Let’s talk about how to build stuff
mockup → prototype → mass production

Bert Bras,
Craig Forest,
Dirk Schaeffer

References:
Product design for manufacture and assembly (G. Boothroyd et al. (Dekker 1994)
Boothroyd and Dewhurst
Kalpakjian, Manufacturing Engineering and Technology
Ullman, The Mechanical Design Process
ME 2110 – Design for Assembly & Manufacturing
SAFETY FIRST!!

• Whatever you do, please do it safely!
  – In case of doubt, don’t do it.

• Adhere to safety rules and policies of Invention Studio, School, College, Institute, State, etc.

• Machines can kill

Michele Dufault
## Some Typical Models Used In Development

<table>
<thead>
<tr>
<th>Phase</th>
<th>Physical (form and function)</th>
<th>Analytical (mainly function)</th>
<th>Graphical (traditional) (mainly form)</th>
<th>Graphical (CAD) (form and function)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concept</strong></td>
<td>Proof-of-concept prototype</td>
<td>Back-of-the-envelope analysis</td>
<td>Sketches</td>
<td>Hand sketches and solid models</td>
</tr>
<tr>
<td><strong>Design</strong></td>
<td>Proof-of-product prototype</td>
<td>Engineering science analysis</td>
<td>Layout drawings</td>
<td></td>
</tr>
<tr>
<td><strong>Final Product</strong></td>
<td>Proof-of-process and proof-of-production prototypes</td>
<td>FEA and detailed simulation</td>
<td>Detail and assembly drawings</td>
<td>Solid Models</td>
</tr>
</tbody>
</table>
Iterative Process

- Design
- Build
- Test

Advantages?
Drawbacks?
Mock Up
Mock up:

• What’s the point?
  – To physically represent your design, 1:1
  – To check the size, shape, proportions, fit of things
  – To test your most critical module

• Time
  – Days

• Volume
  – 1-3

• Cost
  – Free to $100
Other Real World Uses

• Facilitate brainstorming among design team

• Sell your idea
  – Management
  – Investors

• Obtain Feedback for Modifications
  – Customers, Focus Groups, Experts
Mock up Materials –
Must be Cheap & Easily Accessible

- Foam
- Cardboard
- Wood: 2x4, popsicle sticks,…
- Adhesives: tape, glue, epoxy, urethanes
- Fasteners: screws, clips, bolts, pins, zipties
- Legos, playdo, erector set
- Sheet metal (folded, bent, twisted)
- Stock parts (e.g., LEDs, molded handles)
Mock up Manufacturing Processes –
Simple, easy, low cost (DIY)

• Cutting (e.g., scissors, diagonal cutters, snips)
• Sawing (e.g., bandsaw, jigsaw, hacksaw)
• Painting
• Filing
• Molding (incl. clay)
• Drilling (hand tools)
• Grinding, sanding
• Machining
Prototype
Prototype (≠ Mock Up)

• Why?
  – To demonstrate full functionality (engineering)
  – To physically convey the product to the consumer, investor, patent attorney, yourself
  – Test to the fullest extent possible the colors, shapes, textures, weight (industrial design)

• Time
  – Week – Months

• Volume
  – 1-100

• Cost
  – $10 to $10,000 for most products

Remember: You prototype the design! (You do NOT design the prototype)
Prototype manufacturing processes

- **Metal**
  - Band saw
  - Drill press
  - Mill
  - Lathe
  - Grinder
  - Waterjet
  - 3-D printing (laser sintering)
  - Welding
  - Casting
  - Electrical discharge machining
  - Sheet metal forming (shear, brake, corner press)

- **Polymers**
  - 3-D printing
  - Injection molding
  - Thermoforming
  - Laser cutting
  - Casting
  - Band saw
  - Drill press
  - Mill
  - Lathe
  - Waterjet

