CONTINUOUS FIBER COMPOSITE PART COST VS PRODUCTION VOLUME BY MANUFACTURING PROCESS AND MATERIAL

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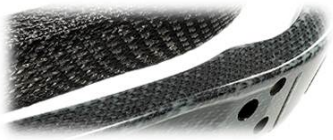
Overview

- Presentation provides practical guidance for:
  - selecting most cost-effective continuous-fiber reinforced plastic material and manufacturing process
  - based on production volume
- Detailed process cost comparison of
  - a positive-draft / 3D-contoured part (such as a fairing, cowling, rib, spinner, hood, or hatch).
- Composite processes evaluated include:
  - resin transfer molding (RTM), vacuum-assisted RTM (VARTM), hand-layup prepreg, wet-layup, automated fiber placement (AFP) thermoset, stamp-formed thermoplastic, and compression-molded thermoplastic.
- Base-lined against traditional stamp-formed aluminum and high-speed machined aluminum processes.
- Practical curves are presented for
  - amortized unit production cost ($/unit) vs. production volume (# of units) for each manufacturing process, as well as ;
  - detailed breakdowns of process steps and capital expenditures

Composite Part Material & Process Options

- Designers have to choose from hundreds of different material systems and dozens of different manufacturing processes

Resins	Fibers	Material Forms	Manufacturing Processes	
Epoxy, BMI	*E-glass*	*Pre-preg*	*RTM/ LRTM*	*VARTM*
Polyimide	*S-glass, S2-glass*	*Dry preform*	*SQRTM*	*Hand lay-up*
PEKK, PEEK	*AS4*	*Plain weave*	*Bladder molding*	*CTLM/FTLM*
PEI, PPS	*IM7*	*2x2 twill*	*Autoclave Skin-stringer*	*Compression molding*
PA6, PA12	*IM10*	*C-ply*	*OAA (Vacuum) honeycomb*	*Pultrusion*
PP, Polyester	*Kevlar*	*UD Tape*	*Filament winding*	*Pushtrusion*
Vinyl ester	*Spectra*	*Short-fiber*	*AFP, ATL*	*D-LFT*
PE, HDPE	*HTS40*	*Long-Fiber*	*Resin Film Infusion*	*Press forming*
PC, PET	*Hemp, Flax*	*Stretch-broken fiber*	*Wet-layup*	*Thermoforming…*
		SMC		

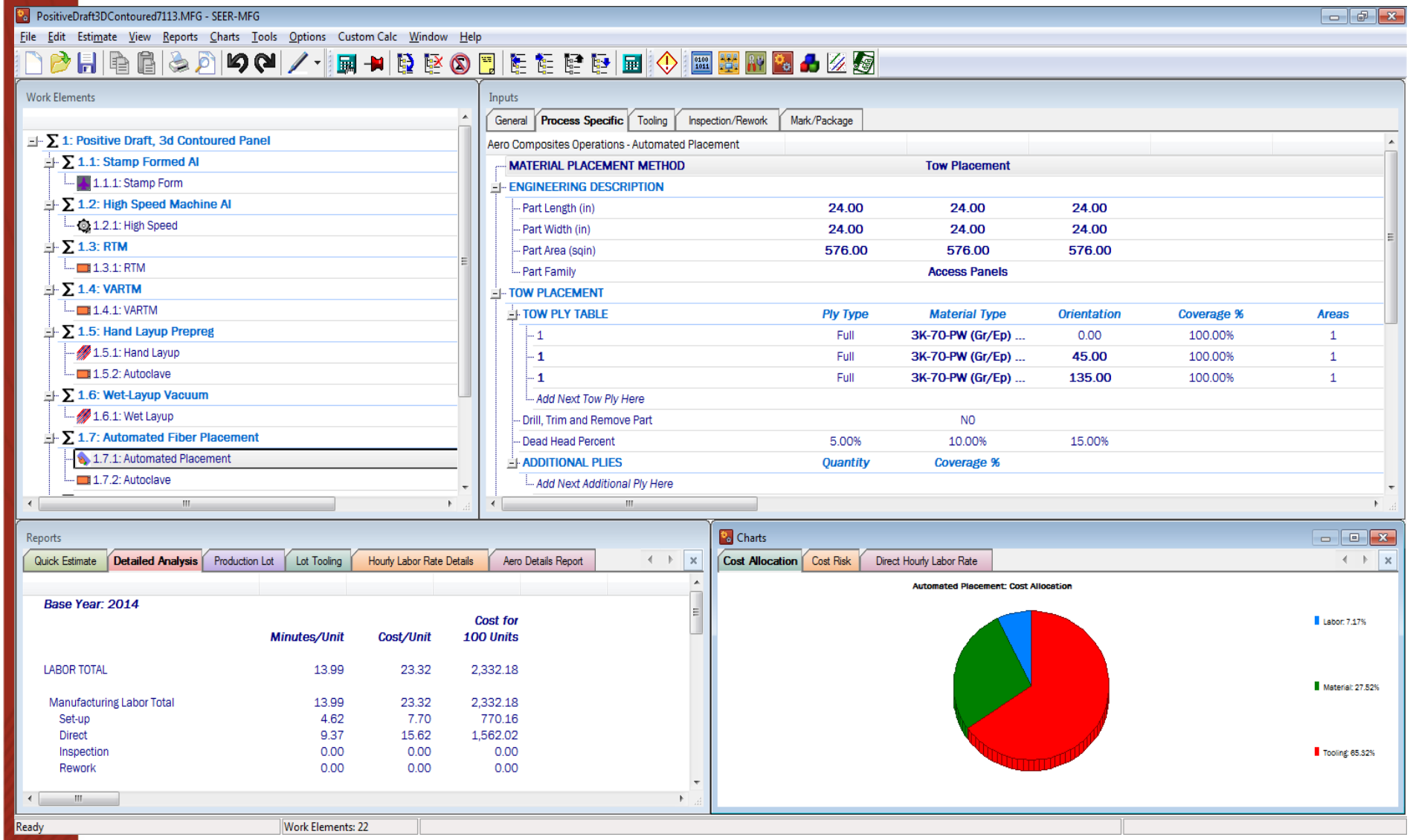

Selection Guidance?

