An Introduction to Design for Manufacture (DFM) and our core manufacturing processes:

- Plastic Molding
- Rapid Prototyping/3D Printing
- Sheet Metal
- Bar & Tube Fabrication
- Metal Casting
- Machining

Instructor: Mike L. Philpott
mphilpot@illinois.edu
Look at retail prices...divide by 3!
Design for Manufacture (DFM) Overview

- Product Development teams need to know cost early in design to do what-if analysis and explore alternative designs before expensive hard tooling decisions finalized.

- aPriori’s integrated CAD/DFM software utilizes 3D CAD’s mathematical definition of the part/assembly to provide instant cost estimates as you create geometry.

- Necessary today due to high overseas competition and overseas sourcing opportunities.

- Need to know early if cost targets are being met - redesign if necessary before it’s too late.
Design for Manufacture (DFM) Example

A simple fork end for Pneumatic Piston

Machine from Solid
Welded Assembly
Casting
Stock Channel
Sheet Metal
Injection Mold

$95 $75 $55 $25 $1.20 $0.30

Piece-part costs

$10 $100 $400 $8 $5,000 $60,000

Tooling costs

Production Volume: Recurring Costs versus Non-Recurring Costs
Design for Assembly (DFA)
Fewer Parts generally means lower overall mfg.cost

Number of Parts: 24  8  4  2
Assembly Time (s): 100  38  10  3
Feature Based Costing (FBC) Research

- CAD-integrated feature recognition and extraction methodology to provide engineers with accurate real-time cost feedback during design.

- Industry/University Collaborative research project: Started in 1992 with UIUC / John Deere Collaboration - now commercialized [www.aPriori.com](http://www.aPriori.com)

*aPriori*

1. Cost Scripting Language
2. Parameterized machine, material, tooling and labor Database

Optimum manufacturing sequence automatically derived from CAD Solid Model based on deterministic routing logic and Genetic Algorithms

## Cost Accounting

### Insights and Cost Reduction Opportunities

### Cost Statement - Calculated Results (one process, one part)

**Direct Variable Costs:**

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>Amount</th>
<th>Formula and Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Cost</td>
<td>$1.22</td>
<td>Part Weight * Raw Material Cost Per Kg / Material Utilization</td>
</tr>
<tr>
<td>Labor Cost</td>
<td>$0.36</td>
<td>Labor Time * Labor Rate</td>
</tr>
<tr>
<td>Direct Overhead</td>
<td>$0.47</td>
<td>Cycle Time * Labor Rate * Overhead Rate</td>
</tr>
</tbody>
</table>

**Subtotal**

| Amount | $6.00 |

**Expendable Tooling**

| Amount | $0.11 |

**Set-up costs**

| Amount | $0.27 |

**Additional Direct Costs**

| Amount | $0.00 |

**Other Direct Costs**

| Amount | $0.38 |

**Piece Part Cost**

| Amount | $6.38 |

**Direct Fixed Costs:**

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>Amount</th>
<th>Formula and Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Tooling</td>
<td>$3.00</td>
<td>CapitalTooling / (AmortizationVolume)</td>
</tr>
<tr>
<td>Fixtures and Jigs</td>
<td>$0.00</td>
<td>CapitalFixtures&amp;Jigs / (AmortizationVolume)</td>
</tr>
<tr>
<td>Programming Cost</td>
<td>$0.03</td>
<td>ProgrammingTime * LaborRate / (AmortizationVolume)</td>
</tr>
</tbody>
</table>

**Amortized Investment**

| Amount | $3.03 |

**Total Cost**

| Amount | $9.42 |

**Recommended Lowest Cost Process**

- If "Amortization Method" chosen: Total Cost $9.42
- If "Payback Method" chosen: Total Cost $13.96

**Amortization Volume**

\[ \text{Amortization Volume} = \text{Annual Production Volume} \times \text{NumberOfParts} \times \text{Product Life} = 5,000 \]
Plastic Molding

Injection Molding: Standard IM, Structural Foam Molding, Reaction Injection Molding (RIM)

KEY COST DRIVERS

- Wall Thickness (typical: 1-2mm)
- Undercuts - side Actions in the mold
- Number of cavities in the mold
Structural Foam Molding
Thick parts => ¼ inch (6mm)
Blow Molding and Rotational Molding

Blow molding
Bottles and small disposable containers

Rotational molding
larger hollow shapes.
Injection Molding

1. Mold Closes

2. Inject Plastic

3. Cooling

4. Mold Opens

Labor Cost = (Mold Close time + Injection Time + Cooling Time + Mold Open time) * $/hr rate
The Mold (Tooling)

Tooling Cost = Cost to design and build this mold tool
Moving Side Cores or ‘Slides’
Moving Internal Cores or ‘Lifters’
Avoiding Moving Side Cores and Lifters

(1) – allow feature to deflect as part is ejected from the mold
Avoiding Moving Side Cores and Lifters (2) – provide relief hole for core

Flat surface uniform in thickness

Core

Mold movement
Common Thermoplastic Materials (1)

Polyethylene - HDPE & LDPE (1.2¢/cu. in)
Lightweight, easy to process, low cost material. Poor dimensional stability and heat resistance. Excellent chemical resistance and electrical properties.

