Design for Manufacturing, Assembly, and Reliability

Module 3D Design for Manufacturing and Assembly

Motivation

Why is this module important?

- Design for manufacturing and assembly (DFMA) can determine how much you pay for production tooling and how much it costs to assemble your product
- DFMA can affect:
  - —Manufacturing cost and quality
  - —Production cycle time-and-fixture costs
  - —Production and supply-chain complexity
  - —Production personnel morale
- Design your product using DFMA guidelines, or you will have to make costly changes later and/or deal with the implications of negative quality

Module Outline

- Learning objectives
- Design for manufacturing (DFM)
  - —Casting and molding
  - —Machining
  - —General rules
- Design for assembly (DFA)
  - —Role of assembly in manufacturing
  - —General assembly guidelines
  - —Boothroyd and Dewhurst methods
  - —Design implications of assembly decisions

Learning Objectives

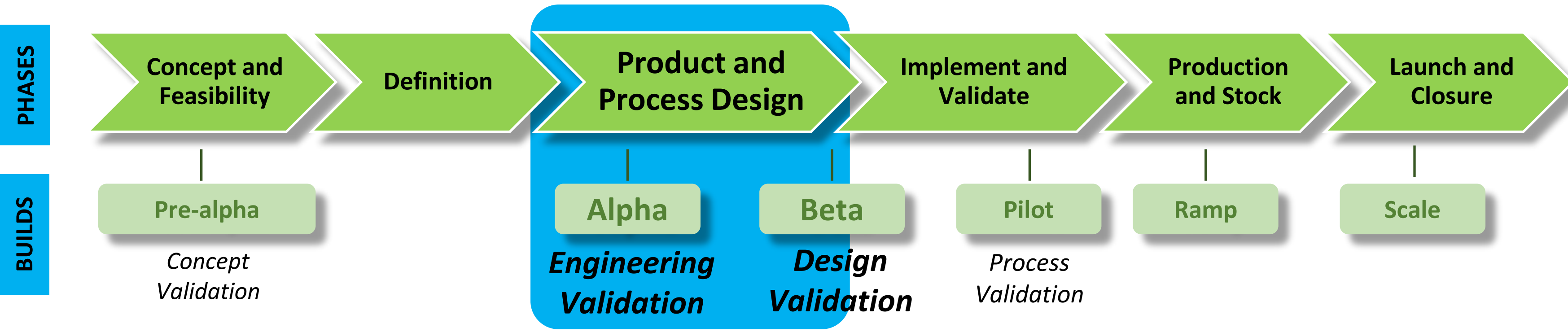
- LO1. Understand general design for manufacturing guidelines for various processes
- LO2. Compare alternative designs to assess the manufacturing cost and complexity
- LO3. Identify opportunities to reduce assembly cost and complexity

What This Module Addresses

- Key DFM considerations to keep in mind for various manufacturing processes
- Key considerations for DFA
- An example of how to assess an assembly to see if assembly cost and complexity can be reduced

Design For Manufacturing

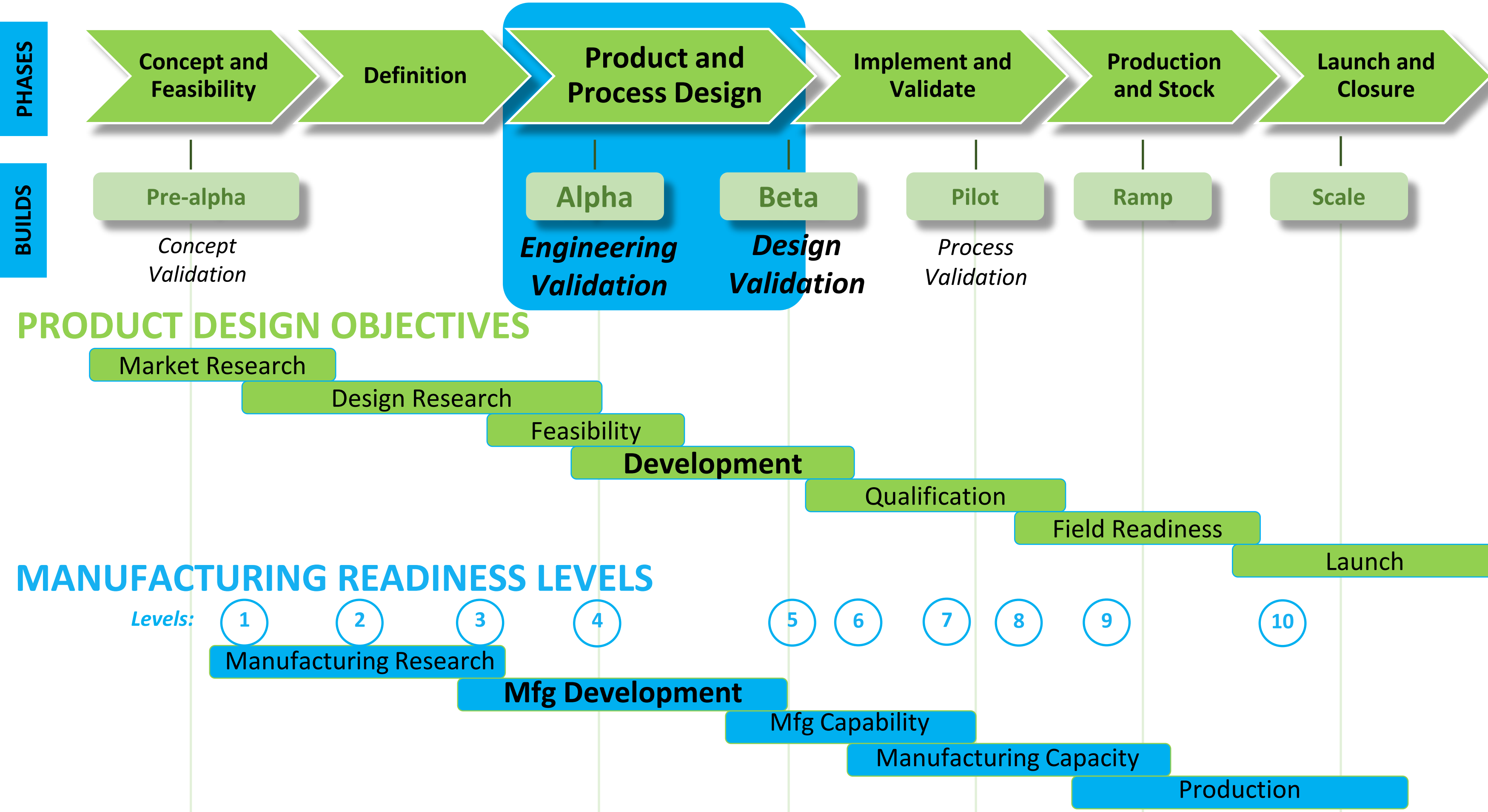
Where does this fit into the development cycle?



