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# APPLYING DESIGN FOR MANUFACTURE AND ASSEMBLY TECHNIQUES TO LARGE SCALE WELDMENTS PRODUCED IN SMALL VOLUMES

Author: Larry Stauffer and Wesley Smith, University of Idaho

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# 1 Introduction

This paper results from our research on two industrial projects we have been pursuing with local manufacturers. We have been collecting information via the participant observation method [1]. One product is a large system for handling corrugated cardboard. It is a large welded steel frame with numerous motors, mechanisms, switches, and sensors attached. The other product is a locomotive for pulling a freight train. The frame is welded steel containing a diesel engine, cooling systems, and numerous components. Both machines are comprised of several thousand parts, are custom built for each application, and shipped around the world. Classical engineering mechanics defines a structure with two-force members as a truss and a structure with multiple-force members as a frame or machine [2]. The products from these two companies contain all three and we will simply refer to all of these welded member as *structures*. In order to apply DFMA to these structures in an effective manner, we have had to modify existing techniques. We have also developed strategies that appear to be applicable to other similar applications.

## 1.1 Background

Design for Manufacture and Assembly (DFMA) techniques are used to decrease the cost of products by considering manufacturing and assembly needs during the design process [3]. DFA is a well structured approach that utilizes field data to estimate the cost to assemble a product. Engineers analyze each part in the assembly, assessing the effort needed to handle and insert it into the assembly. As each part and assembly operation is assessed, it is entered into a spreadsheet, and an overall assembly cost calculated [4]. Design for Manufacture (DFM) is a less structured technique [6]. It seeks to reduce the cost of manufacturing an individual part based on the uniqueness of each manufacturing process. Industry has realized tremendous improvements in cost reduction and improved reliability through DFMA. Double digit decreases in production cost are common [5].

One of the problems with DFMA techniques is that they are tedious and fairly time consuming. They are also geared towards bench top built, high volume products such as appliances, computers, vehicles, and similar products. For many parts in large-scale weldments, published data for handling and insertion times is not available.

## 1.2 Objectives

The purpose of this paper is to present new insights into applying DFMA techniques to large-scale welded structures produced in small volumes. Production of these types of products is typically done by smaller manufacturers that supply niche or local markets. We will address three issues. First, we will discuss the challenges with using traditional DFA techniques and present our methodology for DFA for these applications. Current DFA data applies to small parts that are assembled in a few seconds. Many of the parts in our applications took several minutes to handle, sometimes with multiple people and cranes. Also, the primary assembly method was welding. Second, we will present DFM guidelines that we have found useful for decreasing the cost to make welded frames. While every part is unique, several repeated patterns emerged. We will describe these strategies and present an example of their use. Third, we will discuss the trade-off between reducing cost through DFMA and the cost of the engineering effort.

# 2 A DFA Spreadsheet for Welded Structures

The use of DFA spreadsheets provides the designer with a tool to systematically account for each piece or assembly operation required to create the product [4]. By looking at the spreadsheet the designer can identify large assembly times or part costs and determine what can be condensed, removed, or replaced.

Although these traditionally used spreadsheets are very successful in high volume applications, their data tables are not as useful for large-scale products containing large and unique parts. The process is even less robust when applied to low volume assembly runs, and the practice of welding as the major assembly technique is largely omitted from the spreadsheet time penalty tables.

Shreve [7] studied welding fabrication of batched parts. He defined welding time as: time required for setup, cleaning, handling, fastening, tacking, welding, deslagging, measuring, electrode handling, grinding, rest, and any adjustments for unknown activities. For the parts of the entire weldment, welding time was divided into a common component shared by the entire assembly and an individual component determined by the weld geometry. The assembly time for each part ($t_w$) in an assembly having n separate parts is defined as:

$$
\begin{aligned}
&t_w = \frac{T_{assembly}}{n-1} + t_{part} \\
&where: \\
&t_{part} = t_{insert} + t_{fastening} + t_{tack} + t_{arc} + t_{deslag} + t_{measure} + t_{electrodehandling} + t_{grinding} \\
&T_{assembly} = T_{re-positioning} + T_{setup} + T_{cleaning} + T_{unknown} + T_{rest}
\end{aligned}
\tag{1}
$$

Time components shown in an upper case "T" denote times that are associated with the entire assembly, whereas time components in lower case are functions of the individual weld. The assembly time component ($T_{assembly}$) consists of equipment setup, cleaning, and repositioning required during initial tacking and follow-on welding. In previous work we looked at the application of DFA techniques to weldments, and based on Shreve's definition, introduced a spreadsheet, shown in Figure 1 [8]. The spreadsheet used a cascading series of other spreadsheets to enter information for each welding factor for each part.

