Developing a Design for Manufacturing Handbook

Mohsen Hamidi, Kambiz Farahmand
Department of Industrial and Manufacturing Engineering
North Dakota State University
mohsen.hamidi@ndsu.edu, Kambiz.Farahmand@ndsu.edu

Abstract

Understanding design for manufacturability is paramount, especially when design requirements exceed technology or manufacturing capability. More and more companies who are outsourcing design are facing this problem, where engineering designs have to be modified to match technology or process capability. Companies are left with the dilemma of how to communicate their capabilities to designers. One approach in communicating manufacturing capabilities to designers is to develop design for manufacturing (DFM) and design for assembly (DFA) handbooks. In this paper, a comprehensive handbook of DFM, developed for a manufacturing company, is presented. The handbook was designed and developed for the purpose of providing a common language between the designers and the manufacturing engineers. It includes: process capabilities and specifications, machinery and tooling capabilities in various manufacturing modules, guidelines for helping the designers understand the manufacturing challenges presented as a result of not well thought out design, and the various design examples or shortcuts that would enable the manufacturing of parts and products efficiently and at lower cost, faster time, and best quality approach. The procedures followed include: visiting workshops and interviewing operators and supervisors; gathering data documentation; discussing issues with engineers, managers, and operators; and making recommendations. The technology/design capability handbook serves as a venue for communication between the design and manufacturing engineers and helps bridge the gap that exists in understanding challenges and capabilities for a better and more efficient operation company-wide.

Key words: Design for Manufacturing (DFM), Design for Assembly (DFA)

Introduction to Design for Manufacturing (DFM)

Design for manufacturability is the process of proactively designing products to (1) optimize all the manufacturing functions: fabrication, assembly, test, procurement, shipping, delivery, service, and repair, and (2) assure the best cost, quality, reliability, regulatory compliance, safety, time-to-market, and customer satisfaction [1]. One of the pillars of DFM knowledge-base is concurrent engineering [2]. Concurrent engineering is the practice of concurrently developing products and their manufacturing processes [1]. For example, if existing processes are to be utilized, then the product must be designed for these processes; if new processes are to be utilized, then the product and the process must be developed concurrently [1] to ensure manufacturability. The concurrent engineering approach is intended to cause the developers and designers, from the outset, to consider all elements of the product lifecycle, from concept through disposal, including fabrication, testing, packaging, and delivery in addition to quality, cost, schedule, and user requirements [2]. DFM and DFA approaches are valuable tools in adopting and implementing concurrent engineering [2]. Their philosophy is based on using manufacturing or assembly as a design constraint, thus taking downstream processes like manufacturing and assembly into full consideration during the early design phase of the product [2].

Decisions made during the early conceptual stages of design have a great effect on subsequent stages [3]. In fact, more than 70 percent of the manufacturing cost of a product is determined at this conceptual stage, yet manufacturing is not involved [3]. Early consideration of manufacturing issues shortens product development time, minimizes development cost, and ensures a smooth transition into production for quick time-to-market [1]. Companies that have applied DFM have realized substantial benefits [1]. Costs and time-to-market are often cut in half with significant improvements in quality, reliability, serviceability, product line breadth, delivery, customer acceptance, and, in general, competitive posture [1].

Understanding design for manufacturability is paramount especially when design requirements exceed technology or manufacturing capability. More and more companies who are outsourcing design are facing this problem, where engineering designs have to be modified to match technology or process capability. Companies are left with the dilemma of how to communicate their capabilities to designers. One approach in communicating manufacturing capabilities to designers is to develop DFM and DFA handbooks. In this paper, a comprehensive DFM handbook developed for a manufacturing company is presented.