- DFMA is part of the detailed design process
- Ensuring that your parts can be manufactured and assembled at high quality and low cost may require some iterative design
- How you assembly your parts and the designs used to assembly them will affect your bill of materials (BOM) and bill of process (BOP)

Design For Manufacturing

Where does this fit into the development cycle?



Design For Manufacturing

Basics

- **Design for manufacturing** (DFM) can be used to increase product quality, increase production volumes, and/or decrease costs
  - —This is accomplished through the use of design best practices (i.e., designing parts to work well for the intended process)
- Once a material and manufacturing process are selected, apply the appropriate best practices
  - —Best practices may be in conflict with design requirements
  - —Best practices may be in conflict with other DFM practices
  - —When there are conflicts, it is important to look at what is the most pressing customer or market requirement

Casting And Molding

What is is and when to use it

- **Casting** is a process in which a liquid metal is delivered into a hollow cavity mold. This is used for making complex shapes that would be difficult or uneconomical to make by other methods.
- Traditional techniques include lost-wax casting (which may be further divided into centrifuge casting and vacuum assist direct pour casting), plaster mold casting and sand casting

The casting process is subdivided into two main categories:

- **Expendable** involves the use of temporary, non-reusable molds. and non-expendable casting.
- **Non-expendable mold** need not be reformed after each production cycle. This technique includes at least four different methods: permanent, die, centrifugal, and continuous casting.

Source: Wikipedia

Casting And Molding

What is is and when to use it (cont.)

- **Sand Casting** allows for smaller batches than permanent mold casting and at a very reasonable cost and is unsurpassed for large-part production.
- **Shell Molding** is a form of sandcasting using a finer mixed with a resin so that it can be heated and hardened into pattern. This process is ideal for complex items that are small to medium-sized.
- **Investment Casting** (known as lost wax-casting) can be an expensive process, however, may produce intricate contours, and near net shape, requiring little or no rework once cast.
- **Plaster Mold Casting** generally takes less than a week to prepare, after which a production rate of 1–10 units/hr mold is achieved. The biggest disadvantage is that it can only be used with low melting point non-ferrous materials

Source: modified from Wikipedia

Casting And Molding

Most common defect

When two or more sections conjoin, mechanical weakness is induced at the junction interrupting free cooling

- Replace sharp edges with radii & minimize heat and stress concentration
- In cored parts avoid designs without cooling surfaces
- A rounded junction offers more uniform distribution of strength

Source: Design for Cast and Molded Parts: Bertcher, Brod, Lee, Wehr
http://slideplayer.com/slide/3368211/

Casting And Molding

Process design guidelines

Basic Design Guidelines:

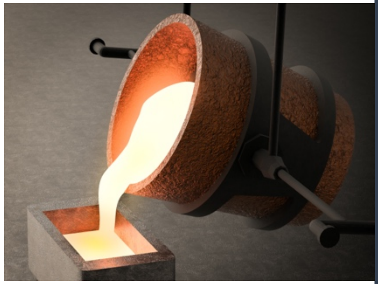
- Visualize the Casting
- Deign for Soundness
- Avoid Sharp Angles & Corners
- Employ Uniform Sections
- Correctly Proportion Inner Walls
- Fillet All Sharp Angles
- Avoid Abrupt Section Changes
- Maximize Design of Ribs and Brackets

Source: Design for Cast and Molded Parts: Bertcher, Brod, Lee, Wehr
http://slideplayer.com/slide/3368211/

Casting And Molding

Process design guidelines (cont.)

- Casting and molding processes depend on the flow and solidification characteristics of various material in their molten states
- Use uniform wall thicknesses whenever possible
  - —This allows for uniform cooling of the part
  - —In some casting operations, thinner part walls for interior features are preferable
- Where possible, make parts thinner and use ribs for rigidity
  - —This will not only make the part lighter but also helps minimize part shrinkage (see example percentages)



Casting And Molding

Process design guidelines (cont.)

- Material will shrink as it cools (account for this change during the design phase)

Metal	Shrinkage (%)
Aluminum	6.6
Copper	4.9
Magnesium	4.0 or 4.2
Zinc	3.7 or 6.5
Low carbon steel	2.5 - 3.0
High carbon steel	4.0
White cast iron	4.0 – 5.5
Gray cast iron	-2.5 - 1.6
Ductile cast iron	-4.5 - 2.7

Casting And Molding

Process design guidelines (cont.)

- Use inserts for a family of parts (i.e., parts with similar shapes)
  - —An insert can be used to change specific features of a part; the whole tool does not need to be altered
- Use a simple parting line
  - —Where two mold sides come together is the parting line
  - —Simple parting lines reduce tool cost/time and increase quality

Casting And Molding

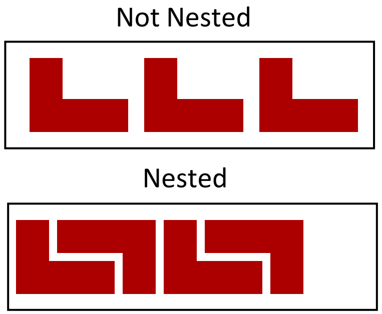
Process design guidelines (cont.)

