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EARLY COST ESTIMATION OF INJECTION MOLDED COMPONENTS

BY

DAVID ARCHER

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

IN

MANUFACTURING ENGINEERING

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OF
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1988

ABSTRACT

The purpose of this study is the establishment of techniques that will enable product designers to quickly estimate the piece price and mold cost of an injection molded component at the concept design stage, before engineering drawings are generated. In using these techniques, the designer is made aware of the comparative costs of alternative design concepts, thus improving the product's cost-effectiveness and increasing the designer's awareness of the injection molding process. The capabilities of injection molding will briefly be compared to the capabilities of other processes with the intent of demonstrating when injection molding, and therefore the techniques derived in this study, may be applicable.

The methodology used to determine the three elements (material, processing, and tooling) of total manufactured cost concentrates heavily on input from molding and mold-making professionals. This is particularly true in the investigation of tooling costs.

The result of this research is a costing procedure that does not assume user knowledge of processing parameters

or machine selection, but requires only designer-specified inputs, such as: part size, description of geometry, and material specified. Included is a comparison of the actual part cost and mold cost of 24 components loaned by local companies, with the costs predicted by the procedures developed in this project. To illustrate alternative choices of manufacturing processes for a given design problem, the total cost of a very simple component produced by three different methods, is plotted against plan area, life-cycle volume, and loading.

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Prince Co.
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Steelcase
Windsor Mold

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NOMENCLATURE

- α = thermal diffusivity [in^2/sec]
- A_b = injection barrel cross-sectional area [in^2]
- A_d = die plate area [in^2]
- A_{gp} = projected area of part perpendicular to mold opening, including thru penetrations [in^2]
- A_p = projected area of part perpendicular to mold opening, excluding thru penetrations [in^2]
- A_s = area of parts outer surface [in^2]
- β_i = proportion of rated power used for injection
- b_{mr} = intercept of machine rate/clamp force relationship [\$]
- C_{av} = average geometric complexity
- C_{c1} = cost of a single cavity/core sets [\$]
- C_{ct} = Total cost of all cavity/core sets [\$]
- C_m = material cost [\$ / part]
- C_{m1} = cost of a 1 cavity mold [\$]
- C_{mb} = cost of mold base [\$]
- C_{mn} = cost of an n cavity mold [\$]
- C_p = specific heat [BTU / lb - °F]
- C_{pm} = cost of pre-manufactured mold base [\$]
- d = part depth (in the direction of mold opening) [in]
- D_d = combined die-plate thickness [in]
- D_{ps} = depth of parting surface [in]
- D_w = depth of nominal wall in the direction of mold opening (part depth of minus height of projections)

F_a = appearance factor (from Table 4)
 F_c = clamp force [tons]
 h = wall thickness [in]
 h_n = wall thickness associated with nth candidate polymer [in]
 h_o = wall thickness associated with candidate polymer requiring minimum wall thickness [in]
 κ = fluid consistency exponent
 K = fluid consistency constant [lb/in²]
 k = thermal conductivity [BTU/sec-in-°F]
 l = part length (perpendicular to mold opening) [in]
 μ = viscosity [lb-sec/in²]
 m = multi-cavity cost index
 m_{mr} = slope of machine rate/clamp force relationship [\$/ton]
 n = number of mold cavities
 p = average cavity pressure [tons]
 P_i = injection power [hp]
 P_i = injection pressure [lb/in²]
 Q = machine shot capacity [in³]
 ρ = material density [lb/in³]
 q = shot size [in³]
 R_m = material unit cost [\$/lb]
 R_{mm} = molding machine rate [\$/hr]
 R_t = average rate charged by toolmaker for mold fabrication [\$/hr]
 τ = shear rate [sec⁻¹]
 S_c = maximum machine clamp stroke [in]
 S_s = injection screw stroke [in]
 T = temperature [°F]

t = time [sec]
 t_c = cooling time [sec]
 t_{ct} = cycle time [sec]
 t_{dc} = machine dry cycle time [sec]
 t_f = fill time [sec]
 T_i = initial temperature of melt [$^{\circ}\text{F}$]
 T_m = mold (cavity wall) temperature [$^{\circ}\text{F}$]
 t_{mc} = mold close time [sec]
 t_{md} = mold dwell for part eject [sec]
 t_{mo} = mold opening time [sec]
 t_r = reset time [sec]
 t_w = increase in fill time due to the need for greater wall thickness. (relative to the polymer under consideration which requires the thinnest wall), sec
 T_x = ave. centerline part temperature at mold opening [$^{\circ}\text{F}$]
 V = part volume [in^3]
 V_o = part volume associated with candidate polymer requiring minimum wall thickness, in^3
 V_r = sprue and runner volume [in^3]
 w = part width (perpendicular to mold opening) [in]
 W = work [in-lb]
 x = distance from cavity wall to centerplane [in]
 X_a = cavity/core manufacturing time associated with part area [hr]
 X_d = cavity/core manufacturing time associated with part depth [hr]
 X_f = cavity/core manufacturing time associated with part finish [hr]
 X_{gc} = cavity/core manufacturing time associated with geometric complexity [hr]

x_{pa} = cavity/core manufacturing time associated with projected area [hr]

x_{ps} = cavity/core manufacturing time associated with parting surface [hr]

X_t = cavity/core manufacturing time associated with part tolerance [hr]

CHAPTER 1

OVERVIEW

Studies have shown that 70 to 90 percent of product cost is set by product design [1,2]. Efforts to increase the productivity of processing equipment or labor can therefore only impact the remaining 10 to 30 percent of total cost. As a result, the top management of many organizations is placing a greater emphasis on taking the time to investigate design alternatives at the early stages of design. After investigating a number of design alternatives, the concept that a design team would most likely choose to pursue, would either be that which shows the highest ratio of performance to cost, or alternatively, exhibits the highest performance level while meeting a pre-determined target cost. Therefore, the ability to make these design decisions is dependant upon the availability of cost estimates for each alternative during the early development phase.

The central goal of this study is the establishment of a procedure that enables product designers to quickly estimate the piece price and mold cost of an injection molded component at the concept design stage, before detailed engineering drawings have been generated. This

procedure assumes no user knowledge of process parameters or machine selection, but requires only designer-specified inputs, such as: part size, description of geometry, and material specified.

To be of practical use, costing procedures for each of the manufacturing processes that could be a part of an evolving design should be made available. While this study is exclusively concerned with the injection molding of thermoplastic components, similar work on machining has already been published [3], and studies of sheetmetal, die casting, forging, and powder metallurgy are expected to be completed in 1988 as part of the URI research program on design for manufacture and assembly. Traditionally, designers only have in-depth knowledge of the few manufacturing processes that they tend to use repeatedly. This often forces them into design solutions that are simply incremental improvements of existing designs. Use of the library of process reports resulting from the research program should broaden a designer's information base, making their use of alternative processes a greater possibility.

Injection molding was chosen for this study because of its increasing acceptance in areas where it was previously thought to be an unsuitable solution. This broadening of applications is primarily due to improvements in material properties and an increased awareness of the processes' ability to produce finished components of widely varying geometry at low unit cost. Although the unit cost of

injection molded components is very low, the fixed tooling costs are conversely very high, requiring manufacturers of low-to-moderate volume products to pay careful attention to the trade-off between unit costs and tooling costs. To do this, the means to estimate the cost of the component and it's associated tooling must be made available at the concept stage, before any design commitments are made. Because of this, early cost estimating is especially valuable to companies producing goods in low-to-moderate volume, and those in industries, where product designs change rapidly and dramatically.

A search of the technical literature reveals that, with the exception of machined components, very little has been published on the estimation of manufactured component costs [4,5,6]. Although numerous volumes are devoted to the general nature of engineering cost estimation, the emphasis is generally on projects such as new plant construction, with coverage of manufactured components often relegated to a single chapter. Even within this context, the information presented may be compared to a blank spreadsheet or accounting form, where cost elements and their interrelationships are defined, but the means to actually estimate these cost elements are not provided. This cost information is generally gained through supplier's quotations once engineering drawings have been generated. By this point, however, schedule pressure generally vetoes any significant changes that appear to be warranted.

The area of estimating tooling costs in injection molding is one where the literature is essentially non-existent, as seems to be the case for tooling associated with other manufacturing processes as well. This weakness is not entirely without reason, as injection molds are extremely complicated and require many processing methods and design features to accommodate the wide range of components that may be produced. The hazard of trying to estimate costs in this environment is that the required construction and metal removal processes are not apparent to the designer.

The contents of this report can be broadly divided into three sections. The introductory section, consisting of the first and the second chapters, outlines the intent of the study, and the principles of injection molding. Chapters 3-6 include a description of the costing procedure developed, while the final section, Chapters 7 and 8, summarizes the use of both the costing procedure and the injection molding process, by detailing estimates of the cost of alternative design solutions for a given application. Also included in this section are comments on the results of the study, and suggested areas of future research.

CHAPTER 2

INTRODUCTION TO INJECTION MOLDING

2.0 INTRODUCTION

The intent of this chapter is two-fold: first, to describe injection molding in enough detail that a reader with little exposure to the process will understand its basic workings and cost drivers, and secondly, to convey some familiarity with the terminology that will be used in subsequent chapters.

Before entering into this discussion, it should be noted that this report covers the injection molding of thermoplastics only. Thermoplastics are polymers (the more accurate term for plastics) that may be reprocessed by remelting without significant degradation of physical properties. This is possible due to a lack of chemical bonding between molecular chains during solidification. Thermosets, on the other hand, undergo a chemical reaction upon polymerization. Following this reaction, the resulting cross-linked molecular network precludes reprocessing. Common examples of thermosets are: epoxies, phenolics, and some formulations of polyurethanes and polyesters. Thermosets may also be injection molded in modified machines, although this is relatively uncommon, compared with the widespread injection molding of thermoplastics.

The injection molding cycle may be broken into three phases: injection, cooling, and ejection/resetting. Figure 1 shows an approximate breakdown of how these elements make up the cycle. Each will be discussed in the sections below, followed by a brief description of mold, and molding machine construction.

2.1 INJECTION

Small pellets of plastic, stored in a hopper above the molding machine, drop into the injection unit (Fig. 2) and are melted (plasticized) through a combination of heat, provided by the band heaters surrounding the injection cylinder, and by shearing. The shearing action is furnished by rotation of the central screw of the injection unit. As plastification takes place, the melt is moved along the rotating screw flights toward the front of the screw until it reaches a reservoir in the end of the barrel, just behind the nozzle. When injection is desired, the injection cylinder moves the screw forward in the barrel, and the melt is injected into the mold cavities at very high (12,000 - 20,000 psi) pressure.¹ The melt enters the stationary half of the mold through the sprue, after which it follows a series of channels (runners) that carry it to each cavity. Entering the cavities through one or more small

~~Reciprocating~~ screws are not the only way to introduce melt into the mold. Plunger machines, utilizing a simple ram and torpedo-shaped spreader to plasticize and inject, were not long ago the industry standard. They have essentially been replaced by reciprocating screw machines, which have the ability to plasticize more quickly and with better control of temperature and shot size.

restrictions, called gates, the melt rapidly fills the cavity. Gates are always the smallest passageway along the melt's path. This causes the material in them to solidify first, thus preventing back-flow out of the cavity. Parts with a sizable surface area will often require multiple gating, as it is desirable to fill the cavity swiftly, before unwanted solidification takes place.

2.2 COOLING

Even after the cavity is full, injection pressure is held on the melt in order to "pack" the cavity. Packing results in an increase in cavity pressure, which is necessary to give the part a good surface finish and prevent depressions ("sinks") from forming as the part contracts during solidification. When the gate has been sealed by frozen material, the screw is retracted so that the injection unit can plasticate the next shot. The pressure profile within the cavity is shown in Fig. 3. Cooling of the melt, which began slowly with its injection into the mold, now takes place more rapidly by conduction as the part and mold surface come into intimate contact. Cooling continues to take place within the mold until the part possesses sufficient rigidity to be ejected from the mold. Part cooling is aided by the recirculation of coolant through passages in the mold. As was shown in Figure 1, cooling is typically the longest element of the mold cycle, and the one that the decisions of the designer, molder, and moldmaker have the greatest influence upon. Factors

influencing cycle time will be discussed in greater detail in subsequent chapters.

2.3 EJECTION AND RESETTING

Part ejection from the mold is a more critical operation than would appear at first glance. Unless the part is essentially flat, it will tend to shrink onto the male side of the mold during cooling, and can require several thousand pounds of force to remove it. This ejection force must be applied in such a manner that the part will be ejected without distortion. This is not to imply that flat parts are immune to ejection problems, as their inherent lack of stiffness requires that ejection forces be evenly distributed to prevent warpage. It should be noted that most thermoplastics start to soften with a consequent reduction of elastic modulus at temperatures over 225°F. This always results in a trade-off between the desire to remove the part from the mold quickly to reduce cycle time, and the need to ensure sufficient cooling to prevent damage during ejection. Due to the uniqueness of each part, and the particular ejection and cooling characteristics of each mold, the final compromise is arrived at by trial and error.

Ejection is typically performed when pins, blades, rings, or occasionally an entire stripping plate, slide out from their resting position flush with the mold surface, and free the part from the mold. The shape, density and distribution of these ejection elements are determined by

part geometry and mold construction (cooling channels in the mold, and any moving slides must be avoided).

In addition to the time taken for ejection, resetting time includes the time required for mold opening and closing. This time is dependent on the velocity profile of the moving half of the mold, and the distance through which it must travel. The magnitude of the mold stroke is mainly dependent on the depth of the part in the direction of mold opening, while the velocity profile is determined by the size and construction of the machine's clamp unit. When the orientation of part depressions or through penetrations prevent the part from being ejected (as in the case of a hole whose axis is parallel to the mold parting plane), that part is said to be "die-locked". In these instances, mechanisms called "slides", or "core pulls" are needed to slide these mold projections out of the way so that the part may be released from the mold.

2.4.0 INJECTION MOLDING MACHINE CONSTRUCTION

The basic components of the injection molding machine are the clamp unit and the injection unit. The capacities of these systems are the major cost drivers of the machine and the determining factors in machine selection. Due to their impact on part cost, the clamp and injection unit will be discussed in the next two sections.

2.4.1 INJECTION UNIT

The basic function of the reciprocating screw injection unit was described in section 1.2. As mentioned, there are alternatives to this design, including plunger and screw designs that separate plastication and injection into separate cylinders, thereby increasing maximum injection rates. The industry standard is, however, the reciprocating screw design. Some of the important specifications that determine the applicability of a machine's delivery system to a given job are explained below.

Maximum injection capacity² (oz or cu. in.) Theoretical maximum shot size the unit may inject in a single stroke.

