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# HEDGE STRATEGIES FOR PLASTICS PART DESIGN

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## Abstract

Risk is inherent in the production of any molded part stemming from, for example, changes in production quantities, uncertainty in molding behavior, redefined product specifications, failures in equipment, and abandoned supplier relationships, and other causes. This paper provides several strategies for hedging these risks by considering the cost of the changes to correct different failure modes in the design. The objective is to improve product performance while reducing time to market and risk.

## Introduction

Continued global competitiveness has increased standards for product quality and performance while requiring reduced product development time and unit cost. In this modern manufacturing paradigm, the efficient development and delivery of robust product and process designs can differentiate the market leader from the follower. The increasing level of competition is evidenced by many trends in the product development: reduction of typical product development time by 10% per year [1]; increasing mass customization and proliferation of product variety [2]; increasing reliance on electronic design and manufacturing environments [3]; continued global dispersion of the product development team [4]; and continued horizontal outsourcing of production. It is not uncommon for 80% of a company's revenue to be derived from products that are less than two years old [5].

### Six Sigma

Six Sigma initiatives have been, and are continuing to be, introduced by many companies as a competitive strategy [6-8]. Generally, Six Sigma programs are believed to provide employees with a heightened sensitivity to quality as well as a rational framework for measuring and improving quality while controlling costs. As such, companies implementing Six Sigma anticipate more robust and desirable products fueling revenue growth while improving profitability through internal productivity gains as well as cost and warranty reductions.

Perhaps the most fundamental tenet of Six Sigma, from which the name is derived, is that six standard deviations of performance should be maintained between the performance mean and the closest specification limit as shown in Figure 1. In the development of Six Sigma, there are two somewhat different philosophies for achieving Six Sigma [9]. First, it has been argued that Six Sigma is necessary in large systems containing many opportunities for defects. Since the system may fail with any given component, reliability theory states that the defects per million opportunities (DPMO) must be extremely low to achieve reasonable yields in production, typically greater than 95%. A second philosophy in Six Sigma pertains to the product development process and ensuring long term stability in the product quality. Specifically, Six Sigma can permit a long term shift of three sigma in the mean or specifications while ensuring three sigma for short term, random variation. As such, a 99.87% yield should be achieved 99.87% of the time.

### Cost of Quality

In plastic part development, the term "optimal" implies more than robust performance. First, the manufactured product must not only meet the requirements of the end-user, but should also be produced efficiently, with minimal cycle time, energy consumption, and material consumption. While the first condition strongly encourages robust performance, the second criterion provides a practical limit on the desirability of that robustness. Specifically, it is desirable to minimize the total system cost, which is a function of 1) the marginal cost, $C_{product}$, of the plastic product; 2) the yield, $P$, of acceptable parts, and 3) the marginal cost, $C_{failure}$, of producing a defective product:

$$C = \frac{C_{product}}{P} + (1 - P) \cdot C_{failure} \qquad (1)$$

These concepts have been well investigated in the management sciences [10, 11]. A trade-off is needed in developing robust products that result in low defect costs yet do not incur excessive compliance costs in fulfilling the product specifications. Figure 1 illustrates these concepts. In general, defect costs will approach zero as quality levels approach 100%. However, such increases in quality levels frequently require increased investment, material consumption, processing time, and inspection such that the compliance costs may increase dramatically at very high quality levels. As such, a good design provides a wide selection of trade-offs with ample opportunity to remedy defects without excessive increases in product costs.

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## Pareto Optimality: The Efficient Frontier

The “efficient frontier” is a term used to imply that one aspect of a design, process, or system can not be improved without adversely affecting other important aspects. This is also called Pareto optimality. It is rarely possible to provide continually increasing performance and continually decreasing costs. Any such gains made from “continuous improvement”, are typically achieved by reducing the inefficiency currently in a system.