Design for Manufacturing (DFM) Handbook

To produce modern and up-to-date products, the company designs new products and parts, as well as makes modifications to exiting products and parts. Design or design changes are done in two ways: 1) by the company personnel in the design department or 2) by designers outside the company. When designers present a design, manufacturing engineers check whether the designed part can be manufactured given the facility's capabilities or incorporated into the existing production line with minimum interruptions to work or material flow. The manufacturing engineer's feedback helps designers make the necessary corrections to develop a design for manufacturability. Actually, manufacturing engineers will always have some manufacturability concerns (in terms of technical feasibility, time, cost, and quality) with regard to new engineering designs. In other words, designers, especially designers outside the company or even outside the country, are not always familiar with all the manufacturing capabilities and limitations of the company. As more and more companies outsource their design process overseas, the disconnect between the designers and manufacturers keeps growing. One of the first steps in bridging the gap is the availability of a handbook for the designers. The DFM handbook is an attempt to assist the designers with this important issue. The handbook will provide a common language between the designers and the manufacturing engineers when it comes to fabrication and mass production.

DFM Handbook Outline

The DFM handbook developed as part of this study consists of an introductory section, six chapters, and one appendix. The introductory section contains DFM and DFA general guidelines. Five chapters are assigned to five main categories of manufacturing processes in the company: fabrication, welding, machining, painting, and assembly. The sixth chapter is assigned to quality control. Chapter one covers fabrication processes (cutting and punching, sawing, beveling, forming, and flattening processes). Chapter two includes welding processes (arc welding, resistance welding, and stud welding processes). Chapters three, four, and five cover machining, painting, and assembly processes, respectively. Chapter six includes some design considerations from the quality control viewpoint. The following are presented and illustrated for each manufacturing process: process specifications and capabilities; machinery and tooling specifications and capabilities; guidelines for helping the designers understand the manufacturing challenges presented as a result of not well thought-out design; and the various design examples or shortcuts that would enable the manufacturing of parts and products with low cost, faster time, and best quality approach. To help readers understand the content, various drawings, figures, charts, and graphs are included in the relevant chapters. The appendix contains pictures to visualize the machinery for readers. Various examples of design guidelines and recommendations along with drawings are presented.

DFM and DFA General Guidelines

It is vital for the designers to understand the significance of designing for manufacturability. Designers, similar to artists, usually follow a similar trend in their designs based on their training and education. The idea of anticipating production, technology, or facility limitations in manufacturing may be quite foreign to the concepts used by the designer. The DFM handbook must emphasize the critical role the guidelines present in minimizing the need for future modifications of the design. The handbook, as part of the general guidelines, emphasizes this point before presenting the nuts and bolts of the design, using various techniques. A brief summary of these guidelines [4], accompanied by select illustration and examples, is presented below.

a. **Simplify the design and reduce the number of parts.**
b. **Standardize and use common parts and materials.**
c. **Design for ease of fabrication.**
   Select processes compatible with the materials and production volumes. Select materials compatible with production processes and that minimize processing time while meeting functional requirements. Avoid unnecessary part features because they involve extra processing effort and/or more complex tooling. Apply specific guidelines appropriate for the fabrication process, such as the following guidelines for machinability:
   - For higher volume parts, consider castings or stampings to reduce machining.

- Use near net shapes for molded and forged parts to minimize machining and processing effort.
- Design for ease of fixtures by providing large solid mounting surface and parallel clamping surfaces.
- Avoid designs requiring sharp corners or points in cutting tools, since they break easier.
- Avoid thin walls, thin webs, deep pockets, or deep holes to withstand clamping and machining without distortion.
- Avoid tapers and contours, as much as possible, in favor of rectangular shapes.
- Avoid undercuts that require special operations and tools.
- Avoid hardened or difficult machined materials, unless essential to requirements.
- Put machined surfaces on same plane or with same diameter to minimize number of operations.
- Design work pieces to use standard cutters, drill bit sizes, or other tools.
- Avoid small holes (drill bit breakage greater) and length to diameter ratio greater than 3 (chip clearance and straightness deviation).

d. Design within process capabilities and avoid unneeded surface finish requirements.

e. Mistake-proof product design and assembly (Poka-Yoke).

