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PLASTICS PRODUCT AND PROCESS DESIGN STRATEGIES

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ABSTRACT

Plastic components are vital components of many engineered products, frequently representing 20-40% of the product value. While injection molding is the most common process for economically producing complex designs in large quantities, a large initial monetary investment is required to develop appropriate tooling. Accordingly, injection molding may not be appropriate for applications that are not guaranteed to recoup the initial costs. In this paper, component cost and lead-time models are developed from industry data for an electrical enclosure consisting of two parts produced by a variety of low to medium volume manufacturing processes including fused deposition modeling, direct fabrication, and injection molding with used tooling, soft prototype tooling, and hard tooling. The viability of each process is compared with respect to the manufacturing cost and lead time for specific production quantities of one hundred, one thousand, and ten thousand. The results indicate that the average cost per enclosure assembly is highly sensitive to the production quantity, varying in range from $243 per enclosure for quantity one hundred to $0.52 per enclosure for quantity ten thousand. The most appropriate process varies greatly with the desired production quantity and cost/lead time sensitivity. As such, a probabilistic analysis was utilized to evaluate the effect of uncertain demand and market delays, the result of which demonstrated the importance of maintaining supply chain flexibility by minimizing initial cost and lead time.

INTRODUCTION

Plastic components are frequently used in engineered products for a variety of reasons, including the wide array of engineering polymers with performance characteristics comparable to metals (but often at a lower cost), the ability to form these materials into very complex shapes, and capable simulation and processing technology that ensure the manufactured components are fit for the intended purpose. The most frequently used set of guidelines for plastic part design are the Design for Manufacture and Assembly (DFMA) guidelines advocated by Boothroyd and Dewhurst [1]. One significant benefit of DFMA is the considerable savings in assembly cost from fewer parts that need to be assembled.

The consolidation of multiple components via the DFMA process into fewer, more complex components tends to drive designers towards the injection molding process, since this process enables the manufacture of custom, arbitrarily complex components of varying size and thickness. Yet, injection molding requires the development of an injection mold. Tooling costs typically vary between 10^4 10,000 and 10^6 1,000,000 dollars, dependent of the size and complexity of the application, with corresponding development times typically varying between one month and one year. Accordingly, these costs and delays may be inappropriate if production quantities are less than 100,000 or otherwise uncertain, if sales might be lost due to extended tool development times, or if fixed costs must be minimized due to liquidity concerns. In such cases, integrated product and process design is required to select the proper manufacturing process and then develop a suitable component design that can be readily manufactured.

Process Selection

Systematic procedures for process selection have been developed based on comparing the desired design attributes (the required material, size, shape, precision and cost) with the capabilities of a large number of processes [2, 3]. Typically, the subset of feasible manufacturing processes is then ranked by economic criteria, after which a process is selected and appropriate detailed designs are developed. Such systems provide some decision support for the novice designer, but frequently do not provide a high level of fidelity regarding lead time and cost estimation.

With regard to low and intermediate volume plastics manufacturing, a wide variety of processes exist that may be considered as alternatives to traditional injection molding. Figure 1 plots the qualitative domains of several processes with respect to required part complexity and production quantity. It is observed that injection molding is generally accepted for producing complex parts in large production volumes, and that fused deposition modeling is accepted for producing complex parts in very low quantities. Other processes may be acceptable for applications of moderate complexity and production quantities. The limits on part complexity for the various processes on Figure 1 are limited by the fundamentals of the process while the lower and upper bounds of the production quantity are respectively limited by the initial and marginal costs of the process. As such, cost estimation is vital to select manufacturing processes for various production quantities.

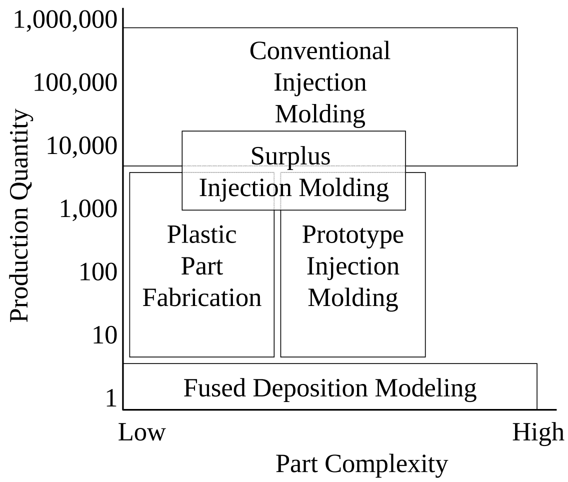

Figure 1: Plastics Manufacturing Processes’ Production Quantities and Part Complexities

Cost Estimation

It has been proposed that between 70% and 80% of a product’s lifecycle cost is “locked in” at the product design stage [1, 4]. Design decisions made during product configuration and detail design largely determine the choice of material, process, product quality, and recycling method etc., all of which contribute to the product lifecycle cost. Early cost estimates enable designers to search for design configurations that minimize cost objectives while optimizing other design specifications. Malstrom and Vernon [5, 6], distinguish between the early and detail cost estimations that are done in industry. Traditionally, the cost estimation department is separate from design because cost estimation requires an intimate knowledge of the relevant manufacturing processes and specific process plans. Hence, cost estimation has been the preserve of skilled technicians who are promoted to be cost estimators after years of experience on the shop floor, or of fresh graduates who have undergone training for two or three years [6]. This separation of design and cost estimating inevitably delays product development and hinders designers’ creativity.