Plastication capacity (lb/hr) The rate that GP Polystyrene can be plasticated with the screw running continuously. Useful only in a relative sense, as continuous plastication is unrealistic.

Recovery rate (oz/sec) The weight of GP Polystyrene capable of being discharged per second, as calculated following a Society of the Plastics Industry (SPI) procedure. An attempt to arrive at a more useable figure than plastication capacity.

Maximum injection pressure (psi) Theoretical maximum pressure the screw can exert on the melt, assuming no losses.

Maximum injection rate (cu. in./sec) Measured maximum rate of melt displacement at maximum pressure.

2.4.2. CLAMP UNIT

The machine's clamp unit resists the forces developed by injection pressure on the plastic melt as it enters the cavities and runner system. If this clamp force were

²Based on General Purpose Polystyrene (spec. grav. 1.04) at 420°F melt temperature

insufficient and permitted the mold halves to separate, even by a few thousandths of an inch, material would extrude between the mold plates and cause the part to "flash".

The magnitude of the clamp force needed in a particular application is a product of the plan area of all parts and runners measured in the mold parting plane, and the average pressure within the cavities. Although the pressure drop between the screw reservoir and the cavity is generally 50%-66% [7], the very high injection pressures result in separating forces that can require the use of machines with clamp ratings well over 1,000 tons.

Besides preventing unwanted mold opening, the clamp unit must open and close the mold to permit part ejection. The velocity profile of this motion is dependent on the design of the clamp unit. These designs fall into three categories: toggle, hydraulic, or hydro-mechanical.

The kinematics of a toggle clamp (Fig. 4a) reveal two properties that are desirable in this application. Through mechanical advantage, a relatively small input force is required of the actuating cylinder to develop the high locking force required. This mechanical advantage may be up to 50:1 [8]. The other advantageous attribute of a toggle clamp is its velocity profile: capable of high speeds near the center of its stroke, and slowing exponentially at each limit. This property aids in overcoming the considerable inertia of the mold and platen at the beginning of motion, and prevents jolting of the machine or mold at its

conclusion. The small actuating cylinder and simple linkage of this design make it the least expensive choice of clamp configurations, even though it is capable of cycling faster than the alternatives. Disadvantages of toggle machines are the difficulty in controlling the clamp force, due to it's direct dependency on mold height, and the significant setup time required to make positional adjustments for different mold sizes.

Hydraulic clamp units (Fig.4b) utilize a small cylinder, sometimes called a jack ram, to open and close the mold while leaving the clamping duties to a much larger cylinder. This arrangement greatly reduces the volume of fluid required during the cycle. Although hydraulic clamps operate more slowly than toggle units, they are easier to setup and more forgiving of unforeseen obstructions to mold closing.

Hydro-mechanical clamps, as one would expect, combine properties of both previous designs. As shown in Figure 4c, a toggle clamp replaces the jack ram of the hydraulic machine to perform mold movement. Clamping is again carried out by a large diameter, short stroke cylinder. This unit combines the faster setup and more precise clamp control of the pure hydraulic design with cycling speeds approaching that of a toggle machine, albeit at a higher price than either.

2.5.0 MOLD DESIGN

This section will cover only the basics of mold construction, leaving the analysis of relationships between component design and cost for Chapter 5. The fundamental elements of any injection mold: the cavities, mold base, runner system and ejection system, will be covered in sections 2.5.1 through sections 2.8, followed by a summary of alternative designs to the standard 2 plate mold.

2.5.1 CAVITIES

The surfaces against which the plastic melt is forced during injection sit in two mold plates. The female side of the impression is generally found in the A plate (Fig. 5) on the stationary half of the mold, and is referred to as the cavity, while the male impression is contained in the moving B plate, and generally called the core. The juncture of the A and B plates is referred to as the mold parting line. Parts that are symmetrical with respect to the parting line make the classification of cavity and core somewhat arbitrary, though the impression mounted in the A plate is generally judged the cavity. It should be noted that some flat, simple parts have all their detail in one mold plate, while the other, flat plate, simply defines a planer surface.

2.5.2 PROCESSING METHODS

The processing methods used to create these impressions are quite diverse, ranging from metal removal to metal

forming techniques. Their principle uses are discussed below.

Conventional Machining - The use of manual milling machines and lathes is still the heart of moldmaking, particularly in smaller shops, or those making a large proportion of single cavity molds. The flexibility, short setup time, and low cost of these machines will insure continuing popularity, notably for one-off work like repairs and mold base preparation.

CNC Machining - An obvious aid to productivity in the construction of multi-cavity molds, an increasing use of CAD/CAM and improved CAD-to-CAM interfaces is expanding the popularity of CNC machining. The competition of an increasing number of manufacturers is boosting machine performance/cost ratios, resulting in greater penetration into moldmaking shops.

Duplicating - Performed on a modified milling machine where the cutter motion is controlled by a pantograph-like arrangement that follows a pattern of the part (often made of wood). Duplicating is used for cutting free-form shapes that cannot be produced by manual machining. It has declined somewhat in popularity due to the availability of mature CNC and EDM equipment, and the inability of the process to fit into a CIM environment.

EDM - Electrical discharge machining, sometimes called "spark erosion", is used to create shapes that are uneconomical, or impossible (e.g. a star-shaped hole) to produce on milling machines. There are two EDM configurations used in moldmaking: conventional, and wire. Wire EDM is used to make odd-shaped through penetrations. It is not used as often in moldmaking as conventional EDM, where a copper or graphite electrode is fed slowly into the workpiece, eroding material by rapid electrical discharge between the electrode and the workpiece. This process is primarily used in the formation of female shapes of a complex geometry, or penetrations requiring sharp intersections of planer surfaces. Material removal rates are lower than available with chip-forming processes, ranging from 0.001 in³/hr for precise work with good surface finishes, to roughing at 25 in³/hr with surface finishes of approximately 1500 micro-inches rms [9]. Although the intermediate step of machining electrodes is a cost penalty not incurred in CNC machining, the range of geometry that can be re-created is more diverse, as the electrode may be constructed of several parts without the tooling obstructions which are a problem in direct cavity fabrication. A major advantage of EDM is the independence of metal removal rates and workpiece hardness. Electrodes may be plunged directly into hardened steel workpieces, eliminating the need to correct dimensional changes induced by heat treating.

HOBGING - A process where the required shape is machined into a master steel hob, which is then hardened and polished. This master hob is then forced into the steel blank at pressures of approximately 100 tons/sq.in., thus creating the desired female impression. This soft impression is subsequently case-hardened and polished. Selection of the correct hobbing steel for die plates is very important in achieving proper flow and the desired final mechanical properties. The P1-P6 series of low-carbon steels are commonly used.

CAST CAVITIES - Casting is sometimes chosen as the desired processing method for cavities and cores requiring a contoured, free-form shape. Impressions of this type are produced relatively quickly and inexpensively, although they don't possess the dimensional accuracy which can be achieved by metal removal methods. Also, low melting point materials do not have the durability of steels. One possible exception to this inferior accuracy and durability is a service offered by 3M Company that creates custom cavities by powder metallurgy. These Stellite-based cavities will replicate the form used to create them within 0.001 in./in. at a hardness of approximately 40 Rockwell C. One significant drawback is the 3x3x3 inch limitation placed on maximum part size.

2.5.3. CAVITY MATERIALS

Because polymers have such a low melting point, moldmakers have a wide latitude in their choice of materials for the construction of cavity and core inserts. Inserts created for production molds by metal cutting processes are nearly always done in steel. The cost of some short run or prototype molds is lowered by specifying aluminum inserts so that higher metal removal rates can be obtained. Cast molds can be done in aluminum, zinc, beryllium copper, or Kirksite. All these materials have significantly higher thermal conductivity than tool steels; 62-100 BTU/ft-°F-hr as compared to 10-21 BTU/ft-°F-hr for tool steels. High conductivity is an advantage in any mold, but particularly in prototypes, where cooling systems are sometimes eliminated to reduce cost. Nevertheless, cavities expected to withstand the abuse and wear of long-term use are always made of tool steels. These steels fall into the broad categories of: pre-hardened, post heat-treated, and stainless. Respective examples of each are: P-20, H-13 and 420. Pre-hardened steels offer the distinct cost advantage of not requiring heat treatment and subsequent dimensional adjustment, though they do not have the same level of strength and wear-resistance of heat-treated steels. Stainless steels are also heat-treated, with resulting hardness approximately equal that of H13 and equivalents, but at a significantly higher cost. In smaller cavities this extra expense is often justified in order to achieve

the corrosion resistance needed in many applications, such as the molding of PVC and some reinforced plastics. Hard chrome plating is an alternative to stainless steel cavity and core inserts, particularly when those inserts are large.

In general, the properties desired in cavity and core insert materials are: wear resistance, toughness, machineability, polishability, dimensional stability and hobbability (where required).

2.5.4 FINISHING OF CAVITIES AND CORES

The cost to bring the surfaces of the cavity/core set up to the required level of finish can be surprisingly high; up to 50% of the total cost of the mold [8]. A fine finish is required for trouble-free part ejection, and more importantly, to impart an appealing, high-quality appearance to the surface of the part. The primary variables determining the number of hours required to finish a particular cavity are set forth below.

1. Part's desired gloss level, or clarity
2. Surface area
3. Geometric complexity
4. Insert material
5. Processing method used to create the surface to be finished

The inclusion of the first three items should not require further elaboration. The primary impact of item 4 is the material's hardness, though there is variation in the degree to which different materials of equal hardness may be

polished. The processing method's impact on the cost of finishing is simply dependent upon the surface finish left by that process. For example, machining requires more finishing work than EDM or hobbing because the cutter marks must be removed. For a machined cavity, the process starts with the removal of rough machining marks with specialized files, called rifflers, followed by a series of passes with finishing stones, starting at approximately 150 grit and ending at around 600 grit. The final step is the application of polishing pastes, which, depending on the required part appearance may range in media size from 60 micro-inches down to 4 micro-inches. If done in multiple stages, and incorporating a low amperage finish pass, EDM cavities require little finishing. Usually an application of polishing paste is all that is needed, though some non-critical parts will require no finishing at all. The finish of hobbled cavities is of a similar level to those created with EDM.

2.5.5 TEXTURING

The surface of some parts require the esthetics of a textured finish. Examples of these finishes are: wood grain, leather grain, checkering, lettering and company or product logos. The chemical photo-etch process used to impart the required texture into the mold cavity is performed by specialized companies, and can be done on nearly all mold materials. Best results are obtained with hard, fine-grained materials. The porosity found in some

cast cavities can create some problems, while resulphurized steels do not yield satisfactory results at all. Areas that are to be textured do not require the degree of polish normally found in untextured surfaces. While finer textures require somewhat better finishes, a finish produced by a 240-320 grit finishing stone is generally sufficient. Because texturing effectively roughens the surface, additional draft must be incorporated on surfaces parallel to the direction of mold opening. An additional 1 to 1.5 degrees of draft for each 0.001 inch of texture depth is recommended [10].

2.6 THE MOLD BASE

In its most elemental form, an injection mold can be considered simply as the cavity/core sets that form the part, surrounded by the mold base. The cooling, runner, injection, and ejection systems are actually sub-systems of the mold base designed to perform the essential services required by the cavities, such as getting the melt into the cavities in a balanced fashion, cooling the part quickly, and ejecting it without damage. The mold base is essentially the frame that holds these systems together. A common method of constructing a mold base is for the moldmaker to purchase a standard unit from an outside source specializing in their manufacture, and then to customize it for the intended application. Purchasing pre-manufactured mold bases is common practice because their commonality of construction lends them to be manufactured with economies of

scale not available to the moldmaker. Figures 6 and 7 show pages from the catalogue of a major mold base supplier. It can be seen that the primary selection specification is the overall height and width of the base plates. In designing the mold, one must be certain that the plan layout of the chosen number of cavities will fit in the mating A and B plates, and that the entire mold will then fit between the tie rods of the machine. Once the plate area is determined, the A and B plate thickness must be specified. The height of the part in the direction of mold opening is the primary factor in determining the overall thickness of the two plates. The relative thickness of each plate is dependent on where the parting line splits the part. The combined plate thickness must be somewhat greater than the part depth to resist bending and compressive stresses, and to permit the passage of cooling channels. Special features, such as unscrewing mechanisms, which operate on a rack and pinion to release molded-in female threads, require additional plate thickness, as do runnerless molds (discussed in Sec. 2.10.). In a similar manner, slides or core pulls require added plate width and/or height. Mold base selection also involves choosing the desired grade of steel. Some of the factors influencing this decision are: machining requirements, existence of slides, or other moving mechanisms, and whether any of the plates will form part surfaces.

Although the purchase of pre-manufactured mold bases eliminates a large amount of machining, there is still a considerable level of effort required to customize this standard product so that it will perform in a specialized application. This work involves the installation of additional components, as well as modification of existing plates. Components can be purchased from the mold base supplier, along with custom machining services. As with mold base purchase, this is generally cost-effective if the moldmaker's requirements are similar to the supplier's standard offerings. The following list describes some of the customization commonly required of purchased mold bases.

- Installation of cooling lines and devices
- Pocketing for installation of cavities and cores
- Machining of the runner system
- Installation of pillar supports to prevent plate deflection
- Attachment of lifting lugs, or other transporting features
- Design and manufacture of auxiliary mechanisms (runnerless systems, slides, unscrewing devices, etc.)
- Fitting of probes to monitor process parameters
- Provision for safety devices required of the company or government agencies
- Final assembly (includes inserting cavities and cores)

2.7 RUNNER SYSTEMS

In any multi-cavity mold, a series of passages is needed to distribute the plastic melt from the central sprue to each cavity. The most critical function of this runner system is to ensure that each cavity receives an equal volume of material. For this to occur, the runners should be of equal length, or "balanced". Examples of good and poor runner systems are shown in Fig 8. In practice, it is unusual to get molds with many cavities to fill evenly without making slight modifications to the sizes of some gates.

The surface finish and cross-section of the runner system are also important to good operation. The surface finish should be as good as the cavity and core surfaces to minimize pressure drops and prevent sticking on ejection. A circular cross-section is preferred, as it presents the minimum surface area for a given volume. This minimizes runner constriction due to melt solidification, although the need to machine both mating mold plates adds to cost. Figure 9 depicts various attempts to approach the effectiveness of the round runner while machining only one plate surface.

2.8 EJECTION SYSTEMS

The type of ejection system used to release a part from the mold is dependent upon the part's configuration. Ejection systems can be loosely divided into three main

categories: individual elements, such as pins, blades or rings, a separate stripper plate that bears on the part's edge, or blasts of air. Stripper plates and air are generally used with parts that are cylindrical and hollow, while individual pins can be placed where required in more irregular parts.