The Japanese concept of Poka-Yoke (mistake-proofing) is oriented to finding and correcting problems as close to the source as possible, since finding and correcting defects caused by errors costs more and more as a product or item flows through a process. The concept of Poka-Yoke involves the following:

- Controls or features in the product or process to prevent or mitigate the occurrence of errors
- Requires simple, inexpensive inspection (error detection) at the end of each successive operation to discover and correct defects at the source

There are six mistake-proofing principles or methods. These are listed in order of preference, or precedence, in fundamentally addressing mistakes:

1. **Elimination** seeks to eliminate the possibility of error by redesigning the product or process so that the task or part is no longer necessary.
   Example: Product simplification or part consolidation that avoids a part defect or assembly error in the first place.
2. **Replacement** substitutes a more reliable process to improve consistency.
   Examples: Use of robotics or automation that prevents a manual assembly error; automatic dispensers or applicators to ensure the correct amount of a material, such as an adhesive, is applied.
3. **Prevention** engineers the product or process so that it is impossible to make a mistake.
   Examples: Limit switches to assure a part is correctly placed or fixed before process is performed; part features that only allow assembly the correct way; unique connectors to avoid misconnecting wire harnesses or cables; part symmetry that avoids incorrect insertion.

4. **Facilitation** employs techniques and combining steps to make work easier to perform.
   Examples: Visual controls including color coding, marking, or labeling parts to facilitate correct assembly; exaggerated asymmetry to facilitate correct orientation of parts; a staging tray that provides a visual control that all parts were assembled, locating features on parts.
5. **Detection** involves identifying an error before further processing occurs so that the user can quickly correct the problem.
   Examples: Sensors in the production process to identify when parts are incorrectly assembled; built-in self-test (BIST) capabilities in products.
6. **Mitigation** seeks to minimize the effects of errors.
   Examples: Fuses to prevent overloading circuits resulting from shorts; products designed with low-cost, simple rework procedures when an error is discovered; extra design margin or redundancy in products to compensate for the effects of errors.

f. Design for parts orientation and handling.
g. Minimize flexible parts and interconnections.
h. Design for ease of assembly.
i. Design for efficient joining and fastening.
j. Design modular products.
k. Design for automated production.

Manufacturing Processes Identification

Each manufacturing process is thoroughly defined in the handbook. As an example, definition and specifications of gas metal arc welding are mentioned below.

- **Gas Metal Arc Welding (GMAW)**

The gas metal arc welding process uses an arc between a continuously fed electrode and the weld pool. The weld process uses an externally supplied shielding gas without the application of pressure.

- **Gas Metal Arc Welding (GMAW) Specifications**
    - It is particularly well-suited to high production and automated applications, as evidenced by its predominant usage of welding robots.
    - The equipment is more complex and costly and less portable than that of submerged arc welding (SAW). GMAW is more difficult to use in hard-to-reach areas because the welding gun is larger than the SAW electrode holder and the gun must be held closer to the work (1/2” to 3/4”).

Processes Capabilities

Capabilities of different processes that can perform similar operations are compared in the handbook. Table 1 shows the capabilities of different methods for punching or cutting holes.

Table 1: Punching or Cutting Holes Methods Capabilities

Method	Torching	Plasma Punching	Laser	Machining
Minimum Hole Diameter	Material Thickness	Material Thickness	Material Thickness	No Minimum
Hole Tolerance	± 1.5 mm	± 0.8 mm	± 0.1 mm	± 0.8 mm (Drilling) ± 0.025 mm (Boring)
Holes Positioning	± 1.5 mm	± 0.8 mm	± 0.25 mm	± 0.01 mm

Process Parameters

To help designers understand the relationship between the independent and dependent parameters of each process, the process parameters and their relationships are specified in the handbook. An example of process parameters for vee-die openings is presented here.

- **Vee-die Opening**

The recommended vee-die opening for mild steel up to 1/2" thick is eight times the metal thickness. For thicker than 1/2" mild steel, it may be necessary to increase the vee-die opening up to ten times the material thickness to minimize cracking of the material. To determine the vee-opening for a simple 90 degree bend, multiply the metal thickness by eight. The answer is then rounded to the next higher 1/8" figure. For example: 14 ga. (0.075") x 8=0.600". This is rounded to a 5/8" vee opening.

Material Utilization Guidelines

To maximize material utilization in the cutting process, a section addressing material utilization is included in the handbook. Material costs constitute the majority of a finished part cost. Increasing material utilization leads to cost reduction. Material utilization is the weight ratio of the finished part to the raw material required to produce the part. Table 2 is an example of the real effect of material utilization on annual cost.