Cost estimation of plastic components requires an estimation of initial tooling costs and also the estimation of on-going processing costs. One of the earlier works in this area by Butler [7] utilized a multiple regression formula that consists of the following parameters: box volume; depth from split line; perimeter, projected area; shape complexity that is based on a simple coding determined by each individual company; number of shape elements; number of side cores, inserts, and their directions; and number of impressions. Similar work was performed by Dixon and Poli [8] to estimate the relative tooling, material, and processing cost of an injection molded part from look-up tables based on comparisons to a standard part. Boothroyd and Dewhurst [1] suggest the use of empirically derived formulas and scaled manufacturing points to estimate the times for the different tasks that are carried out in transforming a purchased mold base to a finished mold; the sum of these times are then multiplied by an average shop rate to estimate the tool construction cost. Fagade and Kazmer developed and validated cost models for hard and soft tooling, and found that the tooling cost was primarily driven by the size of the component and the number of dimensions required to uniquely define all its features [9, 10].

Based on this prior research and known industry practice, it is well established that the cost, C, of manufacturing a batch of plastic components of quantity, Q, is a function of the initial setup and tooling cost, $C_{initial}$, plus the aggregated marginal cost, $C_{marginal}$, that typically includes material, machine, and labor costs per manufactured part:

$$C = C_{initial} + C_{marginal} \cdot Q \cdot \qquad (1)$$

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Figure 2 plots the approximate initial and marginal costs for the plastics manufacturing processes investigated in this study. It is observed that the processes seem to form a pareto optimal boundary that would determine the process selection for a given production quantity. The exact placement of these processes will be subsequently established for an electrical enclosure.

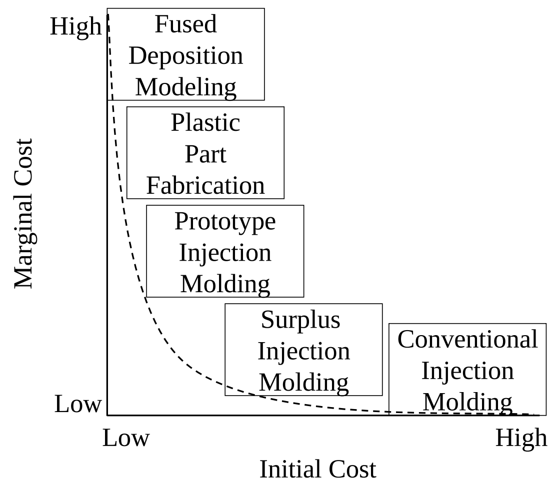

Figure 2: Plastics Manufacturing Processes' Initial and Marginal Costs

Lead Time

Time-to-market determines to a large extent the profit realizable from a high-tech product over its lifetime. According to a McKinsey and Company study, “a high tech product that reaches the market six months late, even on budget, will earn 33% less profit over five years. On the other hand, finishing on time but 50% over budget will reduce a company's profit by only 4%.” [11] The application of DFM guidelines is known to lengthen the concept development time but helps to shorten the other stages of product development.

With respect to plastics manufacturing, Pearson [12] developed a mold lead-time estimation tool and applied it to the plastic parts in 19 consumer coffee makers. Part complexity was defined as the sum of the complexities of the regions of the part requiring simple, moderately simple, moderately complex, and complex electrical discharge machining (EDM) during mold making. Fagade and Kazmer also developed and validated lead time models and cost models for hard and soft tooling, and found that the lead time was primarily driven by the size of the component and the number of dimensions required to define all its features, but highly variable with the utilization of specific pieces of equipment in the mold-making shop [9, 10].

While these studies are of academic interest, they provide little practical guidance. The lead time predictions are typically provided for a single manufacturing process derived from a survey across multiple part geometries and vendors; these studies do not provide accurate comparisons of lead times for multiple processes in specific applications. Accordingly, it is a goal of this paper to describe the lead time, T, as a function of the initial tooling or setup time, $T_{initial}$, and the marginal production time per part, $T_{marginal}$, multiplied by the production quantity, Q:

$$T = T_{initial} + T_{marginal} \cdot Q \, . \qquad (2)$$

Figure 4 plots the approximate initial and marginal production times for the plastics manufacturing processes investigated in this study. It is again observed that the processes loosely form a Pareto optimal boundary that would determine the process selection for a given lead time requirement. The exact placement of these processes will be subsequently established for an electrical enclosure.

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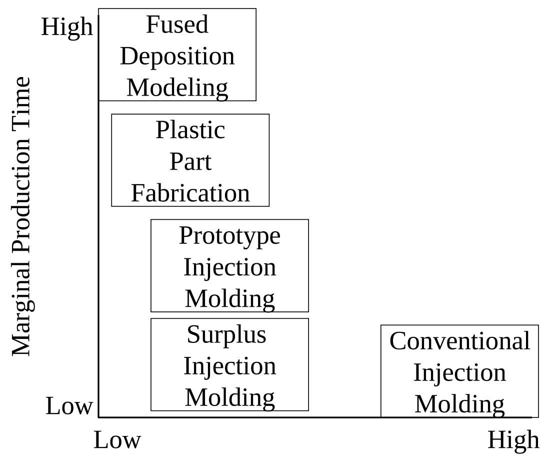

Figure 3: Plastics Manufacturing Processes' Startup and Marginal Production Times

PROCESS SURVEY

The cost and lead time models of several plastics manufacturing processes (including fused deposition modeling, plastic part fabrication, prototype injection molding, surplus injection molding, and conventional injection molding) will be established for an electrical enclosure based on competitive quotes from industry suppliers. The electrical enclosure, shown in Figure 4, is approximately 100 mm in length, 50 mm in width, and 15 mm in height with a 2.5 mm wall thickness. The electrical enclosure is to be made of general purpose ABS, with production quantities of 100, 1,000, and 10,000 parts. Since each process varies with respect to capability, the product was specifically designed for each process to achieve minimal lead times and production costs.