- **Ceramics**
  - Molded and bakes, sintered

- **Composites**
  - Layups
Invention Studio Prototype

Costs

Use the resources …

Laser Cutter

Water Jet

3D Printing

Machine Tools

But use the right resource

http://inventionstudiowiki.gatech.edu/wiki/Main_Page
Waterjet

Figure 1a schematic of abrasive jet

http://en.wikipedia.org/wiki/Water_jet_cutter
http://web.mit.edu/2.972/www/reports/abrasive_water_jet/abrasive_waterjet.html
http://www.omax.com
https://www.youtube.com/watch?v=zwJMHwTqOUA
https://youtu.be/3o6i9FTizuY
Laser cutting

100 µm laser spot size
200 µm hole diameter

75W CO₂ laser
Trotec Speedy 100
Electrical discharge machining

Wire as small as 30 µm!

MS Thesis MIT 2003, Tim Fofonoff

http://www.engineersedge.com/edm.shtml
3D printing

Layer by layer additive process

Fig. 1. Stereolithography.

From Computer Desktop Encyclopedia

http://home.att.net/~castleisland/sl.htm
http://common.ziffdavisinternet.com/encyclopedia_images/_3DPCOLR.JPG
http://www.archinect.com/schoolblog/entry.php?id=34570_0_39_0_C
Invention Studio 3D Rapid Prototyping Printing (Layer Based Manufacturing)
• Melt workpieces and add filler
• Energy comes from gas flame, an electric arc, a laser, an electron beam, friction, and ultrasound
  – Easiest diy welding: MIG (Metal Inert Gas)

Oxyacetylene (3100°C)
  -most common
  -cheap equipment
Casting
Machining
Machining

- width of cut <= tool diameter, ~0.75 tool dia. in most cases
- depth of cut
- chips
- workpiece moves and tool is stationary.

Grinding wheel
- work piece
- coolant
- table

Twist drill
- work piece
- helical chip

Elastic plastic boundary
- neutral axis
- workpiece movement

Vchip
- tool

Chip

http://www.efunda.com/processes/machining/machin_intro.cfm
Design rules for machining

Standardization

1. Utilize standard components as much as possible
2. Preshape the component, if appropriate, by casting, forging, welding, etc
3. Utilize standard pre-shaped workpieces if possible
4. Employ standard machined features whenever possible.
Design rules for machining

Raw Material

1. Choose raw material that results in minimum component cost (raw material + machining)
2. Utilize raw material in the standard forms supplied
Component design for machining

Generally

1. Strive for machining using 1 machine tool
2. Strive to minimizing fixturing
3. Sufficient rigidity when fixtured for machining
4. No interference between tool, toolholder, workpiece, fixture
5. Holes cylindrical, straight and with standard L/D for drilling or boring, normal to part axes
6. Blind holes conical, tapping blind hole considered
Component design for machining

Rotational components

1. Cylinders concentric, plane surfaces normal to axes
2. External diameters increase from outer face
3. Internal diameter decrease from outer face

4. For internal corners, use standard radii
5. Avoid internal features for long components
Component design for machining

Non-rotational components

1. Provide base for fixturing/referencing
2. Prefer faces perpendicular/parallel to base
3. Use standard radii, large radii for internal features
4. Diameters decrease inside the part
Accuracy and surface finish

- Specify **widest** tolerances possible
- Specify **roughest** surfaces possible
- Avoid internal corners on low roughness surfaces
Sheet Metal Forming
Sheet metal forming

FIG. 9.21 Shearing operation.

Shearing

FIG. 9.22 Wiper die bending operation.

Bending

drawing
• Name 5 sheet metal formed parts

• What materials are used

• What can go wrong when sheet metal forming?
Sheet metal forming

**FIG. 9.14** Basic bending tools (a) v-die. (b) Wiper die.

**FIG. 9.15** Basic methods of producing multiple bends. (a) u-die. (b) z-die.

**FIG. 9.16** Multiple bends produced in one die.
Sheet metal forming

FIG. 9.5  Die elements of cut-off and part-off dies. (a) Cut-off die. (b) Part-off die.