- Tapering parts allows them to be easily removed from mold
- Surface quality has significant cost implications
  - —Leave ample room for machining operations
  - —Choose the roughest possible surface finish to reduce cost

Forming And Shaping

Basics

- Most forming processes start with a sheet of material
  - —Minimize scrap by nesting components on the sheet's surface
- Part complexity, material strength, and thickness determine the amount of force necessary for forming and shaping
  - —Complex parts requiring a lot of material separation require a lot of pressure
  - —Complex parts may also require a lot of steps or progressive forming operations

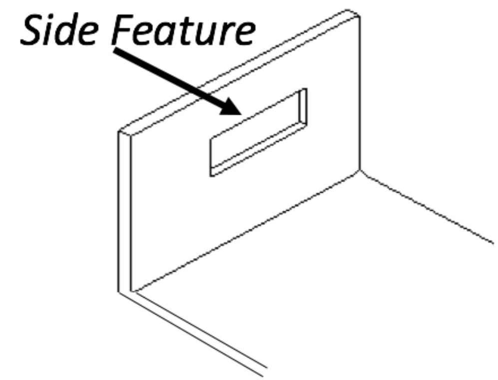


Video: Forming metal stock and sheet metal on hydraulic press (mouse-over image to view)

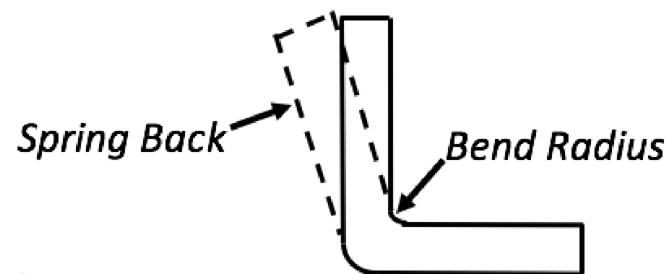
Forming And Shaping

Process design guidelines

- Sheet metal forming and shaping operations
  - —Avoid closely spaced features
  - —Configure wide tolerances for side features



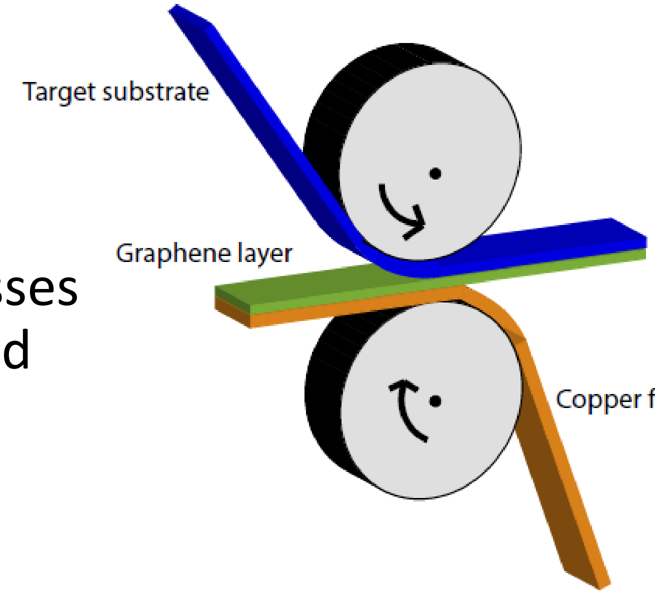
- Springback and bend radii are key considerations for forming and shaping operations
  - —Highly material dependent
  - —Aluminum can have a near-zero bend radius
  - —Hardened steel requires several times the material thickness for bend radii



Forming And Shaping

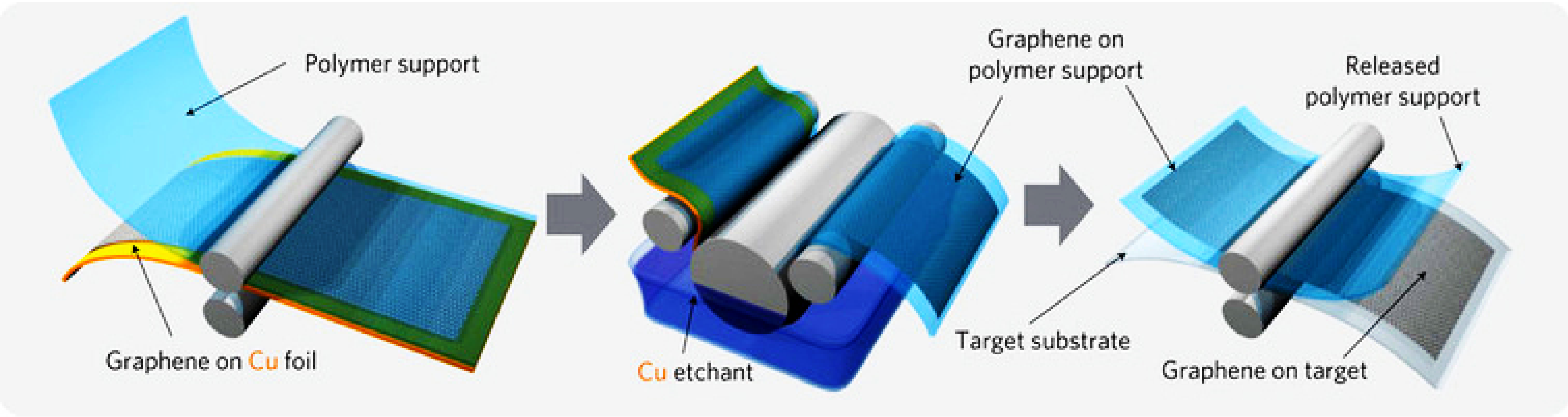
Roll-to-roll

- Roll-to-roll processes are used to make continuous products
- These products can be films, textiles, or other materials
- Keep tolerances as wide as possible (Tight tolerances on large rolls can be expensive)
- Try to combine functions and processes for efficiency (This enables minimized roll and unroll processes)



Forming And Shaping

Example - Roll-to-roll



- Roll-to-roll production of graphene films for transparent electrodes

Machining

Casting and machining versus machining

- Near-net-shape material reduces costs
- Casting may be more expensive initially, but can reduce overall cost
- Forged components can also be produced near the net necessary shape

Note: Casting does not allow for tight tolerances/detail so you cast extra material and then machine out the detail. The trade-off is that casting is usually a separate company with margin needs then marked up by machining company along with time in transit and coordination.

