2019 ICEAA SoCal

Top-Down Composite Manufacturing Estimation

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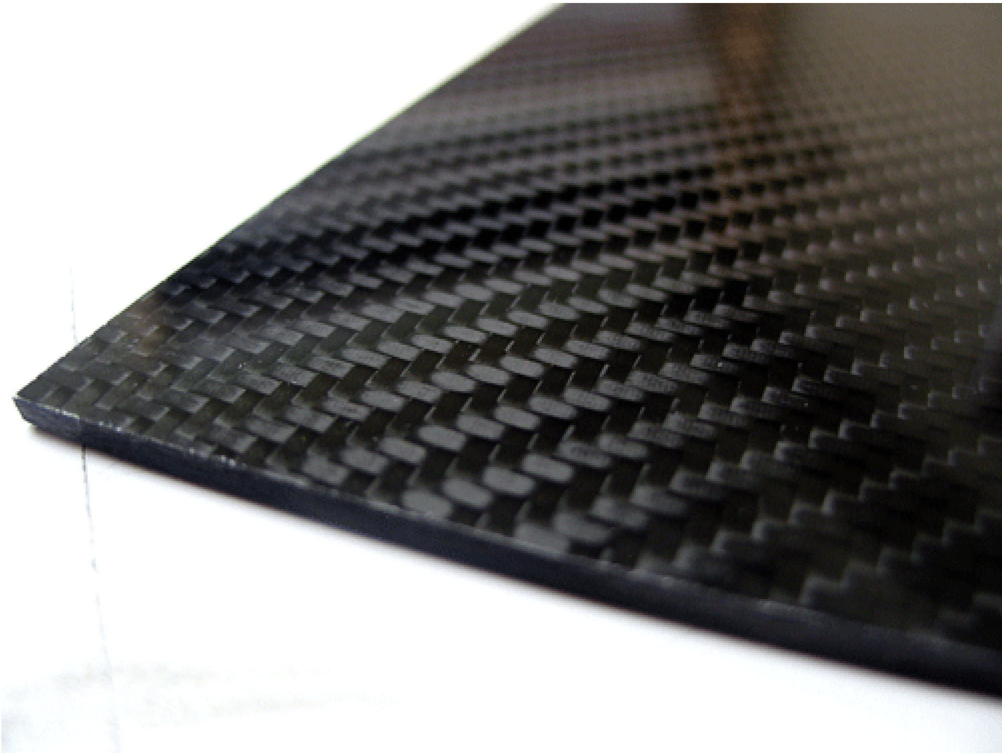
9/10/2019

Estimate with Confidence™

Agenda

- Composite Definition
  - What is it?
  - Why is it used?
- Scope of Project
- Method of Approach
- Results & Validation
- Future Work



What Are Composites?

- Material system with:
  - 2 or more distinct phases
  - Material combination produces different properties than the individual materials
- Are used because:
  - High strength and stiffness
  - Lower weight than metal
  - Fatigue and corrosion less significant
  - Many property combinations possible

