self-inspection program

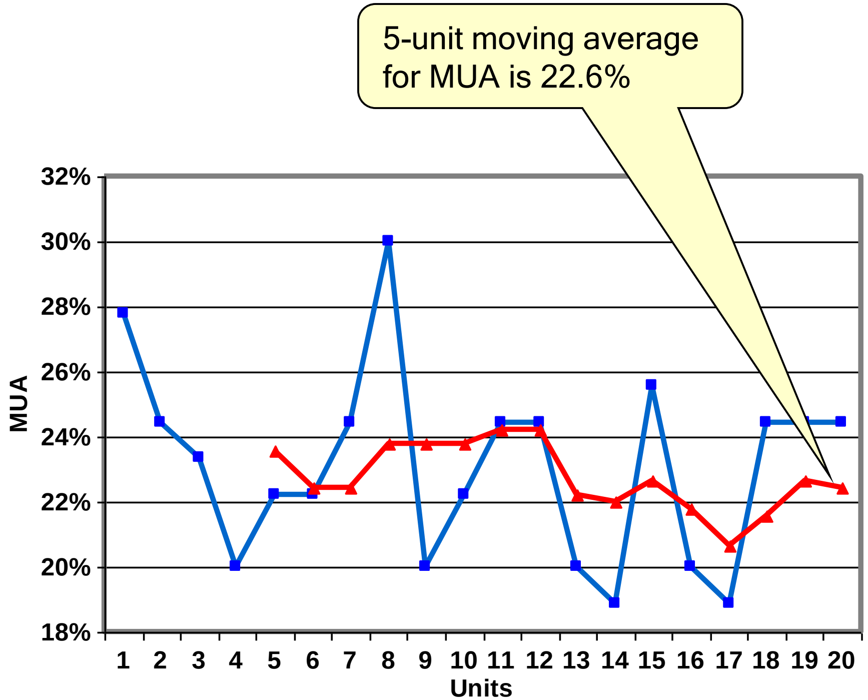
Tip: Scrap Rates ensure that we include costs associated with material loss/waste

Warning: The error is in the denominator: Scrap rate is not a percentage of total material used

Material Usage Allowance (MUA)

- Material usage has been tracked for the last 20 air vehicles of the B2 canopy panel with a stable design - no change for 20 units
- A new design is implemented for the 21st canopy panel

Unit	Raw Material Weight	Delivered Product Weight	Delta/Unit	5-Unit Moving Average
1	115	90	27.8%	
2	112	90	24.4%	
3	111	90	23.3%	
4	108	90	20.0%	
5	110	90	22.2%	23.6%
6	110	90	22.2%	22.4%
7	112	90	24.4%	22.4%
8	117	90	30.0%	23.8%
9	108	90	20.0%	23.8%
10	110	90	22.2%	23.8%
11	112	90	24.4%	24.2%
12	112	90	24.4%	24.2%
13	108	90	20.0%	22.2%
14	107	90	18.9%	22.0%
15	113	90	25.6%	22.7%
16	108	90	20.0%	21.8%
17	107	90	18.9%	20.7%
18	112	90	24.4%	21.6%
19	112	90	24.4%	22.7%
20	112	90	24.4%	22.4%



MUA Example

- Additional inputs:
  - The mass properties engineer estimates the weight of the new panel at 100 pounds
  - The cost of the raw material is $200 per pound

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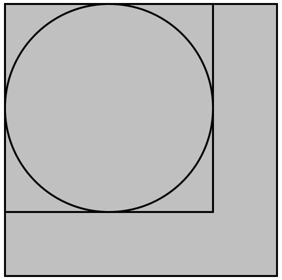
- Solution:
  - The raw material needed for the newly designed panel is: 100 x (1 + 22.6%) = 122.6 pounds
  - The estimated raw material cost is: $200 x 122.6 pounds = $24,520
- Consideration:
  - Estimators need to assess design changes and drawing revision numbers and not assume design stability

Material Cost Estimating Example

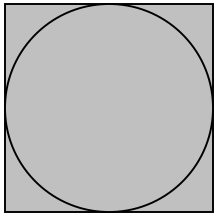
- 3-inch diameter cover plate machined from 4-inch aluminum plate raw stock

Material cost	$10
Machining cost	$5
Total cost	**$15**
Scrap rate	**126.4%**



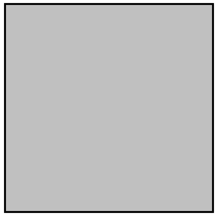
- 3-inch diameter cover plate machined from 3-inch aluminum plate raw stock

