Design for Manufacturing

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Learning Objectives

Understand the role of design in determining final component costs and product lead time

Understand variability in processing and methods for monitoring and controlling this variability

Identify different interchangeability models and how they are used to handle quality requirements
Beyond conventional design

Design for X (DFX) - develop optimal/mature product in: manufacturing, assembly, reliability, service, transport, usability, ergonomics, environment, etc.

Design for Manufacturing and Assembly (DFMA)

Design for Manufacturing (DFM)
• minimizes complexity of manufacturing operations
• uses common datum features and primary axes

Design for Assembly (DFA) (and disassembly!)
• minimizes number of assembly operations
• individual parts tend to be more complex in design

16 total parts (assembly)
1 part (3D printing)

20 total parts (assembly)
1 part (3D printing)
Benefits of DFMA

DFMA design process

<table>
<thead>
<tr>
<th></th>
<th>Concept design</th>
<th>Initial design</th>
<th>Design changes</th>
<th>Data dissemination</th>
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<tbody>
<tr>
<td>20</td>
<td></td>
<td>13</td>
<td>22</td>
<td>6</td>
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40% time savings

Conventional design process

<table>
<thead>
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<th>Data dissemination</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td></td>
<td>27</td>
<td>55</td>
<td>15</td>
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Percentage of design time

Concurrent engineering

Sequential engineering

(Adapted from Bauer, L. Team Design Cuts Time, Cost, Welding Design Fabrication, September, 1990, p. 35.)
A Design Challenge
A Design Challenge

Please take out a sheet of paper.
TAs have a stack.
A Design Challenge

Please take out a sheet of paper.
TAs have a stack.
Write your name on it.
GOAL
Create the most *accurate* paper airplane, with the *fewest number* of folds, as *fast as possible*. 
GOAL

Create the most *accurate* paper airplane, with the *fewest number* of folds, as *fast as possible*.

Throw it at me.
GOAL

Create the most accurate paper airplane, with the fewest number of folds, as fast as possible.

Throw it at me.

Three winners (of those that hit me / make it in the bin)

Points = \(\frac{60 - \text{time elapsed}}{\# \text{ Folds}}\)
Design for Manufacturing

Trade-offs in DFM

Cost
Quality
Rate
Flexibility

Design for Manufacturing
Design of a part, assembly, and manufacturing process with the appropriate quality, lowest cost, fastest and most flexible method.

Easy, right?
Paper Airplanes and DFM

Trade-offs in DFM

Cost

Quality

Rate

Flexibility

# of Folds

Accuracy

Shortest time

Difficulty to implement changes to the part design for a manufacturing method (method was fixed for airplane challenge)
Part and Assembly Design

Specifications

• The intended dimension
• The “ideal” length

Tolerance

• The allowable error
• An acceptable range

1.75” ± 0.05”
Part and Assembly Design

- Parts have tolerances because assemblies have tolerances.
- Assemblies have variation because parts have variation.
- Assembly-level variations are largely due to areas where parts assemble to each other.

“Tolerance is what you need, and Variation is what you get!”
- Dr. Dan Whitney
Part and Assembly Design

Interference

• Space intentionally occupied by more than one body
• Results in deformation of one (or multiple) bodies

Clearance

• Space intentionally left unoccupied

NEMA Motor Shaft & Coupling Bore Interference Fit Chart
Dimensioning Practice

Boeing 777 FBJ (tolerance)

- AUTO CAMSHAFTS
- AUTO VALVES
- GENERAL MACHINE BEARING PRACTICE
- ELECTRIC MOTOR BEARING PRACTICE
- PRECISION LAPPED BEARING PRACTICE

- BALL BRG O. D. FIT TO HOUSING
- BALL BRG I. D. FIT TO SHAFT

CLEARANCE RATIO, C
Part and Assembly Design

Dimensioning Practice

- Boeing 777 FBJ (tolerance)
- DIAM (INCH)
- AUTO CAMSHAFTS
- AUTO VALVES
- GENERAL MACHINE BEARING PRACTICE
- ELECTRIC MOTOR BEARING PRACTICE
- PRECISION LAPPED BEARING PRACTICE

- BALL BRG O. D. FIT TO HOUSING
- PLAN WASHERS
- BRONZE BUSHING BEARINGS
- BALL BRG I. D. FIT TO SHAFT
- CLEARANCE RATIO, C

100 inch Dia.

0.0005” Clearance Ratio
Manufacturing Methods

Selecting a method, based on the part requirements

CNC Machining

- Quality: Best -- Highest precision
- Cost: High
- Rate: Moderate to fast
- Flexibility: Depends

**Strengths:** Strong, durable parts. Very flexible with CNC. Use for critical components.

**Limitation:** Set-up

Additive manufacturing

- Quality: Low to Moderate
- Cost: Low to Moderate
- Rate: Slow
- Flexibility: Extremely Flexible

**Strengths:** Realize complex designs with (almost) fixed setup time. Proof of concept mechanisms.

**Limitation:** Weak parts. High rate of failure
Manufacturing Methods

Selecting a method, based on the part requirements

Laser Cutter
- Quality: Moderate
- Cost: Low
- Rate: Fast
- Flexibility: Extremely flexible