Figure 4: Electrical Enclosure

Fused Deposition Modeling

Fused deposition modeling (FDM) is a rapid prototyping process developed and offered by Stratasys, Inc. Plastic parts are manufactured by depositing a filament on a layer by layer basis directly from 3D CAD data. Due to the deposition of a finite filament diameter, the parts exhibit rough surface finishes of approximately 12 μm. Even so, the strength of parts made from ABS and PC filaments typically achieve 75% of the strength of the injection molded counterparts while dimensional tolerances correspond to SPI commercial grades. Accordingly, FDM is becoming a prevalent process for prototyping and low volume manufacturing.

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The cost structure and lead times of FDM are dependent upon filament diameter, layer thickness, machine cost, and machine availability. For standard conditions (ABS deposition with diameter and layer thickness of 0.25 mm), the deposition rate is approximately 30 cm^3/hour. For this process, the initial setup time approaches zero while the marginal production time is a function of the deposition rate, D, and the volume of the part, V. It should be noted that V should include not only the volume of the plastic used in manufacturing the part, but also the volume of underlying support structures as needed. The cost of parts produced on FDM is then a function of the marginal production time and the hourly rate of the machine and associated labor, R, plus the cost of the material per unit volume, K, times the volume of the part, V. Stratasys has quoted a $60,000 price for the purchase of a Prodigy Plus FDM machine for ABS. Assuming 80% utilization, two-year amortization, 35% maintenance costs, and 35% planning and finishing labor cost, the hourly rate, R is $6.20/hour. The cost of the ABS filament is approximately $0.05/ cm^3.

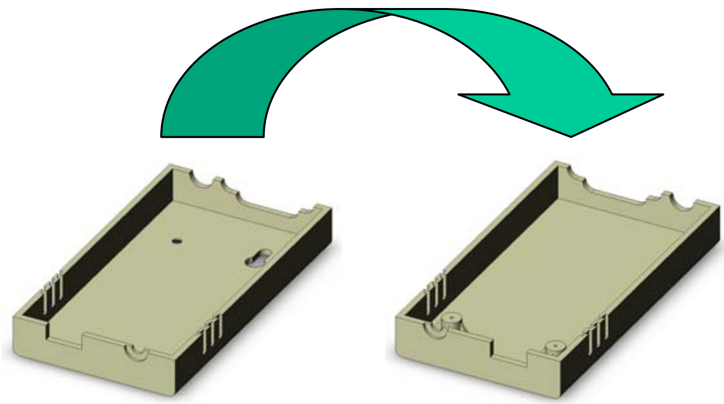

Figure 5: Electrical Enclosure Design

The FDM design is shown in Figure 5. The design has been developed to eliminate one of the components while enabling top down assembly per DFMA practice. The volume of the base and top of the enclosure are 16.7 and 15.8 cm^3, respectively. Accordingly, the marginal production time for the two pieces is approximately 65 minutes, driving a marginal cost of $8.35. For comparison, quotes of $243 and $268 per assembly were also supplied from two independent rapid prototyping services [13, 14], indicating a trade-off between the $60,000 upfront investment to produce the parts internally as opposed to an outsourcing approach with zero initial but higher marginal costs. The lower marginal cost of the internal FDM process is due to the significant recent reductions in the cost of FDM equipment and the assumed 80% utilization rates. If equipment is available, these low marginal costs support related research [15] that FDM may become a common production process for low volume manufacturing.

Direct Fabrication

As an alternative to both FDM and injection molding, plastic parts can be fabricated by machining and forming processes. In fact, the enclosure shown in Figure 4 was fabricated by a “Tool-Less™” process that utilizes a combination of high-speed CNC routing and semi-automated assembly [16-18]. The fabrication process allows the manufacturer to produce parts and enclosures that rival injection molded parts from standpoints of quality, appearance, fit and functionality. The process was developed in Germany in the early 1990’s and has been in commercial use in Europe since 1993. There are currently 14 companies licensed and using this technology in the world today as an alternative to competing manufacturing processes include Pressure Forming, Vacuum Forming, Injection Molding, and RIM. Fabricated parts are claimed to be more expensive on a piece part basis than those from injection molding, but can be less expensive on a program basis for low to mid-volume production.

The enclosure shown in Figure 4 was produced via a design and process more akin to stamping than injection molding. In this process, a lay-flat design is developed as shown in Figure 6 for the enclosure base. 2D NC paths are then generated to provide the lay-flat geometry including bending grooves. After machining is complete, the edges are locally heated and bent into a 3D shape. This groove and bending process does result in witness lines on the external surfaces of the part (shown in the close-up of Figure 6) as well as a reduction in strength and stiffness. Accordingly, fabricated parts may require a slight increase in thickness to obtain the structural integrity of a solid injection molded parts.