Machining Process Guidelines

Process design guidelines

Use the softest material that will meet your needs:

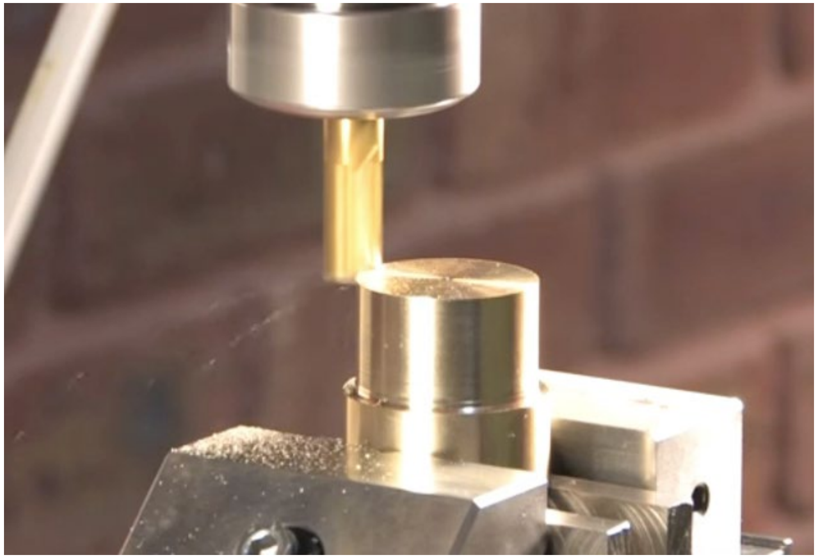
- This allows for increased material removal and reduces tool wear
- Important to ensure that the material is rigid enough to withstand machining forces

Example: Tools must be replaced more often when machining stainless steel than when machining aluminum

Machining Process Guidelines

Subtractive processes

- Minimize machine and tool changes
  —Reduces fixturing and decreases process time
- Reduce the number of setups (re-orienting or re-fixturing a part, and re-locating tooling costs time and money)



Video: Machining a brass part on a milling machine
(mouse-over image to view)

Machining Process Guidelines

Subtractive processes (cont.)

For rotational components:

- Ensure that cylindrical surfaces are concentric
- Diameters of external features increase from exposed face
- Diameters of internal features decrease from exposed face

For non-rotational components:

- Provide a base and try to ensure that all surfaces are parallel or perpendicular to the base
- Restrict plane-surface machining (i.e., slots and grooves) to one surface

Machining Process Guidelines

Subtractive processes (cont.)

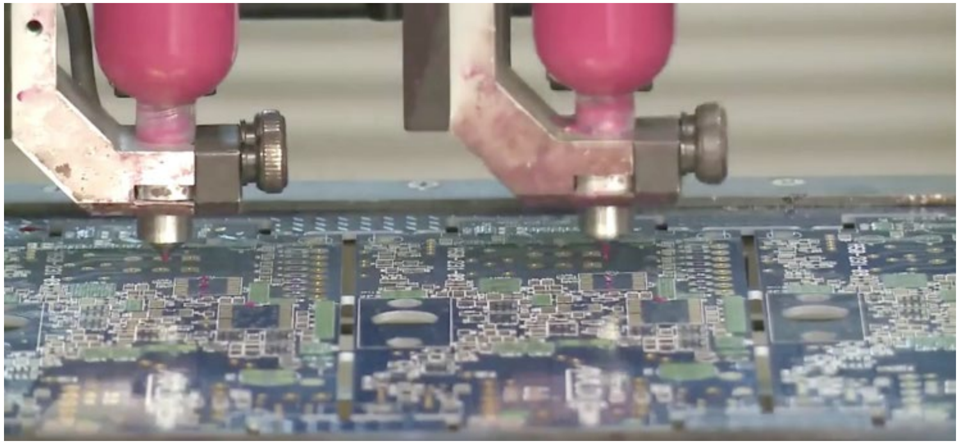
For internal corners:

- Use a radius equal to that of a standard tool corner
- Sharp corners require small tools; either tool changes or slower material removal
- It might be necessary to check with the design team to see if these are critical

Design For Assembly

Basics

- **Design for assembly** (DFA) is the method of designing a product for ease of assembly
  - —Components can be stand-alone or subassemblies
  - —Assembly operations can be manual or automated
  - —Assembly costs can be significant
  - —Assembly costs reduction can lower overall manufacturing costs



Video: Automated printed circuit assembly

Design For Assembly

Assembly efficiency

- Provides motivation for better design or redesign of assembly
- Dr. Geoffrey Boothroyd and Dr. Peter Dewhurst provide a widely used quantitative, software-based method of DFA for determining assembly efficiency of a given assembly
- Design has to be altered to improve assembly (this is not prescribed)