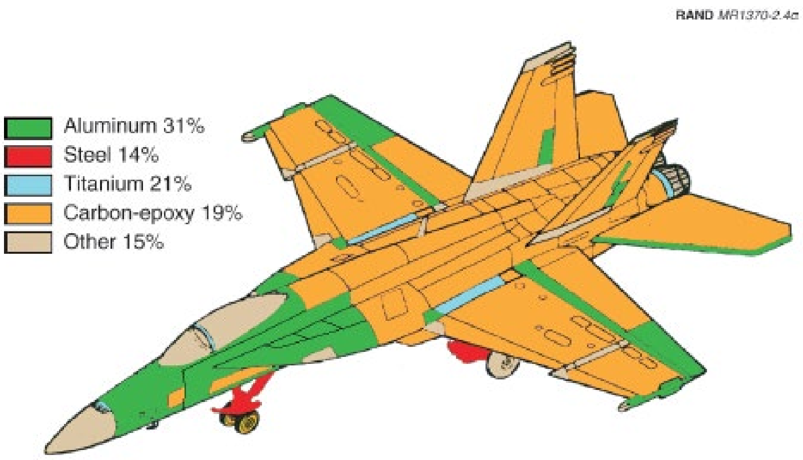


Figure 2.4c—F/A-18E/F Overall Material Use

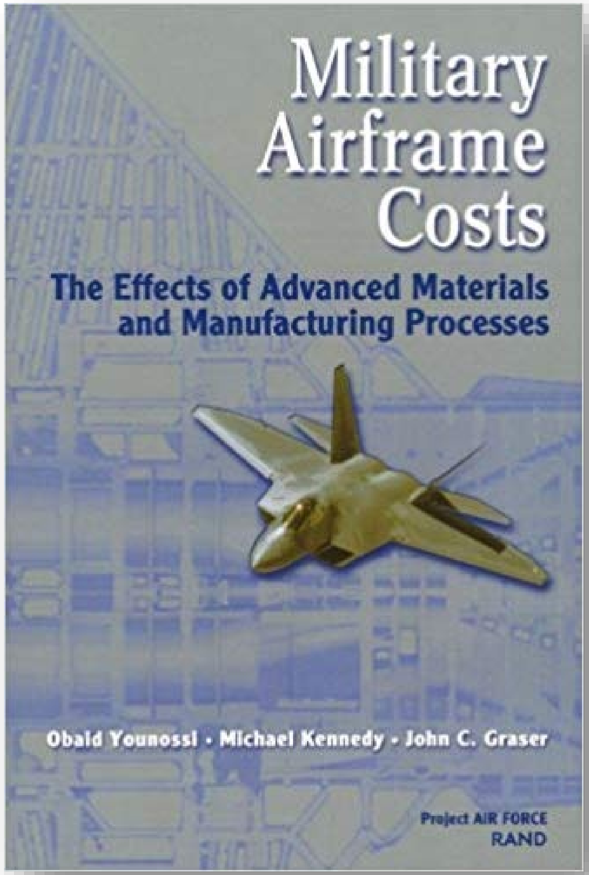
*Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes

Scope of Project

- Create estimating solution for composite manufacturing:
  - Literature review of current market
  - Format data into mathematical model
  - Validate the model
- Model to be improved incrementally:
  - Materials
  - Processes
  - Variables

Source Material

- Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes
  - 2001 RAND Corporation book
  - 1980s, 1990s, and 2000s data:
    - *Boeing*
    - *Lockheed Martin*
    - *Northrop Grumman*
    - *Hexcel*
  - Includes info for:
    - *Physical properties*
    - *Cost/labor ratios*



Late 1980s Cost Ratios from Resetar, Rogers and Hess (1991)

Material	Non-recurring Engineering	Non-recurring Tooling	Recurring Engi-neering	Recurring Tooling	Recurring Manufac-turing	Recurring Quality Assurance
Aluminum	1.0	1.0	1.0	1.0	1.0	1.0
Aluminum-lithium	1.1	1.2	1.1	1.1	1.1	1.1
Titanium	1.1	1.4	1.4	1.9	1.6	1.6
Steel	1.1	1.1	1.1	1.4	1.2	1.4
Carbon-epoxy	1.4	1.6	1.9	2.2	1.8	2.4
Carbon-BMI	1.5	1.7	2.1	2.3	2.1	2.5
Carbon-thermo-plastic	1.7	2.0	2.9	2.4	1.8	2.6

[a]Late 1980s aluminum = 1.0.

*Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes

1990s Cost Ratios Based on Part Data Analysis: All-Airframe Labor Basis, Composites

Fabrication Process	Simple	Medium	Complex	Very Complex
Hand layup	1.3	1.8	2.2	3.0
Hand layup with OLPA	1.1	1.6	1.9	2.6
Automated fiber placement	0.7	1.3	1.7	Not available
Resin transfer molding	Not available	Not available	1.4	2.3

[a] 1990s medium-complexity, conventionally machined aluminum = 1.0.

*Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes

Part and Geometric Complexity Cross-Reference Matrix

Part	Simple	Medium	Complex	Very Complex
Beams			X	
Bulkheads			X	
Chines		X		
Contoured skins		X		
Covers	X			
Diverter lips				X
Doors	X			
Edges				X
Equipment trays		X		
Fittings	X			
Flat skins	X			
Floor panels		X		
Frames			X	
Fuel decks		X		
Fuel tank sidewalls		X		
Hubs				X
Inlet ducts			X	
Inlet lips				X
Keels			X	
Longerons			X	
Multicurvature skins			X	
Panels	X			
Pylons			X	
Ribs			X	
Spars			X	
Spindles				X
Stiffened skins		X		
Webs			X	

*Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes

Material Properties

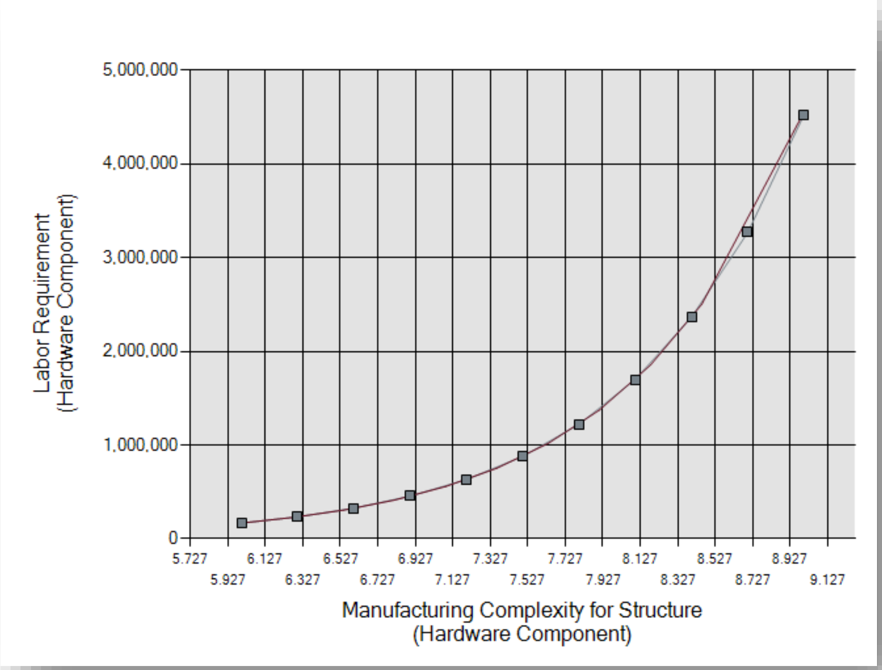
Property	Aluminum (7050-T7451)[a]	Titanium (6Al-4V)[a]	Steel (PH13-8Mo)[a]	Carbon/ Epoxy (IM7/ 977-3)[a]	Carbon/ BMI (IM7/ 5250-4)[a]	Carbon/ Thermo-plastic (IM7/PEEK)[a]
Density (lb./sq in.)	0.102	0.160	0.279	0.057	0.056	0.058
Strength (KSI)	70	134	201	332	349	323
Stiffness (MSI)	10.3	16.0	28.3	22.2	22.2	22.7
Specific strength (K in.)	685	840	720	5825	6230	5570
Specific stiffness (M in.)	100	100	100	390	395	390
Service tempera-ture (degrees F)	250	450	1000	275	325	275

[a]The designations in parentheses refer to the specific alloy or fiber/matrix.

*Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes

Method of Approach

- Calibrate manufacturing complexity (MCPLXS):
  - Aluminum as baseline (MCPLXS = 6)
  - 3 carbon fiber composites:
    - *IM7 Carbon/Epoxy*
    - *IM7 Carbon/BMI*
    - *IM7 Carbon/PEEK*
  - Estimate effects on MCPLXS:
    - *Technology improvement*
    - *Manufacturing process*
    - *Part geometric complexity*



Initial Calibrations

- 2010s projection based on ratios in RAND document
- Indicates roughly 30% labor hour reduction over 20 years

Material	Calibrated 1990 MCPLXS	Projected 2010 MCPLXS
Carbon/Epoxy	6.540	6.244
Carbon/BMI	6.663	6.214
Carbon/PEEK	6.563	6.379

Process Labor Multipliers

- Derived from process-labor ratio tables
- Create ratios based on labor hours of each process vs material averages

Process	Simple	Medium	Complex	Very Complex
Hand Layup	1.045	1.418	1.766	2.392
Hand Layup w/Optical Laser Ply Alignment	0.884	1.260	1.525	2.073
Automated Fiber Placement	0.563	1.034	1.357	
Resin Transfer Molding			1.125	1.839

Process and Geometry

- Use multipliers for each material
  - Thermosets roughly equivalent; thermoplastic 15% more costly