- Automotive Composites Alliance advises product volumes for several composite processes
- Limited process guidance for Aerospace, Low Volume, High Strength Materials

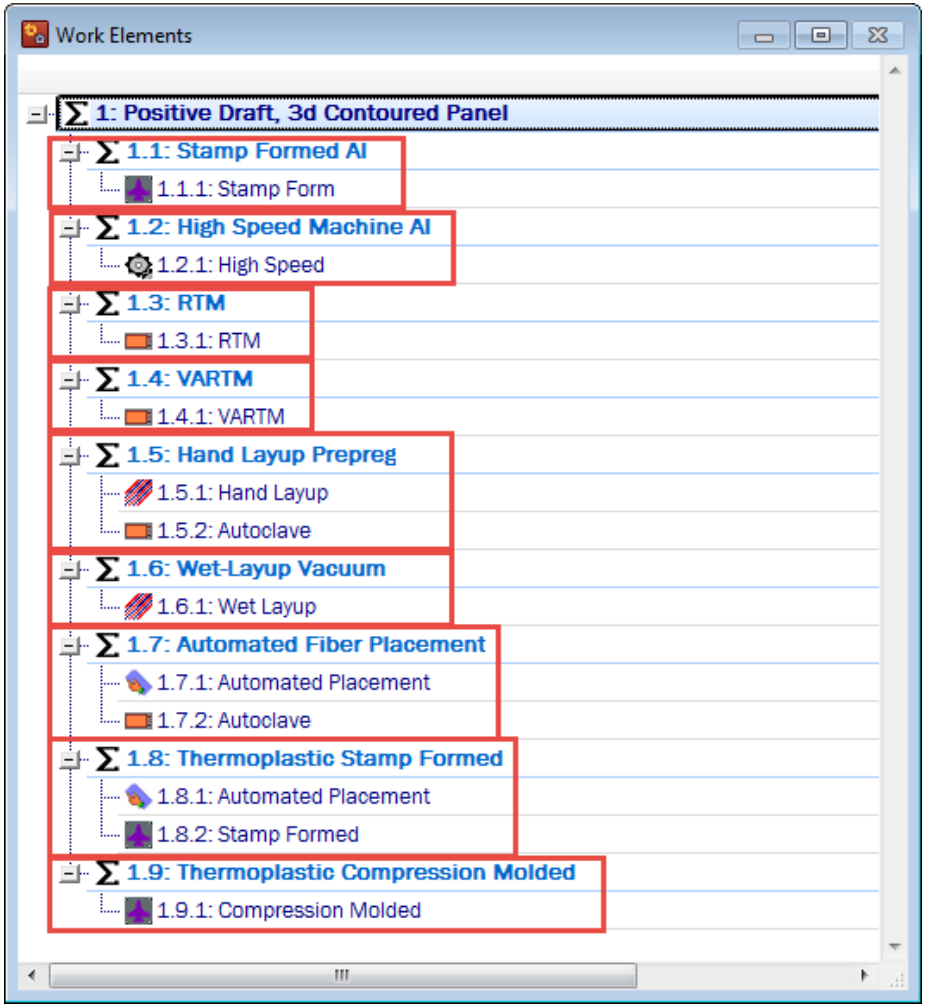
Table 1. Automotive High Volume Composites Manufacturing Process Selection Guide (Ref. 4).

	Production Volume		
Process	**0-5000**	**5000-15000**	**15000+**
Compression Molding (BMC/SMC/LCM)		X	X
Injection Molding (RRIM/BMC/SRIM)			X
Vacuum Infusion (VIP)		X	
Resin Transfer Molding (RTM)		X	
Hand Layup	X		

SEER for Manufacturing Cost Model



SEER-MFG
Detailed Process Cost Trades



- Developed by Galorath Inc.
- Compare process options side by side
- Generates estimates using bottom-up, process-based parametric estimation methodology based on industry labor standards
- SEER-MFG embodies the work of the Composites Affordability Initiative
- Provides engineers with a comprehensive framework for evaluating cost of alternative composite materials against more traditional manufacturing processes

Guidance for Applicable Parts

- Cost guidance is presented for parts with the following characteristics:
  - Positive Draft
  - 3D-Contoured
  - Constant gage
  - High-performance applications
- Some Example Parts:

Formula 125 Racing Fairing (HeGar)

RV-12 Tip Rib (Dog Aviation)

Composite Spinner (Bud Aviation)

