Week 2, September 14

Design for Manufacture (DFM): Concept

Fall 2017

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What is Manufacturability?

Do you know how to make these parts?
More important questions?

- How much does it cost?
- How long does it take?

- These issues are influenced by:
  - Manufacturing process
  - Availability of machines
  - Material
  - Batch size (how many parts)
  - Etc.
Model for manufacturing??

“When we mean to build, we first survey the plot, then draw the model”

William Shakespeare (1564-1616)
Problems in traditional manufacturing

Commercial CAD (CATIA, ProE, I-DEAS, Inventor)

Design

Time lost in redesign

Ouch, it’s not Machinable

Over-the-wall manufacturing

Manufacturing
Definition of DFM

“Process of proactively designing products to:

- optimize the manufacturing functions
  - Fabrication
  - Assembly
  - Test
  - Procurement
  - Service
  - Repair

- assure the best cost, quality, reliability, safety, time-to-market, and custom satisfaction”
  (D. Anderson)

- Also, Design for manufacture, manufacturing, manufacturability
Cost in product development

- 80% of cost is committed at design stage
- Incurred cost for design is less than 10%
Importance of DFM

1. Design decision affects manufacturing cost and productivity
2. Designers play important role not only shaping, but also in manufacturability, cost, life cycle of products
History of DFM (1)

- Eli Whitney (19C)
  - Musket (gun) manufacturer
  - Redesigned a limited tolerance*
  - Used fixtures, gauges, and specially developed machines
    - Each part could be made by semi-skilled workers at a faster and cheaper
  - Changed process from sand casting to forging increased accuracy
Engineering tolerance is

A machine's potential to cope with changes in the following elements of its surroundings and remain functioning.
Whitney’s Musket
History of DFM (2)

Henry Ford (1907)
- Standard parts
- Simple design
- Conveyor system
- Price reduction
  - $2000/car → $350/car
- 1908~1927: 15 million sold

Cadillac, General motors (1909)

T-model (Ford)

Modern Times
Factory Work

Charlie Chaplin – Modern Times; Factory Work
DFM category

1. General rules
2. Process specific rules
3. Product specific rules
4. Design for Assembly (DFA)
5. DFX
   - Environment
   - Recycle
   - Quality
   - Six sigma
   - Etc.
1. General rules of DFM

- Minimum number of parts
- Standard parts
- Modular design
- Multi-functional parts
- The same parts to various products
- Maximum surface roughness and tolerance
- Avoid secondary process
- Use materials easy to manufacture
- Consider number of parts to be manufactured
- Avoid many components
- Minimize handling of parts
Surface roughness vs. Relative manufacturing time depend on Surface finishing method

- Cylindrical grinding
- Surface grinding
- End milling
- Reaming
- Turning
- Flexibility milling
- Shaping & Planing
- Drilling

Surface roughness (㎛)

Relative manufacturing time

* The arithmetic value of filtered roughness profile determined from deviations about the center line within the evaluation length Im.

\[ Ra = \frac{1}{n} \sum_{i=1}^{n} |V_i| \]

* According to DIN 4768/1, DIN 4762/1E, ISO/DIS 4287/1
Tolerances

Figure 2.8  Natural tolerances (NT) = the darker bands, for a variety of common mechanical manufacturing processes. Variations = the lighter bands (from Manufacturing Processes for Engineering Materials by Kalpakjian, © 1997. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ.
Per Part Cost

The relation among an output, selection of machine tools, and economical efficiency of production making.

[Graph showing the cost of materials and the number of parts for different types of machine tools: General purpose machine tool, Special-purpose machine tools, Hand work, and NC machine tools.]
# Product Development Time

