Factories and Design for Manufacture

http://www.youtube.com/watch?v=KEQdn57Kz1Q
How are factories measured

- **Fill Rate**
  - How close is the factory operating to capacity (measured in percentage)
- **Yield**
  - Good product divided by total processed
- **Costs**
  - Cost per product
- **Inventory Control**
  - Least the better
- **Defects**
  - in process
  - escapes
- **Safety**
  - Lost time accidents
What does Factory management worry about to achieve high metrics?

- Reproducibility
  - Do the same thing day after day
  - But get gradually better . . .
- Reduction in variation
  - Reduce all noise sources to the minimum
- Logistics
  - Control inventory at all stages
- Productivity
  - Outputs/inputs
- Delivery
  - Satisfy the customer!
- Quality
  - PPM
- Capital Investment minimization
- Labor Minimization

Metrics
- Fill Rate
- Yield
- Costs
- Inventory Control
- Defects
  - In process
  - Escapes
- Safety
Inventory

- Raw Material
  - examples
- Work-in-Process
  - examples
- Finished Goods
  - examples

Need to Reduce all three
What is the true cost of Inventory?

What is the most efficient Caltech operation in Inventory?
The Logistics Paradox

Having the right materials in the right place at the right time

Don’t run out!

Having the least amount of materials at each point

Skate close to the edge
Capital Investment Minimization

Example of very high Capital
  Semiconductors
  Chemicals
  Aerospace

Examples of very low capital
  Software
  Consulting

Examples of wasted capital
  Automated logistics management systems
  Factory Automation before the process is well understood
  - GM in the ‘80s.
Productivity

What is the effect of Product Design on Factory Productivity?

How do we improve Engineering productivity?

Good companies increase this measure by 6% a year every year.
Costs - Fixed and Variable

- Production Cost
- Total Cost
- Variable Cost
- Fixed Cost

Units of Output
**Costs**

<table>
<thead>
<tr>
<th>Fixed (Volume insensitive)</th>
<th>Variable (Volume Sensitive)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Equipment and Tooling</td>
<td>• Direct Labor</td>
</tr>
<tr>
<td>• Utilities</td>
<td>• Direct Materials</td>
</tr>
<tr>
<td>• Rent</td>
<td>• Consumable Chemicals</td>
</tr>
<tr>
<td>• Taxes on property</td>
<td>• Other expenses which scale with volume</td>
</tr>
<tr>
<td>• insurance</td>
<td></td>
</tr>
<tr>
<td>• Management salaries</td>
<td></td>
</tr>
</tbody>
</table>

How does product design affect these costs?
Product Cost

Total Cost of one item =
Total Fixed Cost/Volume + Variable Cost/Volume

Higher Volume
typically means lower
product cost

This does not take into account non-direct costs
of marketing, distribution, Profit, etc. etc.
Bill of Materials

Indented bill of materials showing cost estimates for the original intake manifold and related components. The EGR (exhaust gas recirculation), PCV (positive crankcase ventilation), and vacuum block components are included here to facilitate comparison with the redesigned manifold assembly.

<table>
<thead>
<tr>
<th>Component</th>
<th>Purchased Materials</th>
<th>Processing (Machine + Labor)</th>
<th>Assembly (Labor)</th>
<th>Total Unit Variable Cost</th>
<th>Tooling and Other NRE, K$</th>
<th>Tooling Lifetime, K units</th>
<th>Total Unit Fixed Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manifold machined casting</td>
<td>12.83</td>
<td>5.23</td>
<td>0.15</td>
<td>18.06</td>
<td>1960</td>
<td>500+</td>
<td>0.50</td>
<td>18.56</td>
</tr>
<tr>
<td>EGR return pipe</td>
<td>1.30</td>
<td></td>
<td>0.15</td>
<td>1.45</td>
<td></td>
<td></td>
<td></td>
<td>1.45</td>
</tr>
<tr>
<td>PCV assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valve</td>
<td>1.35</td>
<td>0.14</td>
<td>1.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.49</td>
</tr>
<tr>
<td>Gasket</td>
<td>0.05</td>
<td>0.13</td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>Cover</td>
<td>0.76</td>
<td>0.13</td>
<td>0.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td>Screws (3)</td>
<td>0.06</td>
<td>0.15</td>
<td>0.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.21</td>
</tr>
<tr>
<td>Vacuum source block assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block</td>
<td>0.95</td>
<td>0.13</td>
<td>1.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.08</td>
</tr>
<tr>
<td>Gasket</td>
<td>0.03</td>
<td>0.05</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.08</td>
</tr>
<tr>
<td>Screw</td>
<td>0.02</td>
<td>0.09</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.11</td>
</tr>
<tr>
<td><strong>Column Totals (Direct Costs)</strong></td>
<td><strong>17.35</strong></td>
<td><strong>5.23</strong></td>
<td><strong>0.95</strong></td>
<td><strong>23.53</strong></td>
<td><strong>1960</strong></td>
<td><strong>0.50</strong></td>
<td><strong>14.48</strong></td>
<td><strong>38.51</strong></td>
</tr>
<tr>
<td>Overhead Charges</td>
<td>2.60</td>
<td>9.42</td>
<td>1.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Bill of Materials