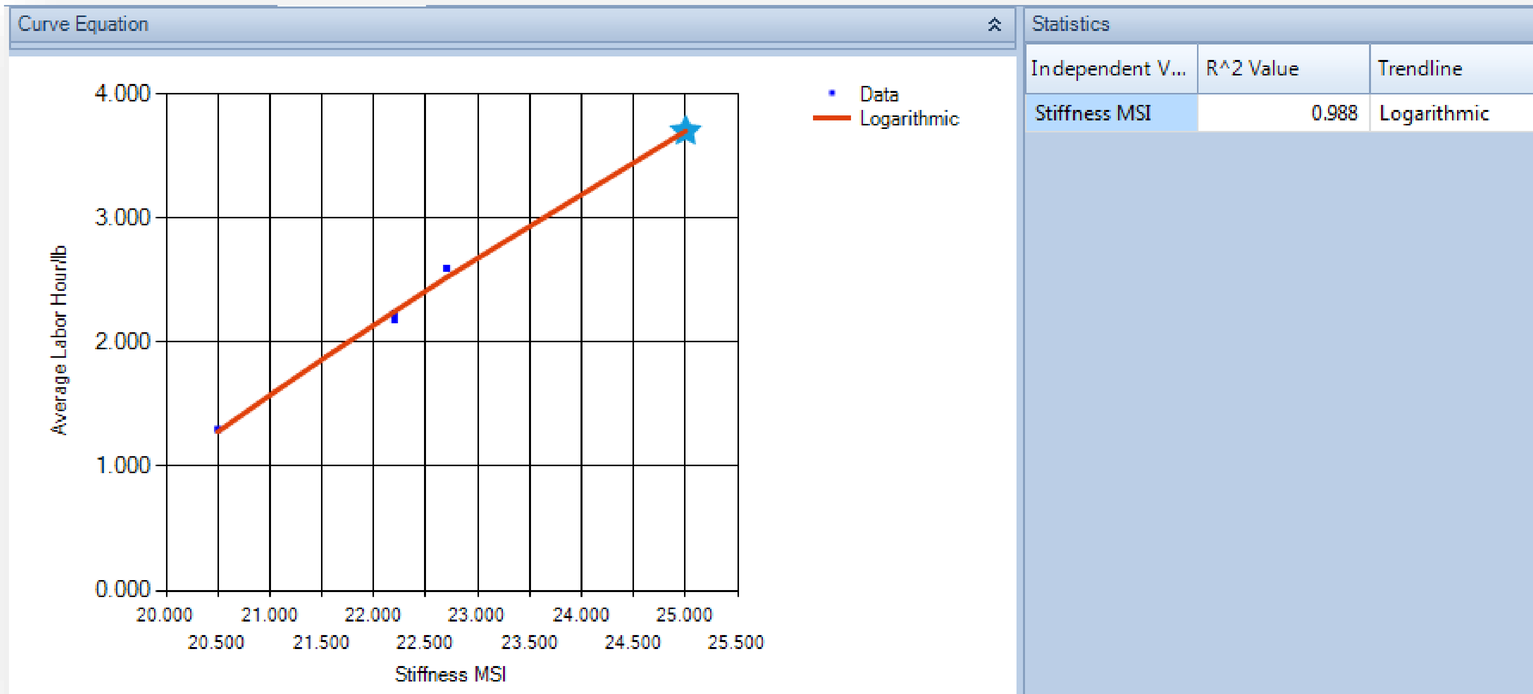
IM7 Carbon/Epoxy	Simple	Medium	Complex	Very Complex
Hand Layup	6.284	6.561	6.762	7.036
Hand Layup w/ Optical Laser Ply Alignment	6.132	6.454	6.628	6.907
Automated Fiber Placement	5.716	6.272	6.521	
Resin Transfer Molding			6.346	6.796
IM7 Carbon/BMI	**Simple**	**Medium**	**Complex**	**Very Complex**
Hand Layup	6.257	6.537	6.739	7.010
Hand Layup w/ Optical Laser Ply Alignment	6.108	6.431	6.604	6.883
Automated Fiber Placement	5.695	6.248	6.494	
Resin Transfer Molding			6.325	6.771
IM7 Carbon/PEEK	**Simple**	**Medium**	**Complex**	**Very Complex**
Hand Layup	6.415	6.690	6.890	7.168
Hand Layup w/ Optical Laser Ply Alignment	6.267	6.589	6.763	7.044
Automated Fiber Placement	5.854	6.410	6.655	
Resin Transfer Molding			6.483	6.931

Scope Expansion

- RAND report only addressed IM7 Carbon Fiber
- More materials needed:
  - High Strength (Standard) CF
  - Intermediate Modulus CF
  - High Modulus CF
  - Very High Modulus CF
- Recreate RAND report process for other CF reinforced composites

Phase II

- Conducted multivariate analysis on material properties
  - Established relationship between Elastic Modulus and labor