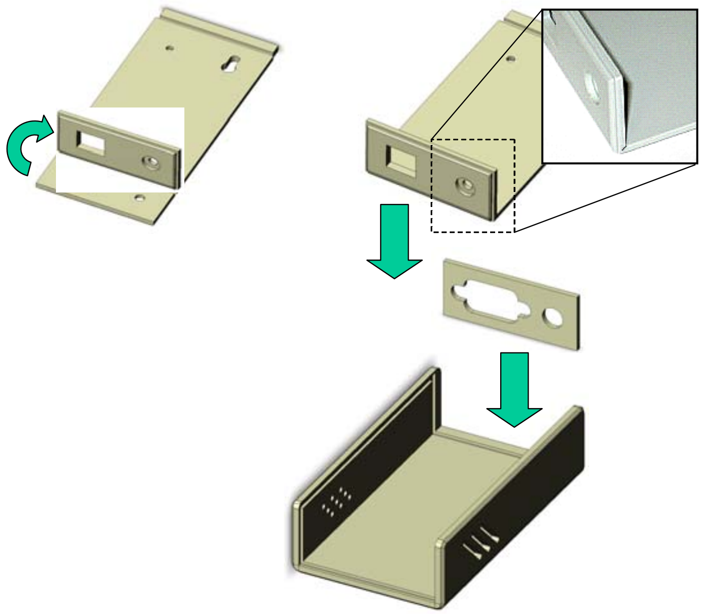

Figure 6: Electrical Enclosure Lay-Flat for Fabrication

The cost structure and lead times are dependent upon the complexity of the product geometry that determines the lineal distance of NC machining and grooving, the number of bends, and the number of assembly operations required to provide additional features such as bosses and ribs. Quotes were provided for the fabricated design shown in Figures 4 and 6. The initial lead time and tooling cost are 3 weeks and $500, respectively, after which sample parts are provided for verification. The marginal production time for the assembly is approximately 1 minute with a marginal cost of $5.00 in 100 unit quantities and $4.00 in 1,000 unit quantities. It should be noted that the fabricated design utilizes an end-piece to provide for multiple electrical connectors across a family of designs. Also, sculptured surfaces can be induced using local thermoforming on the pre-assembled geometry.

Prototype Injection Molds

Prototype molds may be utilized in large commercial applications to provide functional products for pre-production validation and/or marketing purposes. However, prototype molds are being increasingly utilized for applications with low to medium production quantities. Prototype injection molds are typically two-plate mold designs utilizing a straight pull for ejection with no side actions. Prototype molds are typically produced via high speed CNC machining in aluminum in lieu of molds cast from patterns (such as Keltool). While certain grades of aluminum can be highly polished, reduced surface finishes are often specified to reduce lead time and cost. The number of moldings that may be produced from a prototype mold is highly dependent upon the material and process conditions, and may vary from as little as 20 for a glass filled resin injected at high pressure [19, 20] to hundreds of thousands for a natural resin injected at low pressure [21].

Some prototype mold suppliers have automated the mold quoting, mold design, and mold machining process utilizing 3D CAD data and simple rules based on part volume, feature aspect ratios, ejector pin spacing, draft angle, and others [22]. Accordingly, each step of the quote-design-build process is automatically triggered by confirmation of the previous result to generate queries for additional requisite information. This automation significantly reduces time and cost by standardizing business and manufacturing processes. Human inspection of in-process data is typically utilized by the mold supplier to evaluate the goodness of the quote, NC machine paths, and ultimate suitability of prototype molds for a given application.

Since the mold development process is highly automated, the cost and lead time are mostly dependent upon the size and shape of the product geometry that determines the removal volume and associated cutting tool geometry. Some additional costs include the purchase of aluminum stock, mold components such as ejector pins, consumables such as end mills, surface finishing, and engineering labor to specify the ejector pin locations and feed system. Quotes were received for the design shown in Figure 5 [23]. The initial lead time and tooling cost are 15 days and $5,630, respectively. For this supplier, it is also possible to reduce the lead time to 5 days by paying a 50% tooling cost surcharge. In either case, the marginal production time for the assembly is approximately 1 minute with a marginal cost of $15.80 in 100 piece quantities and $5.78 in 1,000 piece quantities. It should be noted that these costs are based on production by the prototype injection mold supplier (who retains ownership of the mold), and may be reduced by acquiring an injection mold for use at a custom molder as discussed in the next two sections.

Surplus Injection Molds

Injection molding is commonly used to provide custom molded products. However, many applications may not require precise aesthetic forms or otherwise have flexibility in the use of plastic parts. For such applications, a secondary market is emerging for surplus injection molds to produce a wide variety of components. Surplus molds are existing molds for similar parts that are no longer needed to produce the original part and may be modified to produce a slightly different part. Such surplus molds can usually be identified, procured, and modified in a matter of weeks to provide components with moderate initial costs but very low marginal costs. Typically, surplus molds can be acquired for approximately 20% of the initial mold development costs, though additional costs are required to modify and verify the surplus mold for fitness in a specific application.

