Additive Manufacturing – Module 12

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Economics

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AM³ Lab — Advanced Manufacturing | Modeling | Materials

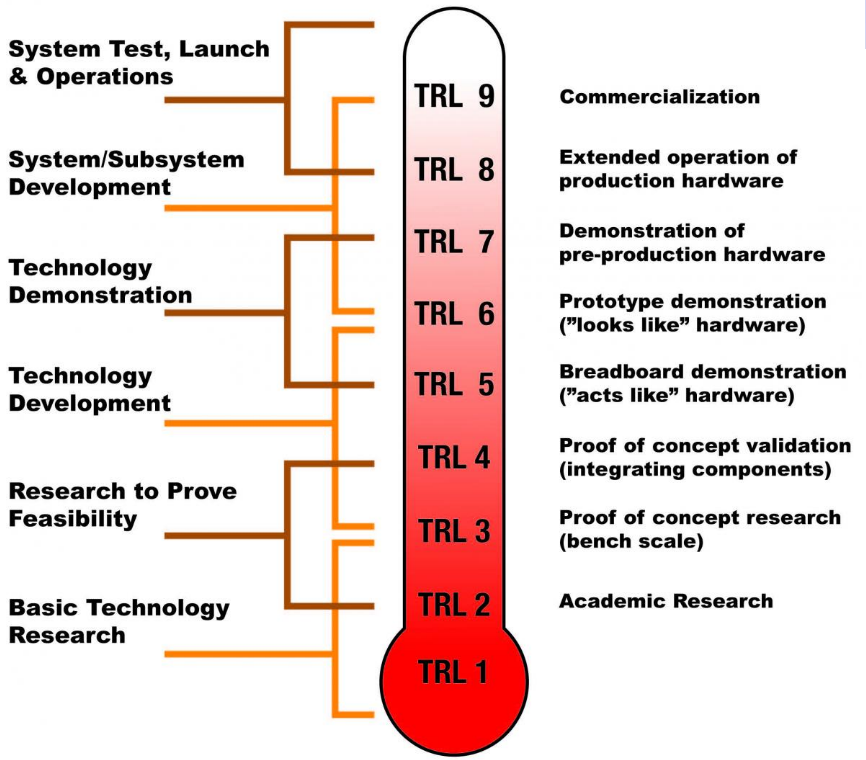
Stereolithography

Overview

Polymer

Photo polymerization

Technology development



Technology readiness level

Manufacturing Readiness Level (MRL)

Phase	MRL	State of Development
Phase 3: Production Implementation	9	Full production process qualified for full range of parts and full metrics achieved
	8	Full production process qualified for full range of parts
	7	Capability and rate confirmed
Phase 2: Pre production	6	Process optimised for production rate on production equipment
	5	Basic capability demonstrated
Phase 1: Technology assessment and proving	4	Production validated in lab environment
	3	Experimental proof of concept completed
	2	Application and validity of concept validated or demonstrated
	1	Concept proposed with scientific validation

Manufacturing readiness level

- **Is the level of performance reproducible?**
- **What will these cost in production?**
- **Can these be made in a production environment by someone without a PhD?**
- **Are key materials and components available?**

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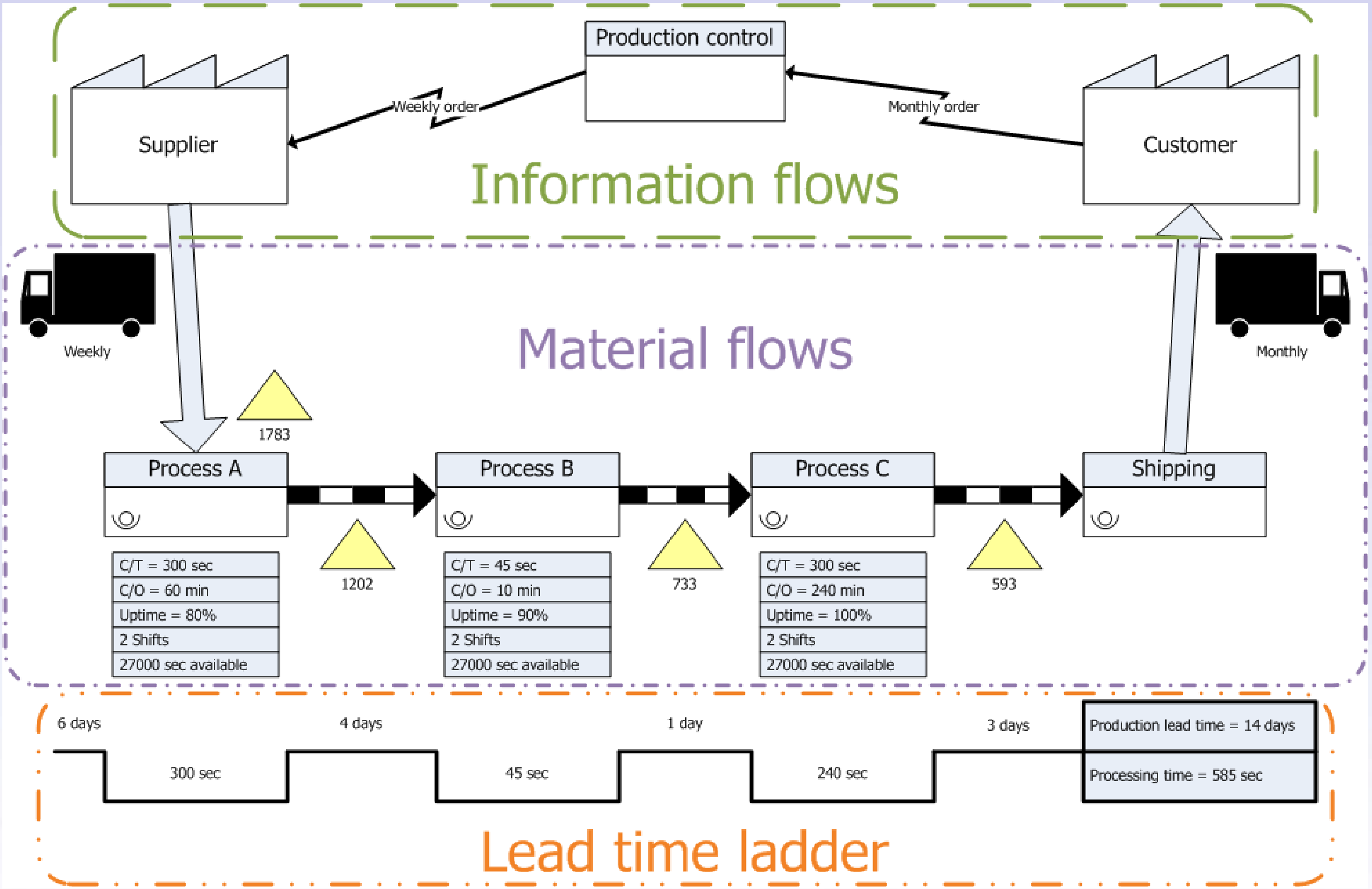
Cost Management