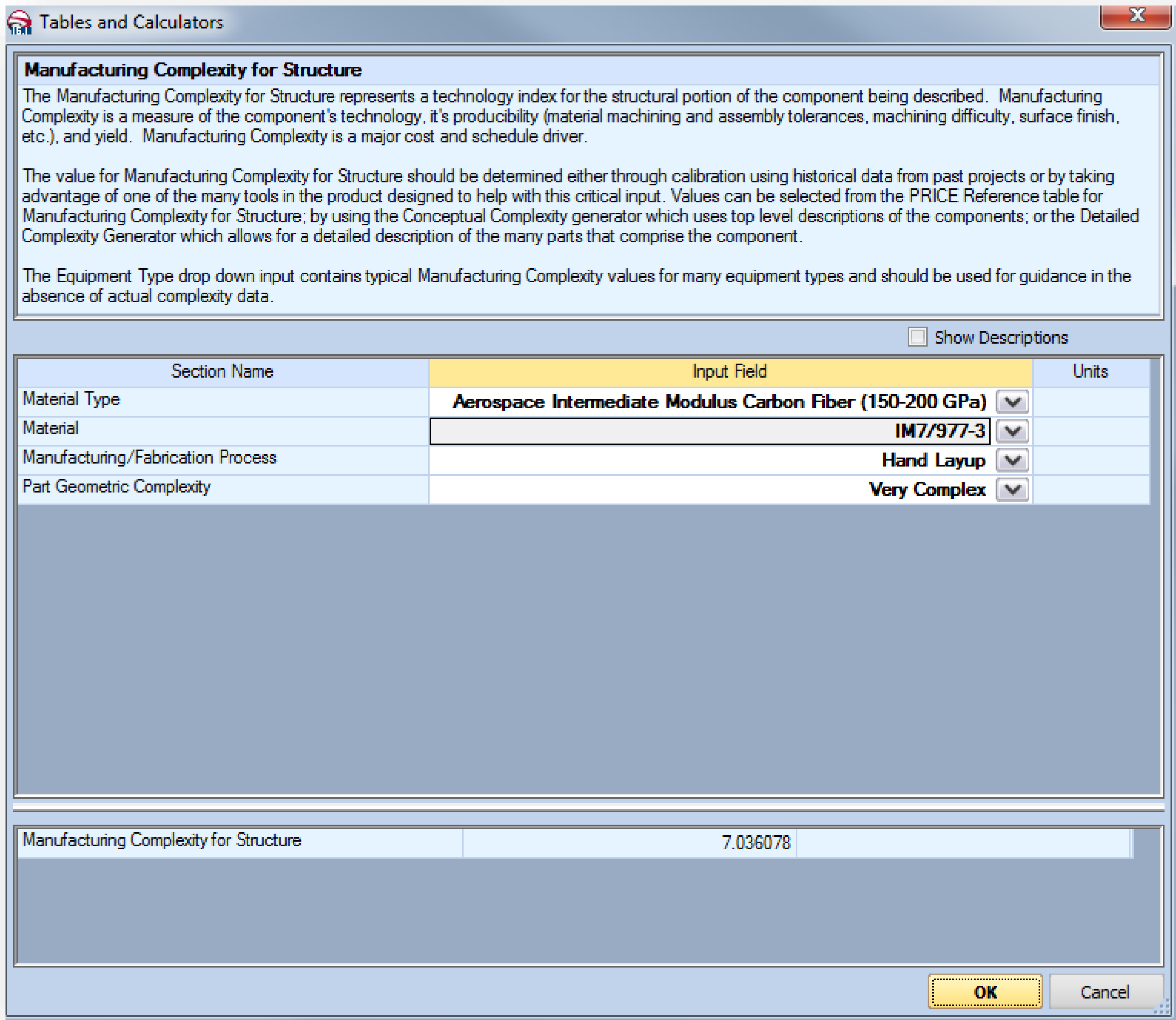


- Recorded data from manufacturer datasheets
  - Hexcel®,Toray®,Nippon®

Phase II Data Sheet List

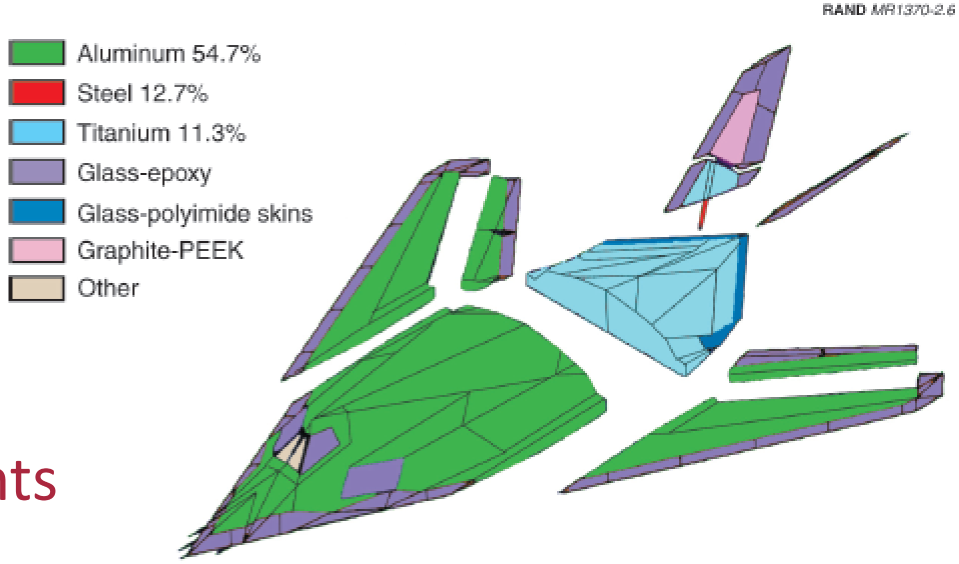
Material	Fiber Tensile Modulus (GPa)	Composite/Fiber Ratio	Composite Tensile Modulus (Msi)	Average MCPLXS
Standard				5.650
T300	230	58.70%	19.580	5.227
T700	235	57.45%	19.580	5.227
34-700	234	58.55%	19.870	5.422
AS4	241	58.51%	20.500	5.752
TR50S	235	60.43%	20.595	5.775
T400H	250	56.00%	20.305	5.650
AS7	248	58.47%	21.031	5.932
Intermediate Modulus				6.589
T800	294	55.10%	23.496	6.496
M30S	294	59.52%	25.382	6.745
IM6/7	303	54.13%	23.786	6.535
IM10	310	61.29%	27.557	6.954
T1000G	294	54.42%	23.206	6.442
IM8	310	58.71%	26.397	6.853
IMA	297	58.92%	25.382	6.745
High Modulus				7.420
M40	392	61.22%	34.809	7.373
M40J	377	61.01%	33.359	7.311
M46J	436	60.78%	38.435	7.505
HS40	441	58.28%	37.275	7.466
HM63	441	57.82%	36.985	7.459
M50J	450	65.56%	42.786	7.629
M35J	343	59.77%	29.733	7.117
Ultra High				7.979
YS-80A	785	59.87%	68.168	8.033
YS-90A	880	59.09%	75.420	8.103
YS-95A	920	58.70%	78.321	8.126
YSH-50A	520	59.62%	44.962	7.684
YSH-60A	630	60.32%	55.114	7.878
YSH-70A	720	59.72%	62.366	7.971
XN-60	620	64.52%	58.015	7.917
XN-80	780	57.69%	65.267	8.002
XN-90	860	63.95%	79.771	8.142
M60J	588	62.07%	52.939	7.839