For the enclosure application shown in Figure 4, a surplus mold with 24 cavities was located [24] that could be modified to permit simultaneous production of 12 assemblies similar to that shown in Figure 7. The purchase cost of this mold is $10,000. These parts molded from the surplus mold have similar volume to that shown in Figure 4, but a different aspect ratio. Accordingly, an additional $15,000 is required to modify the product and mold design to accommodate the features required for ventilation and electrical connections. The total lead time required for procurement, modification, and verification is approximately three weeks.

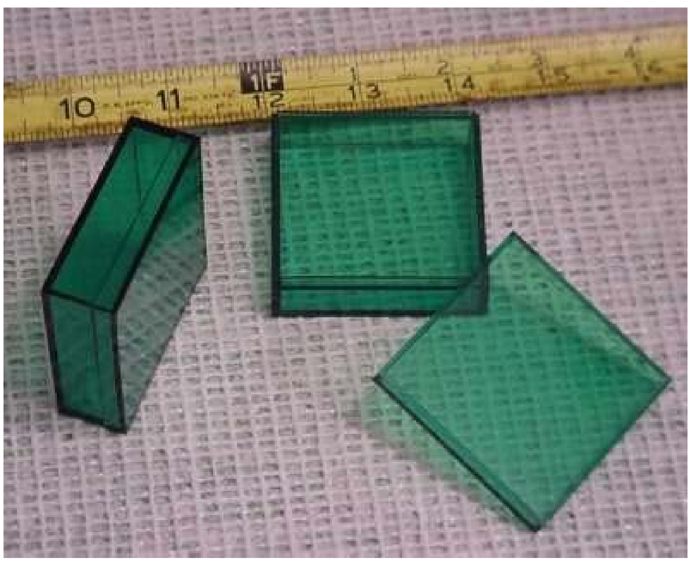

Figure 7: Parts from Surplus Mold as Electrical Enclosure

Once the surplus mold is modified, production would commence at a custom molder. The production rates and cost structures are well established in the industry. Since this was a surplus mold, the cycle time was previously established at 22 seconds per 12 assemblies. Assuming an internal cavity pressure of 80 MPa, the projected area of the cavities would dictate a 550 ton molding machine. The national average rate for this machine including labor is $60.68 [25]. Accordingly, the marginal production cost per piece is $0.0154, or $0.031 per assembly. The material cost of general purpose, platable ABS is $1.90/kg [26]. Knowing the weight of the assembly and feed system, the material cost per assembly is $0.062 per assembly. Accordingly, the total marginal cost per assembly is $0.093.

It should be noted that the use of this specific surplus mold with 24 cavities has resulted in relatively high initial purchase and modification costs, but very low processing costs. It should be understood that a wide array of design and cost issues will arise with the use of surplus molds, and that the initial and marginal costs will vary substantially with the characteristics of available surplus molds.

Conventional Injection Molds

Conventional injection molding utilizes custom mold designs and supply chains to procure custom injection molds and molded plastic parts. Specifically, custom injection molds strive to provide an exact fit between the mold design and application requirements, providing many advantages pertaining to cycle economics, surface finish, tolerances, and cavity geometry compared to other plastics manufacturing operations. Accordingly, conventional injection molds may be preferable in applications where moderate lead times are acceptable, and production quantities may require production tooling capable of supporting one hundred thousand or more moldings.

Mold makers have focused on reducing lead times in response to the previously described processes as well, with one study showing an 87% reduction in the number of design decisions and an 86% reduction in mold making time [27]. While the conventional request for quotes has typically required 30 days, electronic commerce systems such as [28] are becoming increasingly common to provide competitive bids in a minimal amount of time, typically three to five days. Mold cost estimates were obtained for a steel injection mold containing two cavities, one for each side of the housing shown in Figure 5. The resulting cost estimates varied from $12,000 for an injection mold produced in Illinois and delivered in four weeks to $2,200 for an injection mold made in China and delivered in eight weeks.[*] Based on the mold design, the cycle time was estimated as 30 seconds per assembly. Assuming an internal cavity pressure of 80 MPa, the projected area of the cavities would require a 60 ton molding machine. The national average rate for this machine including labor is established at $35.31 [25]. Accordingly, the marginal processing cost per piece is $0.154, or $0.294 per assembly. Knowing the material cost of general purpose, platable ABS is $1.90/kg [26] and the material utilization, the material cost per assembly is $0.0589 per assembly. Accordingly, the total marginal cost per assembly is $0.353 irrespective of which mold is utilized. It should be noted that the marginal cost of the assembly is much higher than that for the previous 24 cavity mold due to the reduction in the number of cavities.

ANALYSIS

Table 1 provides a summary of the initial and marginal lead times and costs for the electrical enclosure. As qualitatively suggested by Figures 1-3, the processes exhibit a very wide range of characteristics. In general, lower initial costs are offset by higher marginal costs and vice-versa. Similar trends are exhibited for lead times. For instance, functional parts can be produced via FDM with zero initial cost and lead time, but at a cost of $243 per assembly and a maximum production rate of 22 assemblies per day. As a counter-example, the use of a surplus mold requires an initial $25,000 and 3 weeks of investment, but can produce assemblies at a cost of $0.093 with a production rate of 48,000 assemblies per day.