Consider the design space of Figure 2, in which the designer is considering what thickness to select for a molded part. In this case, the customer prefers a product that is stiff and low cost, corresponding to the upper left of the figure. The shaded area represents the design space with the available feasible designs by changing a combination of different parameters. By changing thickness and other design parameters, the designer can approach the efficient frontier in the design space.. As the thickness decreases, less material is used and results in a lighter, lower cost product. At some point, however, the part becomes difficult to mold increasing the cost, and at too thin a wall the product becomes unacceptable due to lack of stiffness.

The designer must make a decision that incorporates their knowledge of these critical constraints and select a thickness that is feasible to mold, not too expensive, and is fit for use. By changing thickness and other design parameters (e.g. adding ribs), the designer can improve stiffness and/or cost by approaching the efficient frontier.

## Uncertainty and Risk

Awareness of the efficient frontier can help the decision maker to improve their product by increasing performance or reducing costs. In practice, however, it is not possible to precisely know the boundaries of the efficient frontier and operate at a truly efficient point. This may seem surprising, but it is true for at least three reasons. First, consider that most products have multiple specifications. While many of the specifications are stated explicitly as objective measures of performance, there are many others that are qualitative or not even stated. As such, it is difficult or impossible to exactly identify every constraint in the system. Designers must frequently rely on subjective measures of performance.

Second, knowledge of the product behavior is limited, and will lead to errors in decisions. In the previous example, consider that the thickness affects the material cost, injection pressure, clamp tonnage, yield, aesthetics, shrinkage, stiffness, strength, and many other attributes. Characterizing the behavior of all these performance attributes as a function of thickness and every other factor would be a costly and time-consuming task, only reducing but not eliminating behavioral uncertainty. As such, estimates and safety factors are frequently utilized to ensure that the product requirements are satisfied.

Third, the designer must make final design decisions that balance all the different requirements according to their best estimates. The quality of the final design will depend on their knowledge of the requirements and design behavior, as well as their experience and awareness of customer preferences. As such, the designer may produce a design that isn’t quite what the customer wanted in terms of performance or cost. Design iterations across product generations are frequently needed to improve the perceived quality of the product while reducing costs.

The underlying issue in approaching the efficient frontier is the uncertainty of information, which results in a fuzzification of the decision making problem. The experienced designer will recognize when and what information is needed to make a reasonable decision based on information gained from, for example, analysis, simulation, experimentation, prototyping, etc. in order to reduce the fuzziness of the design problem.

Fundamentally, there is a trade-off to be made between knowledge, risk, performance, and cost as shown in Figure 3. With greater uncertainty, the efficient frontier becomes less defined, with unclear objectives, boundaries, and design behaviors. In the absence of any extrinsic information, the probability of a successful design is entirely dependent on the experience of the designer and his/her willingness to take risks. Of course, a failure may provide valuable information to the designer and lead to new, better design approaches in the future. The designer must weigh the difficulty of the design with their skill, cost of failure and the cost of acquiring needed information to avoid failure.

## Hedging

Nearly all plastic products can be improved with respect to performance and/or cost. For example, there may have been a more suitable but lower cost resin that could have been used. Alternatively, the part design might have been improved to reduce weight or increase stiffness. Perhaps the mold design could have utilized more cavities in the mold, or utilized a more efficient feed system. Maybe the processing could have been optimized to reduce cycle time and scrap. The reality is that performance can often be increased, and costs can often be reduced through better decision making.

The performance and cost of the products is closely tied to the knowledge and risk tolerance of the product development team. For instance, a very knowledgeable designer who was willing to undertake some risk might provide a design with one-half the marginal cost of a less experienced designer. Depending on the design, the lower cost design might or might not have a higher risk of failure than the higher cost design. The important issue, then, is what the corrective actions and costs are in the event of an unsuccessful design.