FIG. 9.6  Blanking die.
Sheet metal forming

**FIG. 9.18** Wiper-die arrangement to produce bend b in Fig. 9.17.

**FIG. 9.17** Part design requiring two bending dies.
Sheet metal forming

shearing

\[ F = 0.7TL(UTS) \]

\[ T = \text{sheet thickness} \]

\[ L = \text{total length sheared} \]

UTS = ultimate tensile strength

bending

\[ F = \frac{WT^2}{L} (UTS) \]

\[ W = \text{width bent} \]

\[ T = \text{sheet thickness} \]

\[ L = \text{length bent} \]
Design rules

- Outer profile with parallel edges defining part width
- Angles $> 15^\circ$

Features a-e
$>2x$ thickness

Relief cutout

FIG. 9.27 Critical dimensions in the design of a sheet metal blank.
Design rules

FIG. 9.32 Punched slots adjacent to a bend.
Design rules

Minimize waste

FIG. 9.33 Design changes of a three-hole bracket for minimization of manufactured scrap.
Assembly & Design for Assembly (DFA)

Also look at
ME 2110 DFX Lecture materials
Let’s talk about assembly
• Assembly costs are 25-50% of mfg costs
• % workers doing assembly is 20-60%

This is a big $$$ deal!!!
Typical Assembly Operations

- Storing
- Handling
  - Identifying, Picking-Up, Moving
- Positioning
  - Orientating, Aligning
- Joining
- Adjusting
- Securing
- Inspecting

Operations can be done:
- Manually
- Automated
  - High-speed automated assembly
  - Robotic assembly
- Both
History lesson

• 1\textsuperscript{st} complex assembly mfg tasks
  – Muskets in 1700’s

• Interchangeable parts in early 1800’s

John Hall’s breech design demonstrated interchangeability at Harper’s Ferry in 1827
Complex products required more assembly

>1,000 parts
The Pratt & Whitney F100 military engine powered the F-15 and the F-16. 

Credits - Credit to Pratt & Whitney: A United Technologies Company

>10,000 parts

Airbus A380 for 853 people

>100,000 parts
Assembly line - Henry Ford

The old fashioned way - limousines are assembled at individual stations by a Pittsburg manufacturer, 1912

End of the Line. The Model T's body is joined to its chassis at the Highland Park plant

Trained workers put together the flywheel - magneto ignition system for the Model T - 1913
Requirements

• Work design (balance steps, ergonomics)

• Design for assembly

• Interchangeable parts
Standardize!

- Standardization of operations, tools and parts
  - Use existing equipment and tools
  - Use standard tools
  - Use standard parts
Assembly Workers & Processes

• Avoid special training of assembly staff
• Maintain safe working conditions
• Observe ergonomic standards
Questions Raised During DFA

• Is it possible to eliminate part of the process?
  – Can the product be assembled if the part is integrated with another part?
• What is the cost to correctly orient and position a part?
• What does it cost to complete the assembly of the part?
Impact of good DFA

FIG. 1.15 Reticle assembly—original design. (Courtesy Texas Instruments, Inc.)

FIG. 1.15 Reticle assembly—new design. (Courtesy Texas Instruments, Inc.)
Design for Manual Assembly Rules

1. Reduce part count and part types
2. Strive to eliminate adjustments
3. Design parts to be self-aligning and self-locating
4. Ensure adequate access and unrestricted vision
5. Ensure the ease of handling of parts from bulk
6. Minimize the need for reorientations during assembly
7. Design parts that cannot be installed incorrectly
8. Maximize part symmetry if possible or make parts obviously asymmetrical
8. Maximize part symmetry if possible or make parts obviously asymmetrical