Value stream mapping: broader and wider view, may group a wide variety of products into a single value stream, typically used for lean production

http://www.strategosinc.com/mpping0.htm

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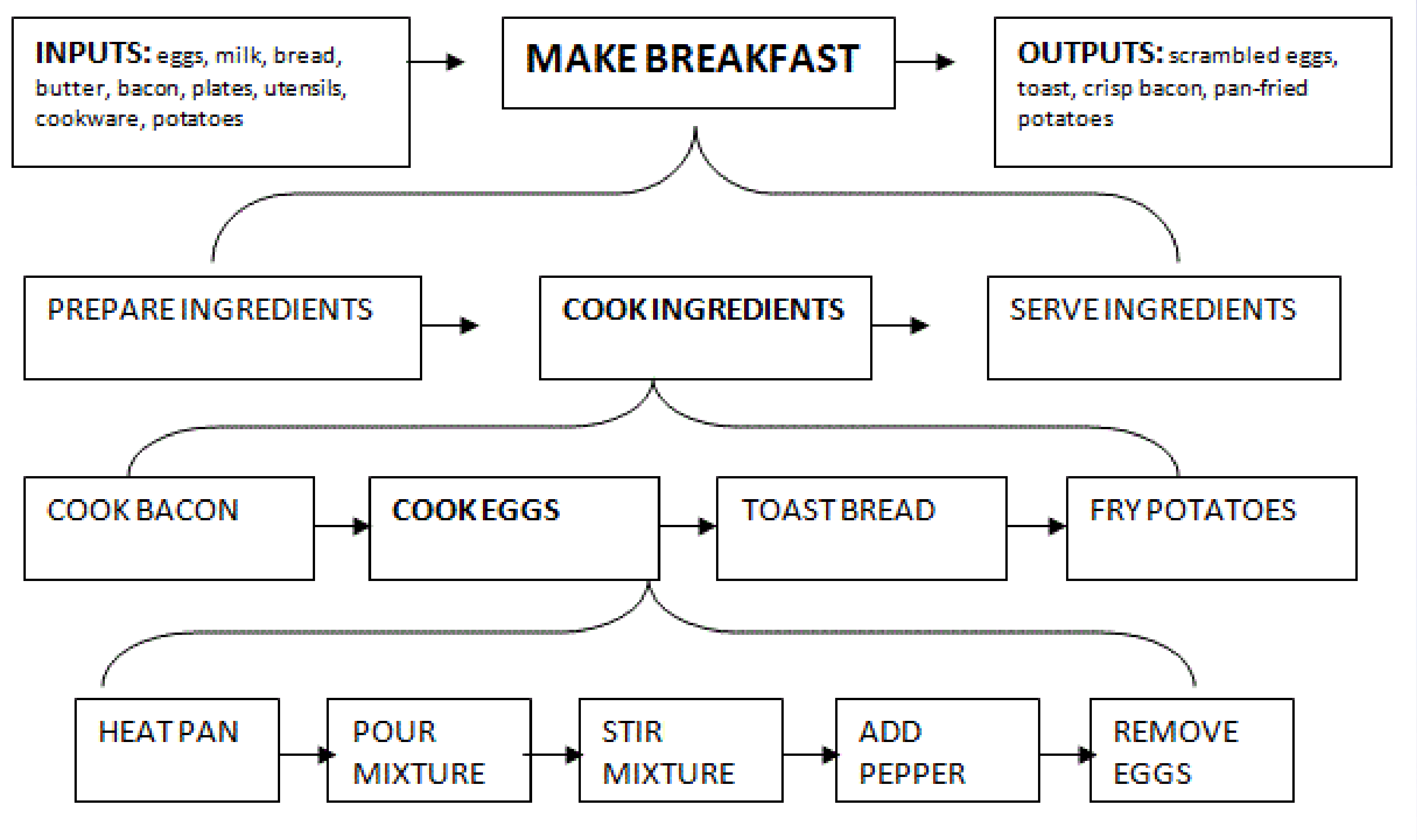
Cost Management

Process mapping for making breakfast



Process mapping: trace the sequence of events for a single product

http://www.strategosinc.com/mpping0.htm http://en.wikipedia.org/wiki/Business_process_mapping

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Product Cost

- Time (process cycle – from design to manufacturing)
- Capital (equipment, space, etc.)
- Operation (energy, maintenance, etc.)
- Materials
- Labor
- Design
- Failure

Economics

Cost Models

- **A general cost model for additive manufacturing**

Cost = P + O + M + L

On a per part basis: cost = p + o + m + l = 1/N *(P + O + M + L)

- **P = machine purchase cost allocated to the build**
- **O = machine operation cost**
- **M = material cost**
- **L = labor cost**
- **N = number of parts in the build**

Assume a machine life of Y years a 95% up-time, the purchase price per build is:

$$P = \frac{\text{PurchasePrice} \cdot T_b}{0.95 \cdot 24 \cdot 365 \cdot Y}$$

$$O = T_b \cdot C_o$$

- **T_b = build time (hours)**
- **C_o = operation cost rate**

Economics

Cost Models

- **A general cost model for additive manufacturing**

$$M = k_s \cdot k_r \cdot N \cdot v \cdot C_m \cdot \rho \qquad L = T_l \cdot C_l$$

- **v = volume**
- **k_s = coefficient for support structure materials (~1.1 to 1.5)**
- **k_r = coefficient for material waste (e.g., non-recyclable powder)**
- **C_m = material cost per unit mass**
- **C_l = labor cost rate**
- **T_l = time required for workers to set up the build, remove fabricated parts, clean the parts, clean the machine, and get the machine ready for the next build**

$$T_b = T_s + T_r + T_e$$

- **T_s = Scan or deposition time**
- **T_r = Recoat time**
- **T_e = Delay time**

