AC 2011-1674: CASE STUDY OF COST-EFFECTIVE DESIGN ALTERNATIVES

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A good story is often the best way to relate technical information to students. This paper presents the story of a small company seeking a cost-effective but attractive way to protect the electronic components of its educational robot. The objective of this paper is to inform students, new to the subject of design for manufacturability, about how there is often more than one way to solve a problem. The case study presented in this paper is based upon actual design iterations to solve the problem of shrouding the small mobile robot. Three alternatives are considered: fabrication from laser-cut plastic panels, thermoforming from plastic sheet, and injection molding. An educator could use this paper as a case study for students to teach them about the choices available when determining the best design and corresponding process to make a cost-effective product. Further, the example of a small educational robot is one that will be of interest to many college students.

The three alternatives represented in this paper cover a wide range of manufacturing processes. The fabrication process represents the classic separation-and-assemble approach. Thermoforming is a near net-shaped process that will require some secondary milling operations to create the desired product. Finally, injection molding is the net-shaped process that consolidates material into a single shape that when ejected from the mold is the desired product. The purpose of this paper is to educate the reader about the special tooling required for each process, the intrinsic design benefits each offers, and ultimately what production volumes will determine the most cost-effective design based upon their respective economies of scale. For example, it is shown that the fabrication method with a low initial cost will have higher relative variable costs than the alternatives. Injection molding is the most capital intensive process but has the lowest variable cost.

The paper is richly illustrated with computer-aided renderings of design details related to each process: a layout of the fabrication approach, section views of a thermoformed part and corresponding mold, and section views of the injection molded part and corresponding mold. The merits of each process is annotated in the CAD drawings and summarized in a product feature versus process table. Further, a comprehensive cost summary table is presented to educate the reader about the capital and incremental costs associated with each alternative. The cost factors quoted are based upon actual quotations from companies specializing in making products using the three alternative processes showcased in the paper. Using the data from the quotations, a graphic illustration of the unit cost change with the order size for each process is presented. Such information is used by the designer to determine the most cost-effective method to accomplish the design objective. In summary, the subject matter, the quality visual information, and the comprehensive cost information make this paper a story of interest for a reader wanting to learn about cost-effective design for manufacturability.
This paper is written to provide a case study for an instructor to share with students that addresses the manufacturing process choices a designer must make to solve a problem. It is written in response to what Eggert\textsuperscript{1,2} has identified as a supply gap in academia's coverage of creative methods and design for manufacture and assembly. The thinking behind this paper is similar to the work done by Post and Narayan\textsuperscript{3} when they saw the need for a workbook of open-ended design for manufacturability problems. This case study is based upon a real customer deciding how best to bring a product to market. The cost data presented is based upon actual vendor quotations.

Product design is foremost about satisfying customer needs. There are, however, more than one way to attempt to achieve this. This paper will present three design solutions to the customer need of a housing to contain the workings of a small, educational robot. The customer needs in this case are to provide

- protection to a circuit board,
- a mounting surface for forward facing sensors,
- a mounting surface for motors and additional sensors,
- a mounting surface for an on/off switch accessed from the outside,
- a means to adjust the spacing between some sensors and the ground, and
- a means of opening the container to gain access to the inner components.

The concept that has been developed to satisfy these needs consists of three parts: 1) a five-sided box that has a slanting front surface for the forward sensors, 2) a base plate that is the chassis for the motors, circuit board, and floor sensors, and 3) a plate that fastens to the front surface which allows for adjustment of the space between the front edge of the box and the ground. A photograph of a prototype of this robot housing that meets these needs is shown in Figure 1. The cover for this device has been made by CNC routing sheets of plastic and then gluing them together in the manner of a three dimensional jig saw puzzle. This method is called a fabricated design because all components of the cover are made by cutting sheets into small parts and then gluing them together. The mounting of components onto the cover is achieved by drilling and milling openings in the cover to suit. The base plate and front plate are made by CNC routing as well and assembled with screws. An alternative design for covering the robot components is shown in Figure 16. This cover was made by thermoforming a sheet of plastic into the shape of the cover and then trimming the formed cover to give the cover its final shape as well as introduce holes similar to those put into the fabricated version. There is a third technology that can be used to make this robot housing, injection molding.