Prototype MCPLXS Calculator



Phase III

- Added materials
  - Fiberglass based on RAND document diagrams
  - Ceramics based on combat vehicle armor data
- "Detailed" Mode
  - User can change:
    - *Operating Environment*
    - *Weight Range Multiplier*
    - *Number of Layers*
- Validate against components
  - F22 Pivot Shaft
  - Booms (Canadarm)
  - Rotor Blades



NOTE: Glass-epoxy, glass-polyimide, graphite-PEEK, and the category "other" constitute 21.3%.

*Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes

Detailed Prototype MCPLXS Calculator

Tables and Calculators

Manufacturing Complexity for Structure

The Manufacturing Complexity for Structure represents a technology index for the structural portion of the component being described. Manufacturing Complexity is a measure of the component's technology, it's producibility (material machining and assembly tolerances, machining difficulty, surface finish, etc.), and yield. Manufacturing Complexity is a major cost and schedule driver.

The value for Manufacturing Complexity for Structure should be determined either through calibration using historical data from past projects or by taking advantage of one of the many tools in the product designed to help with this critical input. Values can be selected from the PRICE Reference table for Manufacturing Complexity for Structure; by using the Conceptual Complexity generator which uses top level descriptions of the components; or the Detailed Complexity Generator which allows for a detailed description of the many parts that comprise the component.

The Equipment Type drop down input contains typical Manufacturing Complexity values for many equipment types and should be used for guidance in the absence of actual complexity data.

☑ Show Descriptions

Section Name	Input Field	Units	Descrip
Material Type	Aerospace Intermediate Modulus Carbon Fiber (150-200 GPa)		Please select either metal or a typ materials are currently categorizec of the final product after integratio the elastic modulus in its natural s
Material	IM7/977-3		The "average" options for the co of all of the materials currently in tl will be updated as more options a
Manufacturing/Fabrication Process	Automated Fiber Placement		
Part Geometric Complexity	Complex		The part geometry adds to labor r part. Examples for each complexit Simple- Covers, doors, flat skins, f Average - Contoured skins, equip structures, stiffened skins Complex - Beams, bulkheads, frar curve skins, pylons, ribs, spars, w Very Complex - Edges, hubs, lips,
Operating Specification	1.80		
Weight Range	20-500 lbs/10-200 kg		
Number of Layers	400		The number of layers needed for t Values can range from 5 layers fo into the 100s or 1000s for total ap

Manufacturing Complexity for Structure	7.753863	

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Canadarm Booms

- Upper and lower arm booms
  - Approximately 23kg each
  - 11-16 layers of filament wound, IM7/PEEK
  - MCPLXS = 6.678
- Model in detail generator:
  - Simple, AFP to simulate filament winding
  - Layers = 14
  - MCPLXS = 6.652
  - Percent Difference = 2.8%

F-22 Pivot Shaft

- Controls the stabilizers of the F22
  - 400 layers of IM7/977-3
  - Automated fiber placement (AFP) fabrication
  - $650k unit cost in FY1997
  - Calibrated MCPLXS = 7.852
- Model in detail generator
  - MCPLXS = 7.754
  - Unit Cost = $579k
  - Percent Difference = 10.9%