Ejector elements can be activated either by mechanical, or by hydraulic means. Mechanical ejection is initiated during mold opening through contact of the ejector plate and a stationary member. This provides relative motion between the stalled pins and the moving core through which they run. This contact results in a loud and abrupt ejection sequence. Hydraulic ejection has the advantages of smoother, quieter motion, while permitting more adjustment in stroke, velocity and dwell.

2.9 ALTERNATIVE MOLD DESIGNS

Alternatives to the standard 2 plate mold are described below, and are illustrated in Figs. 10a through 10c.

3 Plate - Parts and runner system are on opposite faces of a third plate. This permits center gating, which is desirable in cylindrical parts, as well as automatic degating and separation of parts and runners. Unmanned operation of these molds is practical.

Stripper plate - A separate plate, activated by the same means as conventional ejection, bears on the edge of

the part and forces it off the core. Three plate molds are especially effective in the ejection of hollow deep parts. With these parts, the higher bearing area and a pushing rather than pulling action are needed during ejection.

Runnerless - Eliminates the ejection, handling, and reprocessing of the sprue and runners by heating the entire runner system so that it never solidifies. These heated nozzles become, in a sense, an extension of the injection unit. Often used in multi-cavity molds for high volume parts whose requirements don't allow molding with reground material. Typical examples are disposable medical products. These molds are expensive and require more skill and experience of the set up person than with other mold types, but can provide very low-cost processing. The three primary categories of runnerless mold designs are: hot-runner, insulated hot-runner and hot manifold.

CHAPTER 3

MATERIAL COST

3.0 INTRODUCTION

Because injection molding produces finished components in a single automatic operation, the material cost of parts produced with this method is generally a greater percentage of total part cost than is usual in competing processes. This chapter will cover the estimation of these costs, assuming the specific polymer resin has been selected. Descriptions of polymers and their applications will not be presented here, as this information is readily available from a number of sources. A particularly useful introductory treatment is published each spring in the Material Reference Issue of Machine Design [11].

3.1 MATERIAL COST FACTORS

The primary cost drivers determining material cost are as follows:

1. Polymer chosen
2. Part volume
3. Type of mold (cold runner vs. runnerless)
4. Processing requirements
5. Part production volume

Knowledge of Items 1 and 2 permits estimation of the basic material cost of a proposed component. This basic

of limiting the use of regrind is the processing requirement referred to in Item 4.

Production volume, Item 5, can greatly impact part cost by effecting the price paid for material. The price break for large purchases can be substantial, with lowest cost obtained when purchasing resin in railcar quantities (approximately 80 tons). For companies purchasing on a smaller scale, 40,000 lb. truckload quantities are the next common pricing level. The needs of smaller jobs can be fulfilled by purchasing individual bags of resin (usually 50 lb. each). The list price per pound for truckload quantities of 12 common thermoplastics are shown in Table 1. List prices are frequently negotiated by moderate to high volume purchasers. The degree to which a resin may be discounted is difficult to predict, as it is dependent on the volatile forces operating on the plastics marketplace. A February, 1986 survey of the 12 polymers listed in Table 1 reveals that market prices for truckload quantities¹ of these polymers were 0-24% under the list price. Also included in this table is the specific gravity of each polymer, which enables calculation of a more practical measure of material cost; cost per unit volume.

3.2 CALCULATION OF MATERIAL COST

An outline of the elements comprising material cost is shown in Fig 13. If it is assumed that the polymer has

¹Railcar quantities for: polyethylene, polypropylene, and polystyrene

already been chosen, that its purchase price is known, and that an estimation of part volume is available, then the cost impact of the choice of runner system is the only undefined variable remaining in the determination of material cost. Use of runnerless molding eliminates this cost element, as the melt is injected directly into the cavity. This results in the following simple cost equation:

$$C_m = V \cdot \rho \cdot R_m \quad (1)$$

where C_m = Material Cost per part [\$]
 V = Part volume [in³]
 ρ = Polymer density [lb/in³]
 R_m = Price paid for polymer [\$/lb]

The impact of runnerless molding on mold and processing costs will be discussed in those respective chapters. If standard cold runner molding is chosen, and sprues and runners are completely reprocessed, the equation describing material cost remains identical to that for runnerless molding. The labor required to gather sprues and runners and feed them into the granulator is usually carried out at the machine, internal to the machine cycle. As such, the influence of runner system reprocessing on part cost is minimal.

As previously discussed, some applications prohibit the use of regrind. When 100% virgin material is a requirement, then the cost of the material contained in the runner system must be considered part of the component's material cost.

To account for this added cost, an estimate of the volume in the runner system must be obtained.

The relationship between part volume and runner volume illustrated in Fig. 14 was originally published [12] on a weight basis. It was converted assuming the specific gravity of General Purpose Polystyrene (1.04). This relationship may be described by the following equation:

$$V_r = 0.369 * V^{0.52} \quad (2)$$

where: V_r = Volume of runner system per cavity [in²]
 V = Part volume [in³]

It is unclear if the intent of the authors was that this relationship was valid for single cavity molds only. Applicability for multiple cavities could be argued, and will be assumed here, as the runner system volume should increase at roughly the same rate as the number of identical mold cavities. In any case, Eqn.(2) should be viewed as only an approximation, as runner volume is quite dependent on part design. The need for multiple gating is an example of a requirement affecting the accuracy of Eqn.(2), and whose need cannot be predicted by those without extensive experience.

The material cost of parts run in a cold runner mold, and requiring 100% virgin material, can now be calculated as follows:

$$C_m = (V + V_r) * \rho * R_m \quad (3)$$

Now that relationships needed to determine material cost are in place, the processing cost of injection molded components may now be studied.

CHAPTER 4

PROCESSING COSTS

4.0 INTRODUCTION

An estimation of the processing costs of an undecorated¹ injection molded component need only consider the economics of a single automatic operation. This is in sharp contrast to other methods capable of producing complex parts such as machining, where several machines must be considered, or die-casting, which, although very similar to injection molding, produces parts requiring subsequent trimming and plating operations.

Figure 15 illustrates the constituents of injection molding processing costs. One can observe that there are two main branches of this cost tree: the molding cycle time, and the machine rate charged for that cycle time. Since cycle cost is divided into the number of parts molded in a single cycle, the number of cavities in the mold is also a primary cost factor. The investigation of these three cost drivers is the subject of this chapter.

¹This report will not consider the secondary decorating or coating operations required on some molded parts. Examples of these include: pad printing, hot stamping, screen printing, metalizing and painting.

4.1.0 ESTIMATION OF CYCLE TIME

Figure 1 depicted the approximate relative magnitude of cycle time elements for typical parts. These elements are as follows:

1. filling time (excluding packing)
2. cooling time (including packing)
3. mold opening time
4. mold dwell time
5. mold closing time

This section contains a discussion of the effect of important part and process variables on these time elements, and a description of methodologies developed to estimate the duration of each.

4.1.1 FILL TIME

Fill time will be defined in this report as the period of time from the initiation of the forward screw motion in the injection unit, to the point where all cavities have been completely filled and cavity pressure is about to rise dramatically, signalling the onset of packing (see Fig 3). The approach taken to estimate fill time will be to make its duration directly dependent on known or easily obtained quantities. These quantities are: The available power in the machine's injection unit, the shot size (melt volume) needed to fill all cavities in the mold, and the injection pressure. A more fundamental view in terms of fluid mechanics would involve the calculation of flow rates in each channel section along the melt's path. Unfortunately,

the cross-section of the flow path has several discontinuities along its length, (nozzle, sprue, runners, gates, and the cavity). Within each section, the length, area, shape, and pressure drops are almost impossible to estimate with information available to the designer at the concept design stage. Another major roadblock to estimating fill times by analyzing fluid flow is the flow characteristics of the melt itself. All thermoplastics exhibit non-Newtonian flow behavior to varying degrees. That is, the apparent viscosity is not a constant defined as the ratio of shear stress to shear rate. Instead, it is a function of shear rate, and can be approximated closely by the following power law:

$$\mu = K\tau^{\kappa-1} \quad (4)$$

where μ = viscosity, lb-sec/in²
 K = fluid consistency constant, lb/in²
 τ = shear rate, sec⁻¹
 κ = fluid consistency exponent,

Index κ and constant K not only change for each different polymer but, are valid only for a limited range of shear rates. In fact, some polymers used in injection molding are essentially Newtonian in behavior at low shear rates, with their viscosity only becoming shear rate dependent at processing conditions (Fig. 16). One explanation for this behavior is that at higher shear rates Brownian motion is not capable of returning the molecular chains to a tangled, low-energy position. As the chains untangle, they are capable of sliding over one another more

easily, and tend to move further apart. This increased separation decreases the relatively weak Van Der Waal's intramolecular forces. When this happens, increases in shear stress will yield greater increases in shear rates. At very high shear rates (near the upper bound of the 10^3 - 10^5 sec⁻¹ range relevant to injection molding), molecular chains have a very high degree of orientation, resulting in flow behavior that again turns Newtonian. At these high shear rates material degradation begins to occur.

The primary effect that this non-Newtonian flow behavior has on the injection molding of thermoplastics is that, because of its impact on viscosity, shear rate becomes a critical factor in achieving desired fill rates and material properties. In short, the molder has an upper and a lower bound to fill time that he must work within for a particular mold. The lower bound is crossed when the fill rate is too low to fill all cavities in the mold before excessive solidification causes a halt to melt flow. On the other extreme, the maximum possible fill rate for a given mold/machine combination is determined by the power available in the injection unit. In some cases, the maximum fill rate is not utilized due to resulting excessive shear rates. Excessive fill rates during filling significantly decrease impact strength, and introduce molding problems such as flashing and burn marks. Whether it is available power or molding considerations that determine fill rate is dependent on the injection power available relative to the

shot size, and the part's geometry. The part feature predominant in controlling fill rate is wall thickness.

If the nozzle end of the injection unit is represented by Figure 17, then from elementary mechanics, the work done during injection equals:

$$W = p_i * A_b * S_s \quad (5)$$

where W = work, in-lb
 p_i = injection pressure, lb/in²
 S_s = length of screw stroke, in
 A_b = injection barrel cross-sectional area, in²

But power equals work per unit time, and $A_b * S_s$ equals the shot size, q . Substituting these equalities into Eqn.(5), we arrive at the following estimate of fill time:

$$t_f = \frac{p_i * q}{\beta_i * P_i * (12.1 * 10^3)} \quad (6)$$

where t_f = fill time, s
 q = shot size, in³
 P_i = available injection power, hp
 β_i = proportion of theoretical maximum power actually used

Shot size may be determined by adding the sprue and runner volume (Eqn. 2) to the part volume, and multiplying by the number of cavities. Recommended injection pressures for selected polymers are listed in Table 2. Although available injection power may be calculated from published machine specifications, the designer generally does not know what machine a particular part will be molded on.

Therefore, the following continuous empirical relationship

was established by analyzing the product literature of 4 major machine manufacturers [13,14,15,16]:

$$P_i = 0.32 * F_C^{0.83} \quad (7)$$

for $75 \leq F_C \leq 1000$

where P_i = available injection power, hp
 F_C = machine clamp force, tons

A plot of the derived relationship and the original data points is shown in Figure 18. As described in Chapter 2, the machine's clamp force must be sufficient to withstand the separating force created by cavity pressure. This force is found by multiplying the total plan area of all cavities by the average pressure within the cavities. Most estimates of this pressure fall into the range of 1.5-2.0 tons per square inch for the lower melt viscosity commodity polymers like polyethylene and polystyrene, and 2.5-4.5 tons per square inch for the engineering polymers. The proportion of rated injection power used for a particular molding task is very difficult to estimate because it is so dependent on subtleties in mold design and part geometry and on the efficiency of the system. It should be noted that the injection rates quoted in product literature, upon which the calculation of injection power was based, is established without a mold attached to the injection unit; i.e., by injecting the melt into air. This flow rate is therefore a significant overestimation of that present in actual conditions. To account for this discrepancy, and to allow

for less-than-maximum fill rates, 0.30 was found to a good general estimate of the parameter β_1 in Eqn. 6

Mold filling must be completed before the melt has time to solidify through the part's wall thickness. A method to estimate this cooling time will be introduced in the following section.

4.1.2 COOLING TIME

In this section, a method of estimating the time needed to cool the component until it may be safely ejected from the mold will be presented. Before the cooling time relationship is presented, a brief discussion of the thermal properties of polymers may be useful. Polymers are very poor thermal conductors in comparison to metals. This is believed to be the result of a polymer's lack of valence electrons capable of transferring energy. This quality makes polymers effective materials for handles on pots and pans, but it also increases the time needed for plastication during injection, and for cooling in the mold. A graphic presentation of the effect of widely different values of thermal conductivity is shown in Figure 19. Note the slight increase in conductivity when adding glass reinforcement to nylon. This holds true for other polymers, permitting faster cycles than their unreinforced counterparts.

Specific heat, the heat energy required to raise the temperature of a unit mass of material one degree, is another thermal coefficient that influences cooling times. The specific heat coefficients of polymers are higher than

those of metals. Within the family of thermoplastic polymers, there is a fairly clear delineation of specific heat values between the two families of polymers possessing different molecular structures; namely amorphous and crystalline. Crystalline polymers have a more structured, densely packed molecular order. In order to overcome the higher intramolecular forces between these closely packed molecules, greater heat energy is required. Crystalline polymers also require additional energy to overcome (and, during cooling, to draw away) the latent heat of fusion that develops at the melting point. When cooled to the melting point, crystallization results in a sharp drop in specific volume of crystalline polymers. This adds additional material shrinkage to that which occurs when molding all polymers.