Results of Analysis

- Eleven essential parts
- Thirty parts or bought-in elements in total

Formula: $$\frac{A}{A + B} \times 100\%$$

$$\frac{11}{30} \times 100\%$$

… design efficiency is 36.7%

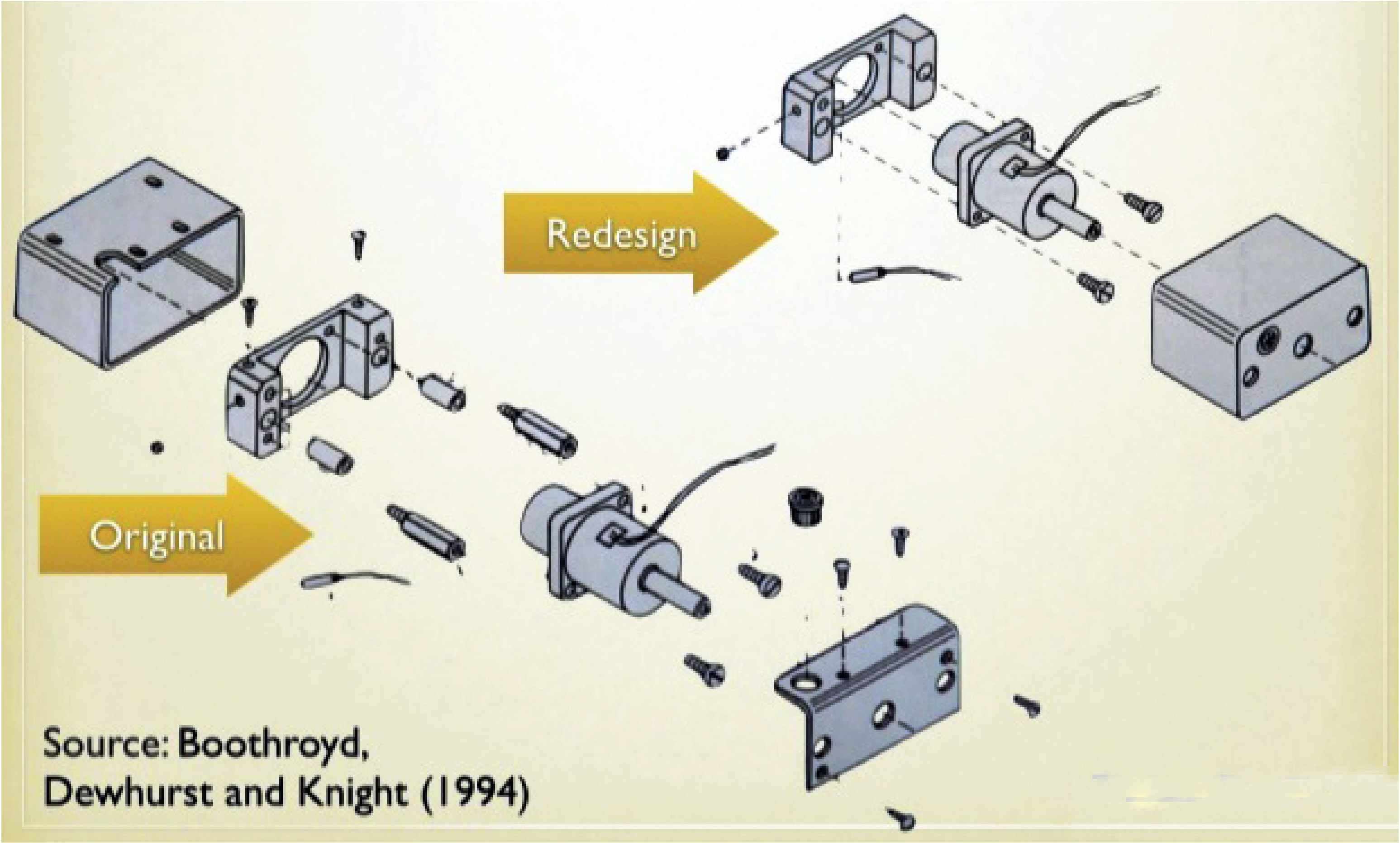
Design For Assembly

Key results

- Product contains few parts, which reduces assembly time and cost (this can also reduce the need for a large inventory and the associated tracking costs)
- Simplification and ease of assembly (manual or automated)
- Easy orientation and insertion of parts (the simpler the assembly, the quicker it can be assembled)

Design For Assembly Benefits

Example



Design For Assembly Benefits

Parts reduction and consolidation

Reduced design costs:

- Fewer parts need to be designed; however, the remaining parts may be more complex

Reduced inventory costs:

- Fewer **stock keeping units** (SKU) have to be maintained and tracked

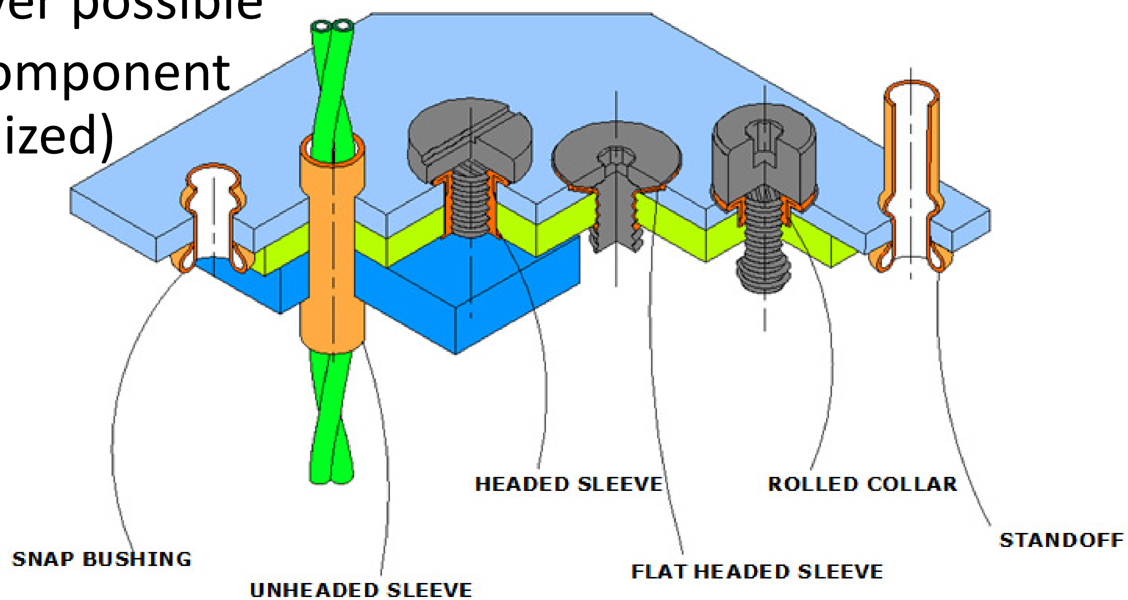
Reduced handling costs:

- Fewer parts need to be sited for assembly
- Lower complexity operation and administration
- Fewer SKUs results in lower tracking and maintenance costs

Design For Assembly

General guidelines

- Avoid mechanical fasteners
  - —Screwing or riveting parts together takes time and can lead to mistakes
  - —Snapfits allow for joining with mechanical fasteners
- Standardize whenever possible
  - —Using the same component (even if not optimized) can reduce cost and assembly complexity



Design For Assembly

General guidelines (cont.)

- Parts should be easily grasped and oriented
- Reduce awkwardly shaped or sized parts
- Unidirectional assembly is preferred (**top-down** is best)
- Provide features to reduce resistance to insertion, such as chamfered holes and parts

Part symmetry should be promoted, or asymmetry exaggerated:

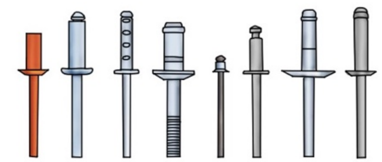
- A part should be able to be assembled either anyway or only one way
- If a part has to be inserted with a specific orientation, ensure that it doesn't fit any other way
- Assembled parts should have self-locating features (it should be easy to "feel" where something should go)

Design For Assembly

General guidelines (cont.)