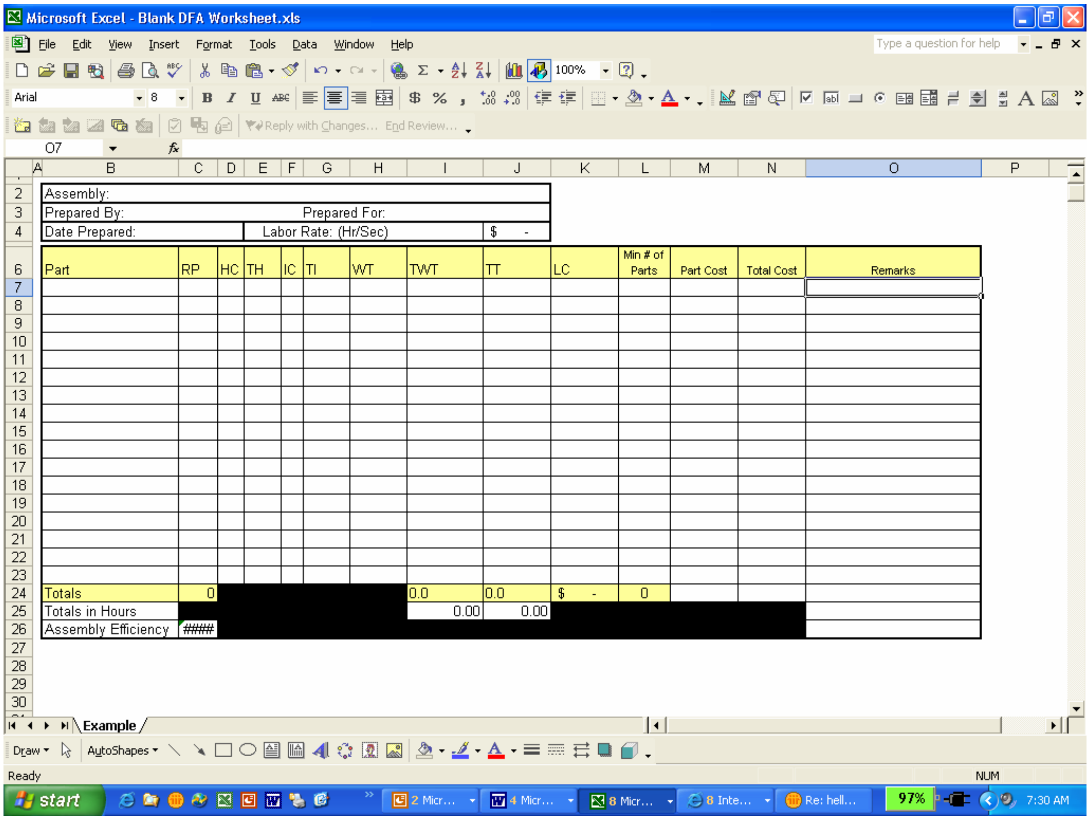


Figure 1. DFA spreadsheet from Rule [8]

This approach gives a good accounting of the assembly effort. It is also good at taking assembly activity for a subassembly and assigning a portion of the time penalty to every part in the subassembly. We have been applying this technique to the industrial projects mentioned above and have found it to be too time consuming for practical use. When applying DFMA in a low production situation one is not allowed to expend too much analysis time because it will significantly detract from possible savings (see section 4 below), so we needed a simpler approach.

We present a modified spreadsheet that simplifies the accounting. We put the primary welding activities directly into the spreadsheet. As shown in Figure 2, columns have been added to address the issues of increased handling and insertion penalties as well as welding and grinding times.