Ultralight Aircraft Access Hatch

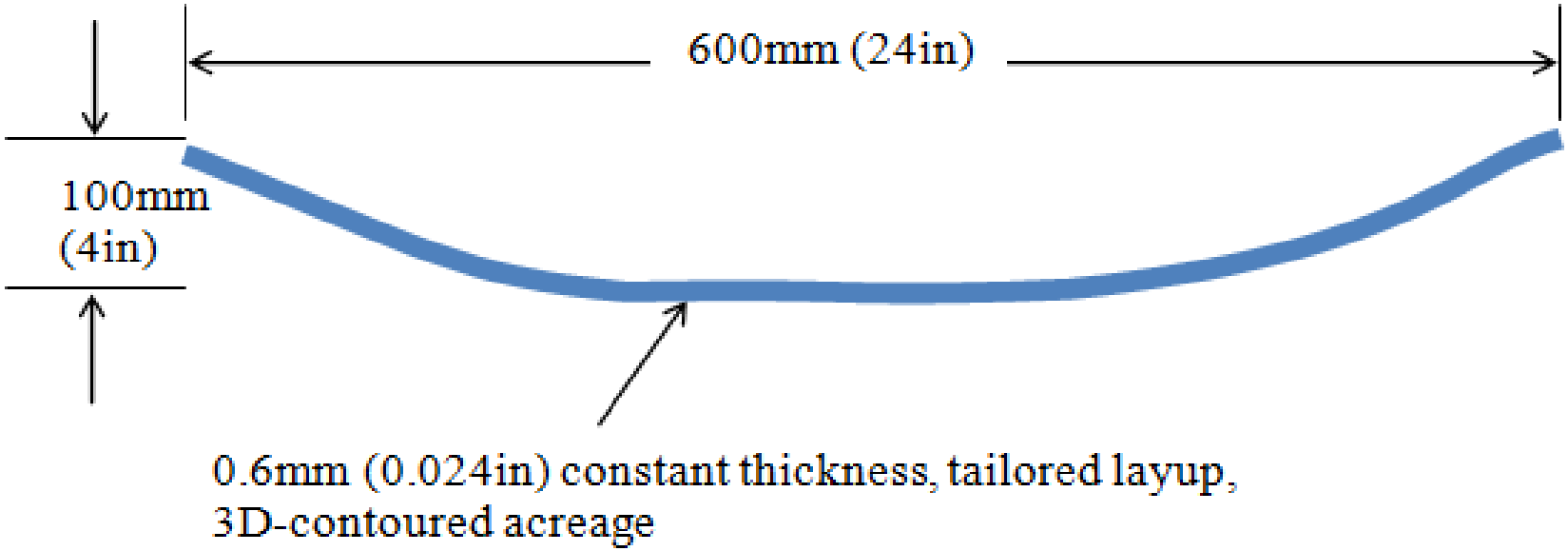
Material & process configurations

- AS4 fiber is assumed for all composite processes.
- Epoxy is assumed for thermoset processes,
- Polyphenylene sulfide (PPS) is assumed for thermoplastic processes as a popular mid-level aerospace engineered polymer

	Layup & Forming Process	Material	Cure Process
1	Stamp-formed	Aluminum – 6061	N/A
2	High-speed machining (2 operations)	Aluminum – 6061	N/A
3	RTM (2 tooled surfaces)	AS4/Epoxy, 2x2 Twill (Thermoset)	Reaction + heated tool
4	VARTM (1 tooled surface)	AS4/Epoxy, 2x2 Twill (Thermoset)	Room temp cure
5	Hand-layup	AS4/Epoxy, 2x2 Twill (Thermoset)	Vacuum, Autoclave
6	Wet-layup	AS4/Epoxy, 2x2 Twill (Thermoset)	Vacuum, OOOA
7	Automated fiber placement	AS4/Epoxy, UD Tape (Thermoset)	Autoclave
8	Automated tape layup, stamp-formed	AS4/PPS, UD Tape (Thermoplastic)	n/a
9	Compression molded thermoplastic	AS4/PPS LFT (Long Fiber thermoplastic)	n/a

Basic Geometry and Layup Assumptions

- Overall Dimensions: 600mm x 600mm x 100 mm (24in x 24in x 4in).
- Layup: 3-ply, 0.6 mm (0.024 in) thick in acreage, tailored laminate. For simplified comparison of different processes, this part is assumed monocoque (no core or stiffeners)



SEER-MFG General Cost Model Parameters

	SF-Al	HSM-Al	RTM	VARTM	HL	WL	AFP	SF-TP	CM-TP
General Parameters									
Direct/Setup Houly Labor Rate ($)	100								
Production Experience	High								
Product Classification	Aero								
Learning Curve	95	95	95	95	85	85	95	95	95
Labor Calibration	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Material Cost / lb	2.8	2.8	50	50	60	50	55	55	55
Material Utilization	1.2								
Mechanization	Nom	Vhigh	Nom	Nom	Nom	Nom	Nom	Nom	Nom
Shape Complexity	Low	N/A	Low	Low	Low	Low	Low	Low	Low
Setup Complexity	Nom								
Setup Amortization	10% * Qty								
In-Process Inspection	2% * Direct								
In-Process Rework	2% * Direct								
Tooling Inputs									
Tooling Design Hourly Labor Rate ($	150								
Tooling Fab. Hourly Labor Rate ($)	100								
Tool Type (1)	CMD	Fixture	CMD	VFT	VFT	VFT	VFT	CMD	CMD
Tool Life (2)	5000	0	5000	3000	100	50	3000	3000	3000
Tool Parts	2	1	2	1	1	1	1	2	2
Tool Complexity	Nom	Vlow	Nom-	Low	Low	Low	Low	Low+	Low+
Tool Prep (mins)	1.68	0.93	3.12	0.98	1.95	1.95	1.35	1.27	1.56
Remove Tools (mins)	0.59	0.34	0.55	0.24	0.34	0.34	0.24	0.52	0.52
Clean Tools (mins)	0.09	0.11	0.13	0.06	0.11	0.11	0.08	0.07	0.08
Package Tools (mins)	0.12	0.15	0.28	0.05	0.14	0.14	0.09	0.06	0.1

Process steps and calculated labor times (in minutes)

	RTM	VA RTM
Injection Pressure (PSI)	100.0	
(Centipoise)	10.0	10.0
Index Mandrel (mins)	0.5	0.3
Load Program (mins)	0.6	0.6
Transfer Part To Resin Transfer Area (mins)	0.9	0.9
Load Preform (mins)	14.3	6.6
Locate Preform (mins)	8.3	4.1
Install Release Film (mins)	17.0	9.0
Pre-Heat Tool (mins)	2.1	
Tool Clamp Time (mins)	1.5	1.5
Trim Time (mins)	5.9	5.9
Dry Time (mins)	26.7	26.7
Load Resin (mins)	0.5	0.5
Drain & Flush (mins)	6.2	5.9
Open Mold (mins)	3.5	3.3
Resin Inj (Witness) (mins)	4.5	7.5
Vacuum Bag (mins)		17.0
Unload Parts (mins)	21.5	21.5
Total	114	111