Because amorphous polymers have a random structure with a dispersion of intermolecular force levels, they do not have a defined melting point, but more accurately, a melting range. Besides these differences in thermal properties, crystalline and amorphous polymers vary in the following physical and mechanical properties:

	Crystalline	Amorphous
Solvent Resistance	Higher	Lower
Light Transmission	Lower	Higher
Lubricity	Higher	Lower
Dimensional Stability	Higher	Lower

Mold Shrinkage	Higher	Lower
Density	Higher	Lower

Returning now to the desired goal of estimating cooling times; although some cooling takes place during injection, the majority of heat is conducted out of the melt once the cavity is filled and a temperature gradient is present between the cavity wall and the centerline of the melt. The cooling of a polymer within the mold cavity will be approximated by considering the heat transfer out of a slab of material held between flat metal plates at constant temperature. This condition is described by the unsteady-state one dimensional heat conduction equation:

$$\rho * C_p * \frac{\partial T}{\partial t} = k * \frac{\partial^2 T}{\partial x^2} \quad (8)$$

where x = distance from the center line of the material slab in a direction normal to the plates, in
 T = temperature, °F
 t = time, s
 k = thermal conductivity, BTU/sec-in-°F
 C_p = specific heat, BTU/lb-°F
 ρ = density, lb/in³

This relationship is often rearranged to be expressed in terms of the single property thermal diffusivity, where:
 $\alpha = k/(\rho * C_p)$ = thermal diffusivity, in²/s

Making the following assumptions: (1.) Die filling is isothermal; (2.) Thermal resistance of the interface is ignored; (3.) Separation of the polymer and die due to shrinkage is ignored. (4.) Cooling from the side walls of

the mold is neglected, the boundary condition solution of (8) is as follows [17]:

$$\frac{T-T_m}{T_i-T_m} = \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)} e^{\frac{-(2n+1)^2 \pi^2 \alpha t}{h^2}} \cos \frac{(2n+1) \pi x}{h} \quad (9)$$

where h = the distance between the plates, (the part's wall thickness)

T_i = initial temperature of the melt, °F

T_m = temperature of cavity wall, °F

In 1959, Ballman and Shusman [18] put forth the following estimation of cooling time based on the first term of Eqn.(9):

$$t_c = - \frac{h_{\max}^2}{\pi^2 \alpha} \log_e \left| \frac{\pi}{4} \frac{(T_x - T_m)}{(T_i - T_m)} \right| \quad (10)$$

where $h_{\max}$ = the part's maximum wall thickness², in
 T_x = Average centerline temperature of part at the conclusion of mold cooling, i.e. the beginning of mold opening, °F

A comparison of the cooling times obtained using Eqn. 10 with the cycle times of a number of widely varying parts, and with several published cooling curves [19,20,21] seem to indicate that, in practice, cooling time increases at a rate somewhat less than the square of wall thickness. The explanation for this very likely lies in the determination of eject temperature.

²If the maximum wall thickness is in a very localized area which does not perform a critical function, the part may be ejected before this area is fully cooled, effectively reducing the value of $h_{\max}$ used. This is also the case where the localized increase has greater contact with the mold than is possible for a simple planer wall.

As wall thickness increases, the temperature differential between the part's surface and centerline also becomes greater. This, along with the effect of a greater area moment of inertia, results in increasing effective stiffness as wall thickness becomes greater. Because ejection is determined by the point at which the part has been cooled enough to display sufficient stiffness for undistorted ejection, it follows that as a part's wall thickness increases, it's ejection temperature (measured at the part's centerline) can be allowed to increase somewhat. Once this assumption has been made, a representative relationship between wall thickness and ejection temperature can be employed. An analytically correct approach would be to determine the relationship between flexural modulus and temperature in the range of interest and then define eject temperature as a function of wall thickness such that constant stiffness is maintained. Unfortunately, the data linking flexural modulus and temperature isn't readily available, particularly in the temperature range of interest. Also, a separate non-linear relationship for eject temperature would most likely have to be developed for each polymer; a time-consuming exercise. To simplify the approach, an attempt was made to account for the assumed dependence of eject temperature on wall thickness in a way that would require a minimum of data collection on the part of the user.

In practice, it is not common to use part temperature as a means of determining cooling time, but rather to use trial and error to find the minimum allowable time. With this lack of empirical temperature data, thermal properties such as heat distortion temperature and maximum use temperature are often used as an approximation of ejection temperature. For this study, a basic eject temperature was arrived at for the 12 polymers covered by averaging the maximum use and heat distortion temperatures found in handbooks and manufacturer's product literature. It was assumed that these temperatures would apply to a wall thickness of 0.25 inches, the top end of the range of commonly utilized wall thickness.

Using a .25 inch wall thickness as a reference point, a single empirical relationship based on Eqn. 10 was sought that could accurately predict the cooling time of a wide range of polymers. The relationship that was chosen, Eqn. 11 below, fills this need for parts with wall thickness greater than approximately 0.06 inches.

$$t_c = 3 - \frac{h_{\max}^2}{\pi^2 \alpha} * \log_e * \left| \frac{\pi (T_x - T_m)}{4 (T_i - T_m)} \right| \quad (11)$$

$$\text{for } 0.06 \leq t_c \leq 0.25$$

where $h_{\max}$ = the part's maximum wall thickness, in
 T_i = initial temperature of the melt, °F
 T_m = temperature of cavity wall, °F
 T_x = Average centerline temperature of part
at the conclusion of mold cooling, i.e.
the beginning of mold opening, °F

Estimated eject temperatures, along with manufacturers recommendations for melt and mold temperatures and calculated values for thermal diffusivity are listed in Table 2. A comparison of cooling times for ABS predicted by Eqn 11 with those predicted by other works [19,20] is shown in Fig. 20. It is unclear whether these referenced relationships are the result of experimental trials, industrial experience, or the solution of heat transfer equations similar to the approach of Ballman and Shusman.

In analyzing Eqn. 11, and the definition of thermal diffusivity, it would be tempting to conclude that amorphous polymers will generally cycle faster than crystalline polymers due to the greater values of density and specific heat associated with the latter. This does not turn out to be the case, as the broad softening range of amorphous polymers generally necessitates a lower ejection temperature than crystalline polymers. The end result is that no clear distinction exists between cooling times for crystalline and amorphous polymers of equal wall thickness.

4.1.3 RESETTING TIME

The resetting portion of the injection molding cycle consists of the total time to open the mold after the cooling phase, eject the part clear of the mold, and close the mold in preparation for the next cycle.

The time required for mold opening and closing is dependent upon the distance traveled by the moving half of

the mold, and the velocity profile of that travel. These factors are in turn dependent on the depth of the part in the direction of mold opening, and the size and type of molding machine used.

Many molding machine manufacturers publish values of dry cycle time in their product literature. This specification refers to the safe minimum time required to open and close the moving plate through the maximum length of its adjustable clamp stroke. If it is assumed that, for any portion of the maximum clamp stroke, the acceleration and deceleration of the moving plate is a constant proportion of the time needed for mold movement, and that and that mold opening is slowed to a rate 2.5 times that used for mold closing [22], the time for mold opening plus mold closing can be described as follows:

$$t_{mo} + t_{mc} = \left| \frac{2d+4}{S_c} \right|^{.5} * 1.75 * t_{dc} \quad (12)$$

where t_{mo} = time for mold opening, s
 t_{mc} = time for mold closing, s
 t_{dc} = dry cycle time, s
 S_c = maximum clamp stroke, in
 d = part depth in the direction of mold opening, in

Four inches was added to the machine's clamp stroke to allow adequate clearance for the forward movement of the part during ejection.

The dwell portion of reset time consists of the time needed for the part to fall clear of the mold. This time for free-fall is dependent simply on the height of the die

plates. Since the height to width ratio of the die plates is an unknown, a mold base with die plates of equal width and height³ will be assumed.

Applying gravitational acceleration to determine free-fall time, the time required for part dwell between the opening and closing stroke is:

$$(13) \quad t_{md} = 0.07 * A_d^{.25}$$

where t_{md} = time for mold dwell, s
 A_d = die plate area, in²

If the die plate area of a major manufacturer's [23] largest standard mold base is substituted into Eqn.(13), t_{md} is found to be only 0.5 seconds. Because the range of time required for free-fall is quite small, most molders simply set a standard dwell time for most jobs. Molders setup reports indicate that this time is frequently set at 1 second. Very large parts, like automotive body panels and bumpers frequently require two men to handle the part out of the mold to prevent the distortion or surface flaws that could occur in free-fall. Dwell times in these cases would obviously be much greater.

Adding a fixed dwell time of 1 second to Eqn 12, we may now express the time required for resetting, t_r , as follows:

³Methods to estimate die plate area will be introduced in Chapter 5.

$$t_r = \left| \frac{2d+4}{S_s} \right|^{.5} * 1.75 * t_{dc} + 1 \quad (14)$$

To calculate resetting time from Eqn.(14), the dry cycle time and maximum clamp stroke of the specific molding machine must be known. Because it is often difficult to get this information directly, the following substitution will be made. Both dry cycle time and maximum clamp stroke are directly related to the machine's rated clamp force, therefore terms in Eqn. 14 containing these variables will be rearranged and expressed in terms of machine clamp force. The machine catalogues of three manufacturers [13,14,16] were studied to determine continuous empirical relationships between dry cycle time and clamp force, and between maximum clamp stroke and clamp force. The results are shown in Figures 21 and 22. These plots may be described by the following linear relationships.

$$t_{dc} = 0.006 * F_C + 1.5 \quad (15)$$

for $75 \leq F_C \leq 1000$

where t_{dc} = dry cycle time, s
 F_C = machine clamp force, tons

$$S_s = 0.031 * F_C + 9.3 \quad (16)$$

for $75 \leq F_C \leq 1000$

where S_s = maximum clamp stroke, in

If, for a particular application, the quantity $(2*d+4)/S_s$ is close to or greater than 1.0, machine size may have to be increased to ensure adequate clamp stroke. This will incur slight cost penalties due to higher machine rates and a possible slight increase in cycle time. In a similar fashion, the shot size required for a particular application should be compared to the shot capacity of the machines available to run the job. As with dry cycle time, the following relationship was derived so that a user need only determine required clamp force to make this comparison.

$$Q = 0.01 * F_C^{1.5} \quad (17)$$

where Q = machine shot capacity, in³

for $75 \leq F_C \leq 1000$

If Q is approximately equal to, or less than the total required shot size q , a larger machine may be needed.

4.2 CHOICE OF OPTIMAL NUMBER OF MOLD CAVITIES

The decision of how many cavities to include in a particular mold is one that carries great impact on component cost. The best choice of number of mold cavities is the optimal compromise between processing and tooling costs. A study conducted by Dewhurst and Kupperajan [24] on this subject focused on minimizing the total cost to produce a component over its production life. This study assumed a continuously variable relationship between the sizes of machines and mold bases, and their respective costs. Their

The index m , is directly dependent on the manufacturing method required to produce the cavity/core sets. For example, the cost of addition cavities produced by hobbing would probably be less than predicted by $m=0.8$, while the cost when strictly employing manual machining would likely be greater than this prediction.

The total cost of molding the expected life-cycle production of a component may now be expressed as:

$$C_t = (N_t/n) * R_{mm} * t_{ct} + C_{ct} + C_{mb} + N_t * R_m \quad (19)$$

where C_t = total cost of all components, \$
 N_t = total number of components molded
 R_{mm} = machine rate, \$/s
 t_{ct} = cycle time, s
 C_{mb} = mold base cost, \$
 R_m = cost of polymer per part, \$
 C_{ct} = total cost of all cavity and core sets, \$

In the next section, it is found that machine hour rates, R_{mm} follow a roughly linear trend with respect to clamp force. Equation 18 may also be substituted for C_{ct} . Making these manipulations, Eqn. 19 now becomes:

$$C_t = (N_t/n) * (m_{mr} * F_c + b_{mr}) * t_{ct} + C_{mb} + C_{cl} * n^m + N_t * R_m \quad (20)$$

where F_c = machine clamp force, tons
 m_{mr} = slope of machine rate vs. clamp force relationship, \$/ton
 b_{mr} = intercept of machine rate vs. clamp force relationship, \$

The analysis of mold cost drivers (detailed further in the next chapter) indicate that although they are driven by different factors, mold base cost and total mold cost follow roughly the same trend as the number of cavities are increased. This allows mold base cost and cavity cost to be

combined into a single variable, C_{mn} , the cost of an n-cavity mold.

$$C_{mn} = C_{m1} * n^m \quad (21)$$

where C_{mn} = cost of an n cavity mold, \$
 C_{m1} = cost of a 1 cavity mold, \$

C_{mn} may be substituted into Eqn.(19) for $C_{mb} + C_{c1} * n^m$.

Also, if full utilization of clamp force is assumed, then:

$$F_C = n * p \quad \text{or} \quad n = \frac{F_C}{p} \quad (22)$$

where p = average cavity pressure, tons

Substituting Eqns.(20) and (21) into Eqn.(19), we arrive at the following expression for total manufactured cost.

$$C_t = N_t * \left| b_{mr} * \frac{p}{F_C} + m_{mr} * p \right| * t_{ct} + C_{c1} * \left| \frac{F_C}{p} \right|^m + N_t * R_m \quad (23)$$

Differentiating Eqn.(23) with respect to F_C , and setting the result equal to zero, the following expression for the optimum number of mold cavities to achieve minimum total cost is arrived at:

$$n = \left| \frac{N_t * b_{mr} * t_{ct}}{C_{m1}} \right|^{\frac{1}{m+1}} \quad (24)$$

It should be noted that cycle time is not constant as the number of identical cavities is varied. Both injection time and reset time are functions of several machine parameters, and will, therefore, vary with machine size. It has been shown that resetting time increases with clamp tonnage. Section 4.1.1 also showed that a machine's available injection power increases non linearly with clamp force. For these reasons, the cycle time of a given part will increase as the number of cavities in the mold is increased. To account for this, the value of t_{ct} used in Eqn. 23 should reflect the correct number of cavities. However at the point at which Eqn.(24) is intended to be applied, the number of cavities is an unknown, and therefore the user must estimate the value. If the calculated number of cavities is significantly different than that used to estimate t_{ct} , the user should recalculate Eqn.(24) with a revised estimate of cycle time.

Because of the need to provide a balanced runner system, it is unusual to utilize an odd number of mold cavities. Radial runner systems can be an exception, but these are not common for most part geometries. To account for this, the number of cavities calculated from Eqn.(24) should be rounded to the nearest even integer.

There are two other instances where the calculated optimum number of cavities may not be the final desired value. The first is when required production rates would require additional cavities. Another reason for non-optimal

cavity usage is the lack of available machines of the desired size. This is particularly common for parts of a large plan area and relatively high production volumes.

4.3 MACHINE RATES

To calculate the cost of the molding cycle for a particular part, that part's cycle time must be multiplied by the rate charged for the particular machine the job is run on. Because cycle cost is a simple product of these two variables, the accuracy of each value is equally important in determining the accuracy of the cycle cost estimation.