The focus of this paper is to illustrate the design advantages of each of these three manufacturing methods which can be used to make this robot housing: fabrication, thermoforming, and injection molding. Cost is an important element of any design decision, thus in addition, the cost factors will be addressed. The product design features possible and the corresponding tooling requirements for each process will be explained through a series of computer-rendered images. The renderings are at a conceptual level, but contain enough information to show the level of complexity involved in making the tooling.

The evolution of the housing design from a set of fabricated parts to a molded cover follows the trend from a material removal process to a net-shaped process to make things. The net-shaped
process has the advantage of making many low cost copies of a product from a mold. The net-shaped process creates parts, once removed from the mold, that require little if any secondary operations to have a finished part. The disadvantage of the net-shaped process is the relatively high initial cost required to design and fabricate the mold and changes are cost prohibitive.

**Fabrication**

The discussion of the design alternatives begins with the pure fabrication method which amounts to cutting and gluing together plastic sheet. Figure 1 is a photo of a working prototype of the subject product. This product is approximately 4 inches long, 3 inches wide, and 2.5 inches tall and is fabricated with 0.125 inch thick sheet stock. Figure 2 illustrates the computer-aided rendering of this design. The contents contained inside the cover are the control and drive components of the robot as shown in Figure 3. The front slanting surface of the cover is used to mount forward looking sensors. For clarity, Figure 4 illustrates the robot housing less the sensors and interior components. The housing consists of several parts that are glued together along with a base plate and blade for sensor adjustment as shown in Figure 5. Some reference dimensions are shown in Figure 5 as well. The six unique parts are shown in Figure 6. Assembly of the cover is done using glue, but the cover and the base plate are attached with mounting blocks and screws as shown in Figure 7. An exploded view in Figure 8 shows this assembly method requires eight screws and four mounting blocks. Two additional screws are used to fasten the blade to the front of the cover.

The process to make the cover begins with a pattern layout that is programmed in a two-dimensional CAD program. A sheet of material, as shown in Figure 9, is then cut with either laser, a water jet, or a router bit using a 2-D CNC capable machine. Figures 10 and 11 illustrate that both the profile of the individual parts and the slots and holes needed in each part are done at the same time with the 2-D CNC cutting machine. After the parts are cut, five parts are assembled to create the cover. The tabs and notches made during the CNC operation are used as the gluing surfaces to assemble the cover parts: top, sides, front, and back. Refer to Figure 12 for an example of the gluing process.

In the design shown, the base plate also has a tab and two notches that are used to align itself with the cover. The cover is not glued to the base plate, but instead fastened to the base plate with a set of eight screws. A small plastic mounting block is used as an intermediary between the cover and the base plate. Four screws hold four connectors to the base plate and four screws then fasten the cover to the four connectors. A total of twelve parts are needed to assemble the cover to the base plate with this design. This is a relatively poor design for assembly solution which will be overcome with the injection molded design shown later.

The labor required to glue the parts together to create the cover is a major shortcoming of the fabrication process. However, the ease of implementing changes to the design of the cover is an advantage. Both the size and shape of the cover are easily modified by changing the 2-D design of the layout pattern. The location of mounting holes and slots are also readily changed the same way.
Forming

A reduction of the labor required to make the cover can be achieved by forming the cover instead of fabricating it. The design for a thermoformed version of this robot housing begins with the profile information shown in Figure 13. The height, length, and pitch of the cover is to be captured in the formed design. However, thermoformed products require draft to facilitate mold release that is not required with the fabrication method. Figure 14 illustrates the draft requirement. In addition, thermoformed products benefit by having corner radii. Figure 15 shows a thermoformed cover intended to substitute for the fabricated version. This cover is placed on the base plate of the fabricated design. As shown in the figure, some of the contents inside now protrude through the cover. This is due to the draft and corner radius requirements of the thermoformed part. Such conflicts can be easily overcome by adjusting the position of the interior components, however, the draft requirement does limit interior space for the formed cover for a given sized base.

As with the fabrication method, the mounting holes for the thermoformed cover are made with CNC, however, now a 5-axis CNC is needed due to the three-dimensional shape of the cover when the mounting holes are made. The switch cutout on the back, the mounting holes and slots for the wheel axle on the sides, and the mounting holes on the front are all made with CNC. These details are shown in Figure 16.