<table>
<thead>
<tr>
<th></th>
<th>Stanley Tools Jobmaster Screwdriver</th>
<th>Rollerblade In-Line Skate</th>
<th>Hewlett-Packard DeskJet Printer</th>
<th>Volkswagen New Beetle Automobile</th>
<th>Boeing 777 Airplane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual production volume</strong></td>
<td>100,000 units/year</td>
<td>100,000 units/year</td>
<td>4 million units/year</td>
<td>100,000 units/year</td>
<td>50 units/year</td>
</tr>
<tr>
<td><strong>Sales lifetime</strong></td>
<td>40 years</td>
<td>3 years</td>
<td>2 years</td>
<td>6 years</td>
<td>30 years</td>
</tr>
<tr>
<td><strong>Sales price</strong></td>
<td>$3</td>
<td>$200</td>
<td>$300</td>
<td>$17,000</td>
<td>$130 million</td>
</tr>
<tr>
<td><strong>Number of unique parts (part numbers)</strong></td>
<td>3 parts</td>
<td>35 parts</td>
<td>200 parts</td>
<td>10,000 parts</td>
<td>130,000 parts</td>
</tr>
<tr>
<td><strong>Development time</strong></td>
<td>1 year</td>
<td>2 years</td>
<td>1.5 years</td>
<td>3.5 years</td>
<td>4.5 years</td>
</tr>
<tr>
<td><strong>Internal development team (peak size)</strong></td>
<td>3 people</td>
<td>5 people</td>
<td>100 people</td>
<td>800 people</td>
<td>6,800 people</td>
</tr>
<tr>
<td><strong>External development team (peak size)</strong></td>
<td>3 people</td>
<td>10 people</td>
<td>75 people</td>
<td>800 people</td>
<td>10,000 people</td>
</tr>
<tr>
<td><strong>Development cost</strong></td>
<td>$150,000</td>
<td>$750,000</td>
<td>$50 million</td>
<td>$400 million</td>
<td>$3 billion</td>
</tr>
<tr>
<td><strong>Production investment</strong></td>
<td>$150,000</td>
<td>$1 million</td>
<td>$25 million</td>
<td>$500 million</td>
<td>$3 billion</td>
</tr>
</tbody>
</table>
2. Process specific rules: Machining

Avoid thin wall

Avoid thin and long boring beam

Avoid turning processing of thin and long component.

Short and firm component does not require tailstock.
Process specific DFM: Drilling

The drill slips to the left.

The drill slips to the right.

The drill enters and comes out with the direction which is vertical to the drill’s axis.

Worst

Bad

Good
3. The Assembly from Heaven

- Can be assembled one-handed by a blind person wearing a boxing glove
- Is stable and self-aligning
- Tolerances are loose and forgiving
- Few fasteners
- Few tools and fixtures
- Parts presented in the right orientation
- Parts asymmetric for easy feeding
- Parts easy to grasp and insert

(Dr. Peter Will, ISI)
The Assembly from Hell - iPhone 4

- The opposite in each case from the previous slide

Assembly components of iPhone 4
- Number of screws: 52*
- Number of components: 14*

Assembly components of Galaxy S3
- Number of screws: 11*
- Number of components: 8*

* Number of screws and components are assumed values.
“The iPhone 5 is the most difficult device that Foxconn has ever assembled. To make it light and thin, the design is very complicated,” said an official at the company who declined to be named. “It takes time to learn how to make this new device. Practice makes perfect. Our productivity has been improving day by day.”

- The Wall Street Journal, October 17, 2012
Assembly of iPhone 4

http://www.youtube.com/watch?v=Q67gLwbpQao
Assembly of Galaxy S3

http://www.youtube.com/watch?v=efXxYbz8DXs
A main assembly for the Epson printer.

The No. of parts:
49 parts

Assembly work:
57 time

Assembly time:
552 sec

The labor costs:
$3.83

(Ref.: Assembly Engineering. January 1987)
### Design for Assembly - good design

#### A main assembly for IBM printer.

<table>
<thead>
<tr>
<th></th>
<th>IBM printer</th>
<th>Epson printer</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of parts</td>
<td>32 parts</td>
<td>49 parts</td>
</tr>
<tr>
<td>Assembly work</td>
<td>32 time</td>
<td>57 time</td>
</tr>
<tr>
<td>Assembly time</td>
<td>170 sec</td>
<td>552 sec</td>
</tr>
<tr>
<td>Labor costs</td>
<td>$1.18</td>
<td>$3.83</td>
</tr>
</tbody>
</table>

(Ref.: Assembly Engineering. January 1987)
Straight Movement

Bad

Spring clip

Hole for taking location

Good

Pin for taking location
Self Location

The pipe is connected to flange.

**Bad**
The cylinder inserts at the hole.

**Good**
The cylinder having step inserts at the hole.

There is the chamfering at the edge.

One part is connected at the other part using bolt.
Design for no-assembly

Comparison of number of parts in a conventional stapler with a one-piece compliant stapler. [Ananthasuresh, Saggere, & Kota 1994]

Design-for-No-Assembly:

- Compliant mechanisms are single-piece flexible structures that generate motions through elastic deformation as opposed to the rigid body rotations and translations.
- Consideration of compliance in design treats elastic deformation as a preferred effect in mechanical design to achieve controlled motion and force transmissions.
- Compliant mechanism is best suited for devices with small range of motion.