Table 1: Process Characterization Summary

	$C_{initial}$ ($)	$C_{marginal}$[†] ($/assy)	$T_{initial}$ (days)	$T_{marginal}$ (min/assy)
FDM (internal)	60,000	8.35	10	65
FDM (external)	0	243.00	0	39
Fabrication	500	4.00	15	1
Proto Molding (rush)	8,445	5.78	5	1
Proto Molding (standard)	5,630	5.78	15	1
Surplus Molding	25,000	0.093	15	0.03
Conventional Molding (rush)	12,000	0.353	20	0.5
Conventional Molding (standard)	2,200	0.353	40	0.5

[*] The mold quotes are significantly lower than those predicted by the previously cited academic references, indicative of significant market changes since the publication of these previous studies.

[†] Assumes a production quantity of 1,000 assemblies. Marginal costs typically vary with quantity discounts, which are reflected in subsequent analysis.

The data of Table 1 again suggests the existence of a Pareto optimal set trading off initial and marginal costs and/or times. The data for this electrical enclosure application are plotted in Figures 8 (a) and (b). It is clear from these figures that certain manufacturing processes are sub-optimal with respect to initial and marginal cost, or initial and marginal lead times. However, the selection of the most appropriate manufacturing process depends on the combination of production cost and lead time, as well as the certainty of the production quantity and time elasticity. More specifically, higher levels of certainty regarding the production quantity will tend to support a larger initial investment to obtain lower marginal costs, thereby maximizing profit. As the production quantity becomes less certain, and as extended lead times erode the possible production quantity, then there is a tendency to reduce supply-side risk by utilizing processes with lower initial costs but higher marginal costs. This latter strategy can reduce long term profitability if production quantities are unexpectedly high, though a second round of manufacturing process development can then be used to reduce marginal costs while utilizing cash flow generated from the initial product offering.

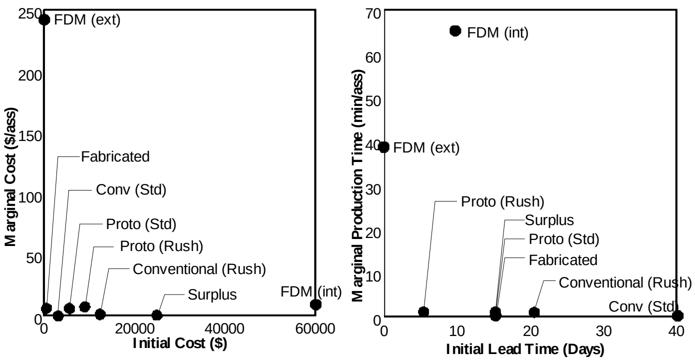

Figure 8: Trade-Offs between (a) Initial and Marginal Costs and (b) Initial and Marginal Times

It is possible to reduce Figures 8 (a) and (b) to a single plot showing the total lead times and costs for specific production quantities, Q_0, of 100, 1,000, and 10,000 parts. As indicated in Figure 9, the costs and lead times of each process are represented by a curve with three data points corresponding to increasing production quantity. It is observed that each of the processes has varying intercepts derived from the initial cost and initial lead time, and varying slopes derived from the marginal cost and production time.

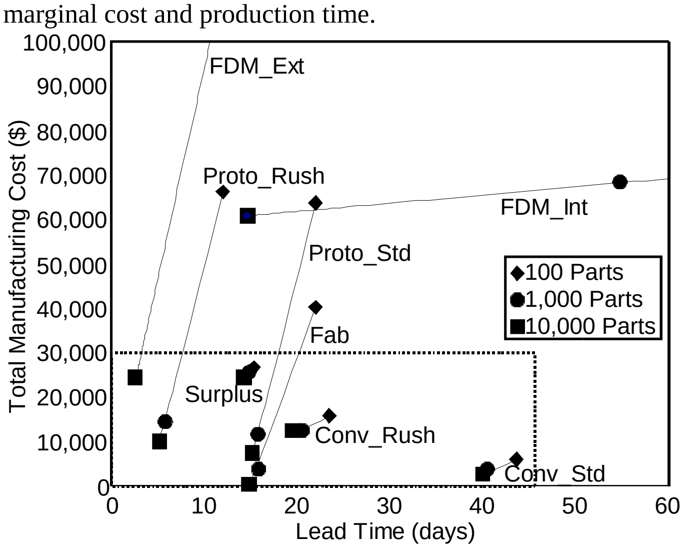

Figure 9: Trade-Offs between Costs and Lead Times

Figure 10 provides an enlarged plot of the dashed region of Figure 9, as well as the Pareto Optimal boundaries for production quantities, Q_0, of 100, 1,000, and 10,000 parts. There are two general conclusions that are drawn from this data. First, the selected process is heavily dependent upon the preferences of the decision maker. For instance, 100 assemblies are available with lead times of 2.6 and 15.1 days at respective costs of $24,000 and $1,000. These data correspond to a lead time:cost ratio varying from 9,500 to 10 – two full orders of magnitude. As such, it would be expected that the decision maker would select the process depending on the application and market requirements.