Analysis of machine cost data [24] shows that the purchase price of an injection molding machine increases in an essentially linear fashion with the machine's rated clamp force. One would therefore expect that the rate charged for use of these machines would increase in a similar fashion. A summary of machine rates published by Plastics Technology in October, 1987 [30] was the result of a survey of 143 custom molders, and was intended to give a national picture of machine rates. The results are summarized in Table 3. These values represent the national average for each range of machine size surveyed. Regional variation was significant, with the highest rates reported in western states and the lowest in the southeast. In order to develop a continuous relationship between machine rate and clamp tonnage, the midpoint of each range (the midpoint of the first range was chosen as 75 tons and the last, open-ended

range was omitted) was plotted against clamp tonnage. The results very closely followed a linear relationship, as expected. This relationship can be described as follows:

$$R_{mm} = 0.041 \cdot F_C + 20.78 \quad (25)$$

$$\text{for } 50 \leq F_C \leq 1000$$

where R_{mm} = rate charged for molding machine, \$/hr

F_C = machine clamp force, tons

As a comparative source of reference, the clamp tonnage/machine rate relationship contained in a 1977 DuPont publication [12] was revised upward to reflect 1988 prices and compared to the Plastics Technology data. The empirical relationship described by Eqn.(25), along with the original Plastics Technology and DuPont data points are shown in Fig. 23. Machine-hour rates reported in Ref. 30 were not determined in a uniform manner. Not all molders included profit and labor in their rate (although a significant majority did so). Other indirect cost considerations, such as; plant efficiency or utilization, packaging, and general and administrative costs have also not been included in the rates calculated in Eqn. 25, but will be reflected in quotes from that source. A study of the components analyzed in this study indicates that increasing the machine rates calculated in Eqn. 25 by an additional 25 to 50 percent, depending on the capabilities and pricing structure of the molder, should reflect the rates used in quotation.

The last piece of information needed to calculate part cost is an estimation of the fixed costs involved in setting up the molding machine. This cost will be calculated as the product of the applicable machine rate and the amount of time required to replace the previous mold with the current one, connect all coolant, electrical and hydraulic lines, purge the previously run material and fine tune process parameters by running test shots. This setup time will fluctuate greatly with the size and complexity (runnerless system, sliding cores, etc.) of the mold in question, and the type of molding equipment available. Microprocessor control enables machines to monitor, and in some cases, correct process parameters. When optimum parameters are established they can be stored on magnetic media and reloaded when needed. This greatly speeds subsequent setup. Quick mold change systems, which enable fully-automated mold changes in as little as two minutes, are available, though not widely used due to very high cost. An estimate of the time required for manual mold change, setup and tryout on standard machines is 2-8 hours [31, 33]. Fortunately, because of the large number of parts run during each setup, the part price is not greatly affected by errors in the estimation of setup cost. For example, if the estimate of setup time was off by as much as 2 hours on a short run of 10,000 parts, the effect on the price of each part is only \$0.008 at a machine rate of 40 \$/hr.

CHAPTER 5

MOLD COST

5.0 INTRODUCTION

Moldmaking, like most business endeavors, has become increasingly competitive as moldmaking industries gain strength in the Far East and in countries like Spain and Portugal. Numerically controlled processing has not significantly altered the fact that moldmaking is an extremely labor intensive exercise, leaving the health of the industry subject to threats from low cost labor markets. It would seem that this environment should convey the need for each manufacturer to document the costs associated with each mold in sufficient detail so that future mold quotes would be as accurate as is realistically possible. The level of resources that should be committed to this task of fully understanding mold costs is directly related to benefits that can be realized from this knowledge. In this respect, it appears that a great deal more emphasis could be spent in detailing cost history before a level of diminishing returns on this effort is reached. Most moldmaking organizations keep cost histories of the molds they produce, though many are not detailed enough to be of value in producing a systematic costing procedure. Even detailed cost histories are not enough, as the ultimate goal

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is not to know precisely what a completed mold cost to manufacture, as this is past history and cannot be changed, but to use this experience to better predict future costs.

Cost estimation involving any goods or services can be described to some degree as an art; it is after all estimation, not accounting. The goal should be to attempt to quantify the experienced estimator's decision making, and to provide a more concrete and informative data base, so that rules can be developed to predict future occurrences. If this were done, predictions could be carried out by those who are less experienced, as the cost synthesis has to some degree been quantified.

The intent of the following two chapters is to demonstrate that mold costs can be predicted with a reasonable degree of accuracy by using a methodology that does not require its user to have any direct experience in moldmaking. Due to the near total lack of published literature on the subject of mold cost estimation, a good deal of the methodology created was based on analyzing the cost trends of mold quotes with respect to part attributes, and from discussion with moldmakers.

The success of this undertaking will probably be judged on how closely predicted costs match the cost set forth in the mold quote. Two points should be remembered when making these comparisons. The first is that costs taken from mold quotes are not actual costs, but the moldmaker's estimate of the material and labor costs required to manufacture and

prove out the mold. The second point is that the cost quoted by several moldmakers for the same job will almost always vary significantly. It is not uncommon to receive quotes where the price of the high bidder is more than double that of the low bidder. Part of this discrepancy can be explained by factors such as the match of the job to the machine capabilities of the particular shop or the different quality levels of materials and components assumed by each moldmaker. However, much of this variation is due to unpredictable and ever-changing factors like the workload of the shop and the desire, or lack thereof, of the moldmaker to work with the company soliciting quotes.

5.1 MOLD BASE COST

In this section the cost of producing a finished mold base, defined as all components other than the cavity and core impressions, will be explored. The methodology used assumes that the mold base will not be fabricated from basic material stock forms, but that a standard mold base will be purchased and subsequently modified. Having made this assumption, mold base costs can be divided into the purchased price of the mold base and the cost of modifications to that standard product.

The important parameters defining the cost of a pre-manufactured mold base are the area of the die plates, and their thickness. Dewhurst and Kupperrajan [24] found that this cost was essentially independent of the height-to-width ratio of the plates and their combined thickness.

It was also shown that the cost of a standard two-plate mold base can be related to die plate area and thickness as follows:

$$C_{pm} = 1000 + 4.20 * A_d * D_d^{.4} \quad (26)$$

(for $62 < A_d < 843$ and $2.75 < D_d < 11.75$)

where C_{pm} = cost of pre-manufactured mold base, \$
 A_d = Die plate area, in²
 D_d = Combined thickness of die plates, in

When a three-plate mold is required, the cost estimate calculated in Eqn.(26) should be increased by 15 percent. To relate A_d and D_d to overall part dimensions, the number of cavities contained in the mold must be known, as well as the clearance between the cavities, and the distance from the cavities to the plate edges. Cavity clearances will vary from mold to mold, depending on various technical considerations, the availability of desired mold base sizes, and the practices of each particular mold designer. The average estimate of several professionals in the field [28, 32, 33, 34] was to allow a minimum of three inches between cavities or to the edges of the plate and a minimum of three inches of stock from the deepest point of the cavity to the back of the plate. These clearances generally increase as the overall dimensions of the part, and therefore the mold base, become greater. Die plate dimensions can now be related to part dimensions through the following approximation:

$$A_d = (1 + 3 + 0.012 \cdot l \cdot w) \cdot (w + 3 + 0.012 \cdot l \cdot w) \cdot n + (3 + 0.012 \cdot l \cdot w) \cdot (1 + w + 2 \cdot (0.012 \cdot l \cdot w)) \cdot n \cdot 5 + (3 + 0.012 \cdot l \cdot w)^2 \quad (27)$$

where A_d = die plate area in²

w = overall part width, perpendicular to mold opening, in

l = overall part length, perpendicular to mold opening, in

n = number of mold cavities

$$D_d = d + 6 \quad (28)$$

where D_d = combined depth of die plates, in

d = maximum depth of part in direction of mold opening

Note that Eqn. (27) is an exact representation of area for a square array of cavities.

The use of auxiliary mechanisms, such as a core pulls or unscrewing mechanisms will necessitate additional clearance to the edge of the plate, and behind the cavity, respectively. For this procedure, a doubling of the clearances mentioned will be assumed when these devices are present.

The modifications required of a standard mold base, as discussed in Section 2.7, are generally quite extensive. The cost of performing this custom work will vary depending on the type of cooling and ejection systems that are required, the number of cavities and the method used to secure them, among others. However, if a variety of molds were examined, the cost of this custom machining and assembly would show close correlation to the original purchased price of the mold base. Two identical estimates [29, 35] of this effect are that the cost of customizing the

mold base, exclusive of any required mold actions, is equal to the original purchased cost. The final cost of a mold base excluding any required mold actions can thus be expressed as:

$$C_{mb} = 2 * C_{pm} \quad (29)$$

5.2 MOLD ACTIONS

For ease of mold cost estimating, the cost of core pulls and unscrewing devices is considered an additive cost to the mold base. In designing a part that is to be injection molded, it is critical to keep in mind the relationship of part features to the direction of mold opening and the mold's parting plane. Features whose duplication requires that areas of cavity or core must be slid out of the way to allow the part to be released, create a requirement for moving cores. To determine how many of these actions are required, all features that can cause a part to be die locked must first be identified. This quantity is not necessarily equal to the number of core pulls required, because often a number of features may be released with a single pull. Generally, all features that have the same axis of penetration into the wall of the component can be released together. For example, four radial holes cored through the wall of a cylinder at any different azimuthal locations require four separate core pulls. If these holes were instead located in a line parallel to the part axis, only a single pull would be

required. Discussions with moldmakers [27, 28, 29, 36, 39] indicate that the simple pull needed to release a round hole would add the equivalent of from 58 to 85 hours of manufacturing cost to the mold. An average of 70 hours will be assumed for each core pull required.

When pulls are needed to release more complicated features than a round hole, the additional cost of creating the feature will be included in the cost of cavity and core impressions, while the basic cost of the mechanism is assumed to remain the same.

When depressions that do not extend through the wall are required on the part's inner surface, standard core pulls cannot be used because the sliding core cannot be activated from the periphery of the mold. To meet this need, a special action, called a lifter, must be used. Lifters permit core sections to move away from the part's inner surface in order to clear the undercut. These mechanisms are generally actuated by the same mechanism as the ejection system. Estimates of the cost the manufacture lifters into the mold range from 1.5 to 2.0 times that required for core pulls [28, 34], therefore 125 hours will be assumed. The number of lifters required in a given application can be determined in the same manner as the number of core pulls.

Unscrewing devices are most commonly used to free molded female screw threads. The core containing the thread impressions is rotated relative to the molded threads, and

thus retracts out of the molded part. These cores are activated by a rack and pinion mechanism. The most common application is in the molding of bottle caps, where 32 cavity molds are not uncommon. The inter-meshing of mechanisms in these cavities requires high precision, and thus high cost. Estimates obtained on the cost of a single unscrewing devices range from an equivalent of 100 to 300 additional hours [27, 28, 29]. Additional devices required for multiple cavity molds are generally identical, and will cost less than the initial device for reasons similar to multiple-cavity fabrication. The same exponential index of .80 will be applied to the number of devices (see Eqn. 18) to calculate the total cost of unscrewing devices.

Multi-cavity unscrewing molds are generally manufactured by mold-making shops specializing in this type of work. Typical moldmaking shops will generally not wish to bid on such a job, or will not be able to produce it as cost effectively. Estimates of these types of specialized molds gained by the procedure developed in this project should be considered very tenuous.

5.3.0 CAVITY AND CORE FABRICATION

The costs detailed in this section will include only those directly involved in the creation of the cavity and core impressions. After studying literature on mold construction and speaking to professionals in the industry, the following component attributes were determined the primary cost drivers:

1. Projected area
2. Depth
3. Tolerance
4. Finish
5. Type of ejector system required
6. Shape of parting surface
7. Geometric complexity

Items 5 and 6, though entirely determined by part design, are not easily recognized by those without experience in mold design. The only reasonably complete analysis of mold costs that could be found in the literature is one published by Sors, et al [36]. This work lists the following major contributors to complete mold cost.

1. Type of mold (2 plate, 3 plate, etc.)
2. Number of parts used in the mold
3. Number of metal inserts molded into the part
4. Number of ejection pins
5. Number of insert blocks needed in cavity and core
6. Part tolerance
7. Projected area of part
8. Cavity and core complexity

Items 1-3 have either already been covered in mold base costs, or were considered to be inappropriate for this study. Some elements of the Sors system pertaining to the remaining 5 items in the list were used in the methodology presented here. The number of hours that each of the seven cost attributes contributes to cavity and core costs will be calculated as described in the following sections.

5.3.1. GROSS PROJECTED AREA

Projected area, along with the depth of the part, determines the amount of material that must be removed, or "roughed out" before detailed machining begins. As opposed

to the definition of projected area used in the calculation of required clamp force, gross projected area should include the area of any through penetrations. The cost associated with projected area also includes the time required to cut runners and gate(s), the fabrication and assembly cost of the ejector elements, and the cost of cavity/core insert material. This cost may be estimated by the following equation.

$$X_{pa} = 0.8 * A_{gp}^{1.2} \quad (30)$$

where X_{pa} = manufacturing time associated with projected area, hrs
 A_{gp} = gross projected area of part perpendicular to the direction of mold opening, in²

This relationship was established in parallel with the cost of complexity (Sec. 5.3.8) by fitting alternative trends to the 24 parts studied in the project. A possible explanation for its slight non-linearity is the fact that as part area increases, a host of potential problems arise with increasing severity which the moldmaker must take into account. Some of these problem areas relate to gating, ejection, mating at the parting line and movement of large mold sections. Most moldmakers add greater allowances for unknowns when quoting for large molds.

5.3.2 DEPTH

Equation 30 was derived on the basis of unit depth. To account for actual depth, X_d , the cost associated with part depth is calculated assuming a metal removal rate of 2

in³/min. This metal removal rate is a typical value for vertical milling operations in pre-hardened steel [9]. Note that X_d is not based on the overall depth of the part, but on the depth of the nominal wall from which all projections and depressions emanate. Adding part depth also increases the cost of cavity and core inserts. Using the metal removal rate given above and a cost of three dollars per pound for P20 steel, the cost associated with part depth can be represented as follows:

$$X_d = \frac{A_p * (D_w - 1)}{120} + 1 * d * w * 0.849 \quad (31)$$

where X_d = manufacturing time associated with depth,
hrs
 D_w = depth of part's nominal wall (1 inch min.),
in

5.3.3 TOLERANCE

From the molder's perspective, the impact of increased part tolerance on mold cost seems not so much the result of more machining hours required to produce the mold, as it is a contingency factor to allow for final fitting, testing, and re-work. Because moldmakers are generally allowed only 10% to 40% of the tolerance specified for the finished component, they often work close to the accuracy limit of their equipment. Therefore, when extremely high tolerance parts are specified, the moldmaker becomes constrained by the limits of his machine and effectively must take some of the working tolerance away from the molder. If it is determined that the mold is out of tolerance to begin with,

or could not possibly produce a part to tolerance because there is insufficient allowance for process variability, the mold may have to go through one or more re-work loops until the discrepant features are corrected. The Sors work presents a plot of tolerance value vs. additional cost (in hours) However, since it is not realistic to assign a single tolerance value to an entire part design, six classes of tolerance level were created. As shown in Table 4, these levels are defined by the blend of tolerances assigned the features of the component. The manufacturing time associated with part tolerance, X_t , can be determined by selection of the representative tolerance level in Table 4.