Highlights and Advantages of Compliant Mechanisms:

- No assembly, no joints and ease of manufacture.
- Less friction, less wear and noise, and no backlash.
- Reduced cost of production.
- Elimination of additional accessories such as springs.
- Provision for non-mechanical actuation.
- A variety of short-range motions.
- Compliance in design = simplicity in manufacture.
Design for no-assembly

Windshield Wiper

- Manufactured in one single step, drastically reducing manufacturing costs

- Micro-compliant compliant mechanism for four-bar

- Micro-compliant compliant mechanism for crimping

*Analog Integrated Circuits and signal processing 29 7 7-15 2001*
Design for no-assembly

- 4D printing

Folding-unfolding process of the prototype of deployable mirror
(Wei Wang, IDIM, SNU)

Robotic bees take flight
(Harvard U.)
DFA - Modular Design

- Example: Lego – building block
Modular Design: example

- Google’s modular smartphone

http://www.youtube.com/watch?v=fEC6myN2mXg
Modular Design: example

- Volkswagen modular platform
  MQB (Modulen Quer Baukasten): Modular Transverse Matrix

Drive systems in MQB

- Conventional
  - TSI petrol EA211
- Electric
  - TDI diesel EA288
  - Plug-In
  - e-DRIVE
- Alternative/renewable
  - EcoFuel CNG
  - BiFuel LPG
  - FlexFuel ethanol

Modular layout of EA211 TSI (MOB)

- Exhaust module with turbocharger and catalytic converter
- Valve cover with integrated valve train module
- Aluminium short block
- Induction module with integrated intercooler
- Oil sump module with integrated oil filtering and supports for ancillary components
Modular Design: example

- Volkswagen modular platform
  MQB(Modulen Quer Baukasten): Modular Transverse Matrix

<table>
<thead>
<tr>
<th>Technical concept</th>
<th>Financial Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previously</td>
<td>Reduction targets from MQB¹ ²</td>
</tr>
<tr>
<td></td>
<td>Unit costs</td>
</tr>
<tr>
<td></td>
<td>One-off expenditure</td>
</tr>
<tr>
<td>Body Platform</td>
<td>~ 20%</td>
</tr>
<tr>
<td>Module</td>
<td>~ 20%</td>
</tr>
<tr>
<td>Module</td>
<td>~ 30%</td>
</tr>
<tr>
<td>Platform</td>
<td>Significant weight and emission reduction</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ MQB: Modulen Querbaukasten
² Reduction targets illustrate benefits from MQB implementation
Source: Volkswagen Group
4. Product specific rules: DFM

- Air intake manifolds
- Original: Cast Al
- Redesigned: molded thermoplastic composite

Example: GM 3.8 liter V6 engine

K T Ulrich & S D Eppinger, Product design and development 2nd edition
Manufacturing cost

EXHIBIT 11-5
Elements of the manufacturing cost of a product.
DFM process

5 steps of DFM Process

1. Estimate the manufacturing cost
2. Reduce the cost of components
3. Reduce the cost of assembly
4. Reduce the cost of supporting production
5. Consider the impact of DFM decision on other factors
Effect of process change
## Cost of original intake manifold

<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></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>0.50</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></td>
<td>0.14</td>
<td>1.49</td>
<td></td>
<td></td>
<td></td>
<td>1.49</td>
</tr>
<tr>
<td>Gasket</td>
<td>0.05</td>
<td></td>
<td>0.13</td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>Cover</td>
<td>0.76</td>
<td></td>
<td>0.13</td>
<td>0.89</td>
<td></td>
<td></td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td>Screws (3)</td>
<td>0.06</td>
<td></td>
<td>0.15</td>
<td>0.21</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></td>
<td>0.13</td>
<td>1.08</td>
<td></td>
<td></td>
<td></td>
<td>1.08</td>
</tr>
<tr>
<td>Gasket</td>
<td>0.03</td>
<td></td>
<td>0.05</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
<td>0.08</td>
</tr>
<tr>
<td>Screw</td>
<td>0.02</td>
<td></td>
<td>0.09</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
<td>0.11</td>
</tr>
<tr>
<td>Total Direct Costs</td>
<td>17.35</td>
<td>5.23</td>
<td>0.95</td>
<td>23.53</td>
<td>1960</td>
<td>0.50</td>
<td></td>
<td>24.03</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>14.48</td>
</tr>
<tr>
<td>Total Cost</td>
<td>20.03</td>
<td>14.62</td>
<td>1.71</td>
<td>38.51</td>
<td></td>
<td></td>
<td></td>
<td>38.51</td>
</tr>
</tbody>
</table>
Cost comparison

### Variable Cost

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost Breakdown</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>5.7 kg aluminum at $2.25/kg</td>
<td>$12.83</td>
</tr>
<tr>
<td>Processing (casting)</td>
<td>150 units/hr. at $530/hr.</td>
<td>3.53</td>
</tr>
<tr>
<td>Processing (machining)</td>
<td>200 units/hr. at $340/hr.</td>
<td>1.70</td>
</tr>
</tbody>
</table>