	HL	WL	AFP
Cut (mins)	2.3	2.3	0.0
Ply Placement (mins)	20.6	22.9	0.3
Debulk (mins)			8.7
Debulking	73.8	65.0	
Additional Plies (Peel Plies) (mins)	9.6	10.7	
Tail Compact (mins)			0.0
Head Rotation (mins)			0.1
Dead Head Time (mins)			0.0
Fuzz Removal (mins)			0.3
Bag Fab. (mins)	0.8		0.8
Cure Prep Set-up (mins)	0.5		0.5
Cure Prep Ops. (mins)	3.0		3.0
Cure Prep Pleating (mins)	0.2		0.2
Cure Process (mins)	19.4		19.4
Debag (mins)	6.8		6.8
Unload Cured Parts (mins)	21.1	15.6	21.1
Deflash (mins)	12.3		12.3
Total	170	116	73

	SF-TP	CM-TP
Load Material on Creel (mins)	2.0	
Layup material on ATL (such as RELAY™)	3.0	
Load & Extrude Compound (min)		8.0
Transfer blank/compound (min)	5.0	5.0
Consolidate blank (min)	5.0	
Fixture for heating (min)	5.0	5.0
Heat in IR (min)	3.0	6.0
Form in press (min)	3.0	3.0
Demold (min)	4.0	4.0
Total	30	31

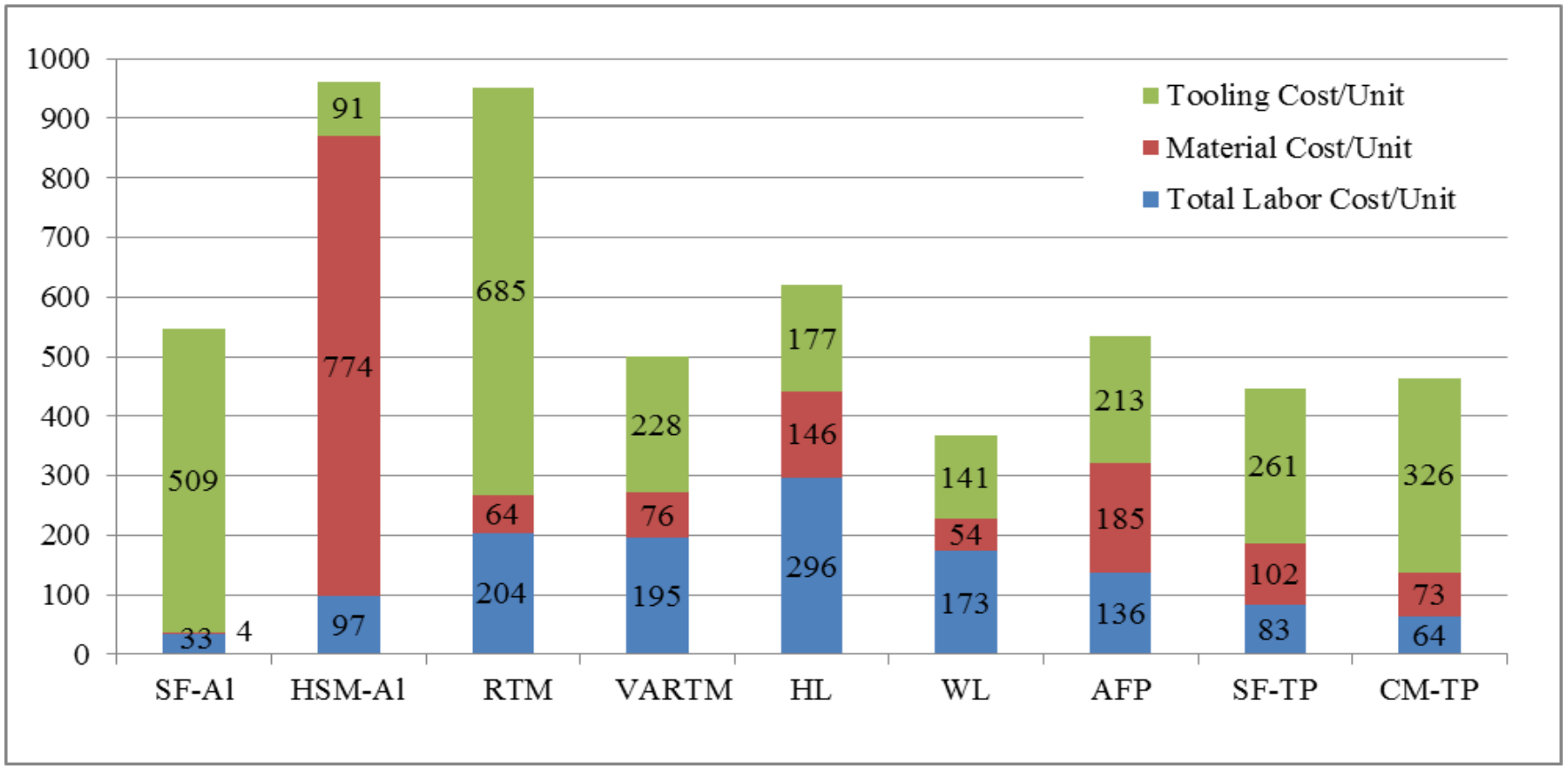
	SF-Al	HSM-Al
Cut to Size Shear (mins)	0.9	
Press Form (Version Press) 1 Hit (mins)	15.9	
High Speed Maching Rough & Finish (mins)		61.0
Unload Finished Parts (mins)	3.0	3.9
Total	20	65