Table 2: Material Utilization Effect on Cost

Average Material Utilization in 2006	Scrap Percentage	Annual Material Cost	Annual Scrap Waste
65%	35%	$25,000,000	$8,750,000

As shown in Table 2, a considerable amount of money could be saved by improving material utilization. To achieve this goal, the following guidelines should be considered in choosing material:

1. Try to use commonly used materials with minimum thickness and minimum cost. (A table in which the materials' thickness, annual usage [sheets or plates per year], and cost per pound are presented is included in the handbook.)

2. Try not to choose special sheet sizes (width and length), other than those mentioned in the handbook.

3. Try not to use materials other than plain carbon, grade 50, HSLA, ROPS.

4. Try to increase number of parts available for dynamic nesting per material, as shown in Figure 1. Different parts with different sizes allow for optimal nesting.

5. Try not to use irregular and unusual sized and shaped parts. As shown in Figure 1, these parts increase the gaps between part patterns in nesting and decrease material utilization.

6. Try to design large parts as two smaller parts to be assembled, rather than one single large part. It allows for the simultaneous use of multiple torches (especially on an oxy-fuel machine) as shown in Figure 1. Also, small parts can fill the gaps in a nesting and increase material utilization. However, this is a delicate issue and could vary from operation to operation. Keep in mind that if a part is divided into two smaller parts, a process is needed to join them together.

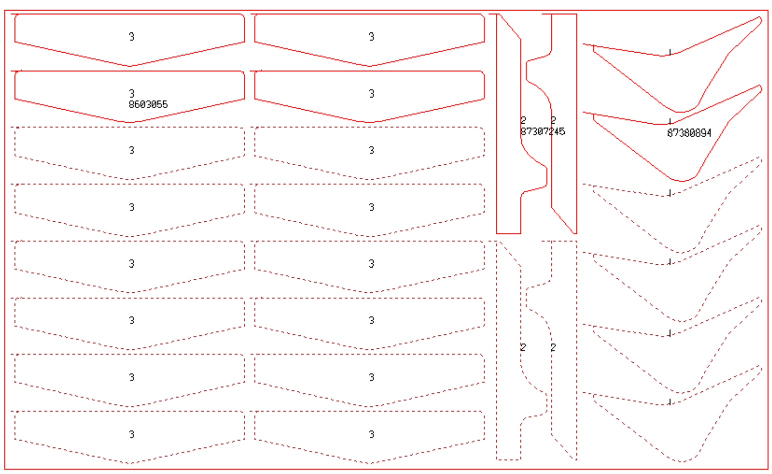

Figure 1: Nesting Example

Machinery Specifications and Capabilities

For each machine, an identification sheet is prepared. In this sheet, general capabilities and specifications of the machine, material specifications, machine accuracy, and tooling being used by the machine are introduced. Two examples are presented in Figure 2 and Figure 3.

Name: **Oxy-fuel Cutting Machine**		
General Capabilities	It is able to cut extremely thick material and is commonly used for cutting steel 1 or more inches thick.	
	It can cut metals in different shapes (curved and straight lines).	
	It can cut holes.	
	The oxy-fuel cutting process is known for its straight edges and minimal cleanup requirement.	
	It provides full process automation of oxy-fuel cutting process, using flame monitoring and correction technology.	

Specifications

Thickness	1/2"	3/4"	1"	2"	3"
Cutting Speed (IPM)	16–22	15–20	13–18	10–12	10–12
Kerf Width	0.06"	0.07"	0.09"	0.11"	0.12"

Material	***Dimension***	Max. Sheet Width: 84" Max. Sheet Length: 132" Sheet Thickness: 0.75" to 3.0"
		It is ideally suited for applications where the part size is small, allowing for the simultaneous use of multiple torches.
	Type	It is limited to use on carbon steel and will not cut aluminum, stainless steel, brass, or copper.
Accuracy	Positioning Accuracy: ± 1.5 mm	
	Repeatability: ± 0.005"	
	Material Profile Tolerance: 2 to 3 mm depending on size and type (preferably 3 to 4 mm as materials achieve greater thickness and size)	
	Minimum hole diameter is equal to material thickness.	
Tools	Up to 12 torches	