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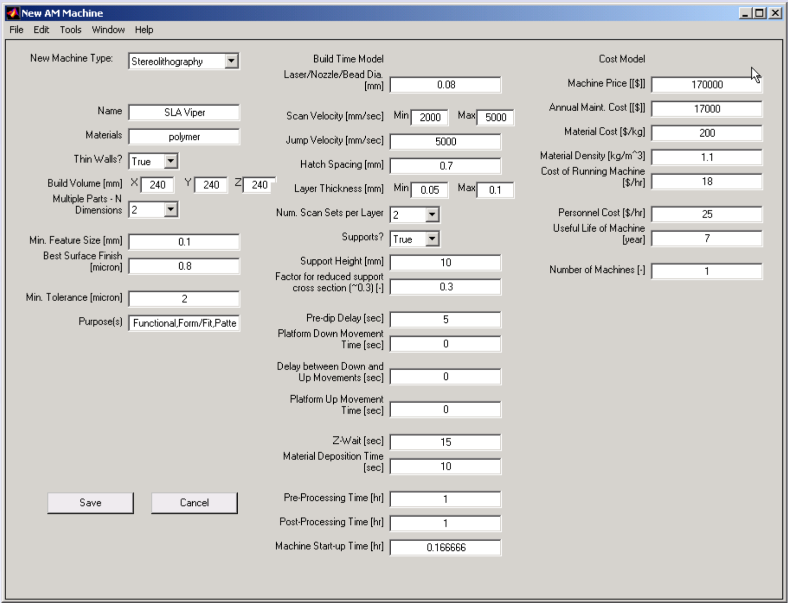
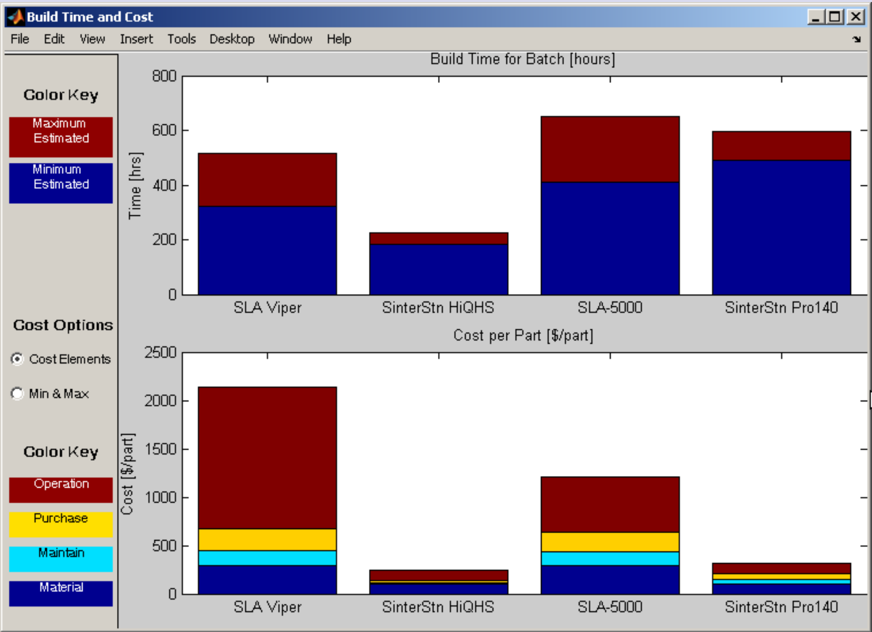
Cost Models

- **A general cost model for additive manufacturing**





RMSelect Software by Dr. David Rosen

http://www.srl.gatech.edu/Members/drosen/RMSelect.zip
http://www.srl.gatech.edu/Members/drosen/RMselection_Manual.pdf

Economics

Cost Models

A cost model for SLS

$$SLS\ Cost_{Total} = C_i + C_d$$

$$C_i = M_r * t_b \qquad M_r = f\left(\frac{C_m, O_p, O_a}{t_p}\right)$$

$$C_d = C_{mat} + (L_T * t_b) + (L_Q * n_p)$$

C_i = Cost of indirect labor ($)

C_d = Cost of direct labor ($)

M_r = Overhead Machine Rate ($/hr)

t_b = Time of Build (hr)

C_m = Cost of the Machine ($)

O_p = Cost of Production Overhead ($)

O_a = Cost of Administrative Overhead ($)

t_p = Period of time for specific accounting cycle (Months, Quarters, Annual)

C_{mat} = Direct Cost of the Material in a Batched Build ($)

L_T = Labor Rate of the Technical Staff ($/hr)

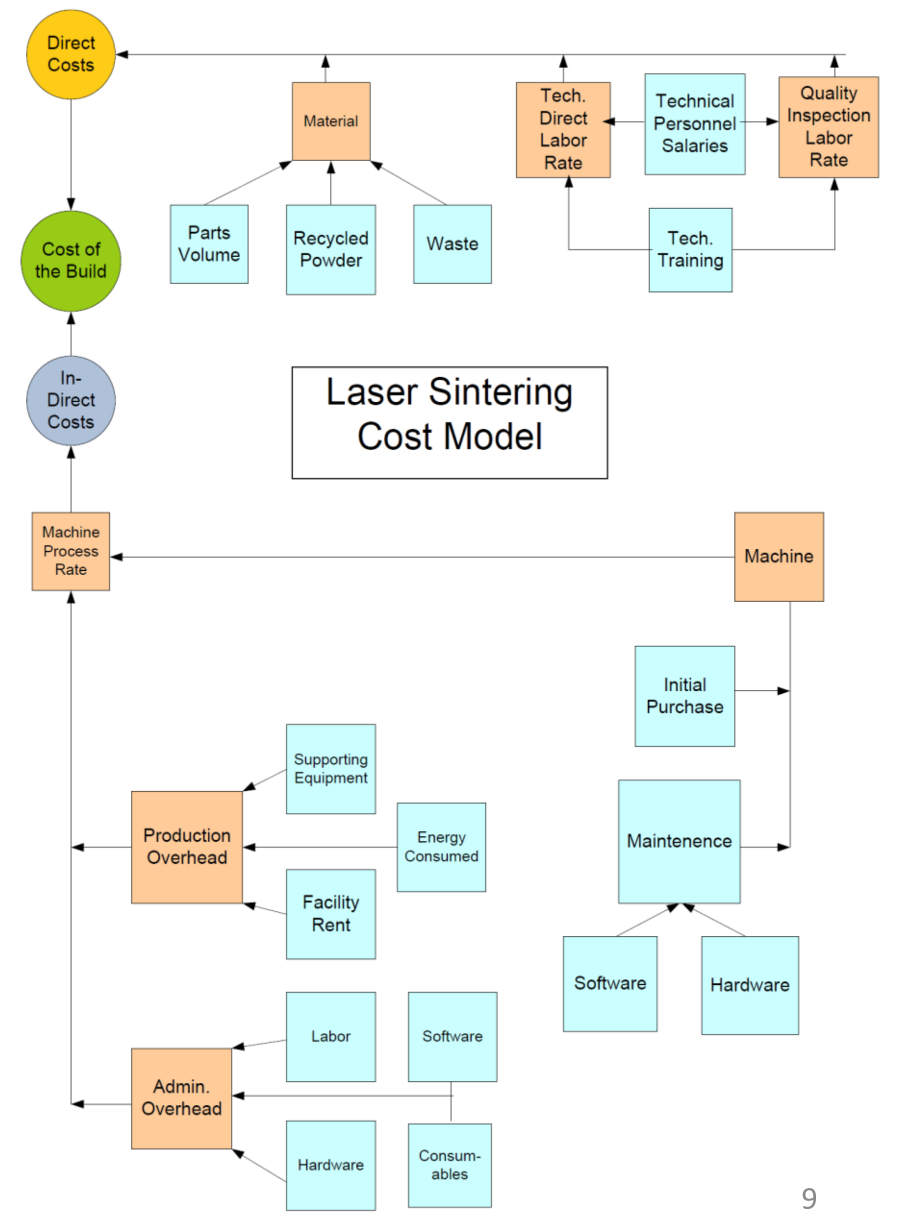
L_Q = Labor Rate of the Inspection Quality Staff ($/hr)

n_p = Number of Parts in the Batched Build (integer)

C_p = Cost of Sintered Material ($)

C_{rec} = Cost of Recycled Material ($)

C_{wst} = Cost of Wasted Material ($)



Chapter 5, Dietrich, David M. "Emerging technology supply chain model for additive manufacturing." (2010).