Test Case Inputs

- Used documentation to estimate
  - Fabrication Process
  - Shape Geometry
- 9 test cases:

Item	Material	Number of Plies	Operating Specification	Weight Range
F-22 Pivot Shaft	IM7/977-3	400	1.8	20-500lbs
Canadarm Booms	IM7/PEEK	14	2	20-500lbs
Rotor Blades	Fiberglass	12	1.8	20-500lbs
Wind Turbine Blades	Fiberglass	14	0.95	Over 500 lbs
120 MM Gun Barrel	IM7/PEEK	50	1.4	Over 500 lbs
AC50 Wingsail	M40	285	1.2	Over 500 lbs
Average Golf Shaft	Very High Carbon Fiber Average	8	0.6	Less than 20lbs
Class A Car Body Panels	T300/700	12	0.8	20-500lbs
Luxury Car Brake Rotors	Ceramic	35	1	Less than 20lbs

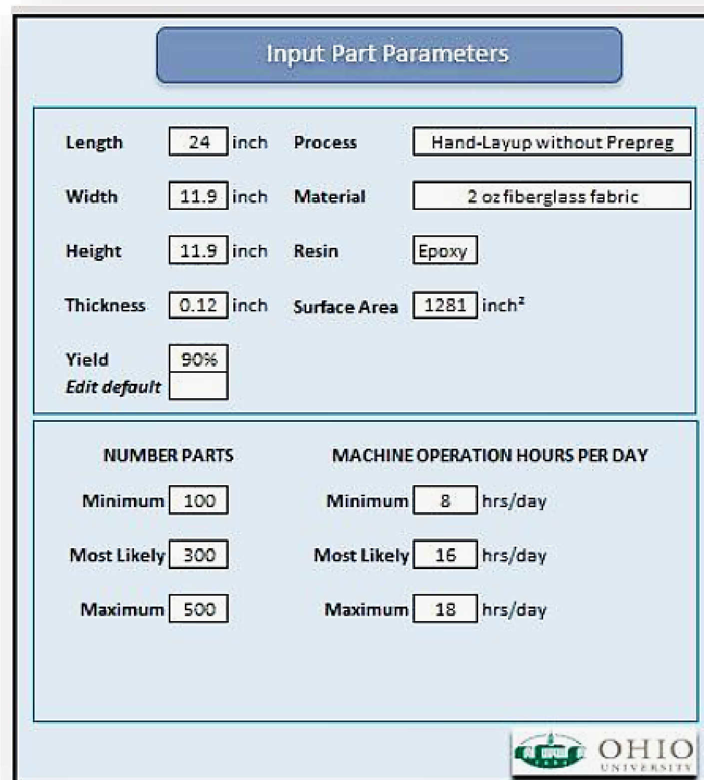
Test Case Results

- Estimate "paperclips to spaceships":
  - 8 different operating environments
  - 7 different material selections
- Average difference of **6.96%**

Item	Reference/Calibrated MCPLXS	Composite Calculator MCPLXS	% Difference AUPC
F-22 Pivot Shaft	7.852	7.754	10.90%
Canadarm Booms	6.678	6.652	2.80%
Rotor Blades	6.450	6.479	3.23%
Wind Turbine Blades	3.900	3.919	2.00%
120 MM Gun Barrel	5.519	5.580	7.76%
AC50 Wingsail	6.571	6.580	1.11%
Average Golf Shaft	5.987	6.084	9.45%
Class A Car Body Panels	4.141	4.249	12.88%
Luxury Car Brake Rotors	6.681	6.789	12.52%
Average			**6.96%**

Cross Model Validation

- "A Break-Down Model for Cost Estimation of Composites"
  - 2018 Ohio University thesis by Aniruddha V. Joshi
  - Created model (Com-CET) based on:
    - *Advanced Composite Cost Estimating Manual (ACCEM)*
    - *Federated Intelligent Production Environment (FIPER)*
    - *Cost Offering Method for Affordable Propulsion Engineering Acquisition and Test (COMPEAT)*
  - Estimates the following based on part parameters:
    - *Material cost breakdown*
    - *Labor cost breakdown*
    - *Capital cost breakdown*



Cross Model Validation Test Case

- "Part A" of validation section:
  - Organization:
    - *Labor Rate is $83/hour including overhead (apply to Production Manufacturing)*
    - *Batch production of 100 is most common*
  - Part:
    - *Weighs 3.12 lbs*
    - *Hand Layup and RTM commonly used (Complex geometry)*
    - *Hand Layup cost is reference*
    - *3 plies of Zoltek 50K (similar to AS4)*
  - Uncertainty:
    - *Application not defined. Material primarily used for automotive, wind/alternative energies, construction*
    - *Expected Operating Environment range 0.8-1.0*