<table>
<thead>
<tr>
<th>Variable Cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>5.7 kg aluminum at $2.25/kg</td>
</tr>
<tr>
<td>Processing (casting)</td>
<td>150 units/hr at $530/hr</td>
</tr>
<tr>
<td>Processing (machining)</td>
<td>200 units/hr at $340/hr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fixed Cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooling for casting</td>
<td>$160,000/tool at 500K units/tool (lifetime)</td>
</tr>
<tr>
<td>Machine tools and fixtures</td>
<td>$1,800,000/line at 10M units (lifetime)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Direct Cost</th>
<th>$18.56</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead charges</td>
<td>$12.09</td>
</tr>
</tbody>
</table>

| Total Unit Cost                                     | $30.65   |

Cost estimate for the original intake manifold. Note that the processing costs for casting and machining reflect the costs for a complete casting line and several machining stations.
Effect of Design on Factory Productivity

• Need to minimize changes
  – excessive numbers of different products running in line
  – Long set-ups
• High Inventory due to lack of re-use
  – Make Vs Source
• Low first pass yield due to mismatch of product design with process capability
  – “hidden factory”
  – Scrap
Lecture Manufacturability

• Movie for final

• HW

• Lecture

• Class Exercise
Design for Manufacturing and Assembly
Manufacturing Cost - an iterative process

1. Compute Manufacturing Costs
2. Components Assembly Mfg Cost
3. Work to reduce
4. Good Enough?
   - Yes
   - No
5. GO!
Estimate Costs from input/output model
Examples

**Fixed (Volume insensitive)**
- Equipment and Tooling
- Factory plant costs
  - Utilities
  - Rent
  - Insurance
- General Management

**Variable (Volume sensitive)**
- Raw Materials
- Direct Labor
- Consumable chemicals
- Other expenses which scale directly with volume

Not always a clear distinction

Question: How does product design affect these costs?
To reduce costs . . .

- Understand manufacturing process cost drivers
  - expensive equipment
  - tight specs and variances beyond factory capabilities
  - use of hard to machine, expensive materials

- Redesign to eliminate processing steps

- Choose appropriate manufacturing scale
  - tooling optimization
To reduce costs...

– Standardize components and use common processes and parts to reduce inventory and special processing
  • Standard chips over custom design
  • Standard fasteners
  • Minimize use of exotic equipment
– Emphasize reuse wherever possible
– Outsource non core processes whenever possible
DFA Design for Assembly

- Use near net shapes for molded parts to minimize machining
- Drive behind complex plastic extrusions
- Drive behind 3D Printing
- IBM PC snapped together from 3-5 parts

 Weniger Teile! (Fewer parts)
Design For Assembly (DFA) Guidelines

– Minimize the number of parts.
– Design for Z-axis assembly.
– Improve assembly access.
– Maximize part compliance.
– Maximize part symmetry.
– Optimize part handling.
– Avoid separate fasteners.
– Minimize fixturing.
– Minimize processes and process steps.
– Eliminate extra operations.
– Minimize subassemblies.
Design for Assembly (DFA Guidelines)

Minimize the number of parts

- Reduces opportunity for defective part/assembly errors
- Reduces assembly cost with fewer steps
- Reduces purchasing, stocking and servicing costs
- Reduces inventory and work-in-process costs
DFA  Ask three questions to determine the minimum number of parts

• Does the part need to move with respect to the rest of the assembly?
  • Yes  slide or rotation

• Is there a fundamental physical reason why the part needs to be made of a different material than the rest of the assembly?
  • No  separate keys on a keyboard (can be achieved by elastomers)
  • Yes  conduct or inhibit electricity
  • No  screws, washers, metal rather than molded in plastic clips

• Does the part have to be separated for assembly access, replacement, or repair?
  • Yes  rf shields, top and bottom halves of housing
  • No  screws, washers, nuts, clips
DFA
To maximize ease of assembly...