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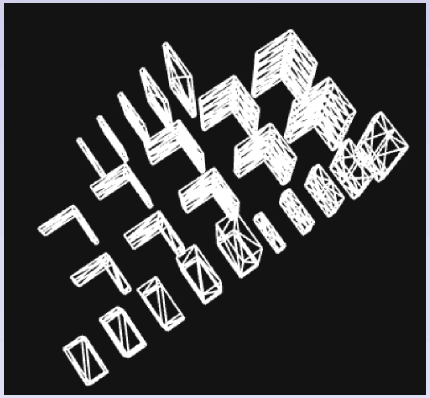
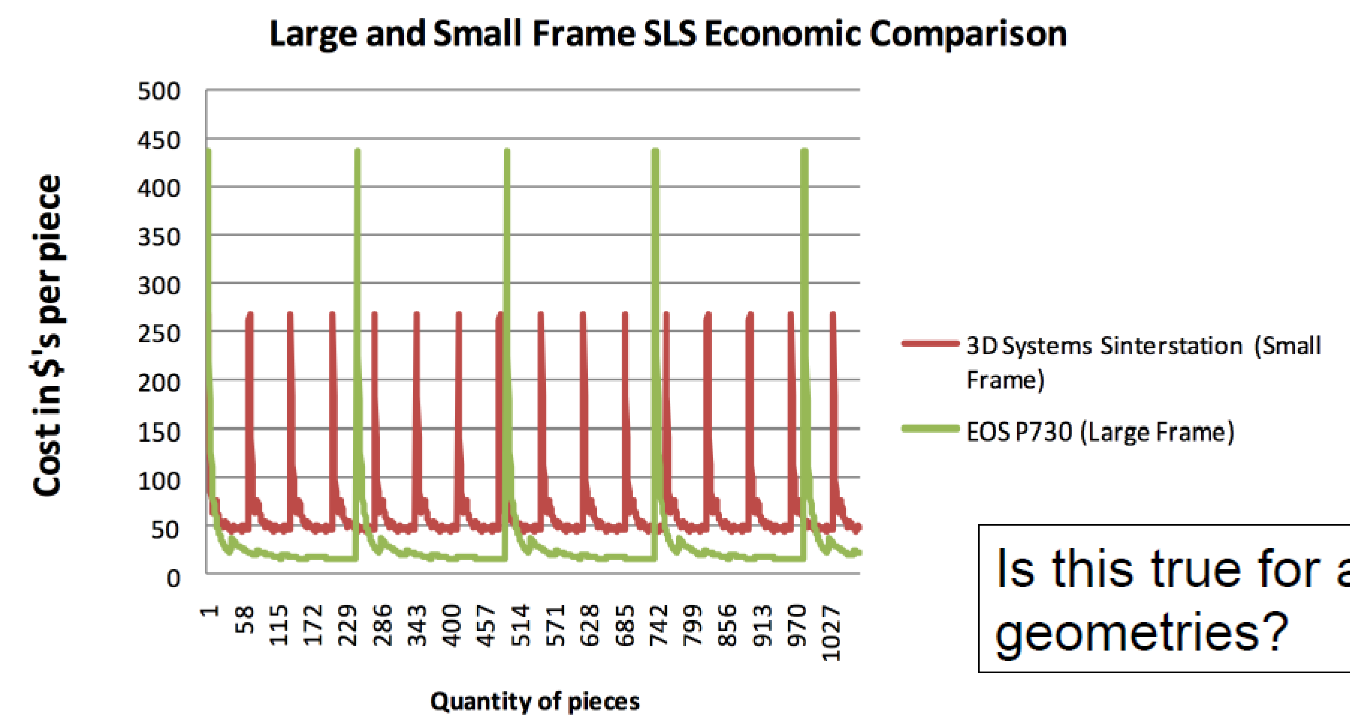
Cost Models

- A cost model for SLS



Parts per build

"Batch Cap + 1" effect



Is this true for all geometries?

Chapter 5, Dietrich, David M. "Emerging technology supply chain model for additive manufacturing." (2010).

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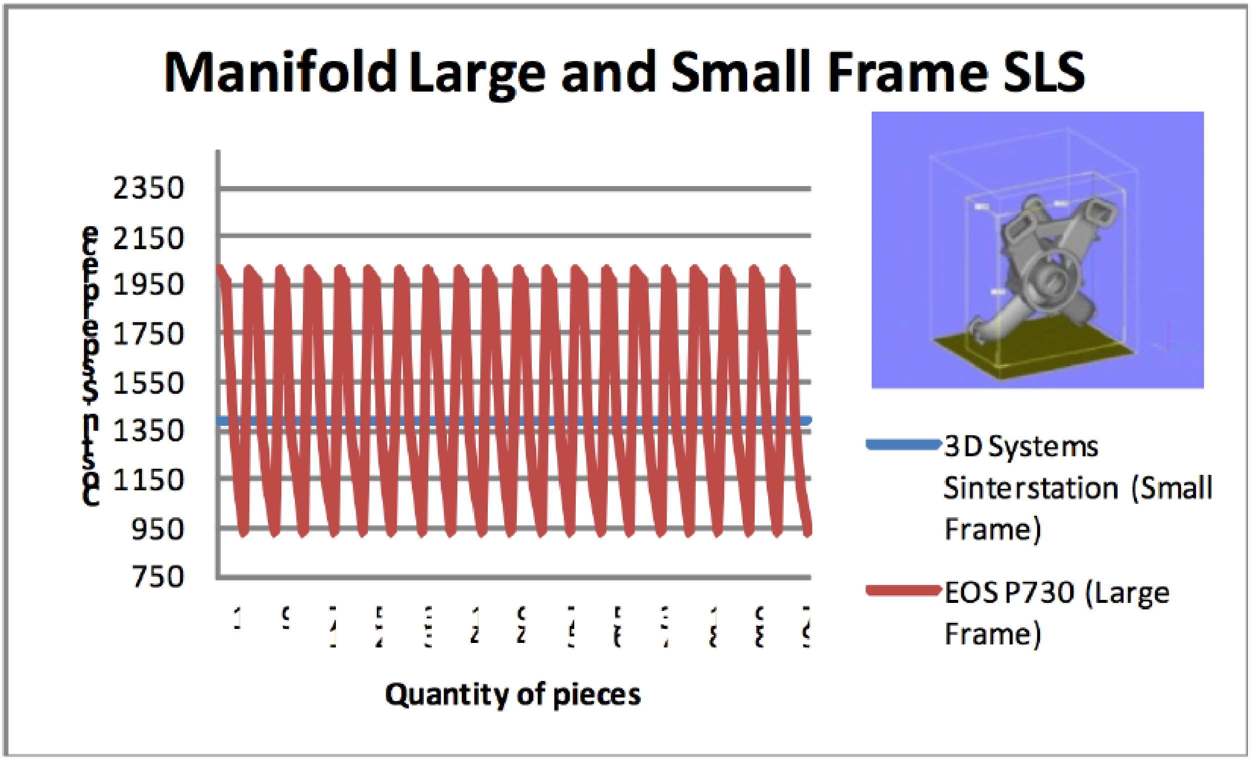
Cost Models