Figure 2: Oxy-fuel Cutting Machine Identification Sheet

<table>
<tr><td colspan="3">Name: Cincinnati Press (175 Ton)</td></tr>
<tr><td rowspan="2">General Capabilities</td><td colspan="2">It can form or bend different types of sheets in different angles.</td></tr>
<tr><td colspan="2">It is a hydraulically driven, servo-controlled press brake.</td></tr>
<tr><td rowspan="8">Specifications</td><td colspan="2">Max. Tonnage: 175 tons</td></tr>
<tr><td colspan="2">Max. Speed at Full Tonnage (inch/min): 49</td></tr>
<tr><td colspan="2">Max. Tonnage at Full Form Speed: 130 tons</td></tr>
<tr><td colspan="2">Standard Stroke Length: 10"</td></tr>
<tr><td colspan="2">Throat Depth: 8"</td></tr>
<tr><td colspan="2">Die Space: Open Height: 17", Closed Height: 7"</td></tr>
<tr><td colspan="2">Total Overall Die Surface: 16'–0"</td></tr>
<tr><td colspan="2">Backgage Axis:<table>
<tr><td>R Travel: 10"</td><td>X1Travel: 1.5"–41"</td><td>Z1 Travel: 0'–12.5'</td></tr>
<tr><td>Y Travel: 16"</td><td>X2 Travel: 1.5"–41"</td><td>Z2 Travel: 0'–12.5'</td></tr>
</table></td></tr>
<tr><td rowspan="4">Material</td><td rowspan="3">Dimension</td><td>Max. Length: 14'</td></tr>
<tr><td>Max. Leg Depth: 41"</td></tr>
<tr><td>CNC backgage is designed for sheets 3/16" (max. thickness) that weigh less than 100 lbs.</td></tr>
<tr><td>Type</td><td>Different types of material such as carbon steel, stainless steel, zinc-plated steel, bronze, and aluminum.</td></tr>
<tr><td>Accuracy</td><td colspan="2">Repeatability Accuracy: ± 0.0004"</td></tr>
<tr><td>Tools</td><td colspan="2">Different types of dies described in the Die Specifications section</td></tr>
</table>

Figure 3: Cincinnati Press (175 Ton) Machine Identification Sheet

Tooling Specifications and Capabilities

Specifications and capabilities of tooling of some critical processes are illustrated in the handbook. In the following, the air bend dies specifications are presented.

- **Air Bend Dies**

Air bend dies with angles of 75 degrees to 85 degrees are used to form angles from very shallow to 90 degrees. If parts are to be formed with air bend dies on a press brake with controls that use mathematical models to determine ram reversal positions, the dies must be cut to a 75-degree angle or less to compensate for all possible material spring-back. In some cases, 30 degree dies can be selected to obtain true air bending of 90 degree angles. An air bend die is shown in Figure 4.

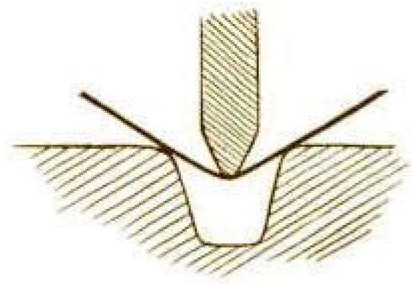

Figure 4: Air Bending Die

Design Considerations

For each process, general design considerations are provided in the handbook. Some of the design considerations for the arc welding process are listed below.

- **Arc Welding Design Considerations**

1. Use the minimum practical size fillet-weld needed:
    - Reduces the cost of filler metal and welding. For example, if weld size is increased from 8 mm to 10 mm, the amount of filler metal needed will be doubled.
    - Minimizes distortion.
    - Maximizes cell production capacity.