(a) asymmetric
(b) slightly asymmetric
(c) will jam
(d) will tangle

(symmetrically)
(pronounced asymmetrically)
(cannot jam)
(cannot tangle)
Additional features that affect part handling

FIG. 3.2 Some other features affecting part handling.
3 - Design parts to be self-aligning and self-locating

No Chamfers

Bottom Part Chamfered

Top Part Chamfered

Both Parts Chamfered

Better
Insertion issues

FIG. 3.3 Incorrect geometry can allow part to jam during insertion.
Insertion issues

FIG. 3.4 Provision of air-relief passages to improve insertion into blind holes.
Insertion issues

**FIG. 3.5** Design for ease of insertion—assembly of long stepped bushing into counterbored hole.
Insertion issues

FIG. 3.6 Provision of chamfers to allow easy insertion.
Standardization of Parts

FIG. 3.7 Standardize parts.
FIG. 3.8 Single-axis pyramid assemb

FIG. 3.10 Design to aid insertion.
FIG. 3.11 Common fastening methods.
FIG. 3.31 Effect of number of threads on time to pick up the tool, engage the screw, tighten the screw, and replace the tool.
FIG. 3.32 Effect of obstructed access on time to tighten a nut.
Design for high-speed automated assembly

- **Automatic part handling**
  - Be easily separated from bulk
  - Be easily conveyed along the track of a vibratory or hopper feeder
  - Be readily oriented in high speed feeding device

- **Automatic insertion**
  - Avoid need to reorient during assembly
  - Parts not secured immediately on insertion are fully located
  - Easily aligned (e.g., leads lips, tapers chamfers)
  - Layered fashion assembly from above
  - Avoid high insertion forces
Design for robotic assembly

Although design for assembly is an important consideration for manually assembled products and can reap enormous benefits, it is vital when a product is to be assembled automatically. The simple example shown in Fig. 5.1 illustrates

asymmetrical - difficult to orient
symmetrical - easy to orient
difficult to feed - parts overlap

easy to feed

Old design

New design

Sharp corners
Difficult to assemble

Radii
Easy to assemble
FIG. 5.17 The use of tapered pegs to facilitate assembly.
FIG. 5.18 Examples of redesign to prevent nesting or tangling. (From Ref. 5.)
FIG. 5.20 Less obvious example of a design change to simplify feeding and orienting.
Design for service

• Repair (you will be doing this a lot)
  – Elements most likely to need service located at outer layers of the product
Design for Disassembly

- Reduce # of components
- Reduce # of separate fasteners
- Provide open access and visibility for separation points
- Avoid orientation changes during disassembly
- Avoid non-rigid parts
- Use common tools and equipment
- Design for ease of handling and cleaning of all components
- Reduce number of different materials
- Enable simultaneous separation and disassembly
- Facilitate the sorting of non-compatible materials
What are the reasons for having 2 separate parts in a design?
What are the reasons for having 2 separate parts in a design?

1. Does the part move relative to all other parts already assembled?
2. Must the part be of a different material?
3. Assembly/Dissassembly?
Assembly of injection molded parts

- **Press fit**
  - Takes advantage of loose tolerances of molded parts
- **Riveting/staking**
  - Heated form tool melts part locally
- **Ultrasonic welding**

- **Snap fits**

FIG. 8.12 Ultrasonic welding joint design by Du Pont.
Impact of good DFA

FIG. 1.15 Reticle assembly—new design. (Courtesy Texas Instruments, Inc.)
Some products are still difficult to make with interchangeable parts

Grinding capability
\[
\frac{0.001}{10} = 10^{-4}
\]

Aerospace requirement
\[
\frac{0.003}{25 \times 12} = 10^{-5}
\]

Thermal expansion
\[
\Delta L = L\alpha\Delta T = (25 \times 12)(13 \times 10^{-6})(2) = 0.01
\]
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Remember: You prototype the design! (You do NOT design the prototype)