- Insert part from the top (z-axis assembly)
- Part is self aligning
- Part does not need orientation
- Part requires only one hand for assembly
- Part requires no tools
- Part is assembled in a single, linear motion
- Part is secured immediately upon insertion
How about customer assembly?
Consider Ikea
Minimize system complexity

• Number of new parts introduced
• Number of new vendors introduced
• Number of custom parts introduced
• Number of new major tools introduced
• Number of new production processes introduced

That’s why Frankenstein isn’t so bad!
Your products are closer to
Error proofing to eliminate mistakes

• Look for possible failure modes or opportunities to be confused and take appropriate early corrective action
• e.g. slightly different parts that are easy to confuse- either eliminate or exaggerate
Error proofing to eliminate mistakes

- Mistake-proof product design and assembly (poka-yoke)
  - assembly process is unambiguous.
  - Components should be designed so that they can only be assembled in one way; they cannot be reversed.
  - Notches, asymmetrical holes and stops can be used to mistake-proof the assembly process.
  - Design verifiability into the product and its components. For mechanical products,
  - Products should be designed to avoid or simplify adjustments.
  - Electronic products can be designed to contain self-test
Effect of Design on Factory Productivity

- Need to minimize changes
  - excessive numbers of different products running in line
  - Long set-ups
- High Inventory due to lack of re-use
  - Make Vs Source
- Low first pass yield due to mismatch of product design with process capability
  - “hidden factory”
  - Scrap
Minimize flexible parts and interconnections

• Avoid flexible and flimsy parts

• belts, gaskets, tubing, cables and wire harnesses.

• Partition the product to minimize interconnections between modules and co-locate related modules to minimize routing of interconnections.
Technology and Manufacturing

• The next great leap → 3D printing
  – Rapid prototyping
  – Rapid Manufacturing
  – Mass Customization
  – Mass Production by parallel print heads
  – Clothing including shoes
  – Implant and Medical Devices
Utilizing Organovo Novotissues™ in Research: living, three-dimensional human tissue models for research and therapeutic applications.

The flexibility of our bioprinting technology, which marries biology and engineering, and its proven application across a wide variety of cells, allows us to target many different tissues for development of human tissue models. We are currently building a number of 3D tissue models for research and drug discovery applications, as well as working to fulfill our vision of building human tissues for surgical therapy and transplantation.
### Global 3D printing market

Estimates and forecast of market value to 2018, in USD

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>$2.5b</td>
<td>$3.8b</td>
<td>$16.2b</td>
<td>45.7%</td>
</tr>
<tr>
<td>3D printers</td>
<td>$0.7b</td>
<td>$1.3b</td>
<td>$5.4b</td>
<td>50.1%</td>
</tr>
<tr>
<td>Services and materials</td>
<td>$1.8b</td>
<td>$2.5b</td>
<td>$10.8b</td>
<td>43.8%</td>
</tr>
</tbody>
</table>

Source: Canalys estimates and forecast, © Canalys 2014
3D printing

For construction

- http://www.youtube.com/watch?v=ehnzfGP6sq4
Learning Curve

EXHIBIT 11.18 Arithmetic Plot of 70, 80, and 90 Percent Learning Curves

Production cost ($) vs. Unit number

- 90% Learning curve
- 80%
- 70%
Because of these learnings we will have improvement the Learning Curve

**EXHIBIT 11.18** Arithmetic Plot of 70, 80, and 90 Percent Learning Curves
Learning Curve

\[ T_N = T_1(N^b) \]

Where:

\( T_N \) = Time for the Nth Unit
\( T_1 \) = Hours to produce the first unit
\( b \) = \((\text{Log of the learning rate}/\text{Log 2})\) = Slope of the learning curve

The basic thesis of the learning curve is that every time the produced volume is doubled, labor per unit will decline by a constant rate, which is normally referred to as the learning rate

<table>
<thead>
<tr>
<th>Nth Unit Produced</th>
<th>Hours for Nth Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td>2</td>
<td>800 = (0.8*1000)</td>
</tr>
<tr>
<td>4</td>
<td>640 = (0.8*800)</td>
</tr>
<tr>
<td>8</td>
<td>512 = (0.8*640)</td>
</tr>
<tr>
<td>16</td>
<td>410 = (0.8*512)</td>
</tr>
</tbody>
</table>
Pricing on the Learning Curve

**EXHIBIT 11.18** Arithmetic Plot of 70, 80, and 90 Percent Learning Curves

- **90% Learning curve**
- **80%**
- **70%**
Learning Curve Pricing

- Set low price (below cost) for initial roll-out of product
- Stimulate sales by low price
- Increase production which lowers cost by economy of scale
- Continue to lower price to increase sales and discourage competition
Exercise

• Consider your product. Give three ways you will make it “easily” manufacturable.