A cost model for SLS

"Batch Cap + 1" effect



Effects of the size of geometry (1 part per build for small frame, 5 parts per build for large frame)

Chapter 5, Dietrich, David M. "Emerging technology supply chain model for additive manufacturing." (2010).

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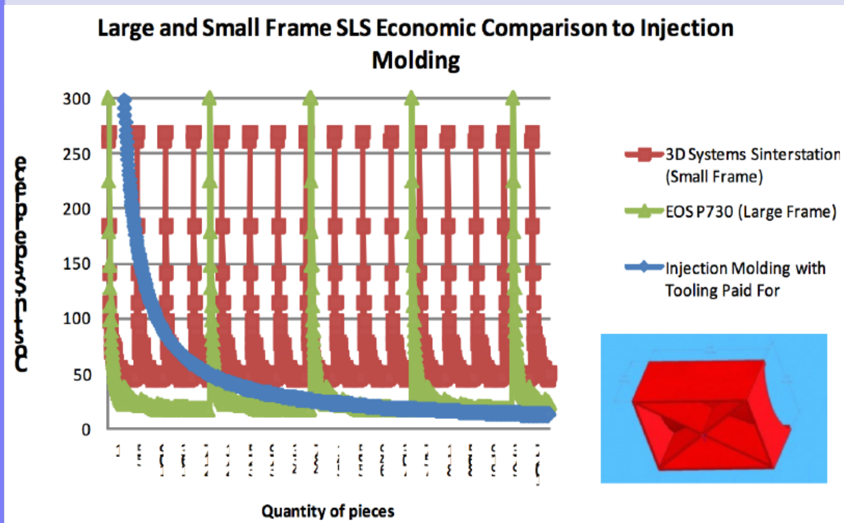
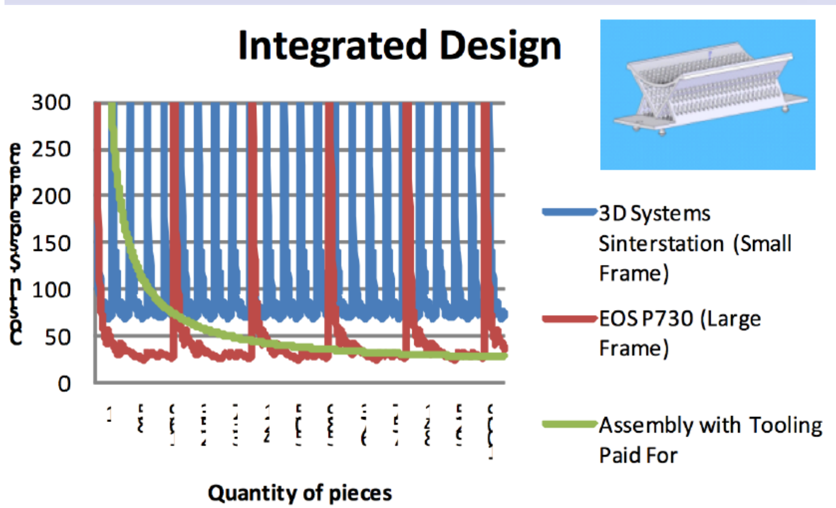
“Batch Cap + 1” effect





Effects of the complexity of geometry compared to injection molding

Chapter 5, Dietrich, David M. "Emerging technology supply chain model for additive manufacturing." (2010).

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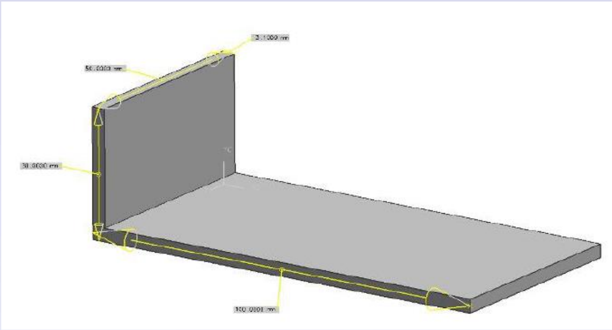
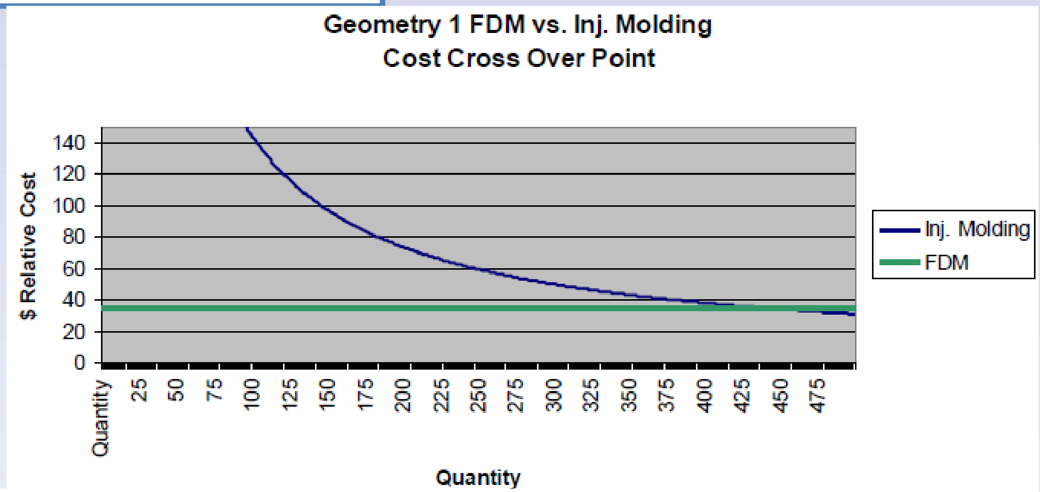
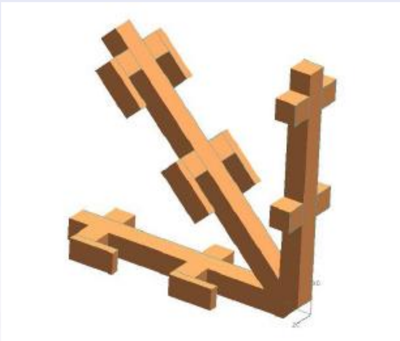
Cost Models