**Strengths:** Very fast, 2D to 3D structures. Moderately strong parts. Very easy to modify parts.

**Limitation:** Chlorine

Waterjet
- Quality: Moderate
- Cost: Moderate
- Rate: Fast
- Flexibility: Extremely flexible

**Strengths:** Very fast, 2D to 3D metal structures. Extremely strong parts.

**Limitation:** Water
Mfg. Metrics - Run Chart

- Measurement of critical dimensions for all/sampled parts
- USL – Upper Specification Limit
  Specification + UpperTolerance
- LSL – Lower specification Limit
  Specification - LowerTolerance
Mfg. Metrics – Shewhart Control Chart

Also called an “X-bar Chart”

• Average measurement of a subgroup of parts

UCL – Upper Control Limit

\[
UCL = \bar{X} + 3\sigma_{sg} \quad \sigma_{sg} = \text{SubGroup Standard dev.}
\]

LCL – Lower Control Limit

\[
LCL = \bar{X} - 3\sigma_{sg} \quad \sigma_{sg} = \text{SubGroup Standard dev.}
\]
Manufacturing Metrics

Run Chart

Control Chart
Sub-Group n=10

Statistical Process Control
Monitor Quality of Parts
Identify Random or Causal Variations
Provides Metric of Success
Run Chart, Fall 2017
Band Saw, n = 50

- USL - Up. Spec. Limit
- LSL - Low Spec. Limit
Need a moment?

Chew it over with Twix!
Twix Fun Size Mass Distribution

Twix Fun Size Weights

Weight (grams)

Occurrences

Source: Dr. Jung-Hoon Chun
MIT 2.008 Sp'17
Process Control and Capability

Source: Dr. Jung-Hoon Chun, MIT 2.008 Sp’17
DFMA principles (interchangeability)

Interchangeable: for a group of parts conforming to a specification, any part can be selected at random and be used in place of another and assemble properly

Degree of interchangeability: probability that parts can assemble when replaced, 3 models for interchangeability:

1. Complete interchangeability 100%
2. Limited interchangeability >0%, <100%
3. Zero interchangeability 0%
Complete interchangeability model

• 100% component interchangeability
• In the below assembly, any shaft can be picked at random to match any bearing (tight tolerances on all parts)

\[
H = [H_{\text{min}}, H_{\text{max}}] \quad S = [S_{\text{min}}, S_{\text{max}}] \quad C = [C_{\text{min}}, C_{\text{max}}]
\]

Clearance \( C = H - S \)

• Final tolerance range is the sum of each component’s tolerance ranges
• Benefit \( \rightarrow \) no need to inspect, ideal for servicing
• Drawback \( \rightarrow \) smallest tolerances allowed
Limited interchangeability model

1. Direct selection
   • Worker measures mating parts and determines if the assembly meet’s customer requirement
   • Benefit: simple way to account for variation in manufacturing
   • Drawback: 100% inspection required, skilled operators

2. Selective assembly
   • Mating parts classified in groups by size
   • Group size limits set so similar sized mating parts can be assembled together and still meet functional requirements
   • Benefit: simplifies measurement and part tracking
   • Drawback: 100% inspection

\[
H = [H_{min}, H_{max}] \\
H_1 = [H_{1min}, H_{1max}] \\
H_2 = [H_{2min}, H_{2max}] \\
H_n = [H_{nmin}, H_{nmax}] \\
S = [S_{min}, S_{max}] \\
S_1 = [S_{1min}, S_{1max}] \\
S_2 = [S_{2min}, S_{2max}] \\
S_n = [S_{nmin}, S_{nmax}]
\]
Limited interchangeability model

Selective assembly (examples)

Vic Firth or Pro-mark Drumsticks

https://www.youtube.com/watch?v=smLFWn9H_C8
https://www.youtube.com/watch?v=6uOqB5hoigE

Apple Iphone

https://www.youtube.com/watch?v=tu0vfBTwKrs#t=5m30s
3. **Compensation or Custom Adjustment**

- One can obtain required fit by introducing compensating element into an assembly
- Compensation elements can be adjustable (e.g., screw-driven) or fixed in size (e.g. shim-type)
- Benefit: enables wide tolerance ranges to be feasible in production and service
- Drawback: 100% inspection, time to adjust/insert

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**Limited interchangeability model**

Zero interchangeability model

Unit manufacturing

• Most primitive method to satisfy assembly conditions
• Principle: All dimensions in assembly made with respect to nominal dimensions, but one dimension is machined to suit the final assembly requirement
• Benefit: simple approach to achieve ideal match
• Drawback: Once disassembled, the mating components cannot be mated with a replacement component and still satisfy assembly requirement

Example: connecting rods
Potential challenges with DFMA

Impact on Development Time and Cost
- May lead to complex parts, requiring special machines/tooling
- Cost benefits of DFMA may be diluted by project delay

Impact on Product Quality
- DFMA may decrease product reliability or robustness

Impact on External Factors
- May reduce flexibility because of the choices of materials, machines, or tooling
- May cause additional cost outside of manufacturing stage - service requirements, warranty costs, etc.
Summary / Learning Objectives

Understand the role of design in determining final component costs and product lead time

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Identify different interchangeability models and how they are used to handle quality requirements