The concept of a “hedge” is useful in design. A “hedge” is defined [12] as “3a: a means of protection or defense, b: any of several means of protection against financial loss, as (1): a bet made against the side or chance already bet on (2): a purchase or sale made not primarily for income or profit but as protection against a known risk.” Thus, the designer can provide hedging mechanisms in the design to correct a failure mode, with the expectation that they later can reduce the cost of the hedge if possible.

From a modeling viewpoint, the expected cost of a product with and without a hedge can be directly compared using equation 1, with differing coefficients for the marginal product and failure costs as well as probability of failure. The expected change in marginal cost of a design including the hedge can be evaluated by subtracting the cost of non-hedging design, $C^{no\ hedge}$, from the cost of the hedging design, $C^{hedge}$:

$$\begin{aligned} E(\Delta C) &= C^{hedge} - C^{no\ hedge} \\ &= \frac{C_{product}^{hedge}}{P^{hedge}} + \left(1 - P^{hedge}\right)\cdot C_{failure}^{hedge} \qquad (2) \\ &- \frac{C_{product}^{no\ hedge}}{P^{no\ hedge}} + \left(1 - P^{no\ hedge}\right)\cdot C_{failure}^{no\ hedge} \end{aligned}$$

Clearly, a hedge is only desirable if the expected cost is less than zero. Such an outcome is likely if the cost of the product with the hedge is not significantly more than the cost of the product without the hedge, but the probability and/or cost of failure of the product with the hedge is less than the probability and/or cost of failure of the product without the hedge. Hedging is not always a simple task, since it requires the estimation of failure probabilities as well as the selection of corrective measures if a failure arises or if cost-saving measures are feasible.

## Common Hedge Strategies

There are many strategies to hedge a design in plastic product development, including: selection of injection molding vs. other processes, supplier payment terms, “steel safe” practices, number of molds, number of cavities, resin selection, temperature selection, clamp tonnage selection, wall thickness selection, number and location of gates, use of painting, hot runner system, use of mold changes, use of stiffeners, and many others.

To demonstrate the concept of hedging, consider a medium volume, consumer electronics product that requires a top and bottom housing measuring 300 mm in length, 200 mm in width, and 100 mm in height. The number of assemblies to be produced is 200,000. This example requires three design decisions, wall thickness (1.6 vs. 2.0 mm), material selection (commodity vs. engineering resin) and number of molds and cavities (1 mold with 4 cavities, two top and two bottom housing; 2 molds with 2 cavities, one top and one bottom housing; or 4 molds with 1 cavity, either one top or one bottom housing) as shown in Figure 4.

Next, the cost, clamp pressures, and stiffness for each of the 12 designs have been evaluated using a Java cost estimator[13]. The design of experiments and results are provided in Table 1. Also shown in the table are the averages and standard deviations for the marginal cost, fill pressure, and flexure strength of the different design alternatives. As shown in Table 1, the marginal costs vary from a low of \$1.03 for design number three to \$2.13 for design number twelve. Clearly, the skill of the designer will play a large role in the profitability of the product.

It is generally preferable to select the lowest cost design that best satisfies the customer requirements. The designer must select which design to utilize, understanding that the design may be adjusted to remove unnecessary cost or improved to correct performance deficiencies. For instance, design number two may be changed to design number one by utilizing a commodity resin rather than an engineering resin if lower flexure strength is allowed. Similarly, design number two may be changed to design number eight by increasing the wall thickness to reduce fill pressure from 196 to 157 MPa. However, such corrective actions incur costs to perform as shown in Figure 4. For instance, trialing and qualifying a different resin may cost \$2,000. As motivated by steel safe practices, changing the wall thickness from 1.6 mm to 2.0 mm may cost 10% of the initial mold cost, while changing the wall thickness from 2.0 to 1.6 mm may cost 20% of the initial mold cost. Purchase prices for the different mold configurations are also shown in the figure.