Polypropylene (1.5¢/cu. in): Outstanding resistance to flex and stress cracking. Excellent chemical resistance and electrical properties. Good impact strength above 15°F. Good thermal stability, light weight, low cost. Some grades can be electroplated.

Polystyrene (1.7¢/cu. in): Low cost, easy to process, rigid, crystal-clear, brittle. Low moisture absorption, and heat resistance. Poor outdoor stability.
<table>
<thead>
<tr>
<th>Resin Code</th>
<th>Technical Name</th>
<th>Typical Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>1</code> PETE</td>
<td>PETE, Polyethylene Terephthalate</td>
<td>soft drink bottles, deli trays, Mylar film, clear shampoo bottles, mouthwash bottles.</td>
</tr>
<tr>
<td><code>2</code> HDPE</td>
<td>HDPE, High-Density Polyethylene</td>
<td>Tupperware, milk jugs, dishwashing detergent containers, juice containers, opaque shampoo bottles, oven cleaner bottles, insecticide bottles, yogurt containers</td>
</tr>
<tr>
<td><code>3</code> PVC</td>
<td>PVC, Polyvinyl Chloride</td>
<td>plumbing pipes, construction materials, vinyl records, opaque shampoo bottles,</td>
</tr>
<tr>
<td><code>4</code> LDPE</td>
<td>LDPE, Low-Density Polyethylene</td>
<td>grocery bags, dry cleaning bags, aquarium tubing.</td>
</tr>
<tr>
<td><code>5</code> PP</td>
<td>PP, Polypropylene</td>
<td>appliance parts, Tic Tac hinge lids, drinking glasses, mustard squeeze bottles, margarine containers, pudding containers</td>
</tr>
<tr>
<td><code>6</code> PS</td>
<td>PS, Polystyrene</td>
<td>styrofoam cups.</td>
</tr>
<tr>
<td>OTHER</td>
<td>Other plastics, including acrylic, polycarbonate, nylon, Kevlar, fiberglass.</td>
<td>compact discs, DVDs.</td>
</tr>
</tbody>
</table>
Common Thermoplastic Materials (2)

PVC (2.2¢/cu. in): Rigid grades are hard, tough, and have excellent electrical properties, outdoor stability, and resistance to moisture and chemicals. Flexible grades are easier to process but have lower properties. Heat resistance is low, and low cost.


Common Thermoplastic Materials (3)

PETE (4.9¢/cu. in)
Crystal clear and hard. Used widely for shampoo bottles. Good moisture, and chemical resistance. Good dimensional stability.

Acetal (5.8¢/cu. in)

Polyurethane (6.1¢/cu. in)
Tough, extremely abrasion and impact-resistant. Good electrical properties and chemical resistance. UV exposure causes brittleness, lower properties, and yellowing.
Common Thermoplastic Materials (4)

Nylon (6/6-5.9¢/cu. in; 6/12 - 9.0¢/cu. in; +glass -16.3¢/cu. in): Family with outstanding toughness and wear resistance. Low Coefficient of Friction. Excellent chemical resistance and electrical properties. Hygroscopic; dimensional stability is poor. Some grades are electroplatable.


Fluoroplastics (30 - 65¢/cu. in): PTFE, FEP, PVDF etc. Family of high cost, low-to-moderate strength. Excellent chemical resistance. Low Friction. Outstanding stability at high temperatures.
Sheet Metal Process Group
Sheet Metal – Common Production Processes

**Soft Tooling** - general purpose programmable machines with low-cost expendable tooling

Typical Routings: (as in aPriori)

Sheet Stock $\rightarrow$ Laser cut $\rightarrow$ [Bend Brake]
Sheet Stock $\rightarrow$ Plasma cut $\rightarrow$ [Bend Brake]
Sheet Stock $\rightarrow$ Water Jet $\rightarrow$ [Bend Brake]
Sheet Stock $\rightarrow$ Turret Press $\rightarrow$ [Bend Brake]