5.3.4 FINISH

As described in Section 2.6.3, finishing of the cavity and core impressions is carried out with a series of manual operations. When a transparent or high gloss appearance is required, finishing will be a significant component of mold cost.

Since finishing must be carried out on the entire surface of the cavity and core impressions, finishing cost is obviously related to surface area. But since the time required to remove machining marks is proportionally greater in the blends of intersecting geometries than over open surfaces, finishing time is assumed to be more closely related to the square root of the cavity's surface area. Because of this, the overall geometric complexity of a component will also greatly impact finishing cost. To

account for the effect of part geometry, a parameter quantifying complexity is introduced. This complexity parameter is assigned a value between one and ten for the part's inner and outer surfaces. The procedure for determining the parameter values is described fully in section 5.3.7. By studying estimates of the cost to finish parts of dissimilar surface area and complexity, the following approximate relationship describing finishing cost was obtained:

$$X_f = F_a * A_s^{.5} * C_{av} \quad (32)$$

where X_f = manufacturing time associated with finishing, hrs
 F_a = appearance factor from Table 5
 A_s = area of parts outer surface, in² (can be approximated by dividing part volume by the average wall thickness)
 C_{av} = average of inner and outer surface complexity levels (from Fig. 25 or Fig. 26)

In cases where a photo-etch texture (see Sec. 2.6.4) is desired, a level 2 finish should be chosen from Table 5.

Moldmaker's estimates [28, 29, 37] indicate that a good approximation for the cost per cavity of a standard texture is 4 percent of the cost of cavity and core fabrication (from Eqn. 34).

5.3.5 EJECTION SYSTEM

Ejection costs assigned to cavity and core fabrication are those costs required to create the ejector elements themselves, and to cut the penetrations needed so that these elements may pass through the core. All costs for

additional machining, assembly and fitting are covered under the mold base cost, C_{mb} . Sors predicts an effective cost of 2.5 hours per ejection pin for making the pin, and drilling and reaming the hole. He leaves it to the reader to input how many pins are required; a task that can only really be handled by experienced moldmakers. In studying the ejector pin density of 15 parts with diverse geometry, densities ranging from 0.2 to 6.6 in²/pin were found. This high degree of variability is not at all unexpected, as the placement of ejector pins is unique to each part's design. As such, ejection costs are extremely difficult to predict. The estimating method that will be used in this system is to assume a density of one pin for each 3 in² of projected area; the mean density of the 15 parts studied. Since this estimated cost is based solely on projected area, it was incorporated directly into Eqn. 29. While it is recognized that ejector pins are not the only means of part removal, the technique outlined above should provide a reasonable estimated of ejection costs at the concept design stage.

5.3.6 SHAPE OF PARTING SURFACE

The most common surface defining the parting plane at the juncture of the die plates surrounding the cavity and core is a plane. In addition to being the most common, planar parting surfaces are also the most desirable as they are reliable in operation, and the least expensive to produce. Planar parting surfaces (referred to in this study as "Type 1") are possible when the edge of the part does not

description, an alternative method of quantifying complexity has been devised, and will be described in the following section.

5.3.8 CALCULATION OF COMPLEXITY

A weakness of assigning the cost due to geometric complexity by the method described above is that it does not permit designers to assess the cost impact of fairly minor design changes.

For example, a designer would not be able to determine the more cost-effective of two different methods of retaining a secondary assembly, as it would be difficult to accurately assign relative complexity levels for relatively minor differences. In an attempt to create a more objective and refined approach to defining complexity, a method of counting surface patches was devised as an alternative to the assignment of complexity level as described in the previous section. Using this approach for complexity description will more readily permit cost comparisons of similar design concepts, and remove most of the user bias in determining complexity levels. These advantages come at the cost of having to examine all surface patches of a prospective design; a time-consuming process for complex parts. The need for describing complexity this accurately is not universal, as in some cases the cost of the mold is insignificant when amortized over the number of pieces molded by it.

Ideally, the cost of the detailed machining of the cavity and core should be estimated by finding representative costs of producing each geometrical primitive, and by defining how that cost varies with the size of the primitive. The hindrances to doing this in a structured, statistical fashion are substantial. Gathering data requires a level of record keeping not found in mold-making establishments. The only practical reason for mold makers to pay for keeping cost records on the basis of individual features, would be the desire to prepare the type of cost estimating procedure that is being described here. If this task has been undertaken, literature searches and conversations with those in the field have not uncovered any results. A commonly cited reason for the absence of this type of detailed study is that each mold has a uniqueness of construction which inhibits the accuracy of a detailed estimation system. While there is some truth to this assertion, it does not seem reasonable to assume that a detailed study of past experience would not substantially aid the accuracy of future quotes. Experience is, or most certainly should be, the basis of all quoting. If recorded and interpreted correctly, the more structured and intimately detailed this knowledge is, the more useful it should be.

As a substitute for this lack of recorded industrial experience, a method of relating machining time to surface geometry was developed by first estimating the over-all cost

associated with complexity for all parts which a mold quote was available. This was done by subtracting out all other mold costs (Sec. 5.1-5.3.8) from the quoted cost. This total cost then had to be allotted to the part features in an accurate fashion. Since detailed information was not available, it was decided that it would be misleading to attempt to quantify the cost of producing each basic shape primitive. The size of each feature was not used as a factor in determining cost for a number of reasons. It would further complicate an already time-consuming procedure, and the lack of an accurate cost model could very well make the inclusion of this relatively minor cost factor useless, or even misleading. Instead, only features that would generally prove particularly costly are identified for special treatment. These features marked for special consideration were depressions in the part, and surfaces that cannot be readily generated by conventional means. All other features are simply counted giving equal weight to each. Features that project outward from the component's nominal wall are created by producing a depression in the mold. This is generally done directly, as a hole would be drilled into a block. Depressions or through holes, on the other hand, must be formed by a corresponding projection in the mold wall. Since it is often not possible or practical to produce mold projections as an integral part of the surrounding cavity by removing the material around it, mold projections are usually created on a separate piece of tool

steel and inserted into the cavity. Because inserting necessitates that additional surfaces must be created so that the insert may be secured, the presence of part depressions or holes carries with it a higher cost than projections. Surfaces that are not reproduced by standard means are those whose shape can be described as free-form because the surface doesn't follow orthogonal planes, or has changes of curvature in more than one direction. A combination of standard features can also fall into this category when their relative orientation dictates that EDM or similar processes would be required to produce them. Examples of this are a square projection in the part, or a cylindrical projection with a keyway cut into it. Figure 26 summarizes the complexity calculator that was established following the above considerations. The relationship between complexity level and the number of manufacturing hours it represents is consistent between the Sors matrix shown in Fig. 25 and the complexity calculator outlined in Fig. 26. Complexity levels calculated following Fig. 26 extrapolate the Sorrs trend, which as noted above does not seem to allow high enough complexity levels. Because a continuous relationship between manufacturing hours and complexity has been established, complexity can be defined with greater resolution, and theoretically has no upper bound. In reality, it appears that complexity levels in the range 1 thru 10, as calculated using Fig. 26, describe the entire range of injection molded part complexity.

As a summary example, the complexity level calculation of a hypothetical component is detailed in Figure 27.

5.4 SUMMARY OF MOLD COSTS

When the seven cost factors covered in sections 5.3.1-5.3.8 have been calculated, they can then be summed to determine the cost of manufacturing a single cavity/core set.

$$C_{c1} = R_t * (X_{pa} + X_d + X_t + X_f + X_{pp} + X_{gc}) \quad (34)$$

where C_{c1} = manufacturing time associated with a single (first) cavity/core set, hrs
 X_{gc} = manufacturing time associated with geometrical complexity, as calculated either from Section 5.3.7 or 5.3.8, hrs
 R_t = rate charged by moldmaker for mold fabrication, \$/hr

Estimates of toolmakers rates currently range from approximately 28-45 \$/hr depending on the region of the country they are located in and the sophistication of their equipment. Molders specializing in large molds may have somewhat higher rates due to greater overhead costs. The user should make an effort to estimate the applicable rates of moldmakers commonly contracted by their company.

Total mold cost may now be calculated by adding the cost of the customized mold base to the total cost of all cavity core sets required.

$$C_{mn} = C_{mb} + C_{c1} * n^m \quad (35)$$

where C_{mn} = cost of an n cavity mold, \$
 C_{mb} = cost of customized mold base, \$

n = number of cavities
 m = multi-cavity cost index

The mold cost estimated using Eqn. 35 assumes that the cavities and core inserts are machined from a pre-hardened steel, like P-20. Prototype molds and molds which are intended to mold a relatively low number of parts often use aluminum as the insert material. Examination of mold quotes for short run parts indicates that aluminum molds cost approximately 80 percent of the cost if manufactured in P-20 steel. The response of one large custom molder [34] confirms this estimate, and further suggests that molds requiring heat-treated steels, such as H-13, are approximately 10 percent more costly than the reference value for P-20, while cast molds like beryllium copper cost about 50 percent this amount.

CHAPTER 6

VALIDATION OF COSTING PROCEDURE

A total of 24 parts, or their engineering drawings, were gathered from several companies involved in the manufacture of both consumer and industrial products. A summary of the attributes of these parts that affect mold cost is shown in Table 6.

Table 7 summarizes the comparisons of mold cost, part cost and cycle time quoted from respective suppliers, with estimates calculated using the described methodology. These comparisons are also presented in Figures 28 thru 30. An analysis of the statistical fit between the estimated and quoted costs yields the following results.

	MOLD COST (\$)	PART COST (\$)	CYCLE TIME (SEC)
Number of observations	24	15	14
Range of quoted cost or time	4.6-72.0 (k\$)	0.08-1.99	15-43
Range of error in estimation	-10457/+8686	-.24/+0.13	-8.4/+6.4
Standard deviation of error	4,421	0.11	3.90
Mean error	+752	-0.07	+0.90
Mean error as a % of the quote	+4.3%	-6.0%	+4.2%

The agreement between estimated and actual values are generally good: accurate enough to fulfill the intended purpose of providing early cost estimates in order to choose the best combination of materials and processes.

It should be noted that the part cost and cycle time estimates presented in Figs. 29 and 30 are not necessarily for the same set of components. For most of the parts on which information was gathered, only one of the two pieces of information was available. For nearly all components studied, material cost and hourly rates for moldmaking had to be estimated, as actual values were not available.

In order to examine how total costs are allotted, all components for which a single cavity mold was quoted were assumed to have a total production volume of 100,000. The total cost to process these 100,000 parts were divided into material, processing, and tooling cost so that the relative magnitude of these costs could be compared. The results of this analysis, shown in Fig. 32, reveal that for this total level of production, total mold, processing, and material costs are approximately equal when using a single cavity mold.

CHAPTER 7

MATERIAL AND PROCESS SELECTION

7.0 INTRODUCTION

Within this chapter, basic considerations in the selection of thermoplastics will be covered. This discussion is by no means intended to be complete in coverage, as the focus will be on processability rather than a summary of property values. To illustrate the use of early cost estimation, a cost comparison of the production of a simple cover plate, in sheetmetal, by injection molding, and by die casting will be presented. The size of the plate and the required load bearing capacity will be varied to determine if these variables impact the relative costs of these processes. Finally, because early cost estimation is sometimes used to aid in the selection of competing designs which utilize the same process, two sets of cost estimates will be developed for an actual injection molded part obtained from an auto manufacturer.

7.1 MATERIAL SELECTION

The material cost of an injection molded part is generally the largest component of total cost. As with the selection of other engineering materials, polymer selection is generally made by comparing the properties of several candidate materials to desired target levels. Property values can be gathered from supplier literature, though the

scope of this information varies significantly from supplier to supplier. When referring to property values listed in material guides, it is important to note the conditions under which they have been obtained. This is particularly true for thermoplastics, which have some unique properties that don't need to be considered when designing in metals. Most important of these is the degradation of many properties with elevated temperature and long term loading. Increasing service temperature will result in reduced tensile strength, stiffness, and accelerated heat aging, although impact strength will improve somewhat. Thermoplastics also have a tendency towards reduced elastic modulus, or "creep" under continuous loading. This effect becomes more pronounced as application temperatures increase. Figures 12a and 12b show the effect of temperature and creep on general purpose 6/6 Nylon. This data also reflects the hygroscopic characteristic present to some degree in all thermoplastics, but most prevalent in non-reinforced Nylons. Outdoor exposure, or contact with a variety of chemicals is often detrimental to the performance of thermoplastics. Exposure to UV radiation is the major cause of degradation in outdoor exposure, and since 20%-25% of all plastics are exposed to the outdoors [40], many suppliers market UV stabilized grades for these applications.

Referring to Table 1, note that the measure of stiffness used with thermoplastics is referred to as

flexural modulus. This index is determined by beam bending, rather than tensile testing, as is generally the case with metals. This occurs because as opposed to metals, most thermoplastics have markedly different strength and moduli in tension and in compression. A polymer's Deflection Temperature¹ is that which will cause a 5.0 x 0.5 x 0.5 inch simply-supported beam to deflect by .010 inches under its own weight. All properties of unreinforced polymers in this table reflect those of general purpose, medium viscosity grades. In examining Table 1, one can see the significant property improvement possible with the addition of reinforcing agents, the most popular being glass fibers. These fibers are approximately .0005 in. in diameter, by .020-.032 in. long, and are added in the proportion 10-40 percent by weight. The following summarizes the effects of fiber reinforcement on properties.

- Higher flexural modulus
- Higher creep resistance
- Higher tensile strength
- Higher specific gravity
- Higher deflection temperature
- Higher heat conductivity
- Lower impact strength (Higher at low temps)
- Lower mold shrinkage
- Lower thermal expansion

Fiber-filled resins are also more costly than the unreinforced grades of the same resin.

Once a group of candidate polymers have been chosen, final selection is often made by choosing the lowest-cost solution that meets all performance requirements. Several

¹Previously called Heat Distortion Temperature

methods of ranking candidate materials are possible. The most obvious of these would be to compare target and actual property values in some linear fashion. For example, the ratio of the two would produce a score of 0.90 for a property value 10% under target, and 1.1 for one 10% in excess. The problem with this approach becomes apparent when actual values are far from the levels desired. Property differences at the extremes, beyond the desired levels, should be given less weight than those close to the desired level. To illustrate, if the desired deflection temperature of an air conditioner enclosure were 200 °F, a 40 °F difference between two candidates is not as important at 100-140 °F, or 300-340 °F as it is at 180-220 °F. This observation leads to the relationship shown in Fig. 33, where the reward for a incremental property advantage is heightened near the target value, and reduced as the actual value departs significantly from this point. One cannot claim a uniquely correct mathematical description for this relationship, nor, due to the subjective nature of ratings, search for an empirical relationship.