Thermoforming Mold and Trimming Fixture

The labor saving from thermoforming comes at a modest cost. Figures 17 through 26 depict the mold and fixtures that must be designed and fabricated to perform the forming and required trimming. A thermoforming mold is a single mold half that can be CNC machined or cast from aluminum. The sequence of Figures from 17 through 20 depict the thermoforming process using atmospheric pressure to form a heated sheet of plastic. After the sheet is formed, the web of excess plastic shown in Figure 21, must be trimmed away. The trimming and 5-axis CNC machining of the mounting holes is done with a vacuum fixture. Figures 22 through 26 depict the basic design and use of a vacuum fixture for this product. Thermoforming requires the additional capital investment of a mold and a trimming fixture to create a lower labor intensive cover for the robot. However, both the mold and the trimming fixture can be used to make many parts.

Injection Molding

The set-up required to trim the cover can be avoided if the cover is injection molded instead of thermoformed. Figure 27 shows an injection molded version of the cover. The mounting features and other cutouts on the cover are present when the part is removed from the mold. No secondary processes are required. In addition, Figure 28 illustrates another labor saving feature that can be incorporated when molding parts: the assembly of the cover to the base plate is done with only four screws by using molded-in bosses. There is no need for the intermediate connector blocks. Both the fabricated and the thermoformed covers required eight screws and four connector blocks to fasten the cover to the base plate. The injection molded design required only four screws. This design change is both a labor saving and an inventory cost saving innovation. Again, this advantage does not come at no cost. The design time and fabrication
requirements for an injection mold are some of the highest in the manufacturing industry. However, if done well, injection molding results in lower piece part cost for products that are made in enough volume to justify the initial investment.

**Injection Mold Design**

Injection molding, unlike thermoforming, requires two mold halves to be made. The air space remaining between the mold halves when they close creates the molded part. A computer-aided rendering of the lower mold half, the B plate, is shown in Figure 29. This plate forms the interior detail of the cover while the mating plate, the A plate, defines the exterior of the cover; refer to Figure 30. The cutout features of the part, slots and holes, are made by mold features placed primarily on the B plate as shown in Figure 29. Four unique mold features are used.

1. Kiss offs create slots.
2. Core pins create the mounting holes.
3. Core pins and tapered pockets create molded-in bosses for assembly.
4. Side action creates the cutout for the switch on the back.

Figure 31 illustrates how the side action closes when pushed by a cam pin placed in the A plate. Figure 32 shows the closed mold prior to and following injection with molten plastic. The molded part prior to mold ejection is shown in Figure 33. The kiss off, metal to metal contact between the A and B plate, is a common hole forming feature with injection molding. A detail of this feature is shown with a section view in Figure 34.

Another advantage of injection molding is that all the parts needed for the housing assembly can be made during the same molding cycle. The resulting family mold is depicted in Figure 35. This practice naturally lends itself to good inventory control as only parts needed to complete an assembly are made.

**Evolution of Designs**

The evolution from a fabricated cover to a formed cover to a molded cover is summarized in Figure 36. The shapes of the thermoformed and injection molded covers are similar but the molded cover required no secondary operations. Another way to view the evolution is to look at how the manufacturing process for the cover changed from being 100% material removal, to approximately half material removal, to no material removal. The molded cover is a net shape process, depicted in Figure 37. The advantage of having no secondary operations comes at the price of a loss in flexibility to change features such as mounting locations. Figure 38 summarizes the evolution of the critical design elements going from fabrication to molding.

**Economics of Production**

Price is a critical driver for choosing one production method over another. The switch over points for the unit cost of a product as the volume of production increases are shown in Figure 39 for the three processes of this study. The reason injection molding is so competitive at higher volumes is because the stock materials to mold parts are lower in cost than for fabrication and thermoforming. Molding uses plastic pellets. The alternative processes use sheet stock which has
a higher cost per pound because sheet stock is made by processing pellets. The other major advantage for molding is the absence of secondary processes to have a part ready to use or assemble. Finally, molding is a highly automated process where in many cases pellets go into the molding area and parts are conveyed out with little if any labor intervention.