Com-CET Results

- Compare 2 results against Com-CET:
  - Average AUPC generated for Operating Environments 0.8-1.0
  - AUPC generated from Operating Environment 0.9
    - *Common in all expected industries*
- Results:

	Actual AUPC	Com-CET Estimate	PRICE Average	PRICE Median
Unit Manufacturing Cost	$925	$1,004	$938	$924
Percent Difference		8.54%	1.41%	-0.12%

Manufacturer

COM-CET

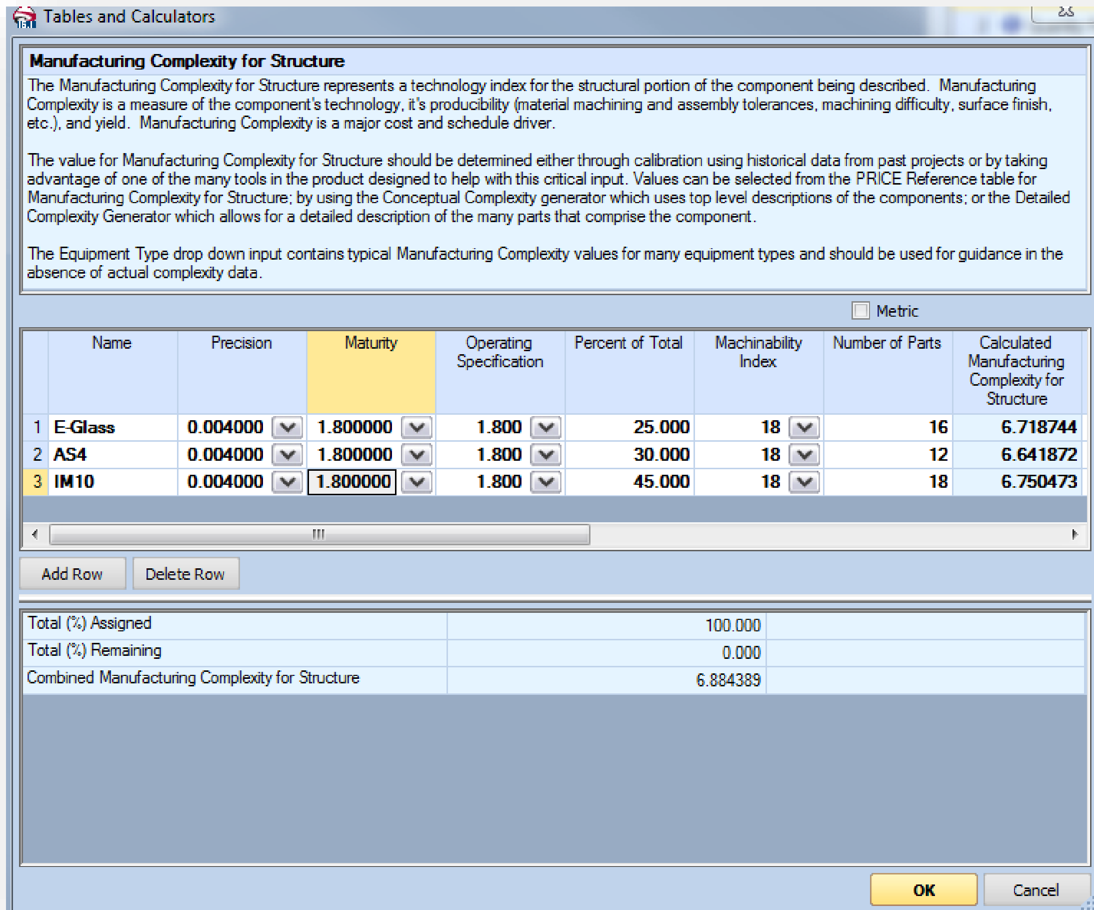
PRICE

Future Work

- Add more reinforcing materials:
  - Aramids (Kevlar)
  - Boron
  - Cermets
- Add more fabrication processes:
  - Vacuum assisted processes
  - Pultrusion
  - Filament Winding

Future Version

- “Designer Mode”
  - User can change:
    - *Curing Process*
    - *Ply Orientation*
    - *Multiple materials*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Metric

	Name	Precision	Maturity	Operating Specification	Percent of Total	Machinability Index	Number of Parts	Calculated Manufacturing Complexity for Structure
1	E-Glass	0.004000	1.800000	1.800	25.000	18	16	6.718744
2	AS4	0.004000	1.800000	1.800	30.000	18	12	6.641872
3	IM10	0.004000	1.800000	1.800	45.000	18	18	6.750473

Add Row | Delete Row

Total (%) Assigned	100.000
Total (%) Remaining	0.000
Combined Manufacturing Complexity for Structure	6.884389

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Questions?