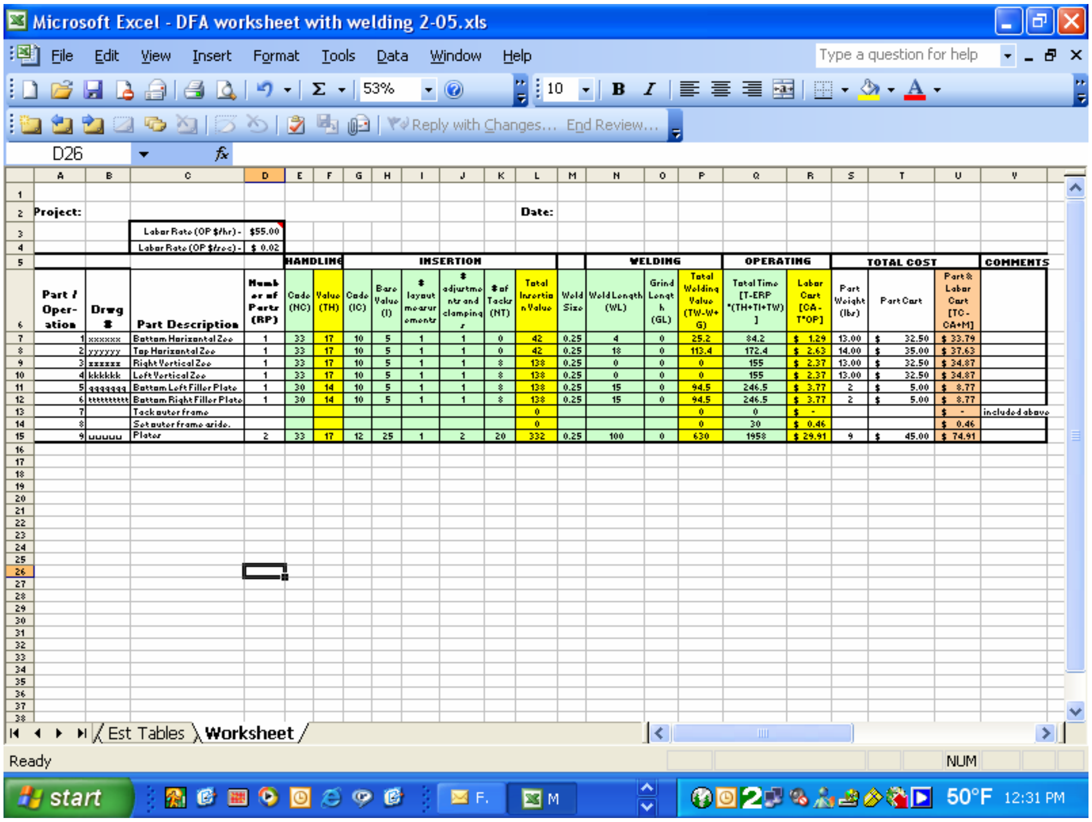


Figure 2. Updated DFA spreadsheet or weldments

The DFA spreadsheet includes handling columns just like traditional spreadsheets but includes an expanded insertion column and welding column. The insertion column tracks time penalties for the number of adjustments and clamping requirements, the number of layout measurements, the number of tack welds as well as a base insertion value. The time required to weld an assembly together depends on variables such as the weld size, total weld length, and grinding time to leave the weld in the proper state for the next process. We also added columns to include the material cost. When evaluating these types of steel structures the cost of the material is equal, if not more than the labor cost.

We deleted the column for tracking if the part is theoretically necessary or not. In these types of structures very few parts can be shown to be theoretically necessary by the traditional screening questions (Botthroyd, et. al, 2002). Theoretically, the basic structure can be made of one piece and whatever other pieces are needed for service and assembly access. Since this type of structure is not practical, we found no value in tracking this metric. We have also deleted the design efficiency metric for the same reason.

So in summary, we list the assembly labor as three parts – handling, insertion, and welding. We further breakdown the insertion process as the traditional insertion time, time to make measurements for laying out the part, time to adjust part position and clamp it in place, and time to tack weld the part in place. We further breakdown the welding time based on the time to lay the weld material and time to grind the weld. All of these times are added to determine an operational time for each part or separate assembly operation. Finally, the cost of the part is added in. Summing the operational and material cost of every part and separate assembly operation results in a cost estimate of the subassembly.