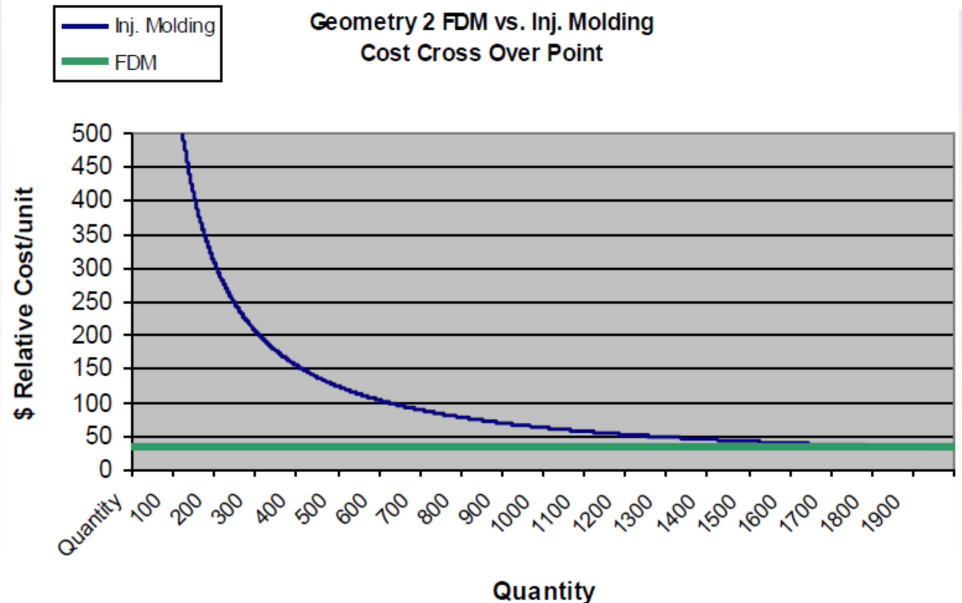
- **A similar cost model for FDM**







More undercuts



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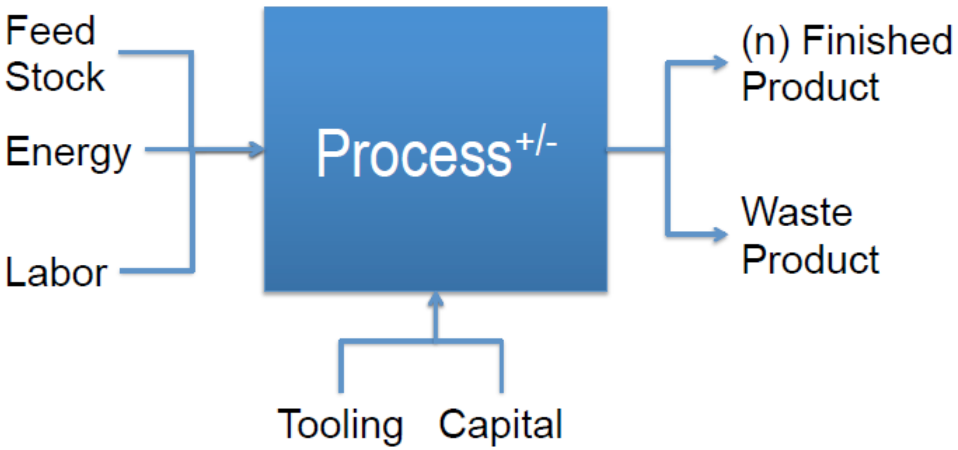
Cost Models

A cost model for comparison with machining

- + (additive) (FDM)
- - (subtractive) (machining)



$$\alpha_{+} = \frac{M_{Feedstock}}{M_{Part}}$$

$$\alpha_{-} = \frac{M_{Billet}}{M_{Part}}$$

Buy to fly ratio: α

Credit: Dr. S. Suresh Babu @ UTK&ORNL

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Cost Models

- **A cost model for comparison with machining**

- **Energy consumption**

Machining:

$$E^{-}_{Part} = E^{-}_{Density} M_{Part} (\alpha^{-} - 1)$$

Additive manufacturing:

$$E^{+}_{Part} = E^{+}_{Density} M_{Part} (\alpha^{+})$$

- **Assume** $\alpha_{+} \sim 1$
- **Then the condition for additive manufacturing to be more economical in energy consumption is:**

$$\alpha^{-} > \frac{E^{+}_{Density}}{E^{-}_{Density}} + 1$$

Credit: Dr. S. Suresh Babu @ UTK&ORNL

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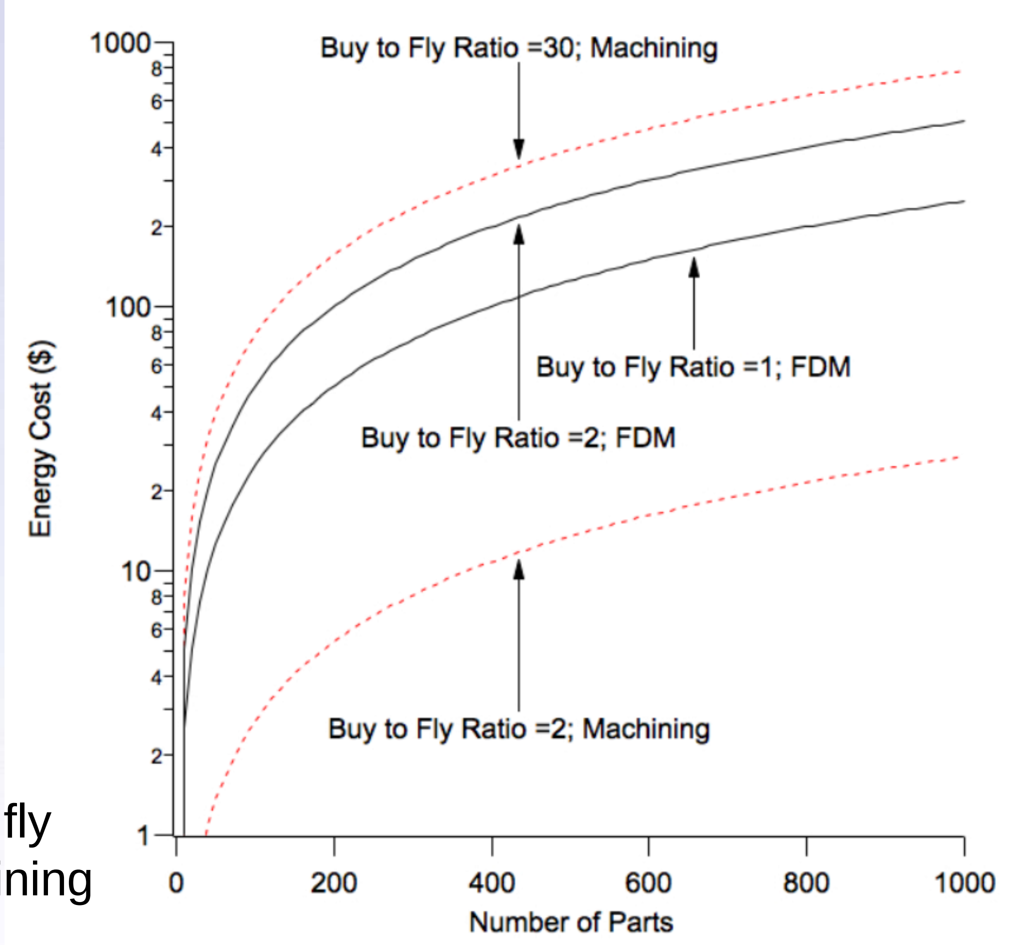
A cost model for comparison with machining