### Fixed Cost

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost Breakdown</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooling for casting</td>
<td>$160,000/tool at 500K units/tool (lifetime)</td>
<td>0.32</td>
</tr>
<tr>
<td>Machine tools and fixtures</td>
<td>$1,800,000/line at 10M units (lifetime)</td>
<td>0.18</td>
</tr>
</tbody>
</table>

### Total Direct Cost

- Overhead charges: $18.56
- Overhead charges: $12.09

### Total Unit Cost

- $30.65

---

**Custom component for the original intake manifold**

---

### Assembly cost estimation

**For the PCV valve assy. of the redesigned intake manifold**

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Handling Time</th>
<th>Insertion Time</th>
<th>Total Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve</td>
<td>1</td>
<td>1.50</td>
<td>1.50</td>
<td>3.00</td>
</tr>
<tr>
<td>O-rings</td>
<td>2</td>
<td>2.25</td>
<td>4.00</td>
<td>12.50</td>
</tr>
<tr>
<td>Spring</td>
<td>1</td>
<td>2.25</td>
<td>6.00</td>
<td>8.25</td>
</tr>
<tr>
<td>Cover</td>
<td>1</td>
<td>1.95</td>
<td>6.00</td>
<td>7.95</td>
</tr>
<tr>
<td>Total Time</td>
<td></td>
<td></td>
<td></td>
<td>31.70</td>
</tr>
<tr>
<td>Assembly</td>
<td></td>
<td></td>
<td></td>
<td>$0.40</td>
</tr>
</tbody>
</table>
Redesigned intake manifold

<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 housing</td>
<td>3.85</td>
<td>1.56</td>
<td></td>
<td>5.41</td>
<td>350</td>
<td>1500</td>
<td>0.23</td>
<td>5.65</td>
</tr>
<tr>
<td>Intake runner insert</td>
<td>0.83</td>
<td>1.10</td>
<td>0.13</td>
<td>2.05</td>
<td>150</td>
<td>1500</td>
<td>0.10</td>
<td>2.15</td>
</tr>
<tr>
<td>Steel inserts (16)</td>
<td>0.32</td>
<td>1.00</td>
<td></td>
<td>1.32</td>
<td></td>
<td></td>
<td></td>
<td>1.32</td>
</tr>
<tr>
<td>ERG adapter</td>
<td>1.70</td>
<td></td>
<td>0.13</td>
<td>1.83</td>
<td></td>
<td></td>
<td></td>
<td>1.83</td>
</tr>
<tr>
<td>PCV valve</td>
<td>0.85</td>
<td></td>
<td>0.04</td>
<td>0.89</td>
<td></td>
<td></td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td>Valve</td>
<td>0.02</td>
<td>0.16</td>
<td></td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>O-rings (2)</td>
<td>0.08</td>
<td></td>
<td>0.10</td>
<td>0.18</td>
<td></td>
<td></td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>Spring</td>
<td>0.02</td>
<td></td>
<td>0.10</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
<td>0.12</td>
</tr>
<tr>
<td>Cover</td>
<td>0.04</td>
<td></td>
<td>0.06</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>Vacuum source block</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Direct Costs</td>
<td>7.71</td>
<td>2.66</td>
<td>1.71</td>
<td>12.08</td>
<td>500</td>
<td>0.33</td>
<td>9.52</td>
<td>21.93</td>
</tr>
<tr>
<td>Overhead Charges</td>
<td>1.16</td>
<td>4.79</td>
<td>3.08</td>
<td></td>
<td></td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>43% reduction of cost</td>
</tr>
</tbody>
</table>

If they sell 1 million cars, cost saving can be $16.58 million just from the manifold.

These were:
- 24.03
- 14.48
- 38.51

Exhibit 11-16
Cost estimate for the redesigned intake manifold.
“Design” applying the DFM principle

“Plot”
DFM vs MFD

**Design for Manufacturing, DFM**
Paradigm in 1990s
Cost reduction

- **Design**
  - Reduction of degree of freedom for design by limitation of manufacturing processes
  - Flat cellphone

- **Manufacturing**
  - Simple design with consideration of assembly
  - Back panel

**Manufacturing for Design, MFD**
(Design Realizing Manufacturing, DRM)
Emerging paradigm
High added-value

- **Design**
  - Increasing degree of freedom for design by expansion of manufacturing processes
  - Curved display design

- **Manufacturing**
  - Edge (Glass process)
  - Curved display

**Problems**
- Design and manufacturing processes focused on cost and productivity
- Limitation of material and its property

**High added-value**
How?
Hybrid processes
Expanding Manufacturing Domain