# 3 DFMA Guidelines to Improve Weldments

Guidelines play an important role in both DFA and DFM analysis. The DFA improvement process follows three main steps: simplify the product architecture, replace subsystems with new technologies, and then apply guidelines. Simplification means to consolidate parts and incorporate the functionality of one part into another, usually adjoining part. New technologies are simply different approaches to accomplishing the same function. For example, rather than simplify a mechanical linkage we alternatively replace it with an electrical mechanism. After these two steps, the very nature of the parts is generally set. At this point, the designer would apply guidelines to make improvement to the parts to which you are committed. In DFM, guidelines are also used. DFM guidelines are a primary resource for providing guidance on how to improve the manufacturability of a part [5]. Guidelines are the heuristics, or rules-of-thumb, that designers employ to think of specific changes that make the parts easier to manufacture.

In this paper we will address two guidelines that aid in the manufacture and assembly of weldments. They are (1) to replace multiple member structure with sheets and (2) notch parts to reduce welding time.

## 3.1 Replace multiple-member structures with sheets

In large systems we often encounter structures made of multiple members that are welded together to provide support and location for components. Figure 3 is an example of such a system. The vertical member provides support for system weight and the horizontal supports provide stability and position for the vertical members. The diagonal members accommodate non-vertical loadings. Sometimes the corners are supported by gussets and sometimes just the mass of the weldment is sufficient. This type of structural configuration is popular because it is provides optimal strength for its weight and the material cost is relatively low. However when the cost of assembly for the subassembly is considered, especially when the structure must support other components, the economics are questionable.

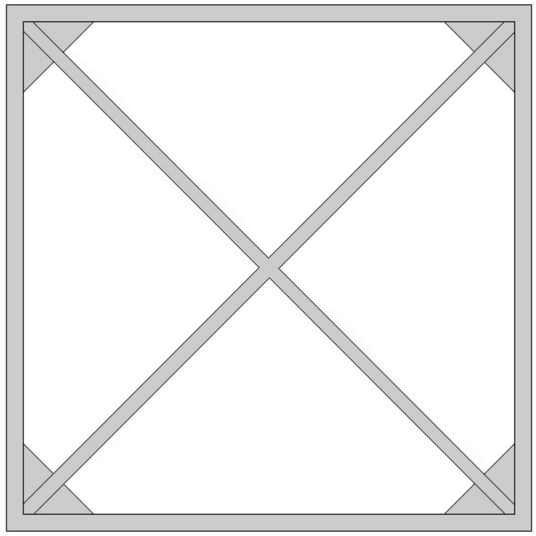

Figure 3. Example of a welded multiple-member frame

One alternative is to replace a multiple-member structure with a sheet. This concept is a special case of the DFA simplification principle to reduce part count by incorporating the functionality of a part into another, existing part. The advantage of a sheet is that the welding is eliminated. Figure 4 shows how many individual parts are replaced by a single sheet. The cutting, coping, fitting, fixturing, welding, grinding, inspection, and so forth has been eliminated. Figure 5 shows two walls perpendicular to each other, replace by a single formed sheet or perhaps welded to a central post. Again, the simplification is dramatic.