The key to the success of molding lies at the economies of production. The unit cost of a product is a primary driver in selecting a design. The unit cost is the total cost to produce products divided by the number of products made. Total cost of production includes a fixed cost and incremental costs. Fixed costs, in the context of manufacturing the robot housing, are the design and tooling fabrication costs. Incremental costs are the cost for material, labor, and amortizing of the special machines needed to make the products. This latter cost is called the machine rate.

\[
\text{Unit Cost} = \frac{\text{Total Cost}}{\text{Quantity Made}} \tag{1}
\]

\[
\text{Total Cost} = \text{Fixed Cost} + \text{Incremental Cost} \times \text{Quantity Made} \tag{2}
\]

\[
\text{Unit Cost} = \frac{\text{Fixed Cost}}{\text{Quantity Made}} + \text{Incremental Cost} \tag{3}
\]

The quotations from various vendors to fabricate, thermoform, or mold the robot housing components resulted in the following cost items:

<table>
<thead>
<tr>
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<th>Fixed Costs</th>
<th>Incremental Costs</th>
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<tr>
<td>Fabrication</td>
<td>$208</td>
<td>$7.38/ea</td>
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<tr>
<td>Thermoforming</td>
<td>$3,000</td>
<td>$3.00/ea</td>
</tr>
<tr>
<td>Molding</td>
<td>$15,000</td>
<td>$.075/ea</td>
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</table>

The fixed costs for the fabrication approach is the time to design a two-dimensional lay flat pattern of panels that can be glued together. There are no special tooling requirements except for a vacuum table to hold the sheet while it is cut. A low cost fixture may be built to facilitate the gluing of parts for the cover. Thermoforming requires the design of a single-sided mold and a trimming fixture. Thermoforming molds can be made of composite wood for short runs and cast aluminum for larger volume runs. Trimming fixtures are typically cast rigid foam that can hold the formed part using vacuum. Finally, injection molding which saves so much on labor costs once the part is made requires an extensive level of design and complex machining to make the two mating mold halves. The tolerances required when designing and building an injection mold are some of the most demanding of all the plastic processing technologies. Further, injection molding involves very high pressures which require the molds be made of high strength steel. Mold inserts can be made of aluminum to reduce the cycle time for cooling. Injection molding has fixed costs that are orders of magnitude higher than any fabrication process and about an order of magnitude higher than tooling costs for thermoforming.

The cost data depicted in Figure 39 is the unit cost as the market demand, or order size, increases. The shape of the unit cost function is hyperbolic with the asymptote becoming the
incremental cost. Molding does best at large volumes because of the relatively lower material cost and net-shape processing. These lower unit costs, however, are not achieved until several thousand products are marketed due to the very high initial cost of the tooling. This is why thermoforming with its lower capital investment and flexible modification options might prove most attractive to a product like this which might have market sales in the few thousands. Thermoforming offers some of the benefits of net-shaped manufacturing with the flexibility of a pure fabrication process.

Conclusion

Although injection molding appears to be the lowest cost process to make the housing, it is not necessarily the best method for the product in question. The question of market sales has yet to be answered. Further, the agile nature of the fabrication and forming methods to making slight product design changes throughout the product's history might prove valuable to the company developing the product. The final decision will be made after the company's team of designers and marketing representatives have reviewed the summary of the design alternatives presented in Figure 40. This team will review again the unit cost data and reflect upon the pros and cons of each design option to arrive at an optimal choice for their product.

It is hoped the reader of this paper will have a better appreciation of the economics of production and the product design choices that exist between pure material separation and net-shaped manufacturing processes.

References


Figure 1. Photograph of prototype robot housing made with fabrication method.

Figure 2. Computer-aided design of robot cover made by cutting and gluing sheet stock.
Figure 3 Contents protected by cover.

Figure 4 Parts made to house components.

Cover requires 8 glue joints to assemble. 8 screws needed to fasten Base Plate to Cover.

Cover made of glued together Top Plate, Front Plate, 2 Side Plates, and Back Plate.

Sensors mount to Front Plate.

Blade (sensor adjustment).

Blade and Base Plate fasten with screws.

Base Plate (motor mounts, cover mounts, floor sensors).

Sheet stock 1/8" thick.

Figure 5 Fabricated robot housing is five glued parts, a Base Plate, and a Blade.
Figure 6 A total of seven parts are fabricated for robot housing.

Figure 7 Mounting blocks used to connect cover to base plate.

Mounting blocks holds cover to base plate.
Figure 8 Assembly hardware for fabrication method: 12 parts.

Figure 9 Fabrication begins with a blank, a sheet of .125 thick ABS plastic.

Assembly of Cover to Base requires four mounting blocks and eight screws.