7.2 IMPACT OF MATERIAL SELECTION ON PROCESSING COST

When comparing the probable relative costs of a group of candidate materials, it is necessary to consider the impact each would have on processing costs. This impact results primarily from the influence of material selection on the wall thickness required to resist the anticipated

loading. This calculation in turn permits the estimation of required part volume for each material.

Differences in required wall thickness not only result in changes in the volume of material required, but cause cycle time to vary; as fill time and cooling time are most dependent on material volume and wall thickness, respectively. First, let us consider the effect of material selection on fill time. From Eqn. 6, fill time is directly related to shot size, therefore a 20% increase in wall thickness results in an identical 20% increase in fill time. To be of practical value in material selection, this effect should be expressed as a penalty in cycle time. As described in Section 4.1.1, the estimate of fill time used in this cost model is dependent on the injection power available, injection pressure, the fraction of available injection power actually used for injection, and the volume of material forced out of the injection unit. Because these variables are largely independent of the material chosen², a common cost penalty associated with the increase in fill time due to increased wall thickness may be applied to all materials. Equation 7 gives an empirical relationship between injection power and machine clamp force. If an average cavity pressure of three and a half tons per square inch is assumed, this relationship may be expressed as follows:

²Although injection pressure is dependent on material, the variation in suggested injection pressures is not great for most engineering polymers (See Table 1.)

$$P_i = 1.12 * A_p^{0.83} \quad (36)$$

where P_i = available injection power, hp
 A_p = projected area of part, in²

Assuming that 30 percent of the theoretical maximum injection power is actually utilized, and that an injection pressure of 18,000 lb/in² is a good average for engineering polymers, Eqn. 36 may be substituted into Equation 6, resulting in the following expression for fill time:

$$t_f = 5.96 * \frac{q}{A_p^{0.83}} \quad (37)$$

where t_f = fill time, s
 q = shot size, in³

If several material candidates have been identified and the respective part volume requirement calculated, then the increase in fill time due to increased wall thickness may be calculated as follows:

$$t_w = 5.96 * \frac{V_o * ((n_n - n_o) / n_o) * ((h_n - h_o) / h_o)}{A_p^{0.83}} \quad (38)$$

where t_w = increase in fill time due to the need for greater wall thickness. (relative to the polymer under consideration which requires the thinnest wall), s
 n_o = number of cavities associated with candidate polymer requiring minimum number of cavities
 n_n = number of cavities associated with nth candidate polymer
 V_o = part volume associated with candidate polymer requiring minimum wall thickness, in³
 h_o = wall thickness associated with candidate polymer requiring minimum wall thickness, in

h_n = wall thickness associated with nth
candidate polymer, in

The cost associated with this increase in cycle time may be calculated by multiplying Eqn.(38) by the applicable machine rate. Sprue and runner volume have not been considered in this calculation because it is only of consequence for very small shot sizes. This condition results in short fill times and therefore, insignificant increases in fill times due to increases in wall thickness. However, when the mold under consideration has a high number of cavities, and molds a low cost commodity, the effect of t_w can have significant impact on part cost.

A more universally significant impact of material selection on cycle time is the effect on cooling time. By examining Eqn.(11), one can see that the variables controlling cycle time are the part's thermal diffusivity, its wall thickness, and a temperature ratio based on mold, injection and ejection temperatures; all three of which are dependent on the material chosen. Because of this multiple dependency on the material chosen, the most straightforward method of calculating a cycle time penalty related to cooling is to simply calculate each cooling time directly from Eqn.(11).

In order to make the relative impact of material selection on cycle time easier to visualize, Table 8 presents a normalized index of the relative cooling times for the thermoplastics whose properties were listed in Table

1. These indices are calculated assuming three different design objectives: 1.) Design with equal wall thickness, 2.) Design for equal stiffness, and 3.) Design for equal strength. For the latter two considerations, it was assumed that added strength or stiffness was gained by simply increasing wall thickness. The results of Table 8 are presented graphically in Fig. 34.

In addition to its affects on cycle time, material selection impacts processing costs due to the relative processability of each material. This attribute is difficult to define quantitatively, but may be loosely defined as the sum of a number of factors relating to the ease and accuracy with which the polymer may be processed. Table 9 includes the two most common measures of processability, melt flow and shrinkage.

Dealing first with melt flow, there are several measures of the flow characteristics of a polymer melt, none of which can be used with a great deal of accuracy in predicting flow in an actual molding application. These indices are more accurate when used in a relative sense, although the differences between actual conditions and the test conditions will somewhat cloud this distinction. All of the polymers listed in Table 9 are available in more than one MFI (melt flow index). Greater flow is achieved by reducing the polymer's melt viscosity, at the cost of a reduction in some physical properties. Mold shrinkage affects the dimensional accuracy with which a part may be

molded, as the greater its magnitude, the more difficult it is for the molder to compensate for it. Shrinkage is generally greater in crystalline polymers than amorphous compositions, and shrinkage is greatly reduced in all polymers by the introduction of reinforcing agents like glass fibers. Due to molecular alignment, shrinkage is anisotropic, being greater in the direction of flow, than in the transverse direction. This is particularly evident in fiber reinforced material. Table 8 also lists general qualitative ratings of processability and relative chemical resistance compiled from handbooks [39,41]. The rating for solvent resistance reflects an average resistance to a number of chemicals. The only effective way to assure proper material selection for solvent resistance is to check the precise chemicals of interest.

7.3.0 MATERIAL AND PROCESS SELECTION

The ultimate goal of the research of which this report represents a part, is to guide designers in the selection of materials and processes. In this section the cost of a very simple component will be estimated if it were processed by injection molding, by sheetmetal stamping, and by die casting. The results permit the user to choose the most cost-effective design for any value of production volume. This exercise is intended to emulate use of the presently unfinished family of cost estimating modules being developed in the Department of Industrial and Manufacturing Engineering at URI. It should be noted that the use of

material and process selection tools should not begin at this cost estimation stage, but rather these cost models are the final step in the synthesis of the design concept. The path leading to this point is envisioned as starting first by analyzing design concepts with respect to design for assembly [42]. This does not imply that minimizing assembly costs is the ultimate goal of all designs, but rather that DFA analysis attempts to organize and optimize product structure by minimizing the number of parts in the assembly and by rewarding the design of multi-featured parts which allow for easy handling, insertion and assembly. Only at this point, when the proposed product structure and the required features of each component have been laid out, can material and process selection take place. For the type of cost comparison presented in this section to be of the greatest value, the materials and processes included must be chosen with care so that the most promising candidates are part of the selection process, and time is not wasted analyzing selections that do not appear to be a likely success. Because establishing the correct candidate list requires knowledge of a wide range of processes beyond the experience of most design engineers, research is currently being conducted to establish a relational data base to be used as a material and process selector. By asking general questions concerning product requirements, i.e.: overall size, weight, loading and chemical resistance, a list of candidates for materials and processes can be developed.

7.3.1 DESIGN OBJECTIVES

The component to be studied in this cost comparison is a simple cover plate used to seal a square aperture in some kind of enclosure. Figure 35 depicts this plate in the two configurations studied here: flat and ribbed. The following design and production requirements were assumed:

1. Cover must be removable, though not regularly.
2. Corrosion resistance is required.
3. Sealing of anything other than dust and light is not required.
4. Production volume is fairly low. Costs will be analyzed for total production of from 4,000 to 28,000 covers.
5. Covers will be used over a 2 year period, with production orders placed twice per year.

In order to present a greater range of comparison, two separate design objectives were chosen for study. The first was to assume a maximum allowable deflection for a series of cover plate sizes ranging from 1 inch on a side to 16 inches on a side. The allowable deflection was chosen as 0.030 inches for a concentrated central load of 10 lbs., applied normal to the plate surface. The second design objective was to fix the size of the plate at 12 inches and vary the load applied from 10 lbs to 120 lbs, while allowing the same 0.030 maximum deflection. While it is recognized that both these objectives are simply different ways of measuring the

same property, namely flexural modulus, they are both commonly used design parameters and should be handled separately.

In order to analyze comparable designs, it was assumed that the method of attachment for all designs was by four screws. Because of this, an estimation of assembly costs was not required. In practice, many injection molded components of this type would be designed with integral snap elements that would eliminate the need for screw fastening. In the next section, the cost of providing these features in the mold will be compared to the savings in assembly costs and fastening hardware.

7.3.2 CALCULATION OF COST ESTIMATES

The following combination of materials and processes were analyzed as solutions to the two proposed design objectives.

Variable Size

- Injection molded - Talc-filled Polypropylene
- Injection molded - Thermoplastic Polyester (30% glass reinforced)
- Sheetmetal - C1010 Steel
- Sheetmetal - 5052-H32 Aluminum

Variable Load

- Injection molded - Talc-filled Polypropylene
- Injection molded - Thermoplastic Polyester (30% glass reinforced)

Sheetmetal - C1010 Steel

Die-Cast - ASTM AG40A Zinc

Both polypropylene and glass-filled polyester were chosen because they represented near extremes in terms of unit cost and modulus. Die-casting was chosen in the second exercise so that a cost comparison between die-casting and injection molding could be made, as these are such similar and closely competing processes. Die casting was not included in the first exercise because the lower requirements for load resistance would have required wall thickness too small to permit ribbing. The first step in the comparison was the calculation of the wall thickness required to maintain deflections at or below the permitted value of 0.030. For the sheetmetal components, this thickness was rounded up to the minimum available gage for the chosen material. This can be a significant cost disadvantage, particularly for aluminum use where standard thickness step up in fractions of an inch. Steel sheet thicknesses less than 22 gage can present processing problems, and were therefore not used. With injection molding and die casting, the infinite possible graduations in wall thickness carry no cost penalty. Even more important, ribbing is a very cost-effective method of reducing the volume of material required in die-cast or injection molded parts. Ribbing not only reduces material costs, but it lowers cycle times by permitting thinner walls. For the present comparisons, rib patterns generating

the required area moment of inertia were defined with the aid of a DuPont design guide [43].

Because this comparison is being made for relatively low production volumes, it was assumed that the sheetmetal parts would be punched on an N.C. turret press without the need to purchase special tooling. The amount of scrap produced in the web between the parts becomes greater with increasing plate size because it is more difficult to lay out the pattern efficiently on the sheet. Although there is usually a salvage value of approximately 10 percent of purchase price, it is not substantial enough to alter the final result of process selection and for this reason will not be included in this comparison. Times for stamping and finishing were estimated, after some modification to fit the proposed situation, through standards published by Ostwald [24]. Cycle times for die casting were estimated based on shot weight [42].

The mold cost of a die cast component is somewhat higher than an injection mold would be for the same component, although their construction is nearly identical. Part of this difference can be explained by the more costly mold materials required to resist the extreme temperature cycles present in the die casting process. This aspect of thermal shock also increases the maintenance costs of die-casting tools. On the other hand, the surface of cavity impressions used in die-casting do not have to be finished to the high degree that is required in injection molds.

Flash is always present at the parting line of die cast components due to the extremely low viscosity of molten metal, requiring a secondary piece of tooling, called a trim die, to remove this flash. For this example, an estimate of the additional cost of the die cast tooling and trim die over that of the comparable injection mold is 20% [43].

Nickel plating, common for die cast components was assumed the finishing method. As estimated using [24], this cost should be approximately equal to that of painting sheetmetal plates of the same plan area.

7.3.3 ANALYSIS OF RESULTS

The total estimated costs of producing cover plates, designed for variable size and for variable load are summarized in Tables 10a-10d and 11a-11d. Figure 36 presents plate cost vs production volume for the 2 inch and 12 inch plates, the total production volumes ranging from 4,000 to 28,000 units. The divergence in costs in going from the 2 inch to the 12 inch plate is explained by the increasing influence of material cost. Moreover, the break-even production volume required to justify injection molding increases when the plan area of the part increases, as machine rates are very sensitive to this variable. In Fig. 37, costs are displayed for the entire range of plate sizes at a constant production volume of 10,000 pieces. This figure clearly shows the high material cost of aluminum sheetmetal parts, as the relatively high cost per cubic inch is magnified by higher scrap costs, the much coarser

graduations in material thickness and the inability to reduce part volume by ribbing when designing in sheetmetal. For the other materials, note that the relative costs are unchanged as production volume is varied. As can be expected, this is also the case when designing for variable loading (see Fig. 38).

Wall thickness of the zinc parts range from 0.040 to 0.090, which essentially covers the entire range of recommended wall thickness for zinc die cast parts. This fact, coupled with the results of Fig. 38 seems to lead one to conclude that die casting is not competitive when considering a factor for which it would seem better suited to than injection molding; namely stiffness. However, referring back to the beginning of this chapter, it must be noted that if consideration of constant long-term loading and extreme use temperature were required, then this conclusion would almost certainly change.

In examining Figs. 36 through 38, the reader may be surprised that the polypropylene designs are consistently more cost effective than those molded in glass-filled polyester. Even though it is talc-filled, polypropylene is an inexpensive polymer not generally considered a prime material choice where stiffness is the major design consideration. While this study projects that injection molded polypropylene is the most cost effective combination of material and process for total production volumes of greater than approximately 14,000 units, the impact of the

very long cycle time associated with injection molded parts of a large wall thickness is not fully accounted for. For the relatively low 4,000-28,000 total output assumed in this study, a one cavity mold is underutilized even if operating at very long cycle times. But if required production rates are raised to a level high enough that multiple cavities are more economical, the polypropylene parts will require more than double the number of cavities than for parts made in polyester due to the much greater cycle time required. In this case the penalty in additional tooling cost would be substantial.

7.3.4 ASSEMBLY COSTS

In order to make a direct comparison of equivalent designs, the method of attachment was universally assumed to be by threaded fasteners. In many designs however, snap elements are utilized for the attachment of injection molded parts. A characteristic common to all snap elements is an undercut that provides the retaining capability. When the axis of this undercut is other than parallel to the direction of mold opening (which is generally the case), ejection of the part from the mold is inhibited or prevented. Some thin-walled parts with undercuts, such as snap-on lids, can be stripped from the mold due to their ability to flex. When sufficient flexure is possible, the part protrusions will pass over the undercuts in the mold. Since the need for expensive core pulls are eliminated when undercuts can be stripped from the mold, this type of

integral fastener is the most cost-effective method of securing components. Nevertheless, stripping undercuts is not generally possible when the feature is prominent because flexure is limited by allowable strain. The very low levels of allowable strain characteristic of glass reinforced polymers make them poor candidates for use with stripped parts. Allowable short term strain for this family of materials is about 1.5%, as compared to approximately 4.5% for non-reinforced grades [46].