Energy consumption comparison

- Energy Density Comparison
  - Machining = 2.78 J/kg
  - **FDM =25.78 J/kg**
- Energy Cost = $/kWh = 0.07
- Mass = 0.5 kg

$$\alpha^- > \frac{E^+_{Density}}{E^-_{Density}} + 1$$

Critical buy to fly ratio for machining



Buy to fly ratio becomes a way to quantify design complexity!!!

Credit: Dr. S. Suresh Babu @ UTK&ORNL

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Cost Models

- A cost model for comparison with machining
- Total cost

But total cost includes many aspects for each of the additive/subtractive processes

- Energy - C_E
- Labor- C_L
- Design- C_D
- Capital- C_c
- Tooling- C_T
- Feedstock- C_F
- Failure - C_{Fail}

$$\$_E^{+/-} = E_{unit} E_{Part}^{+/-}$$

$$\$_L^{+/-} = L_h M_{Processed}^{+/-} / m_{Rate}^{+/-}$$

$$\$_D^{+/-} = L_{Design}^{+/-} t_{Design}^{+/-} / \left[N_{products}^{+/-} \alpha^{+/-} \right]$$

$$\$_C^{+/-} = R_c M_{Processed}^{+/-} / m_{Rate}^{+/-}$$

$$\$_T^{+/-} = C_T / N$$

$$\$_F^{+/-} = C_{Feedstock}^{Unit} M_{Processed}^{+/-}$$

$$\$_{Fail}^{+/-} = C_{fail}^{Unit} R_{fail}^{+/-} N_{products}^{+/-} / \alpha^{+/-}$$

Credit: Dr. S. Suresh Babu @ UTK&ORNL

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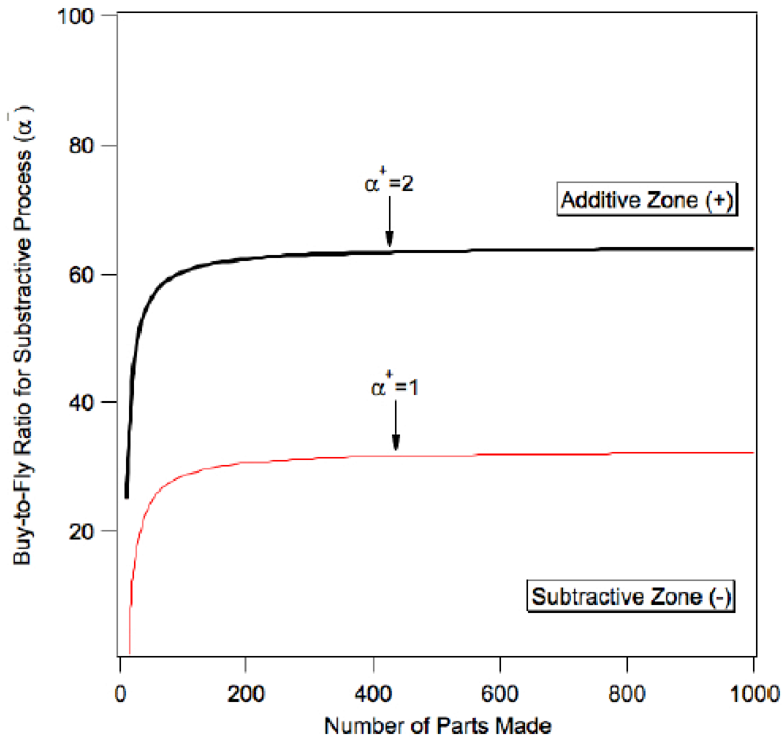
Cost Models

- A cost model for comparison with machining
- Total cost

Baseline case with FDM; buy to fly ratio for AM is assumed between 1 and 2

- Case 1: Shows the effect of tooling cost!



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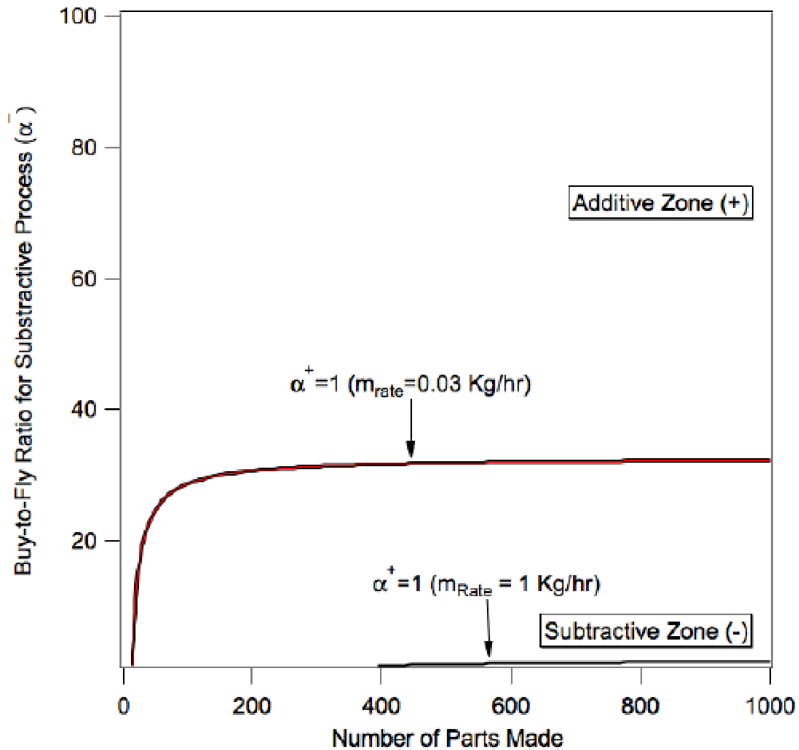
Cost Models