Material cost	$7
Machining cost	$4
Total cost	**$11**
Scrap rate	**27.3%**



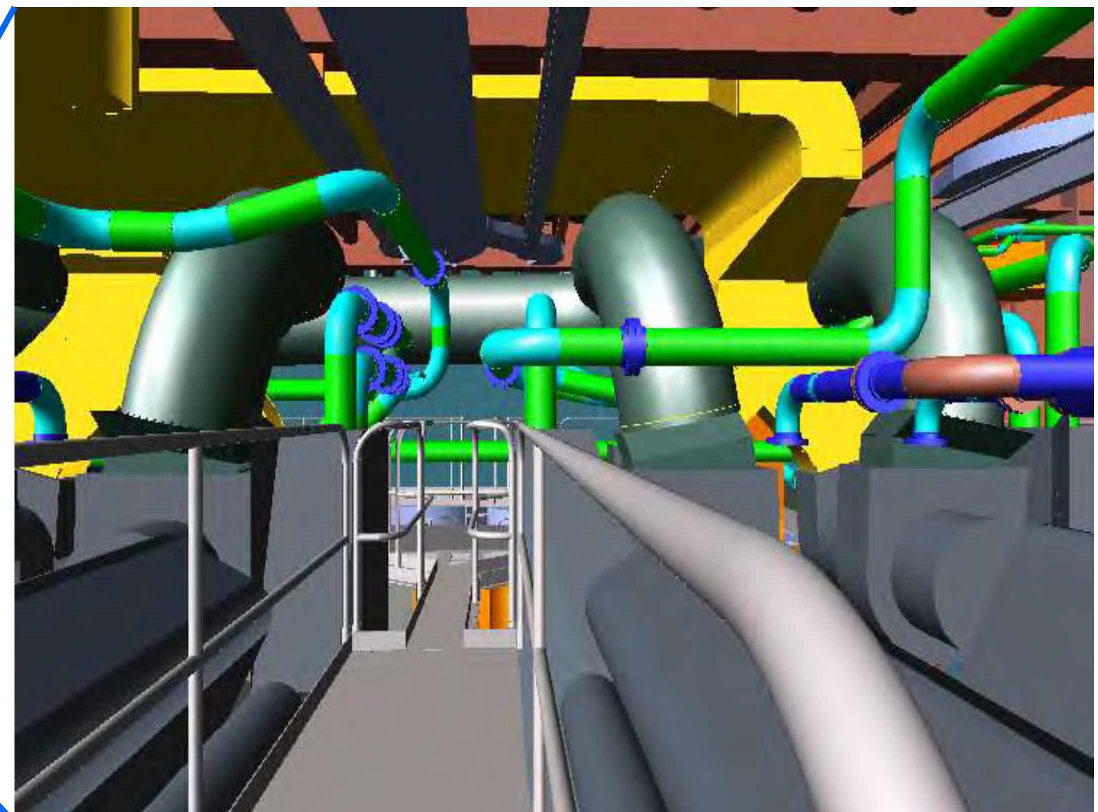
- 3-inch aluminum plate raw stock is used to produce square cover plate

Material cost	$7
Machining cost	$0
Total cost	**$7**
Scrap rate	**0.0%**



Material Take-Off List (MTOL)

- CAD drawing of ship compartment
- Generate <u>Material Take-Off List (MTOL)</u>



CAD graphics courtesy of Northrop Grumman Shipbuilding - Gulf Coast.

MTOL Example

- MTOL table includes standard items and factors
  - In this case, linear feet (LF) of pipe and cost per foot for different diameters

FIREMAIN PIPE			
	1”	4”	6”
Length (LF)	10	100	30
Unit Cost/LF	$50.00	$30.00	$60.00
Cost	$500.00	$3,000.00	$1,800.00

- MTOL quantities also support Labor estimating

Material Manufacturability

- Material Mix
- Manufacturability of Metals/Non-Metals
- RAND Study Findings
  - Weighted Material Cost Factor (WMCF)
  - Effect on Recurring Manufacturing Labor Costs
  - Relative Factor based on Late 1980s Aluminum Fighter Airframe
- Example:
  - Airframe is 25% aluminum, 30% titanium, 35% graphite epoxy composites, and 10% steel
  - **WCMF** = (0.9x0.25) + (1.61x0.3) + (1.58x0.35) + (1.27x0.1) **=1.388**

Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Process, Obaid Younossi, Michael Kennedy, and John C. Graser, Rand, MR-1370-AF, 2001

Manufacturing Summary

- In this module, we have covered manufacturing-specific issues such as:
  - Development vs. Production
  - Production Set-up Activities
  - Production Run Characteristics
    - Labor Estimating
    - Rates Estimating
    - Materials Estimating