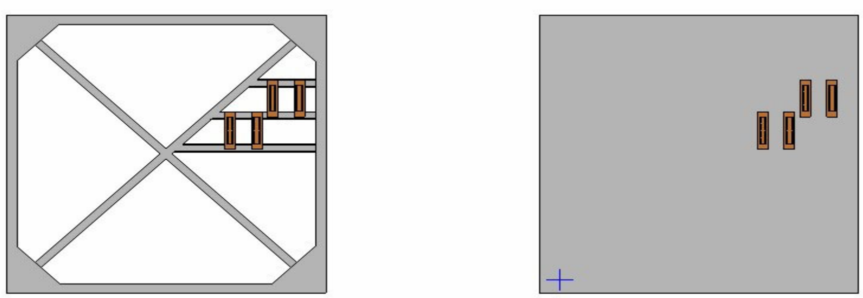

Figure 4. A simple steel sheet replaces the welded frame

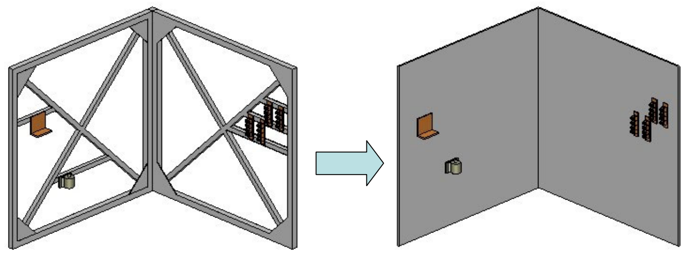

Figure 5. A 90 degree formed steel sheet replaces the welded frame

Applying this guideline can result in several benefits. Primarily, the benefit is the reduction of the number of parts. This change has a big impact on the indirect activity such as handling, purchasing, scheduling, etc. Another benefit is the elimination of welding and the pre- and post-activities that support it. Whenever a multiple-member structure gets made there are numerous pre-welding activities at the work cell. Parts must be measured, positioned, and clamped. If the volumes are high enough to justify the cost, a fixture can be made to streamline some of this activity. After the welding process, the assembly is cleaned and sometimes ground and inspected. Utilizing a sheet simply eliminates all of this activity. There are also problems associated with using a sheet. Primary is the size and weight. Multi-member weldments are very efficient with respect to their strength to weight. When a single sheet is under load it has regions that support the stress and excess material where stress is fairly low. This poor efficiency results in inefficient use of the material (see Figure 3). Another problem can be the handling. If the sheet is large it might require two people to handle it or perhaps a crane. In these cases the handling time for a single sheet may be higher than the total handling time for several structural members. But even if the handling time is longer the total assembly time is usually less. Performance can also be an issue. A sheet is very strong in tension but it could buckle under compression or experience large deflections and vibrations depending on the loading.

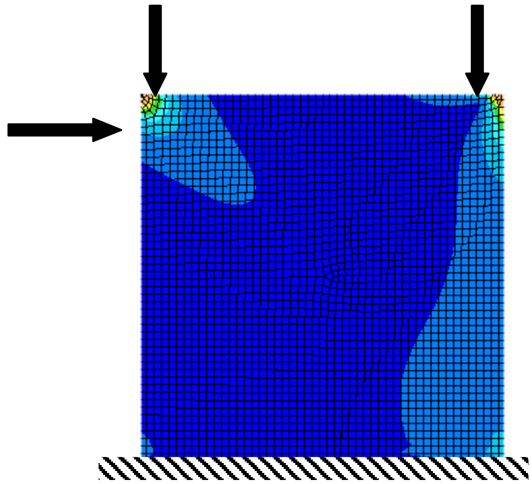

Figure 3. Stress distribution across a sheet

Like any guideline, this one can not be applied blindly. Each situation is different and must be examined to determine if any of these issues will outweigh the benefits. But in many applications a sheet can function with good performance and substitute for a multiple-member structure.

## 3.2 Notch parts to reduce welding time

Weldments, especially in large scale small volume production, tend to be over designed with respect to the loads that must be supported. This is especially true at the welded joint. Often, it is not worth the engineering time to evaluate the stress, especially when a large scale product contains hundreds of welded joints. On observing the welds on hundreds of joints we have noted that most are continuous fillet or bevel welds. There are several good reasons for continuous welds. A common heuristic when joining two parts is to make a continuous weld on both sides, three fourths the part thickness [9]. This process will make the weld as strong, or stronger, than the part itself. If strength is not an issue and the joint is long, sometime one will find an intermittent weld. That is, a weld that is continuous for a specified length and then no weld for a specified length, in a repeating pattern. A continuous weld can also make for a clean joint. If the weld material does not completely seal the joining surfaces of welded members, foreign materials such as dirt and moisture, can get trapped in the crack. This issue is particularly acute when tubing is used for structural members. Continuous welds also provide for an aesthetically pleasing joint. When we think of industrial machine frames and structures a continuous weld can communicate a strong, quality joint.

There is one major disadvantage of the continuous weld – cost. The size of a member is often dictated by spatial constraints, not strength. In these cases the member is larger than strength needs would require. A logical solution is to reduce the size of the surface to be joined. This concept is best explained by the following example (Figure 7). Suppose a bracket is required to support a motor of weight *P*. From a stress point of view, the bracket would ideally be designed as a cantilever beam with a tapered cross section of thickness *a*. However, the motor mounting requirements are such that the beam needs to be of thickness *d*, where $d > a$. The typical engineering solution would be to let the spatial constraint be primary which requires more welding than if strength requirements were primary. An alternative, however, is to use the spatial constraint at the motor mounting region but then reduce the beam size according to the strength constraint at the joining surface. This is achieved by notching the beam. Although, the same effect could be achieved by using an intermittent weld, there are three reasons the notched approach is superior. First, it takes the guess work or measurement work out of the process. When an intermittent weld is specified a welder must pre-score the weld location and length, use a gage, post-measure, or all of these. With a notched surface, a continuous weld can be made along the entire mating surface and no measurements are needed. Second is cleanliness. As mentioned above, a continuous weld eliminates the mating crack that can collect dirt and moisture. And three, there is always a tendency to miss the intermittent weld specification, especially in low volume manufacture. Welders will often just "weld what's there" without referring to the prints. The notched part takes advantage of this human tendency.