2. Design joints that have good stress transition.

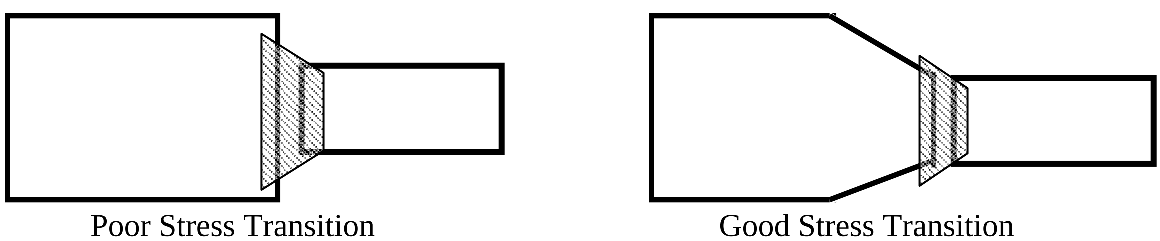

Figure 5: Stress Transition

3. Ensure welded attachments are not placed in high stress areas that may cause fatigue failures later.

4. Avoid joints that require multiple starts and stops of several welds at the same point.

5. If possible, position welds so that they can be welded in the flat position.
    - Take into consideration the type of fixtures that will likely be used.

- Avoid welding in the vertical and overhead positions, if possible. These will require additional welding skill and increase welding cost due to reduced welding speeds.

6. As it is shown in Figure 6, if Sheet A is to be welded along a line parallel to the edge of Sheet B, the distance of d (the distance between Sheet A and the edge of Sheet B) should be at least equal to

d = L + P1 + P2 + T + 3 mm,

where L is the weld size, P1 is positioning tolerance, P2 is profile tolerance, and T is sheet tolerance.

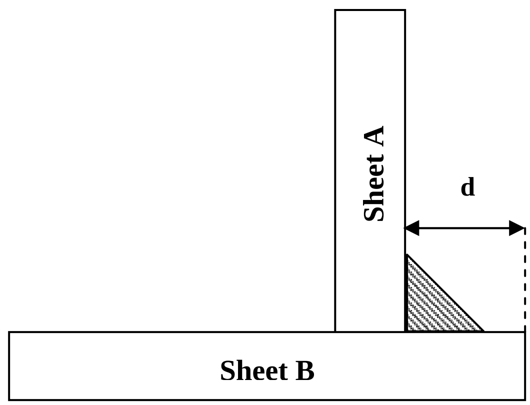

Figure 6: Minimum Distance Required for Welding

For example, if the weld size is 12 mm, Sheet A's positioning tolerance is ± 1.5 mm, and Sheet B's tolerance is 2 mm, then

d = 12 + 1.5 + 0 + 2 + 3 = 18.5 mm.

In Figure 7, a part of an arm is shown. Part A is the arm and Part B is the boss. If the weld size is 10 mm, Part B's positioning tolerance is ± 1.5 mm, Part A's profile tolerance is ± 2 mm, and Part B's profile tolerance is ± 1.5 mm, then the minimum distance between Part B and the edge of Part A should be equal to

d = 10 + 1.5 + 2 + 1.5 + 3 = 18 mm.

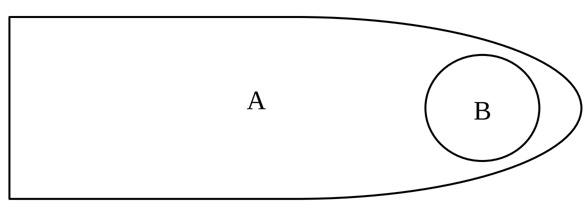

Figure 7: Minimum Distance Required for Welding

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Quality Control Considerations

One quality control consideration is presented as follows:

Do not use excessive and unneeded origins or datum in drawings. Having many origins in a given drawing increases the inspection time and decreases precision of dimensioning for quality control purposes. However, for functionality purposes, using some extra origins is inevitable. As shown in Figure 8, there are many dimensions with a few origins.