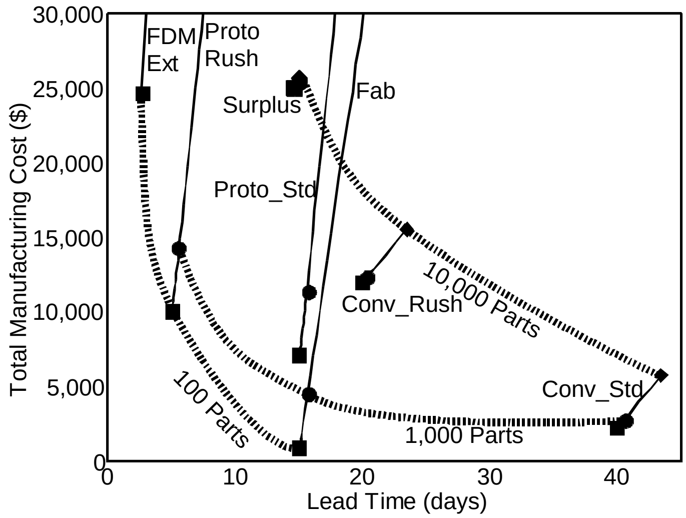

Figure 10: Pareto Optimal Plots indicating Trade-Offs between Costs and Lead Times

There are many specific observations drawn from Figure 10. First, FDM is preferred for very low production volumes when low lead times are necessary, though the process' high marginal costs and low production rates will preclude its selection for higher production quantities. Prototype molding is a preferred process for moderate lead times and costs; however, the prototype mold should utilize rush rather than standard service otherwise other processes may be preferred. Fabrication is preferred to achieve lower costs when slightly longer lead times are allowable. When even longer lead times are allowable or a higher production quantity is needed, then surplus and conventional injection molding become the preferred processes. The specific observations support the second general conclusion that no single process is dominant for a given production quantity, minimal costs, or minimal lead times. Accordingly, the decision maker will always have to trade-off multiple performance measures to select a manufacturing process.

To explore the effect of uncertainty on process selection, assume that the actually demand, D, is normally distributed with a mean equal to Q_0 and a coefficient of variation of 0%, 10%, and 100%. This problem is similar in many ways to the newsboy problem in operations research [29], in which a vendor needs to determine how many perishable newspapers should be ordered on a given day, knowing that papers not purchased at the end of the day will lead to unrecovered costs and that a shortage of papers will lead to lost revenue. Define $G(Q,D)$ as the total cost incurred when Q units are ordered and D is the unknown market demand. If the order quantity exceeds the demand, then an overage cost, c_o, will be incurred due to the expense of manufacturing products that were not sold. If the demand exceeds the order quantity, then an underage cost, c_u, will be incurred due to the lost profit on units that could have been sold. The total cost is expressed as:

$$G(Q,D) = c_o \max(0, Q-D) + c_u \max(0, D-Q). \qquad (3)$$

The expected value of this function is:

$$\mathrm{E}[G(Q)] = c_o \int_0^Q (Q-x) f(x)dx + c_u \int_Q^\infty (x-Q) f(x)dx. \qquad (4)$$

where $f(x)$ is the probability density function of the demand. The solution of this problem is well established in the operations research literature and textbooks [29]. The application of Leibniz's rule to the derivative of E[$G(Q)$] provides:

$$\frac{d\mathrm{E}[G(Q)]}{dQ} = c_o \int_0^Q f(x)dx + c_u \int_Q^\infty - f(x)dx$$
$$\frac{d\mathrm{E}[G(Q)]}{dQ} = c_o F(Q) - c_u (1 - F(Q)) \qquad (5)$$

where F is the cumulative probability of the demand. Further inspection shows that the second derivative is positive and that the costs can be minimized for an optimal order quantity Q^* such that:

$$\frac{d\mathrm{E}[G(Q)]}{dQ} = 0 \Rightarrow F(Q^*) = \frac{c_u}{c_o + c_u} \qquad (6)$$

This last quantity is known as the critical ratio, and represents the proportion of satisfied demand. For applications with higher profit margins and corresponding underage costs, the critical ratio increases to better satisfy the demand.

Based on the above analysis, the expected total underage and overage costs are calculated for each of the manufacturing processes as a function of the allowable lead time and the total number of parts required. This assumed an underage cost of

$200 per part, and a standard deviation of the demand equal to 50% of the mean demand. Also, it was assumed that a day has 24 hours available for production.

Figure 11 shows the most cost effective method for different allowable lead times (on a logarithmic scale) and parts required. It can be seen, that for large quantities and large lead times, surplus molding is the most cost effective approach. For small production quantities, the cost of conventional molding (standard) undercuts the cost of surplus molding. Although conventional molding has a higher marginal cost than surplus molding, the lower initial cost makes this method ideal. For even smaller production quantities, the cost of fabrication exceeds even the cost of conventional molding due to the very small initial cost.

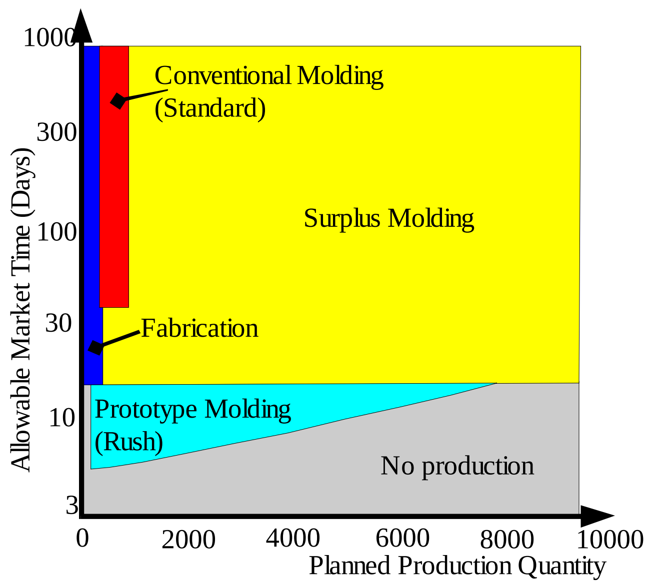

Figure 11: Optimal Manufacturing Process based on Planned Quantity and Market Time

If the lead times are below 15 days, a rush prototype molding job is the only possible approach for some cases. However, there are many situations where there is either no feasible method at all, or the feasible method is more expensive than simply accepting the cost of the lost sales. In this case, it is best not to produce anything but merely accept the losses.