The best design is ultimately tied to the final performance requirements of the application. If there was no uncertainty, then the designer could simply scan the list and select the most appropriate, lowest cost design. In most product development efforts, however, there is always uncertainty regarding the performance of the design and customer requirements. Table 2 provides three different scenarios of increasing difficulty with respect to flexure strength, injection pressure, and mold breakdown. The designer now has to choose a design based on the likelihood that an easy scenario is expected in 25% of the time, the medium scenario is expected 50% of the time, and the hard scenario is expected the remaining 25% of the time. Of course, this scenario itself is also be subject to uncertainty.

To select the design, the designer must consider the strengths and weaknesses of each alternative, as well as the actions and related costs of changing each alternative if the application is easier or harder than expected. Table 3 provides the corrective actions for each of the design alternatives in the easy, medium, and hard scenarios. For every design alternative, the authors have indicated in bold what actions the designer would need to make to provide the lowest cost design that meets the requirements. For instance, the cost of design two could be reduced from \$1.70 to \$1.40 by switching from an engineering resin to a commodity resin while meeting the relaxed stiffness requirements of the easy scenario. As another example, the cost of design two must be increased from \$1.70 to \$2.02 to increase the wall thickness to provide greater stiffness required in the hard scenario. It should be noted that these costs include the cost of the corrective actions and, as such, design two is not as economical as design one in the easy scenario or design eight in the hard scenario. Designs one and eight had similar mold configurations as design two, but were more suitable for the varying requirements of the different scenarios.

For each of the scenarios, the design alternative with the lowest cost has been highlighted. The costs range from a low of $1.03 for the easy scenario to $1.11 for the medium scenario and $1.46 for the difficult scenario. This example provides the following conclusions:

- First, there is a different ‘best’ design alternative for each scenario. This could be expected, since the ‘best’ design alternative is the lowest cost design that exactly satisfies the requirements of each scenario and does not require any changes.
- Second, the cost of the plastic product will vary substantially based on the exact needs of the application. This simple example suggests that the costs of a plastics product may fluctuate by 30% given changes in thickness and material alone, justifying the fine tuning of the final design in pre-production trials.
- Third, the selection of the best design early in product development is not a simple task. For this simple case study, several hours of design and analysis were required to consider the adjustments for each design alternative to best satisfy each scenario.
- Fourth, the mold configuration was never changed across the design scenarios since the high purchase cost of a new mold could not be amortized. The wall thickness was changed in 36% of cases to reduce cost or reduce fill pressure or increase flexure strength; the resin was changed in 50% of cases for similar reasons.
- Fifth, the best overall design, alternative number nine, did not have the lowest cost for the easy scenario. However, it had the lowest cost for the medium scenario and the second lowest cost in the hard scenario.

## Conclusions

The final cost of a plastic product is dependent on part performance and requirements that may not be known until the end of the product development cycle. (The authors note that prices may be fixed in the quoting process, another hedge strategy to transfer uncertainty in cost and performance to the supplier.) In the face of this uncertainty, the product development team has a significant role regarding profitability. Hedging provides a mechanism for correcting an insufficient design if a failure arises, or for reducing costs if requirements can be relaxed. The best hedge strategies are those that do not incur much cost but can provide substantial changes in performance and cost.

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Table 1: DOE factors and responses