**Hard Tooling (aka Stamping)** - Processes requiring custom made high-cost molds or die sets

Production Rate

Sheet Stock $\rightarrow$ Standard Press
Sheet Stock $\rightarrow$ Stage Tooling (aka Tandem die)
Sheet Stock $\rightarrow$ Transfer Press
Coil Stock $\rightarrow$ Progressive Die

Large Stampings (eg car Body Panels)
Small Stampings
Laser Cutting
Bend Brake Process

‘Soft Tooling’ for straight bends – No Custom Tooling (ie no Hard Tooling)

Bend Brake (aka Press Brake)
Turret Press Process

‘Soft Tooling’ for straight bends – No Custom Tooling (ie no Hard Tooling)
Bend Brake – safety!
Sheet Metal – Common Production Processes

**Soft Tooling** - general purpose programmable machines with low-cost expendable tooling

*Typical Routings: (as in aPriori)*

- Sheet Stock ➔ Laser cut ➔ [Bend Brake]
- Sheet Stock ➔ Plasma cut ➔ [Bend Brake]
- Sheet Stock ➔ Oxy Fuel ➔ [Bend Brake]
- Sheet Stock ➔ Turret Press ➔ [Bend Brake]

**Hard Tooling (aka Stamping)** - Processes requiring custom made high-cost molds or die sets

*Production Rate*

- Sheet Stock ➔ Standard Press
- Sheet Stock ➔ Stage Tooling (aka Tandem die) Large Stampings (eg car Body Panels)
- Sheet Stock ➔ Transfer Press
- Coil Stock ➔ Progressive Die Small Stampings
**Progressive Die** – coil fed, automatic, high-speed single press with multiple stations; coil strip transfers the part
Progressive Die Tool – a tool custom designed and built to produce stamped metal parts at high speed on a Progressive Die Press (a reciprocating press)
Progressive Die in Operation – 30 ppm
Progressive Die in Operation – 100 ppm

Used for Small High-Volume Stampings
Stamping Die (i.e. Tooling) Example

- Stock Lifter
- Stamp Retainer (stamp not shown)
- Stock Guide
- Guide Pin (with cage bearing)
- Trim Die Block/Steel
- Lower Adaptor (was Die Block Holder)
- Lower Die Shoe
- Bottom Plate
- Bottom Parallels
**Standard Press** - manual presses operated in batch mode, typically low-to-medium volume applications
Stage Tooling – manual presses organized in a production line with manual transfer of parts between presses (popular in low labor cost countries, non-automotive)
Manual Transfer inside a Press!
Tandem Die - manual or automatic presses organized in a production line
manual or robotic transfer of parts between presses (often a mix of manual or
robotic)
Transfer Press – sheet fed, single press action with multiple dies attached to platen and transfer mechanism
Transfer Press in Operation

Used for Large High-Volume Stampings
Rapid Prototyping Principles

SLA

3D Printing

SLS
Rapid Prototyping Systems

- StereoLithography (STL)
- Selective Laser Sintering (SLS)
- Fused Deposition Modeling (FDM)
- Polyjet - 3D Printer
- Composite 3D printer
- Direct Metal Laser Sintering (DMLS) – on order
- Laminated Object Manufacturing
- Hot Plot
- Solid Ground Curing
- Light Sculpting
- Solid Creation System
- Solid Object Ultra-Violet Laser Plotting
- Computer Operated Laser Active Modeling
- Electro-Optical Systems - Stereos
Rapid Prototyping at BMW

Cool video (click on pics)
Rapid Prototyping
MechSE Ford Lab
Meet the Mark One: the world's first Carbon Fiber 3D printer...
Stereo-Lithography Apparatus (SLA)
Polyjet Process
SLS - Sintered Laser System
EOS – Direct Metal Laser Sintering
3D Scanning & FDM – Fused Deposition Modeling
**STL Format: B-rep, solid object**

- An STL file is saved with the extension "*.stl," case-insensitive.

- STL is a triangular facet based representation that approximates surface and solid entities only. Entities such as points, lines, curves, and attributes such as layer and color will be ignored during the output process.

- An STL file consists of a list of facet data.

- Each facet is uniquely identified by a unit normal (a line perpendicular to the triangle and with a length of 1.0) and by three vertices (corners).