General assumptions for estimates

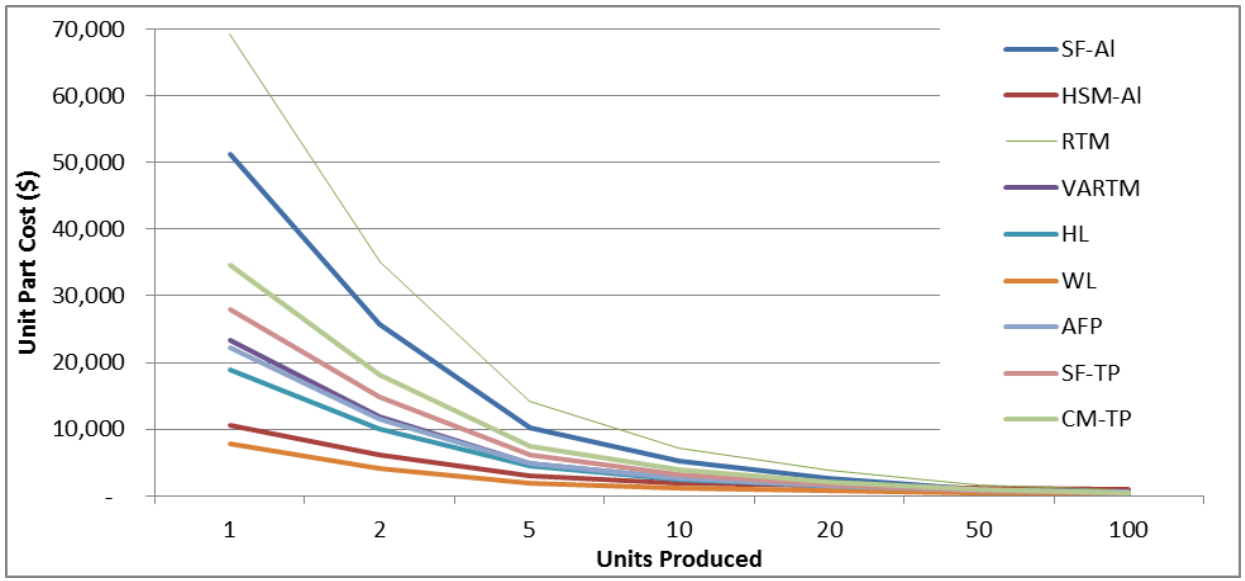
- Trimming operations are not part of this model. Likewise, inspections and quality assurance are omitted for simplification. QA generally runs ~25% per part for aerospace-grade parts.
- Mark/packaging not included.
- Includes engineering and manufacturing development costs for first articles, but does not include engineering analysis, testing, material/process specifications, documentation, etc.
- For extremely low volume part production, estimate does not factor in minimum order material quantities.
- Amortization does not include capital expenditures.

Per unit cost at unit 100

- The per-unit cost at unit 100, amortizing tooling and setup. The chart also shows the cost contribution from tooling, labor, and material