Figure 12 shows the total cost per part of the optimal production process based on the production quantity and the allowable lead time. The axes are identical to Figure 11, but the chart has been rotated for an improved view. The areas in Figure 11 can be found again in Figure 12. Most cost effective is surplus molding, having the lowest cost per part. Conventional molding (standard) is only slightly more expensive per part than surplus molding for the optimal areas. There is, however, a sharp increase in the price for both fabrication and prototype molding (rush). Of course, producing no parts will occur the cost of a lost sale of $200.

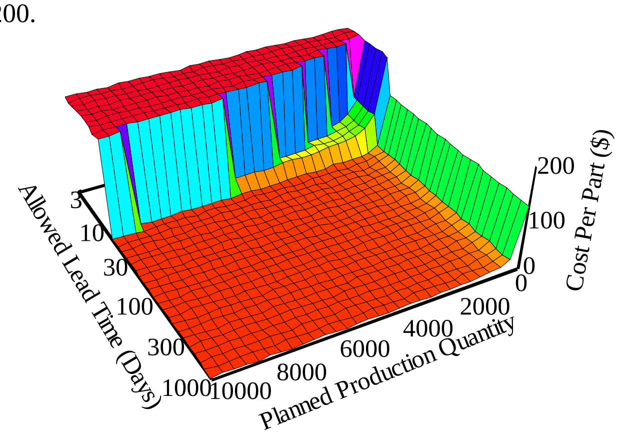

Figure 12: Cost of the Optimal Manufacturing Process based on Planned Quantity and Market Time

In general, producing more parts will reduce the cost of the parts, as the initial cost is spread over more and more parts. With respect to the lead time, however, small differences in the allowable lead time can make a huge difference in the cost.

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There are a number of sharp steps in the cost for the same production quantity and different lead times, as for example between producing no parts, prototype molding (rush) and surplus molding. A small difference in the allowable lead time can make a huge difference in the cost, requiring a careful trade-off between the allowable market lead time and the cost of the parts.

A few notes are warranted about the foregoing analysis and discussion. First, the above analysis utilizes a cost basis and assumes that all manufacturing processes provide identical product functionality. Rather, the authors are aware that FDM provides very rough surface finishes, fabricated parts utilize planar surfaces, and surplus molding may not provide suitable geometry. However, the affect of such phenomenon on part pricing are truly difficult to quantify *a priori* so it is left to the designer to verify which processes will provide functionally satisfactory parts.

Second, the above analysis utilized actual quotes from multiple suppliers. It is the authors’ opinion that the quotes are useful for comparing the manufacturing processes. However, it should be expected that the quotes would vary substantially by application, negotiation and/or contract terms, dynamic plant capacity at the manufacturers, etc. In particular, sensitivity analyses not included in this paper indicated that the surplus molding process is preferable for higher production process, and that the FDM processes can become very competitive if marginal costs are reduced. As such, the paper has attempted to provide the underlying causality so that designers may apply the methodologies to their own applications.

Finally, the authors support the design and supply chain axiom that flexibility ought to be preserved. The results of this paper and earlier research suggest that the higher marginal costs of low volume manufacturing processes are more than offset by their lower initial costs and reduced lead times. Indeed, the desirability of these processes only increases with uncertainty regarding the lead times or absolute level of demand. For startup and small companies with limited resources, such outsourcing is further desirable to minimize cash flow and reduce drain on internal project management and manufacturing resources. Two issues, however, require further research. First, further work is required to develop a multi-stage manufacturing methodology that utilizes low volume processes during the uncertain product start-up phase followed by higher volume processes to thereby maximize profit and minimize risk over a product lifetime (somewhat akin to [30]). Second, further work is also required to consider the combination of high volume standard components and low volume custom components to maximize profit and minimize risk across a suite of products (somewhat akin to [31]).

CONCLUSION

A wide variety of processes are available for manufacturing of plastic components in relatively low production quantities. As could be expected in an efficient market, all of the processes are competitive under certain conditions. As such, the designer is thereby challenged to determine the most appropriate process given their market and application requirements. It is our experience that delays in the selection of manufacturing processes can consume a significant amount of the available development time, thereby artificially forcing the development team towards expensive manufacturing processes with very short lead times. To avoid such delays and minimize uncertainty, it is suggested that product developers of medium volume applications consistently utilize the same manufacturing process. For an electrical enclosure, the most suitable processes were prototype molding (rush), fabrication, surplus molding or conventional molding (standard), depending on the planned quantity and the allowable lead time. Using the revenue earned from the sale of these products, a second round of development could be subsequently performed, if needed, to provide components with significantly lower costs in greater production volumes.

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