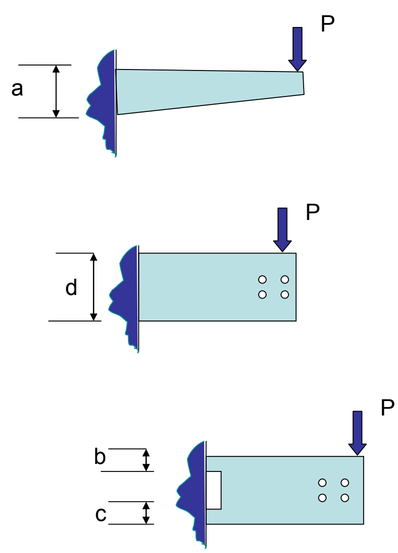


Figure 7. Example of notch concept

There is a drawback to the notched concept, and that is producing the notches. Weldments tend to be made from three kinds of parts: cut structural members, cast or machined shapes, or cut and formed sheet/plate. If structural members are cut to length then the joining surface of the member would require an extra cut. If the member is cut with a laser or other automated equipment, the notched shape can easily be programmed. For a cast part, a reduced surface can also be made a part of the mold. There is little that can be done when welding off-the-shelf parts such as weld nuts, brackets, or studs.

An example of this approach can be seen in the mounting bracket in Figure 8. The size of the bracket is dictated by the size of the space between the mounting holes. Simply cutting the channel to length and welding it on, however, results in an over design with respect to strength. One approach is to call out an intermittent fillet weld along the joining surface. Based purely on strength, a total weld length of 10% or 20% of the joining surface would be adequate depending on actual load expectations. For stability, however, this length would probably need to be divided into three segments, as in Figure 9. While this solution reduces the welding cost it also introduces new problems as discussed above. So the preferred design would be Figure 10. If the bracket is made from a formed, laser cut sheet the manufacturing cost is nearly the same as that of Figure 8. If the bracket is made from a cut piece of stock channel then the extra cost of cutting the stock on a mill or making a double cut with a saw needs to be evaluated.