| Design | Wall | MxC | Resin | Cost | Pres | Flex |
|---|---|---|---|---|---|---|
| 1 | 1.6 | 1x2+2 | Com | 1.39 | 178 | 1.00 |
| 2 | 1.6 | 1x2+2 | Eng | 1.70 | 196 | 1.40 |
| 3 | 1.6 | 2x1+1 | Com | 1.03 | 163 | 1.00 |
| 4 | 1.6 | 2x1+1 | Eng | 1.30 | 179 | 1.40 |
| 5 | 1.6 | 4+1 | Com | 1.72 | 148 | 1.00 |
| 6 | 1.6 | 4+1 | Eng | 2.09 | 163 | 1.40 |
| 7 | 2.0 | 1x2+2 | Com | 1.41 | 142 | 1.56 |
| 8 | 2.0 | 1x2+2 | Eng | 1.74 | 157 | 2.19 |
| 9 | 2.0 | 2x1+1 | Com | 1.11 | 130 | 1.56 |
| 10 | 2.0 | 2x1+1 | Eng | 1.41 | 144 | 2.19 |
| 11 | 2.0 | 4+1 | Com | 1.74 | 119 | 1.56 |
| 12 | 2.0 | 4+1 | Eng | 2.13 | 131 | 2.19 |
| | | | Average | 1.58 | 154.00 | 1.54 |
| | | | St. Dev. | 0.37 | 22.86 | 0.45 |

Table 2: Failure modes and probabilities

| | Scenarios | | |
|---|---|---|---|
| **Difficulty** | Easy | Medium | Hard |
| **Likelihood** | 25% | 50% | 25% |
| **Max Pressure** | 196 | 163 | 157 |
| **Min Flexure** | 1.0 | 1.4 | 1.8 |
| **Cavity Failure Rate** | 0 | 0 | 25% |

Table 3: Corrective actions of hedged designs for easy, medium, and hard scenarios

| | Original | | | | Easy | | | | Medium | | | | Hard | | | | **Expected** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Run** | **Wall** | **MxC** | **Resin** | **Cost** | **Wall** | **MxC** | **Resin** | **Cost** | **Wall** | **MxC** | **Resin** | **Cost** | **Wall** | **MxC** | **Resin** | **Cost** | **Cost** |
| 1 | 1.6 | 1x2+2 | Com | 1.39 | 1.6 | 1x2+2 | Com | 1.39 | **2.0** | 1x2+2 | Com | 1.49 | **2.0** | 1x2+2 | **Eng** | 2.03 | 1.600 |
| 2 | 1.6 | 1x2+2 | Eng | 1.70 | 1.6 | 1x2+2 | **Com** | 1.40 | **2.0** | 1x2+2 | **Com** | 1.50 | **2.0** | 1x2+2 | Eng | 2.02 | 1.605 |
| 3 | 1.6 | 2x1+1 | Com | 1.03 | 1.6 | 2x1+1 | Com | 1.03 | **2.0** | 2x1+1 | Com | 1.19 | **2.0** | 2x1+1 | **Eng** | 1.60 | 1.253 |
| 4 | 1.6 | 2x1+1 | Eng | 1.30 | 1.6 | 2x1+1 | **Com** | 1.04 | **2.0** | 2x1+1 | **Com** | 1.20 | **2.0** | 2x1+1 | Eng | 1.59 | 1.258 |
| 5 | 1.6 | 4+1 | Com | 1.72 | 1.6 | 4+1 | Com | 1.72 | 1.6 | 4+1 | **Eng** | 2.10 | **2.0** | 4+1 | **Eng** | 2.22 | 2.035 |
| 6 | 1.6 | 4+1 | Eng | 2.09 | 1.6 | 4+1 | **Com** | 1.73 | 1.6 | 4+1 | Eng | 2.09 | **2.0** | 4+1 | Eng | 2.21 | 2.030 |
| 7 | 2.0 | 1x2+2 | Com | 1.41 | 2.0 | 1x2+2 | Com | 1.41 | 2.0 | 1x2+2 | Com | 1.41 | 2.0 | 1x2+2 | **Eng** | 1.95 | 1.545 |
| 8 | 2.0 | 1x2+2 | Eng | 1.74 | **1.6** | 1x2+2 | **Com** | 1.56 | 2.0 | 1x2+2 | **Com** | 1.42 | 2.0 | 1x2+2 | Eng | 1.84 | 1.560 |
| 9 | 2.0 | 2x1+1 | Com | 1.11 | 2.0 | 2x1+1 | Com | 1.11 | 2.0 | 2x1+1 | Com | 1.11 | 2.0 | 2x1+1 | **Eng** | 1.52 | **1.213** |
| 10 | 2.0 | 2x1+1 | Eng | 1.41 | **1.6** | 2x1+1 | **Com** | 1.20 | 2.0 | 2x1+1 | **Com** | 1.12 | 2.0 | 2x1+1 | Eng | 1.46 | 1.225 |
| 11 | 2.0 | 4+1 | Com | 1.74 | 2.0 | 4+1 | Com | 1.74 | 2.0 | 4+1 | Com | 1.74 | 2.0 | 4+1 | **Eng** | 2.14 | 1.840 |
| 12 | 2.0 | 4+1 | Eng | 2.13 | **1.6** | 4+1 | **Com** | 1.89 | 2.0 | 4+1 | **Com** | 1.75 | 2.0 | 4+1 | Eng | 2.13 | 1.880 |
| Average | | | | 1.577 | | | | 1.435 | | | | 1.510 | | | | 1.893 | 1.587 |