- The normal and each vertex are specified by three coordinates each, so there is a total of 12 numbers stored for each facet.
BLOCK

facet normal 0.000000e+00 -1.000000e+00 0.000000e+00
outer loop
vertex 0.000000e+00 0.000000e+00 0.000000e+00
vertex 1.000000e+00 0.000000e+00 0.000000e+00
vertex 0.000000e+00 0.000000e+00 0.000000e+00
endloop
endfacet

facet normal 0.000000e+00 0.000000e+00 -1.000000e+00
outer loop
vertex 1.000000e+00 0.000000e+00 0.000000e+00
vertex 0.000000e+00 0.000000e+00 0.000000e+00
vertex 1.000000e+00 0.000000e+00 -1.000000e+00
endloop
endfacet

facet normal 0.000000e+00 0.000000e+00 0.000000e+00
outer loop
vertex 0.000000e+00 0.000000e+00 0.000000e+00
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vertex 0.000000e+00 0.000000e+00 0.000000e+00
endloop
endfacet

facets normal 1.000000e+00 0.000000e+00 0.000000e+00
outer loop
vertex 1.000000e+00 1.000000e+00 0.000000e+00
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facet normal 0.000000e+00 0.000000e+00 0.000000e+00
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vertex 0.000000e+00 -1.000000e+00 0.000000e+00
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endfacet

endfacet

endfacet

endfacet

endfacet

endfacet

endsolid BLOCK

An Example

STL File – Block.stl
The density of triangle facets change according to the geometry.

And it Changes with Chord Height affecting final surface resolution.
Bar and Tube Process Group
Tube/Bar Bending Processes
Bend Brake (aka Press Brake)

Not suitable for Tube, only solid bar forms
Rotary Draw Bending with Mandrel

Reduces crushing of inner bend radius
High Speed Wire Forming

For more info go to www.AlMmachines.com
Tube Laser Process
Rectangular/Square Tube
laser cut hand bending
Rectangular/Square Tube
Laser Cut - Creative Weldless Connections
Punching Process
Tube Punching
Punching Process
Bar Punching
End Forming Processes

Reduction

Expansion

Chamfering

Flaring

Flanging

Flattening

Forming

Slotting

Notching
End Forming Video
Circular Sawing Video
Multiple Parts - Bundling
Tube/Bar Bending Processes
Compression/Ram Bending
Primary Metal Casting Processes

1. Die Casting
2. Sand Casting
3. Permanent Mold Casting
4. Investment Casting
Die Casting

A non-ferrous metal is injected into a metal mold cavity under high pressure

- Pressure is maintained during solidification, then mold is opened and part is removed, often by robotic manipulator
- Use of high pressure to force metal into die cavity achieves high production rates

Die Casting Animation Video Clip
Sand Casting – Patterns required

Pattern – a model of the part, slightly *enlarged to account for shrinkage and machining allowances*

Types of patterns used in sand casting:
(a) solid pattern, (b) split pattern, (c) match-plate pattern (d) cope and drag pattern
Urbana Courthouse Clock Tower Renovation - 2009
Seth Thomas Mechanical Clock - 1876

1883 Buckeye Bell
Foundry Bell and Hammer

Dial with Drive, minute balance weight, insulated drive shaft

Four Way Gearing to Drive the hands on the Four Dials

Gears of the Striking Train

Restoration: 2002 - 2009
Horizontal Automatic Sand Casting

- Vertical or Horizontal Mold Making Machines
  - 200 to 600 parts/hr
  - Patterns and cores placed in by robotic device

Horizontal Molding Machine video
Investment Casting (Lost Wax Process)

A pattern made of wax is coated with a refractory material to make mold, after which wax is melted away prior to pouring molten metal.

- "Investment" comes from a less familiar definition of "invest" - "to cover completely," which refers to coating of refractory material around wax pattern.

- It is a precision casting process - capable of producing castings of high accuracy and intricate detail.

Lost Wax Video
Permanent Mold Casting
Product Design Considerations

1. Geometric simplicity that allows for shrinkage and reduces the need for cores.

2. Reduce sharp angles by rounding corners and reducing stress concentrations areas that may cause hot tearing and cracks.

3. Increase draft angles (interior and exterior).

   Minimums:
   - Draft = 1° for sand casting
   - Draft = 2° to 3° for permanent mold processes
Draft

• Minor changes in part design can reduce need for coring

Design change to eliminate the need for using a core: (a) original design, and (b) redesign.
4. Dimensional Tolerances and Surface Finish:
   - Sand casting: poor dimensional accuracies and finish
   - Die casting and investment casting: better dimensional accuracies and finish

5. Machining Allowances:
   - Additional material, called the *machining allowance*, is left on the casting in those surfaces where machining is necessary
Introduction to Machining
Common Machining Operations

(a) Straight turning
(b) Cutting off
(c) Slab milling
(d) End milling

Aka: Material Removal Processes
Really Big “Engine” Lathes

www.practicalmachinist.com
CNC Lathe: aka “Turning Center”
(carriage is mounted toward back, “upside down”)

CNC = Computer Numerical Control (features are machined to size and location by a computer)
CNC MILL or “Machining Center”

Links:
CNC machining engine block from solid
Milling an Impeller