- When use of springs is unavoidable
  - —Leaf springs: can be placed and loaded
  - —Extension springs: require force to be loaded
  - —Compression springs: have to be held down for assembly
- When use of mechanical fasteners is unavoidable
  - —Snapfits: parts “snap” together easily
  - —Bending of plastic: parts come together
  - —Rivets: require quick forming
  - —Screws: require correct alignment and insertion

Leaf Springs



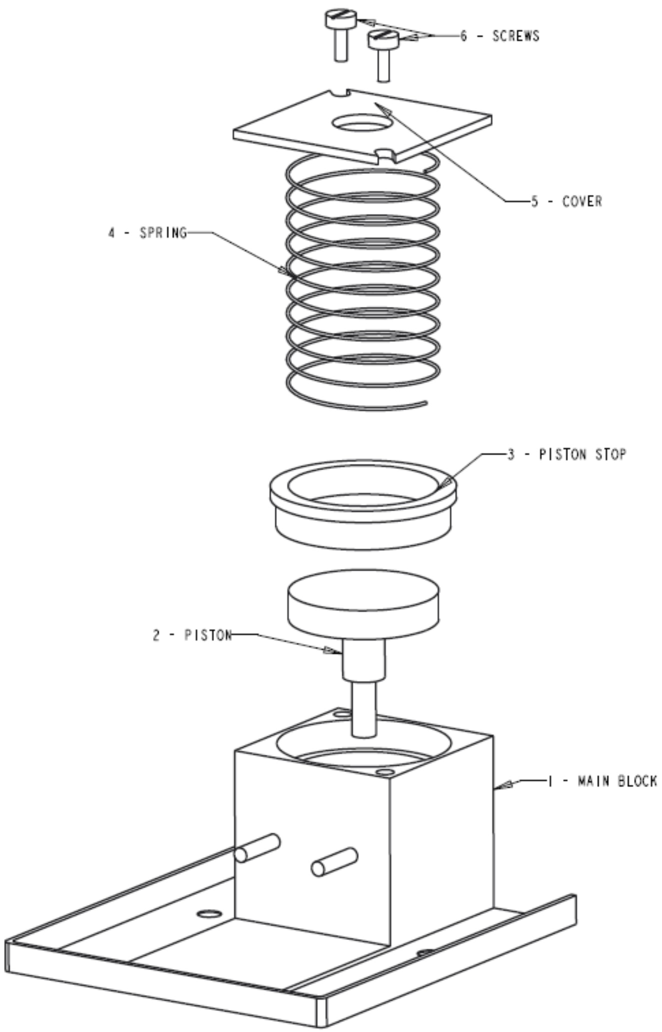
DFA Methodology

Boothroyd and Dewhurst

- Dr. Geoffrey Boothroyd and Dr. Peter Dewhurst provide a widely used quantitative, software-based method of DFA for determining assembly efficiency of a given assembly
- This software-based methodology uses rules to determine an ideal assembly time based on the necessary parts
- It then compares this ideal assembly time to the projected assembly time based on parts attributes and assembly processes
- This produces a DFA index score; the higher the score, the more efficient the design

Assembly

Example – Original design

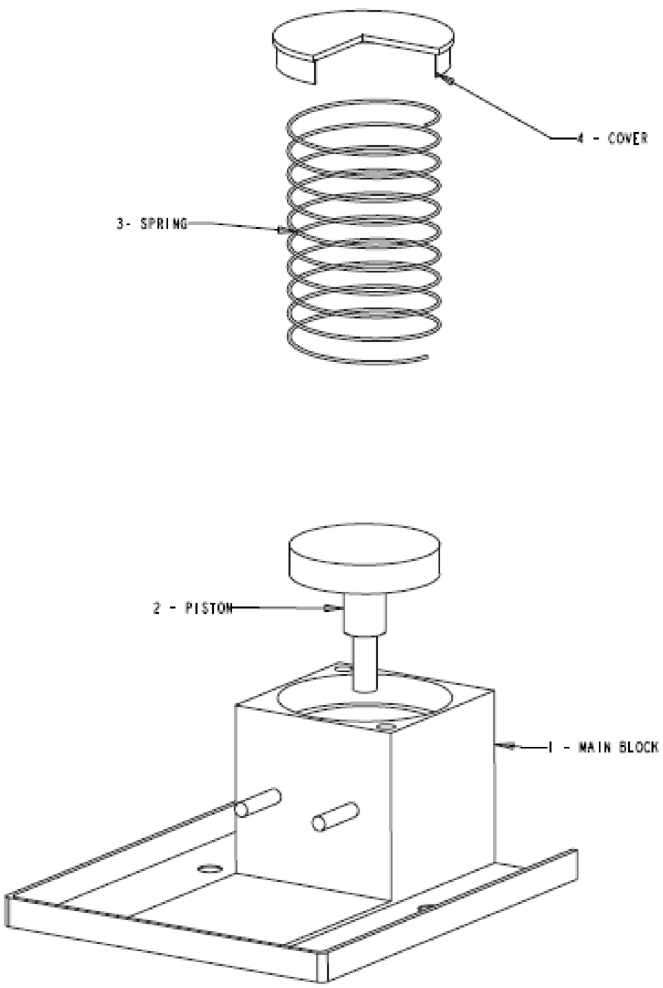


The original design has six distinct parts:

- A piston and piston stop to be inserted in the main block
- A compression spring
- A cover that must be oriented correctly and held down during assembly
- Two screws that need to be inserted simultaneously
- Takes 37 seconds to assemble

Designed For Assembly

Example – Altered design



- Altering the design by removing the unnecessary piston stop simplifies the assembly process
- Replacing the fasteners and screw-on cover with a snapfit cover simplifies the design
- This reduces the need to orient the cover by promoting symmetry
- Eliminates the need to hold down the cover during assembly
- Takes 15 seconds to assemble

Design For Assembly

Calculating DFM Index

- DFM-index is indicates how easy it is to assembler a component and can be expressed as:

$$DFA = 100\ N_m\ t_m\ /\ t_a$$

- Where:

DFA = Design for Assembly Index

N_m = theoretical minimum number of parts

t_m = minimum assembly time per part (s)

t_a = estimated total assembly time (s)

Source: www.EngineeringToolBox.com

Design For Assembly

Examples - calculating DFM Index

Assembling Components with Ideal Design:

- With an ideal design there is a minimum of parts and no assembly difficulties. The ideal DFA-index for assembling one component in one second can be calculated as

$$DFA = 100\ (1)\ (1\ s) / (1\ s) = \mathbf{100}$$

Assembling a Component from Parts:

- A component requires 200 seconds in total to assemble. The are 6 parts and the minimum assembly time per part is *3* seconds. The DFA-index for this component can be calculated as:

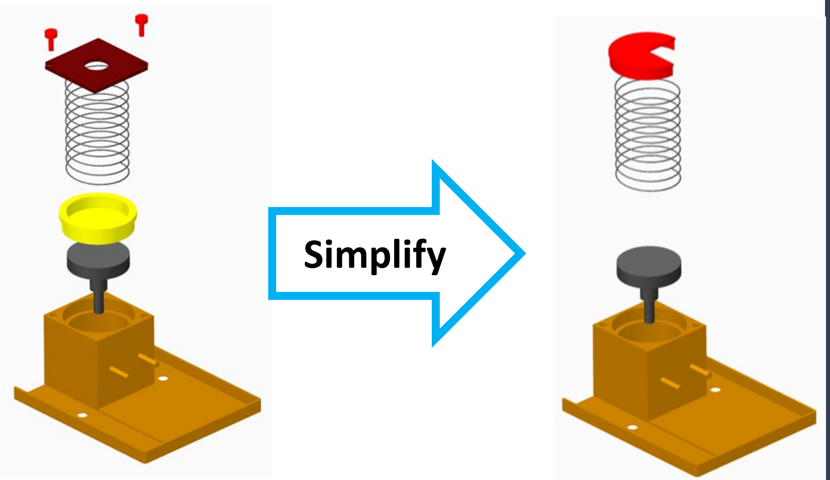
$$DFA = 100\ (6)\ (3\ s) / (200\ s) = \mathbf{9}$$

Source: www.EngineeringToolBox.com

Design For Assembly

Example – Altered design

- Employing the Boothroyd and Dewhurst DFA methodology reduces the assembly time from 37 seconds to 15 seconds
- The DFA index increases from 32 to 79
- This is in addition to not having to track the extra parts (the screws and the cover)
- The simplified assembly reduces costs and improves product quality
- Fewer parts and a simplified assembly process means fewer opportunities for errors and assembly problems to occur



Parts Consolidation

Design and cost implications

To realize the numerous benefits associated with parts consolidation, several factors must be taken into consideration:

- Product architecture
  - —Is this part used by other products?
  - —Is this part cost-off-the-shelf? (i.e., is it readymade?)
- Cost implications
  - —Consolidation may require the use of different materials and manufacturing processes (i.e., steel stamping versus die casting)
- Design and manufacturing process complexity

Disassembly

Maintenance and recycling

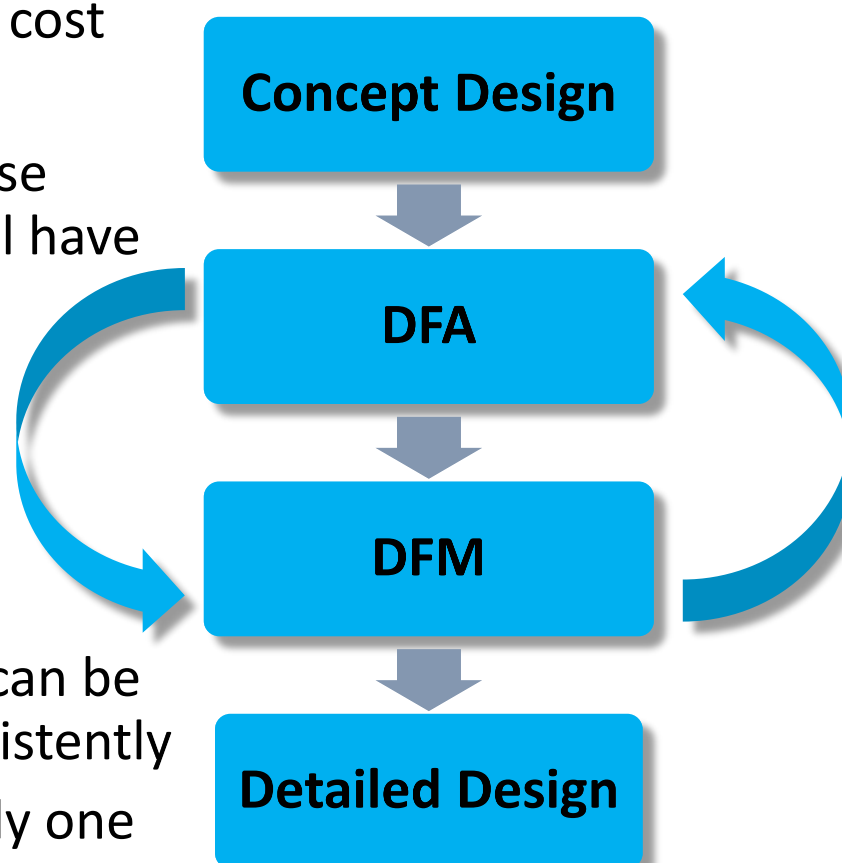
While parts consolidation and simpler component fastening guidelines are beneficial for assembly, disassembly for recycling and maintenance also need to be considered:

- Maintenance considerations
  - —Are consumable components easy to access and disassemble?
  - —Can the product be easily disassembled to maintain different systems and reassembled using common tools?
- Recycling implications
  - —Are dissimilar materials being joined together in ways that are difficult to separate? (i.e., steel rivets in aluminum components)
  - —Does the disassembly time (cost) outweigh the value of the potentially reclaimed materials?

Design For Mfg And Assembly

DFMA basics

- Cost: DFMA can lower product cost and increase quality
- Parts consolidation may increase certain piece costs, but you will have to evaluate overall effects
- Assembly costs can be significant
- Quality: DFMA can improve quality
  - —DFM ensures that the parts can be manufactured correctly consistently
  - —DFA ensures that there is only one way to assemble a part: the correct way



Manufacturing Scale-Up Challenge

We got it to work, now what?

Source: Arborlight

Design For Manufacturing

Case study – LED daylight emulator

- Company description
  - —Daylight emulator: fake skylight with color tunable LED light that can simulate daylight (sunrise to sunset) with user-facing mobile app or linked to outdoor daylight sensors
- Company type
  - √ —Product
  - —Material
  - —Manufacturing process
  - —Manufacturing service
  - —Manufacturing operations

Source: Arborlight

Technology Readiness Level

Case study – LED daylight emulator (cont.)

Basic Tech Research	Feasibility Research	Tech Development		Tech Demonstration	System Commissioning		System Operation	
Basic principles observed and reported	Technology concept and/or application formulated	Proof of concept analyzed and experimented on	Component or system validation in lab environment	System validation, testing in operating environment	Prototype/ pilot system verification in operating environment	Full scale prototype verified in operating environment	Actual system complete and functioning in operating environment	Actual system tested and data collected over lifetime of system
1	2	3	4	5	6	7	8	9

Year 1 progress

Year 2 progress

Year 3 progress

Year 4 - Retreat

Source: Arborlight

Manufacturing Readiness Levels

Case study – LED daylight emulator (cont.)