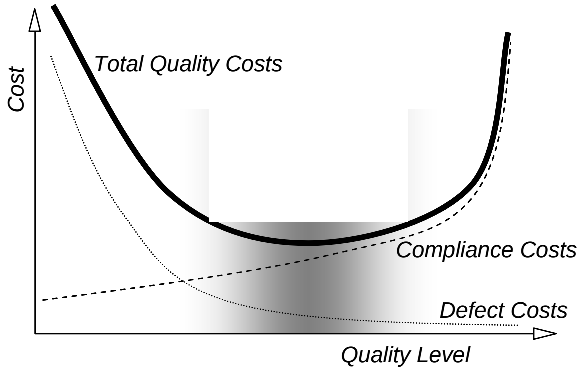

Figure 1: Model of defect & compliance costs

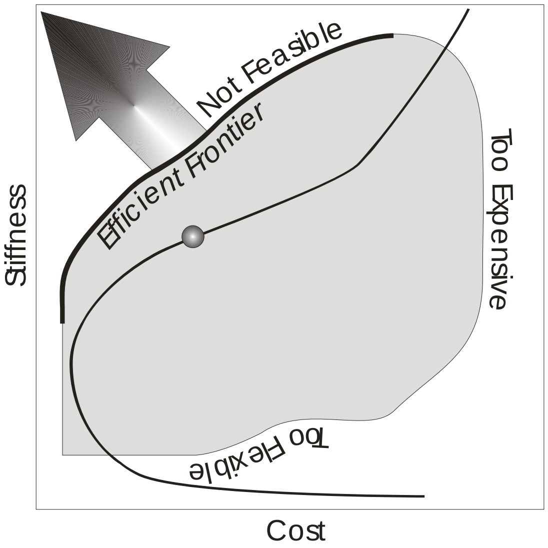

Figure 2: Efficient frontier in a design problem

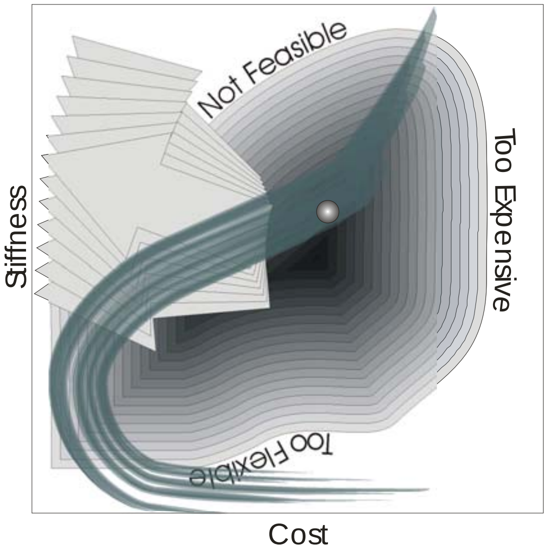

Figure 3: Efficient frontier in an uncertain design problem

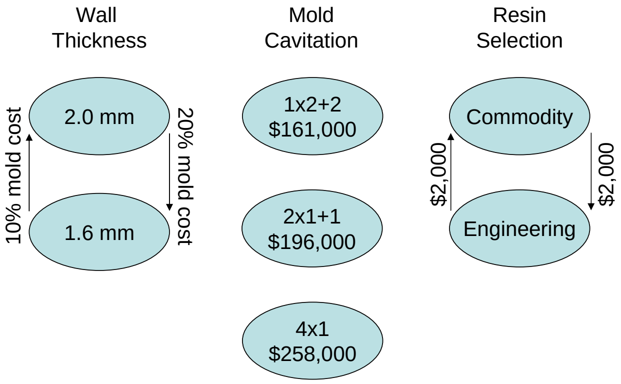

Figure 4: Cost structures of a molded part

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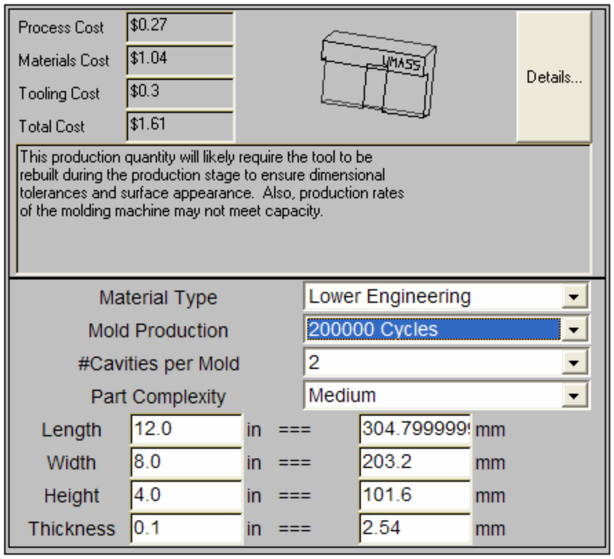

Process Cost $0.27
Materials Cost $1.04
Tooling Cost $0.3
Total Cost $1.61