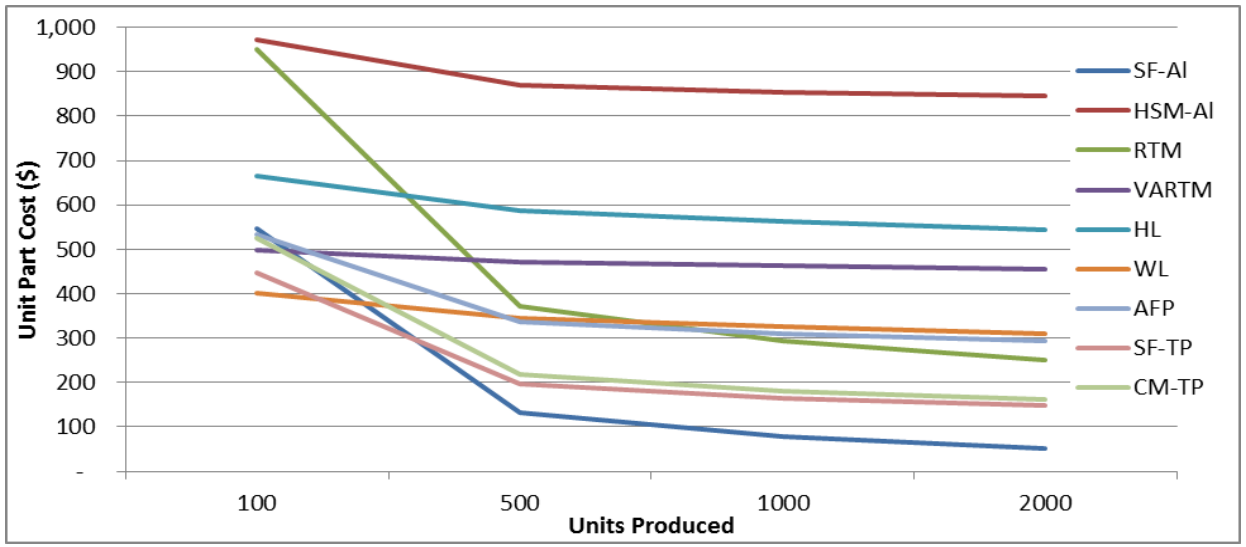


Cost @ Lot

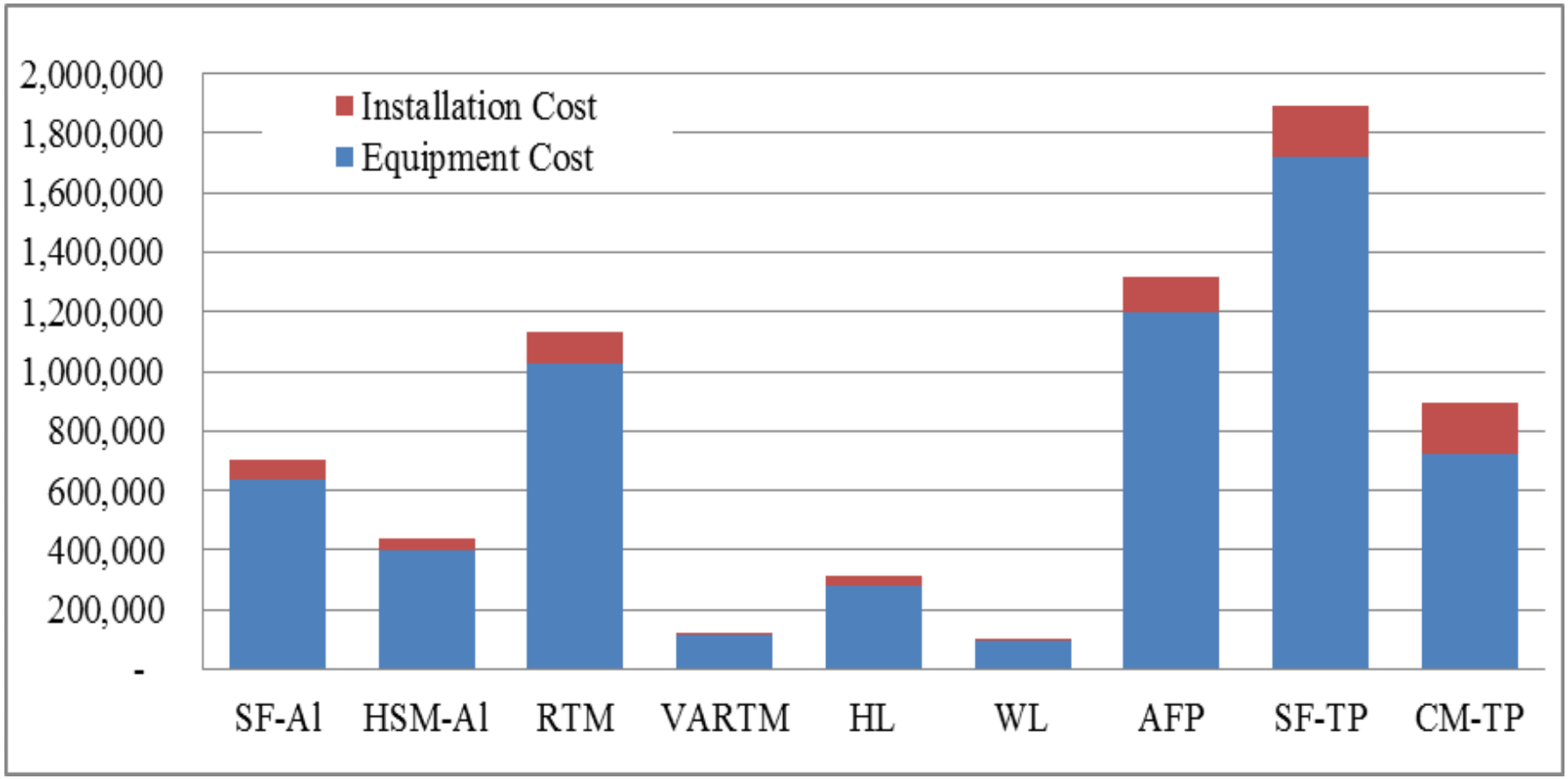


- Cost at Lot ($):
- Units 1-100.