Material Solutions Analysis				Technology Development		Engineering and Manufacturing Development		Production and Deployment	Operations and Support
Basic manufacturing Implications Identified	Manufacturing Concepts Identified	Manufacturing Proof of Concept developed	Capability to produce the technology in a laboratory environment	Capability to produce a prototype components in a production relevant environment	Capability to produce a prototype system or subsystem in a production-relevant environment	Capability to produce systems, subsystems or components in a production-relevant environment	Pilot line capability demonstrated. Ready to begin Low Rate production	Low Rate Production demonstrated. Capability in place to begin Full Rate Production	Full Rate Production demonstrated and lean production practices in place
1	2	3	4	5	6	7	8	9	10

Pre-alpha → **Alpha prototypes** → **Beta prototypes** → **Pilot prototypes**

Design For Manufacturing

Case study – LED daylight emulator (cont.)

- Manufacturing readiness level (MRL) 4

DFM or scale-up challenges faced:

- First generation luminaire product cost too high (BOM $5,000), traditional skylight $1,000 ($2–4K installed)
- Stamped optical mixing chambers with tooling was too expensive $800/each (x4 = $3,200)
- Product too big at 16” depth, needs to meet ASHRA industry specification standards of 8” depth
- Capital cost for in-house production too expensive
- Auto headliner product required new DFM and packaging challenge

Source: Arborlight

Design For Manufacturing

Case study – LED daylight emulator (cont.)

Experience facing those challenges:

- Worked with experienced product engineering firm to redesign chamber to optimize depth of optical mixing chamber to maintain performance of color mixing while reducing manufacturing cost
- **DFM**: switched from stamping to extrusion process with flexible tooling to reduce cost
- **DFA**: eliminated parts to reduce cost/labor; limited installation concerns
- Secured multiple contract assembly partners to reduce capital cost; ensured inventory and product lead times
- **Design for operating environment**: auto headliner required experienced tier 1 partner to support NVH; packaging demands

Source: Arborlight

Design For X

What are we designing for?

Design for manufacturing (DFM):

- Reduce BOM, material trade offs, cost reductions

Design for assembly, manufacturing process (DFA, DFM process):

- Reduce BOP or process steps, reduce labor
- Reduce capital equipment, tooling costs
- Reduce scrap, improve yield

Design for durability, design for operating environment:

- Consider NVH, loading conditions, temperature operating environment, engineer for lifetime

Design For X

What are we designing for? (cont.)

Design for system integration:

- Consider form/fit/function, system operating dynamics, transient impacts on connecting components

Design for maintenance and serviceability:

- Product design to incorporate ease of service

Design for packaging and logistics:

- Consider product protection, shipping logistics, transportation costs

Design For X

What are we designing for? (cont.)

Design for sustainability:

- Use of bio-based materials, allow for recyclability, biodegradable products and packaging
- Reduce waste materials in operations, cradle to cradle waste to input materials

Design for customer use and market acceptance:

- Customer interface, acceptance, installation
- Market regulations, certification requirements

DFMA

Key themes

- **Customer**: DFMA ensures that the assembly and manufacturing processes meet customer requirements
- **Supplier**: well-designed manufacturing and assembly processes help suppliers deliver a quality product (this reduces the amount of iteration required during quoting and scale-up)
- **Business plan**: How scalable is your assembly plan? Doing things by hand and requiring "tweaks" may work at low volume, but is it scalable?

DFMA

Key themes (cont.)

- Implementing DFMA is an iterative process
  - —Parts need to be redesigned to ensure their manufacturability
  - —Parts consolidation and alteration may be required to improve assembly processes
- Implementing DFMA can reduce risk
  - —Parts that are well designed for manufacturability reduce the risk of manufacturing errors
  - —Fewer SKUs reduces risk of stock-out or other problems

Resources

- Boothroyd Dewhurst, Inc. http://www.dfma.com/
- Boothroyd, G., Dewhurst, P., and Knight, W., *Product Design for Manufacture and Assembly,* 2nd Edition. Marcel Dekker, New York, 2002
- Poli, C., *Design for Manufacturing: A Structured Approach*. Boston, Butterworth-Heinemann, 2001

List Of Terms

In glossary

- **Design for Manufacturing (DFM)** is the general engineering practice of designing products in such a way that they are easy to manufacture.
- **Design for Assembly (DFA)** is a process by which products are designed with ease of assembly in mind. (Repeat from 3A)
- **Manufacturing Readiness Level (MRl)** - is a measure developed by the United States Department of Defense (DOD) to assess the maturity of manufacturing readiness
- **Engineering Validation** measures and analyzes the process, audits and calibrates equipment and creates a document trail that shows the process leads to a consistent result to ensure the highest quality products are produced. (Repeat from 2C)
- **Design Validation** is testing aimed at ensuring that a product or system fulfills the defined user needs and specified requirements, under specified operating conditions. (Repeat from 2C)
- **Development** is the systematic use of scientific and technical knowledge to meet specific objectives or requirements. (Repeat from 2C)
- **Manufacturing Development** or Engineering & Manufacturing and Development (EMD)phase is where a system is developed and designed before going into production. (Repeat from 2B)
- **Casting** is a manufacturing process in which a liquid material is usually poured into a mold, which contains a hollow cavity of the desired shape, and then allowed to solidify.
- **Expendable** component or part (such as bolt, nut, rivet) for which no authorized repair procedure exists, and/or the cost of repair would exceed cost of its replacement.
- **Non-Expendable Mold Casting** in metalworking is a process in which liquid metal is poured into a mold that contains a hollow cavity of the desired shape, and then allowed to cool and solidify. Traditional techniques include lost-wax casting, plaster mold casting and sand casting.

List Of Terms

In glossary (cont.)

- **Sand Casting** is a metal casting process characterized by using sand as the mold material.
- **Plaster Mold Casting** is a metalworking casting process similar to sand casting except the molding material is plaster of Paris instead of sand.
- **Shell Molding** is an expendable mold casting process that uses a resin covered sand to form the mold. As compared to sand casting, this process has better dimensional accuracy, a higher productivity rate, and lower labor requirements.
- **Investment Casting** is an industrial process based on lost-wax casting, one of the oldest known metal-forming techniques.