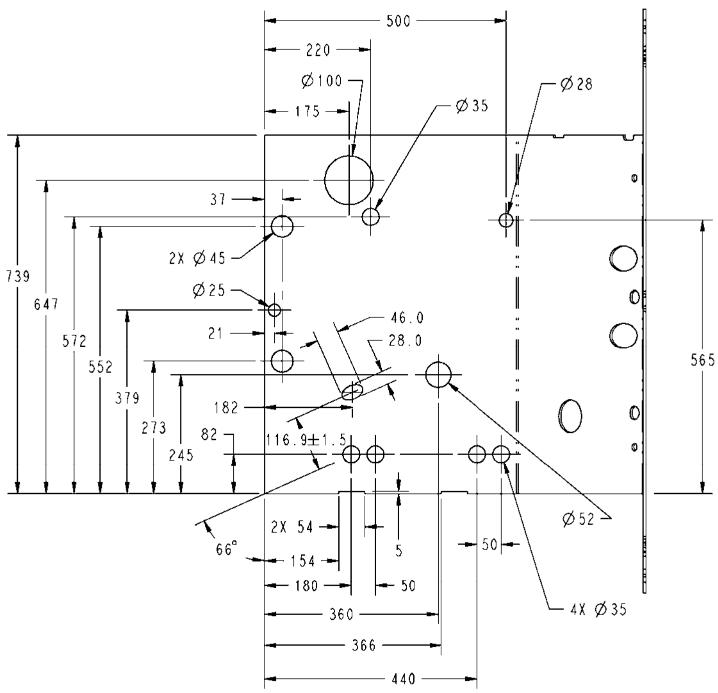

Figure 8: Many Dimensions with a Few Origins

Development Process of the Handbook

To design and affiliate the handbook, the company's manufacturing engineering department was in constant communication and collaboration with the developers of the DFM handbook. The task required a thorough understanding of the engineering design process and requirements, along with manufacturing/company limitations. The manager, the advanced manufacturing manager, and manufacturing engineers in different areas (fabrication, machining, welding, painting, quality assurance, and assembly) were involved at all stages of the development process.

The approach was to first tackle the five manufacturing areas, including fabrication, welding, machining, painting, and assembly. This included interviewing operators, reviewing the manufacturing process, talking to the manufacturing engineers and supervisors, and

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documenting all design and manufacturing issues, including capabilities and examples. In detail, for each manufacturing area, the procedure presented below was followed.

Step 1: Visiting workshops and interviewing operators and supervisors.
Step 2: Gathering related documents and data (in office and shop). These documents included some original documents provided by vendors such as proposals, catalogs, and brochures and some documents developed in-house as part of various studies performed on machinery, processes, tooling, material utilization, and so on.
Step 3: Reading, identifying, and discussing critical issues to manufacturing and production.
Step 4: Discussing issues with operators and supervisors.
Step 5: Reviewing current designs.
Step 6: Performing design feasibility and production limitation study.
Step 7: Developing various handbook sections including drawings, pictures, and recommendations.
Step 8: Presenting the findings/documentation to manufacturing engineers.
Step 9: Discussions and finalizing recommendations.

Conclusion

In this paper, a comprehensive handbook of design for manufacturing, developed for a manufacturing company, is presented. The handbook was designed and developed for the purpose of providing a common language between the designers and the manufacturing engineers. It includes: process capabilities and specifications; machinery and tooling capabilities in various manufacturing modules; guidelines for helping the designers understand the manufacturing challenges presented as a result of not well thought-out design; and the various design examples or shortcuts that would enable the manufacturing of parts and products efficiently and at lower cost, faster time, and best quality approach. The technology/design capability handbook serves as a venue for communication between the design and manufacturing engineers and helps bridge the gap that exists in understanding challenges and capabilities for a better and more efficient operation company-wide. The handbook also assists anyone not familiar with various manufacturing processes in visualizing and understanding the relationship between part design and the ease or difficulty of part production. Through this handbook, designers will gain insight that will allow them to assess the impact of their proposed design on manufacturing. The handbook was reviewed by designers, manufacturing engineers, and managers, and recommendations were evaluated and feasibility was assessed. Guidelines and recommendations would have to be addressing critical design issues impacting manufacturability to be included in the handbook. It was also determined that many of the issues addressed in the handbook are common to most products manufactured in the same facility and even to most fabrication operations. The general consensus was that the handbook will ultimately help the company produce products at lower cost, faster time, and best quality.

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Biography

KAMBIZ FARAHMAND is currently a Professor and Department Head in the Industrial and Manufacturing Engineering department at North Dakota State University. Dr. Farahmand has more than 23 years of experience as an engineer, manager, and educator. He is a registered Professional Engineer in North Dakota and Texas and past president of IIE Coastal Bend Chapter.

MOHSEN HAMIDI is currently a doctoral student in the Industrial and Manufacturing Engineering department at North Dakota State University.