- Cost at lot ($):
- Units 100-2000



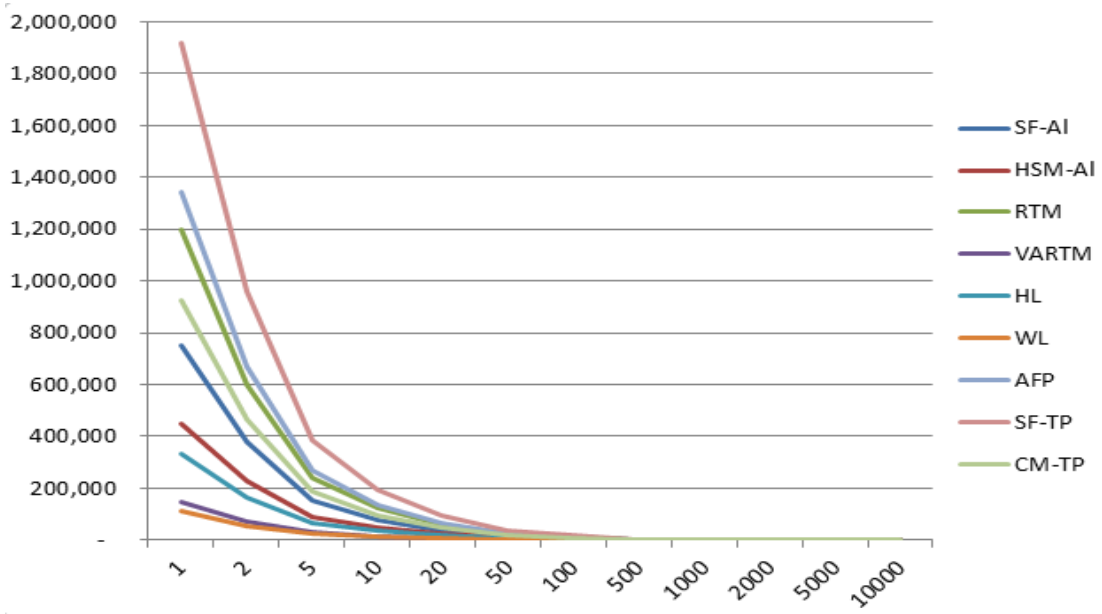
Capital Expenditure across process



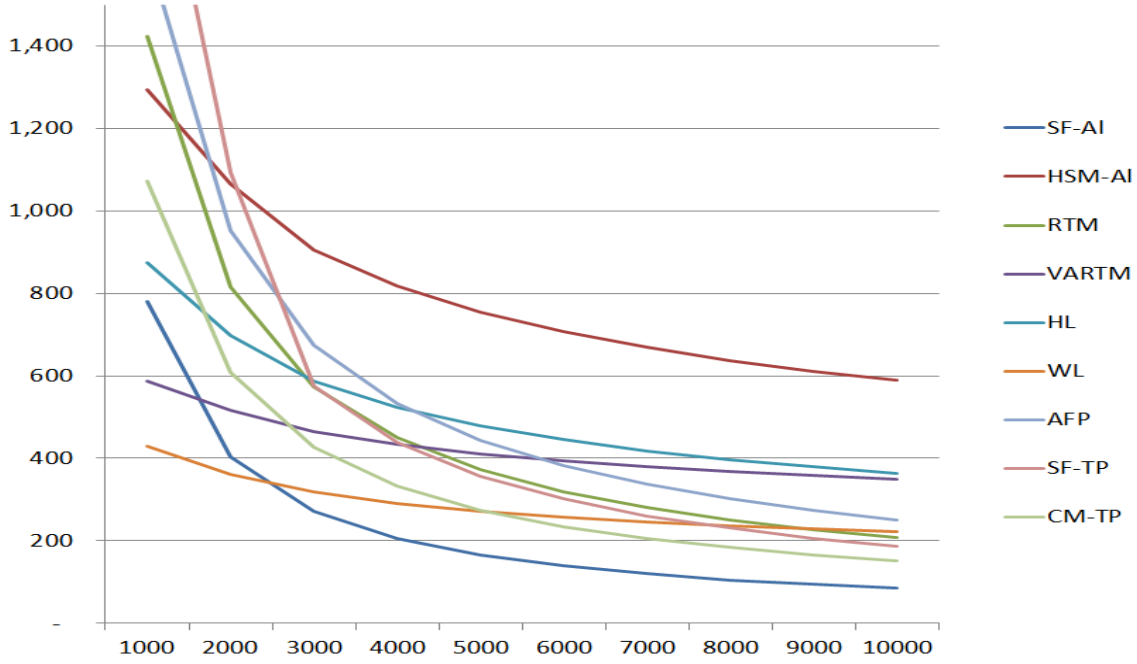
Cap$ breakdown by process

Equipment	CapEx $	m^2	Install $	SF-Al	HSM-Al	RTM	VA RTM	HL	WL	AFP	SF-TP	CM-TP
Hydraulic Press	600,000	37	60,000	y							y	y
Shear / Guillotine	37,500	84	3,750	y								
High Speed CNC	400,000	28	40,000		y							
Laser Ply Locator	170,000	58	17,000					OPT	OPT			
Automated Tape Layup	1,000,000	56	100,000							y	y	
IR Charge Heater	120,000	21	12,000								y	y
Vacuum Forming Equipment	75,000	19	7,500				y	y	y			
Resin Pump	16,000	3	1,600			y	y					
Sump Pump	12,000	67	1,200			y	y					
RTM - Fluid Cell Platen Press	1,000,000	74	100,000			y						
Autoclave (2 m)	200,000	19	20,000					y		y		
Automated Ply Cutting Table	150,000	58	15,000					OPT	OPT			
Work benchs & cutting mats	10,000	23	1,000									
Freezer	9,000	19	900					y	y			

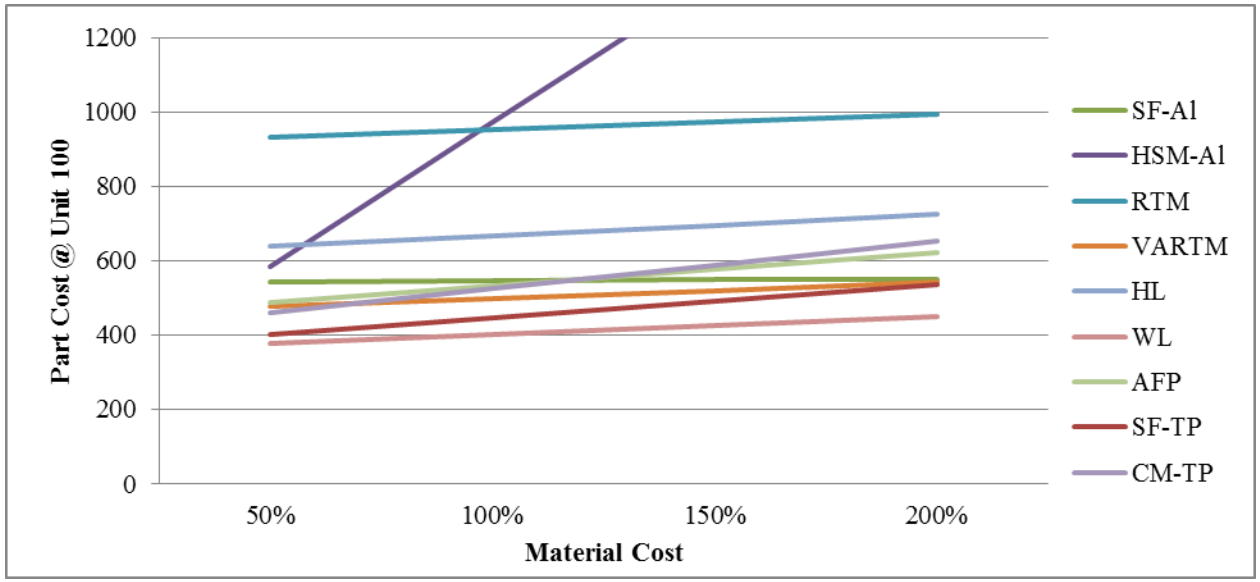
Including Capital Equipment



- Stamp-forming, compression molding, and RTM are not as cost effective below 2000 units, but excel 4000+