- A cost model for comparison with machining

- Total cost

Buy to fly ratio for AM is assumed to be 1

- Case 2: Shows the effect of increasing the deposition rate



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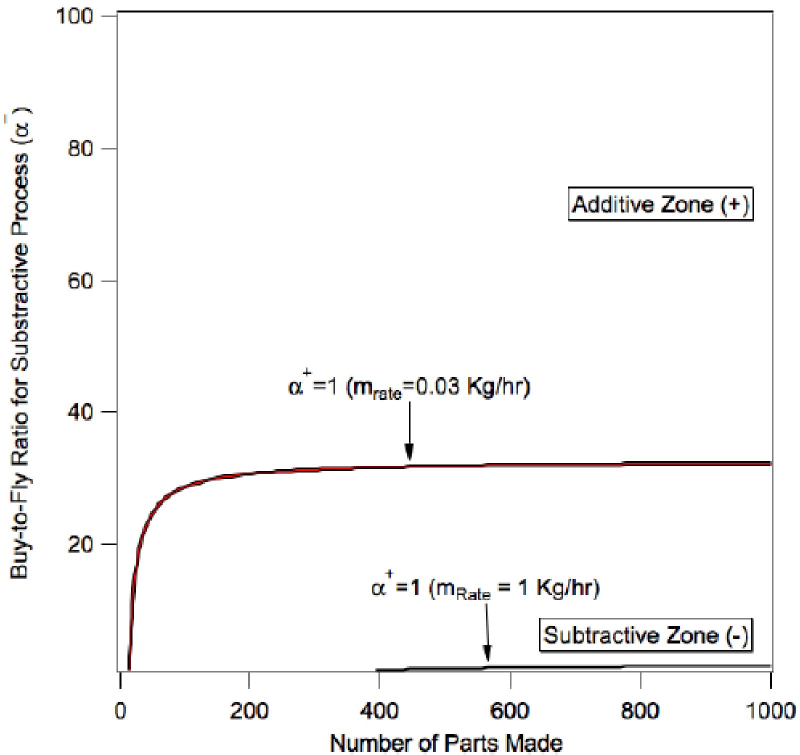
Cost Models

A cost model for comparison with machining

Total cost

Baseline case with FDM; buy to fly ratio for AM is assumed to be 1

- Case 3: Shows the effect of decreasing the labor rate and increased tooling costs



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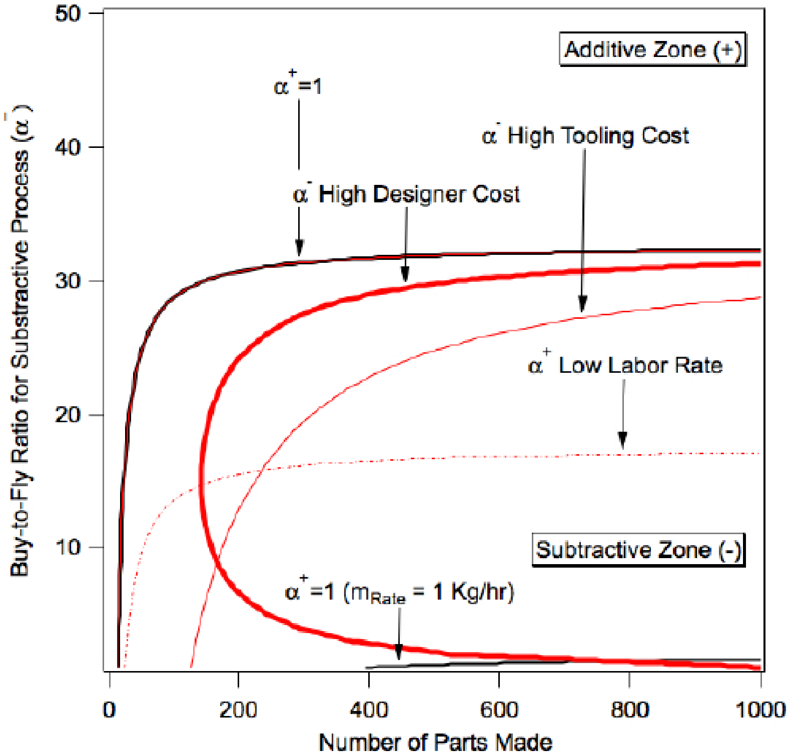
Cost Models

- A cost model for comparison with machining
- Total cost

Baseline case with FDM; buy to fly ratio for AM is assumed to be 1

- Case 4: Shows the effect of complex design; Initial design engineering time cost!
- 30,000 hrs. of design for TM; 80 hrs. of design for AM

$$\$_D^{+/-} = L_{Design}^{+/-} t_{Design}^{+/-} / \left[N_{products}^{+/-} \alpha^{+/-} \right]$$



Credit: Dr. S. Suresh Babu @ UTK&ORNL

Economics

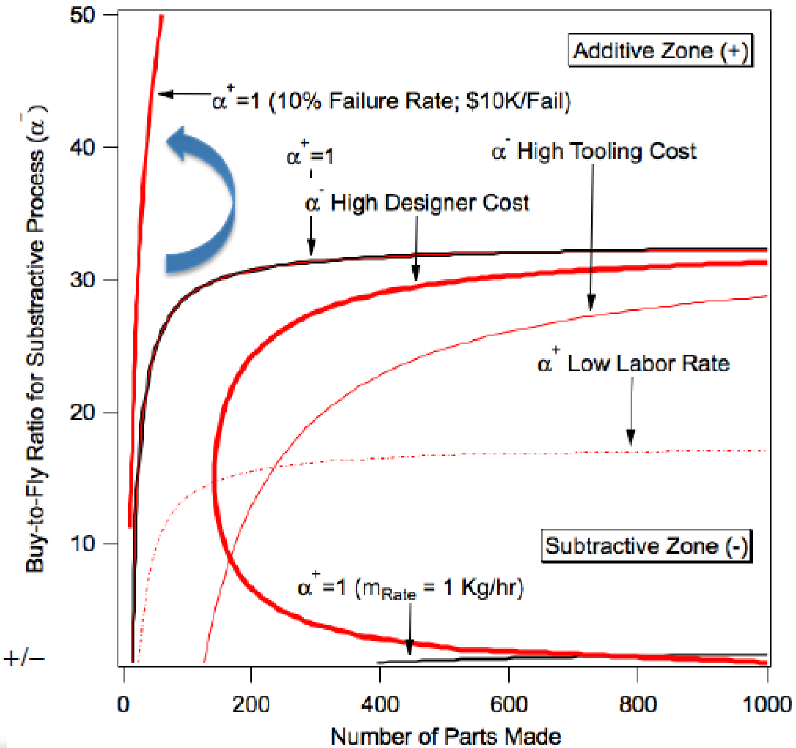
Cost Models

- A cost model for comparison with machining
- Total cost

Baseline case with FDM; buy to fly ratio for AM is assumed to be 1

- Case 5: Shows the effect of failure rates in AM;
- \$10K/failure
- 10% Failure

$$\$^{+/-}_{Fail} = C^{Unit}_{fail} R^{+/-}_{fail} N^{+/-}_{products} / \alpha^{+/-}$$



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