Blade requires two screws.
Figure 10 Blank is CNC trimmed to create slots, holes, and perimeter with notches and tabs.

Figure 11 Trimmed blank CNC cut into individual parts with tabs and notches.

Figure 12 Cover assembled by gluing tabs to notches
Figure 13 Side Plate captures critical housing features: height, length, and pitch.

Figure 14 Draft is required when parts thermoformed or injection molded.

Figure 15 Formed cover replaces fabricated cover: draft causes controller board to protrude.
Figure 16  a) Thermoformed cover back view, b) Thermoformed cover front view

Figure 17 Forming setup

Figure 18 Section view of forming setup

Figure 19 Mold contacts sheet

Figure 20 Sheet vacuum formed into cover
Formed cover with web

Vacuum trimming fixture

Formed sheet on trim fixture

Section view of vacuum fixture

Web trimmed from cover

Trimmed thermoformed cover
Figure 27 Injection molded version of cover: mold features create holes during molding.

Figure 28 a) Molded bosses facilitate assembly, b) Base Plate fastens to bosses
Figure 29 Critical features of one-half of an injection mold that create holes in cover.

Figure 30 Cavity between the A and B plates define molded shape.
Figure 31 Injection molding side action that forms undercut feature is driven by cam pin.

Figure 32 a) Closed mold ready for plastic injection, b) Molded part with runner
Figure 33 Molded part ready for mold ejection, highlighting openings created by kiss offs.

Figure 34 Section view of mold to show metal to metal contact, Kiss Off, creating slot
Figure 35 B plate for injection molding showing all parts molded: cover, blade, and base plate.
Figure 36 Design alternatives for robot housing.

Figure 37 Design evolution toward net-shaped manufacturing.
Figure 38 Evolution of design elements in covers.
Figure 39 Switch over points for fabrication to forming to molding.
# Manufacturing Process Options

<table>
<thead>
<tr>
<th>Process Name</th>
<th>FABRICATE</th>
<th>FORM</th>
<th>MOLD</th>
</tr>
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<tbody>
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<td>Forming &amp; Separation</td>
<td>Molding</td>
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<td><strong>CAD planning</strong></td>
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<td>CAD of Molded Part,</td>
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<td>Fabricate Mold and Trim</td>
<td>Fabricate A and B plates**</td>
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<td><strong>Preparation</strong></td>
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<td>CNC machine 2 mold</td>
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<td></td>
<td></td>
<td>fabricate trim fixture</td>
<td>halves &amp; mold actions</td>
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<td><strong>Fasten Base to</strong></td>
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<td>8 screws, 4 mounting blocks</td>
<td>4 screws, fasten into molded bosses</td>
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<td><strong>Cover</strong></td>
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<td><strong>Shape of Housing</strong></td>
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<td>made by mold shape,</td>
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<td></td>
<td></td>
<td>cannot change</td>
<td>cannot change</td>
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<td><strong>Sensor Mounting</strong></td>
<td>made by CNC, easy to change</td>
<td>made by CNC, easy to change</td>
<td>made by mold action,</td>
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<td><strong>Locations</strong></td>
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<td><strong>Repeatable shape</strong></td>
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<td><strong>Special Design</strong></td>
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<td><strong>Design Advantages</strong></td>
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<td>Less labor and more</td>
<td>Tightest tolerances on shape and</td>
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<td></td>
<td></td>
<td>repeatable shape.</td>
<td>mounting features.</td>
</tr>
<tr>
<td></td>
<td>Easiest to change mounting options.</td>
<td>Retains easy to change</td>
<td>Lowest assembly labor due to to</td>
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<td></td>
<td></td>
<td>mounting options.</td>
<td>molded-in bosses.</td>
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<td></td>
<td></td>
<td></td>
<td>Lowest inventory for</td>
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<td></td>
<td></td>
<td></td>
<td>assembly (only 4 screws)</td>
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<tr>
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<td>Draft limits head space for same base plate.</td>
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<td></td>
<td>High inventory (part count) for assembly.</td>
<td>Wall thickness can vary.</td>
<td>Very costly start-up costs.</td>
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<td></td>
<td>Highest assembly labor cost.</td>
<td>Moderate assembly cost.</td>
<td>Mounting option changes impractical.</td>
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Figure 40 Summary of manufacturing options for housing.