This production quantity will likely require the tool to be rebuilt during the production stage to ensure dimensional tolerances and surface appearance. Also, production rates of the molding machine may not meet capacity.

Material Type: Lower Engineering
Mold Production: 200000 Cycles
#Cavities per Mold: 2
Part Complexity: Medium
Length 12.0 in === 304.799999 mm
Width 8.0 in === 203.2 mm
Height 4.0 in === 101.6 mm
Thickness 0.1 in === 2.54 mm

Figure 5: Java cost estimator

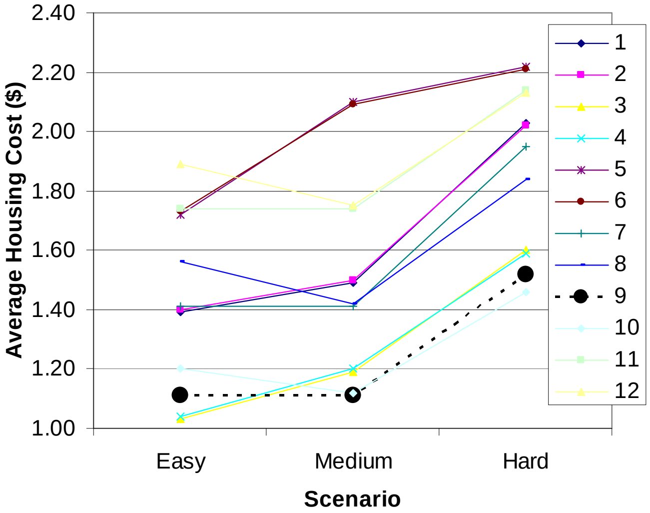

Figure 6: Cost of different designs & hedge alternatives