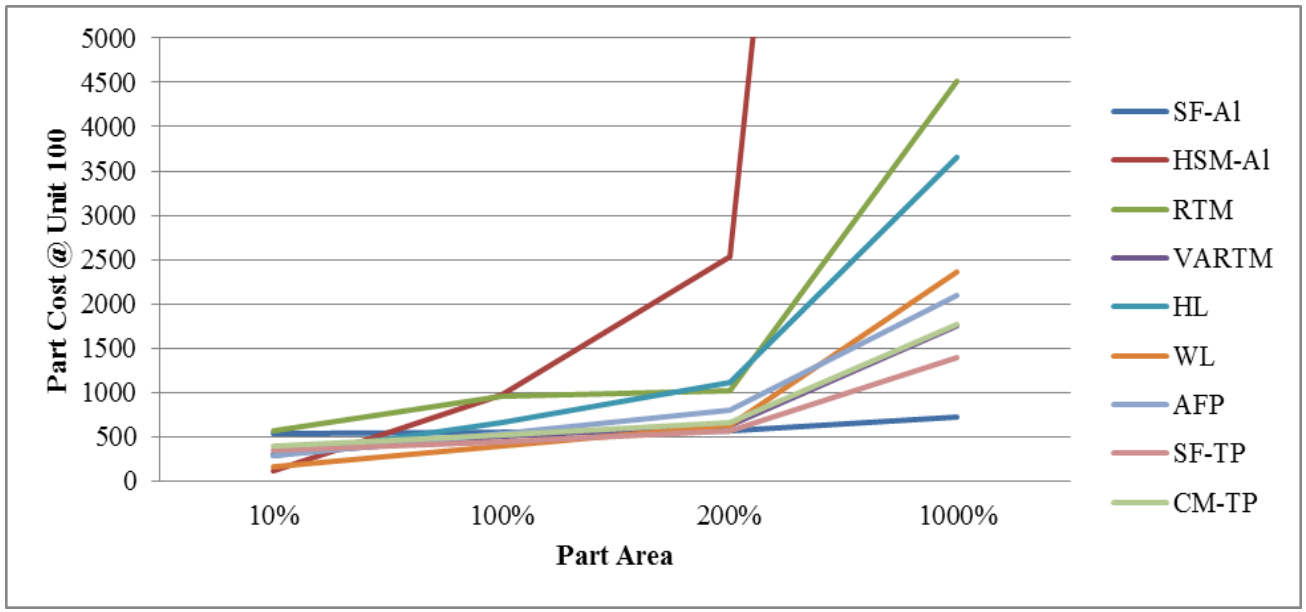
Sensitivity to material cost @ unit 100



% nom	SF-Al	HSM-Al	RTM	VA RTM	HL	WL	AFP	SF-TP	CM-TP
50%	544	586	931	477	638	377	487	400	460
100%	546	973	952	499	666	401	533	446	525
150%	549	1360	974	520	695	425	578	491	589
200%	551	1747	995	542	724	449	622	535	654

- The material cost in the SEER model is scaled from 50% of the baseline cost (such as switching to a glass fiber or lower grade carbon fiber), to 200% (such as switching to a more expensive carbon fiber or resin)

Sensitivity to part size (area) @ unit 100



% nom	SF-Al	HSM-Al	RTM	VARTM	HL	WL	AFP	SF-TP	CM-TP
10%	528	119	563	295	284	160	278	344	400
100%	546	973	952	499	666	401	533	446	525
200%	567	2528	1011	631	1114	626	798	559	663
1000%	727	26953	4517	1748	3664	2356	2095	1393	1771

- The part area on the x-axis is normalized to the 600 mm x 600 mm (24 in x 24 in) baseline size

Conclusions

- Results purely based on cost, they do not factor in the laminate performance (weight, fatigue, corrosion, etc.) for overall $/kg efficiency.
- For low quantities, high speed machined aluminum, wet layup, or hand layup are the most cost effective.
- For high quantities, RTM or stamp-formed, compression molded processes are the most cost effective.
- Stamp-forming, compression molding, and RTM are not as cost effective below 2000 units, but excel 4000+
- The estimates can be quickly factored for changes in material cost and part size using the curves in Figure 8 and Figure 9 above

Table 9. Most cost effective process by production volume.

	Production Volume (units)				
	1-20	20-50	50-200	200-500	500-2000
Stamp Formed Al				X	X
High Speed Machine Al	X				
RTM					X
VARTM			X	X	X
Hand Layup Prepreg	X	X			
Wet-Layup Vacuum	X	X	X	X	
Automated Fiber Placement					
Stamp Formed Thermoplastic			X	X	X
Compression Molded Thermoplastic				X	X

Future Work

- The following papers will expand the design curves to include other part families, including:
  - Adjusting estimates for adding local thickness variation (such as doublers) or stiffening features (such as honeycomb core or foam)
  - 2D profiles (pultrusions/extrusions such as stringers & channels)
  - Negative draft parts
  - Cylinders
  - Alternative industries

BACKUP

Cost at lot ($): Units 1-2000

Unit	1	2	5	10	20	50	100	500	1000	2000
SF-Al	51,157	25,683	10,305	5,181	2,618	1,062	546	132	79	52
HSM-Al	10,638	6,095	3,028	2,003	1,488	1,093	973	870	854	845
RTM	69,262	34,995	14,202	7,268	3,795	1,660	952	372	294	251
VARTM	23,311	11,902	4,954	2,633	1,467	742	498	472	464	456
HL	18,996	10,048	4,423	2,521	1,549	894	666	588	563	543
WL	7,781	4,170	1,903	1,124	717	435	401	344	326	311
AFP	22,192	11,527	4,833	2,607	1,492	767	532	337	309	292
SF-TP	27,883	14,760	6,086	3,209	1,771	756	446	196	164	147
CM-TP	34,571	18,182	7,479	3,922	2,144	905	524	219	181	162