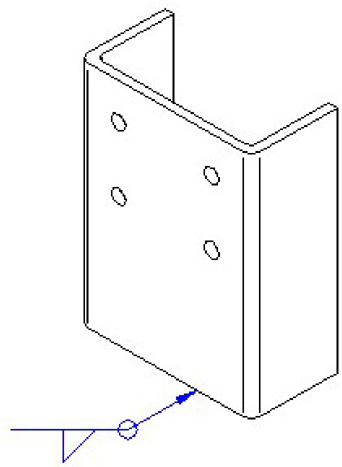

Figure 8. Original mounting bracket

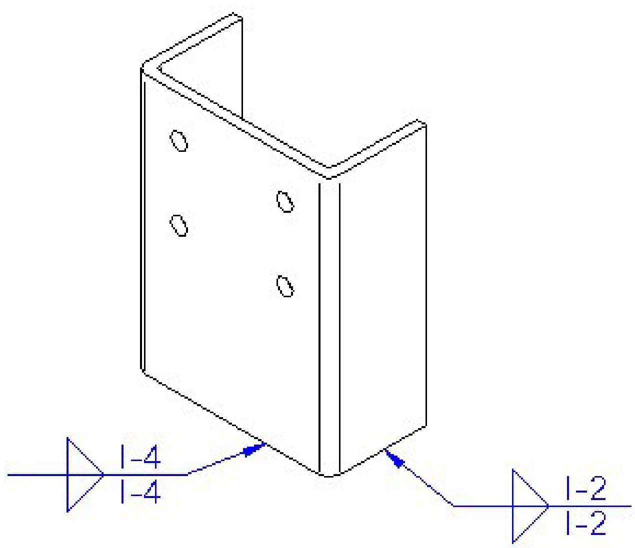


Figure 9. Improved mounting bracket

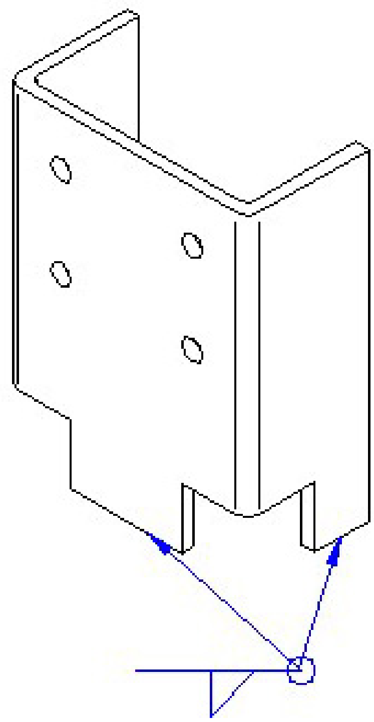

Figure 10.  Preferred mounting bracket design

# 4  Balancing Improvement Savings with Analysis Cost

In the typical applications of DFMA production volumes are high, resulting in great savings for each incremental improvement.  In low volume production, however, the potential savings for design changes must be examined closely with respect to the increased engineering cost.  In some cases the cost to engineer the better design solution may exceed the manufacturing savings.  In these cases, a welded structure that is more expensive to build but less expensive to design is a better solution.  A great deal of the cost benefit analysis will depend on the stage of design.  If DFMA is done up-front during the initial design of the product then the additional analysis cost to implement a DFMA derived design idea are minimal, if at all.  However, nearly all large-scale low volume products are based on a previous design with a customization for a different feature or capability.   New design approaches arising from a DFMA analysis will probably require a change to existing processes.

The analysis costs that need to be considered can take many forms.  Some examples are:

- Engineering costs.  The time taken to go through the engineering analysis of the old design, apply the guidelines, and specify the improved design.
- Reviews.  Time and efforts to present the improvements to management, customers, or production personnel to discuss the suggested changes and outline the potential benefits to be realized.
- Approvals.  Once the design changes have been reviewed, approval must be received by management and, in some cases, internal and external customers.
- Drafting.  The approved design will need to be drafted and modeled, to meet company documentation requirements.

- Purchasing. If necessary, new technologies or materials will need to be located and procured. This may take considerable "shopping around" to find the correct pricing and quantities.
- Process changes. As with any change, production and support staff will need to be aware of the changes and given adequate training to ensure the improved design is produced correctly. This may also require, depending on the improvement, a reevaluation of the current production layout, process, and scheduling, as the improved process will likely affect the time to complete the task.
- Qualification of suppliers. Though not common, there may be design ideas that require the use of a different supplier for the part. In these cases, the supplier will need to be qualified and added to the company's procurement list.

The largest benefit of applying guidelines comes when they are incorporated into the initial design, rather than attempting to retrofit good practices into existing assemblies. This increased benefit is the result of bypassing the unnecessary costs associated with the analysis of an existing design, as much of the analysis costs are basically time to gain approval to make the changes. For an existing product, the cost to design was already spent, requiring additional time, effort, and resources to accomplish the same result that can be produced the first time with the application of the guidelines.

While it is more advantageous to apply the guidelines to the initial designing effort, it is obviously still profitable to improve existing products and designs. The use of a DFA spreadsheet can be useful in examining these costs, and calculating an initial estimation of the likely savings and payback before spending all the time, effort, and money going through additional analysis on an idea that, in the long run, was really not cost effective.

# 5 Conclusion

Current DFA techniques are not easy to apply to large-scale weldments produced in small volumes. However, the general approach is still valid and extremely valuable for reducing assembly cost. We have developed a technique specifically for these types of products and parts. We have also developed design strategies that help one make improvements in the assembly effort for these types of products. Finally, we have provided guidelines that help one determine if DFMA can be economically applied.

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Dr. Larry Stauffer
University of Idaho
College of Engineering
322 E. Front St., Boise, ID 83702
United States of America
Phone:  (208) 364-6180
Fax:  (208) 364-3160
Email:  stauffer@uidaho.edu