When the part configuration or required level of retention precludes the possibility of stripping the part to release die-locked features, sliding cores must be designed into the mold. Whereas integrating strippable fastening elements onto a part can be done without increasing mold cost significantly, the requirement for sliding cores carries with it a considerable cost penalty. When a moderate-to-large number of parts are to be produced on the mold, this additional cost can be amortizing over enough units that the installed cost will be lower than is possible when separate fasteners are used.

The cost comparison previously described, was conducted assuming the use of separate fasteners for the injection molded parts because the type and number of fastening elements used would vary over the range of sizes studied, causing discontinuities in the results. To compare installation cost of separate and integral fasteners, Table 12 summarizes the cost of installing the six inch plate

assuming the following installation systems: four self tapping screws; four sets of nuts, bolts and washers; four machine screws and Pemsert hardware; and by using four integral snap elements created by two separate sliding cores. Assembly costs were estimated using Boothroyd-Dewhurst Design for Assembly [44] analysis, assuming a burdened labor rate of 30 \$/hr. In Fig. 39, the assembly cost of each system is plotted for a range of production volume, amortizing the estimated \$4,550 cost of slides into the snap-fit assembly cost. Examination of this confirms what is readily apparent in current designs; that snap elements are an extremely cost effective method of joining components. What seems not to be so apparent to many manufacturers is that low-volume production does not preclude taking advantage of the benefits of injection molding when assembly costs are considered.

7.4 EFFECT OF PART ATTRIBUTES ON COST

A valuable benefit of making this type of procedure available to product designers is that it gives them guidance in a quantitative rather than axiomatic fashion. To illustrate how design variations may be judged quantitatively, Fig. 40 illustrates the impact on mold cost of a 20 percent increase in the average values of each part attribute in Table 6.

A more specific example of evaluating design alternatives involves a heater system component (Fig. 41) obtained from an automotive manufacturer. In examining the

part, it was evident that the thickened pads greatly increase the cycle time over what would be possible had the part been designed with a constant 2mm wall thickness. As an exercise in comparing alternative designs, this part was redesigned so that the mounting pads were cored out, leaving a constant 2mm wall (Fig. 42). Although it was certain that the cycle time, and therefore piece part cost would drop significantly, it seemed that the increased cavity detail needed to create the ribbing would just as surely result in the need to maintain some minimum production volume for the change to be cost-effective. The missing element in this train of thought is that, if the cycle time reduction is great enough, fewer cavities will be required to maintain the same production rate, making it possible to reduce both piece part cost and mold cost. That situation turned out to be the case for this redesign. The estimated 63 percent decrease in cycle time permitted a reduction in the number of cavities required from six to two. Although the cost of a single cavity/core increased due to greater cavity complexity, the need for only two cavities permitted an estimated 28 percent decrease in total mold cost. The net result of this proposed redesign is an estimated 21 percent decrease in part cost, as shown in Table 13.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8.0 SUMMARY OF RESEARCH

A methodology has been developed that will permit the user to estimate the cost of producing components by thermoplastic injection molding. The inputs required of this costing procedure have been chosen so that the user need not have extensive knowledge of the injection molding process. Due to a lack of literature published on the subject, this methodology was developed with a heavy reliance on the analysis of part and mold quotes gathered from industrial sources. The results of comparing the estimates of part and mold cost calculated using this methodology show a mean difference of +4.3 percent for mold costs, -6.0 percent for part costs, and +4.2 percent for cycle time. Twenty-four parts of widely varying size and geometry were studied in order to make this comparison.

8.1 APPLICATION OF RESEARCH

The methodology outlined in this report has been developed for use by designers as a tool in optimizing material and process selection at the concept design phase. Early cost estimation techniques are most effective when

used in conjunction with design for assembly (DFA) analyses, so that both assembly and manufacturing costs are minimized.

The author believes that there is a very strong parallel between the goals of DFA and those of material and process selection (the result of early cost estimation). The central theme of DFA is simplification of the product structure through reduction in the number of parts in the assembly. In addition to a decrease in assembly and material costs, there are additional benefits of parts reduction which are more difficult to define, such as reduced inspection, purchasing and inventory costs, and less chance of part shortages. In a similar fashion, if materials and processes are chosen to minimize the number of operations required in processing, similar benefits are realized. A common reason for delays in product shipments is the late arrival of parts from a vendor, or the shipment of defective parts. Both these phenomena are more directly related to the number of processing steps than the complexity of each step. Since the probability of success (acceptable parts) in a series of processing steps is the multiple of the individual success rates, successful processing, and the number of steps required to complete processing, are inversely related. Although comprehensive processes like injection molding are complex, this is more often reflected in longer initial setup rather than in a higher reject rate. Each time a component is moved from one processing operation to another, the possibility of a delay

in completion increases, as well as the probability of creating a defective component. Schedule and quality problems are often increased when the need for processing by multiple vendors is present, as is common with finishing, and heat-treating. In these instances, increased shipping time and the difficulties of maintaining high priority for a job at each vendor often cause late final delivery to the manufacturer. Quality also suffers when multiple vendors are utilized because secondary processes are often contracted by the primary vendor. This can cause a loss of control and a breakdown in communication concerning the desired part specifications.

These observations on the advantages of minimizing processing steps are not intended to suggest that only net-shape operations like injection molding be considered during the conceptualization of product designs. On the contrary, the quick and inexpensive design evaluations possible with a full complement of cost estimation modules should lead designers to explore all avenues at the earliest stages of design. The application of these observations would come about when the use of early cost estimation on design concepts results in the identification of two or more designs that appear to be roughly equal in overall performance and cost. In those instances, the design requiring the least number of processing steps should generally be chosen. Once again using a DFA analogy, when snap features were first promoted as an alternative to

threaded fasteners, it was because this was perhaps the most effective method of reducing parts count and assembly time. Many manufacturers felt comfortable with threaded fasteners and were apprehensive of designing with snap features, feeling that they carried a much higher risk due to creep, yield, or fracture. As some manufacturers decided to take this risk, it became apparent that, when designed and used correctly, snap features were in fact much more reliable than threaded fasteners. Those organizations that were among the first to use snap features not only got a head start on bringing more cost effective goods to market earlier, but developed a new expertise first-hand and gained confidence in taking the road of innovative design.

8.2 FUTURE WORK

Areas of future investigation can be divided into those pertaining specifically to early cost estimation of injection molded components and those that apply to early cost estimation in general. Areas of this report on injection molding that could be strengthened or expanded deal mainly with estimating the mold cost due to part complexity. A more exhaustive analysis should be done on the cost of tooling a wide range of geometrical primitives of varying size and configuration (depression/projection, orientation to parting plane, etc.). To get meaningful results, this type of survey will have to be based on responses from a number of moldmakers. Given the width and breadth of this investigation, it will most likely have to

be done with the direct support and interest of a large corporation with a extensive base of moldmaking vendors. In developing this work, an effort should be made to make the complexity calculation feature based, rather than surface based. In this way, common features like bosses, ribs and gusset plates may be explicitly chosen. This would obviously speed the calculation of complexity, and make results less user-influenced.

An ideal platform for all these cost estimation modules is integration into a CAD package so that cost estimates are continually calculated and updated as the part is created or revised. Although this is not available at present, even if it were, the basic premise of early cost estimation would be lost, as present state of the art in solid modeling does not permit the designer to use his workstation or personal computer like a sketchpad. Until solid modeling becomes responsive enough that competing design concepts are commonly evaluated on it, integrating early cost estimation with CAD will be of limited value, because once a concept has been chosen and the product begins to take shape, process selection has essentially been determined.

All discussion on future work to this point has focused on the area of mold costs. This should not come as a surprise, as extensive research is continually being done on materials and processing by both industry and academia. Advances in polymers over the years has been the main catalyst in the steady infiltration of plastics to the point

where they are presently consumed in greater volume than steel [19]. During this period, the refinement of the reciprocating screw, leaps in available machine power, and most recently microprocessor control has allowed molding machines to process these new polymers at their physical limits with precision and repeatability. These advances in machines and materials were possible because of the huge investment made by the corporations that manufacture these products. In contrast to the few hundred large companies that manufacture molding machines or raw thermoplastics, the moldmaking industry consists of tens of thousands of small independent businesses. Obviously, these small companies do not have the available capital to work on advancing the technology. This state of affairs is not limited to injection moldmaking, but is true of most forms of toolmaking. More work needs to be funded in this area because it appears that the trend in process selection is toward those providing near-net shapes. Areas for potential advancement that would fill the more immediate needs of manufacturers involve reducing the lead-time for mold construction, and lowering mold cost for parts with low production volume. Better CAD-CAM links and more standardization in mold construction should support this effort.

TABLE 1.
MATERIAL PRICES and PROPERTIES

	Cost per lb	Tensile Strength 10 ⁵ psi	Flexural Modulus 10 ⁵ psi	Notched Izod ft-lb/in	HDT @256 psi F	Specific Gravity
HIGH-DENSITY POLYETHYLENE	\$0.65	4.1	1.7	0.5	120	0.95
HIGH-IMPACT POLYSTYRENE	\$0.63	3.0	3.2	2.0	180	1.06
POLYPROPYLENE 40% TALC FILLED	\$0.68	4.6	4.3	0.5	167	1.23
ABS (general purpose)	\$1.23	6.8	3.8	0.9	204	1.06
ACETAL (homopolymer)	\$1.64	10.0	4.1	1.4	277	1.42
NYLON 6/6	\$2.13	11.2	1.7	2.1	194	1.14
NYLON 40% MINERAL FILLED	\$1.55	9.0	6.0	0.7	446	1.51
POLYCARBONATE (general purpose)	\$2.09	9.0	3.4	15.0	270	1.20
POLYCARBONATE 30% GLASS FILLED	\$2.77	19.0	11.0	2.0	295	1.43
MODIFIED PPO (general purpose)	\$1.63	7.0	3.2	7.0	190	1.08
MODIFIED PPO 30% GLASS FILLED	\$2.20	17.0	11.0	2.3	300	1.27
PET 30% GLASS FILLED	\$1.64	23.0	13.0	1.9	435	1.56

TABLE 2.
MATERIAL PROCESSING PARAMETERS

	Inject Pressure psi	Thermal Diffusivity *10 ⁻⁴ in ² / sec	Inject Temp F	Mold Temp F	Eject Temp F	Temp Ratio
HIGH-DENSITY POLYETHYLENE	14000	1.760	450	80	125	0.122
HIGH-IMPACT POLYSTYRENE	14000	1.350	425	80	170	0.261
POLYPROPYLENE 40% TALC FILLED	14000	1.180	425	100	190	0.277
ABS (general purpose)	15000	1.940	500	130	180	0.135
ACETAL (homopolymer)	17000	1.410	420	200	265	0.295
NYLON 6/6	16000	1.550	555	195	265	0.194
NYLON 40% MINERAL FILLED	17000	2.600	570	200	275	0.203
POLYCARBONATE (general purpose)	17000	1.930	575	195	260	0.171
POLYCARBONATE 30% GLASS FILLED	19000	1.990	625	215	285	0.171
MODIFIED PPO (general purpose)	15000	1.940	450	180	215	0.130
MODIFIED PPO 30% GLASS FILLED	18000	2.090	600	200	250	0.125
PET 30% GLASS FILLED	17000	2.640	560	220	290	0.206

NOTE: Eject temperatures are approximate values for parts of high wall thickness (approximatly .250)

TABLE 3.
CUSTOM MOLDER'S MACHINE-HOUR RATES

	Machine Clamp Rating (tons)				
	75	200	400	625	875
Plas. Tech. (4/87)	\$23.15	\$28.00	\$34.64	\$45.80	\$54.63
Plas. Tech. (10/87)	\$23.40	\$28.38	\$36.17	\$46.20	\$57.53
DuPont (1977)	\$19.00	\$23.50	\$28.50	\$34.75	\$41.75
DuPont ('77*1.25)	\$23.75	\$29.38	\$35.63	\$43.44	\$52.19

TABLE 4.
ASSIGNMENT OF APPEARANCE LEVELS

NOTE: Tolerances are assumed to be on dimensions of 6 inches or less. Effective tolerances on dimensions greater than 6 inches are reduced by the ratio of 6 inches/actual dimension.

Tolerance Level	Description	Additional Mfg. Hrs.
1	All tolerances are .01 in.	3
2	Most tolerances are .01 in. A few are .005 in.	7
3	All tolerances are .005 in.	11
4	Most tolerances are .005 in. A few are .002 in.	21
5	All tolerances are .002 in.	35
6	Most tolerances are .002. A few are .001 in.	56

TABLE 5.
ASSIGNMENT OF APPEARANCE LEVELS

Finish Level	Description of Part's Finish Requirements	Appearance Factor, Af
0	Minimum Required (finish for ejection only)	1.0
1	Opaque, commercial (SPE #3 - SPE #4)	1.8
2	Transparent, low grade (visible flaws permissable)	2.3
3	Opaque, high gloss (SPE #2)	2.8
4	Opaque, highest gloss (SPE #1)	3.5
5	Transparent, high quality (surfaces with constant cross section. Optical quality not covered)	6.8

TABLE 6
PART ATTRIBUTES

ATTRIBUTE	MINIMUM VALUE	MAXIMUM VALUE	AVERAGE VALUE
Projected Area (in ²)	0.6	406.0	66.2
Volume (in ³)	0.1	92.0	14.5
Length (in)	1.1	26.4	9.5
Width (in)	0.5	26.4	7.2
Depth (in)	0.2	11.6	3.0
Max. wall thickness (in)	0.06	0.19	0.12
Appearance (Table 5)	1	4	2.3
Tolerance (Table 4)	1	4	2.2
Parting surface	1	3	2.0
Texture	\$259	\$2,218	28% ¹
Number of Core Pulls	0	2	25% ²
Part Complexity	1.1	10.1	4.0

¹Percentage of parts studied requiring texture
cost of texture using these average part values: \$614
ave. cost of texturing for parts in the study: \$687

²Percentage of parts studied requiring core pulls

TABLE 7.

COMPARISON OF ESTIMATED AND QUOTED COST

Note: Values in any particular row do not
refer to the same part

	Mold Cost		Part Cost		Cycle Time	
	Quoted	Estimated	Quoted	Estimated	Actual	Estimated
1	\$4,600	\$5,016	\$0.08	\$0.09	15	16.8
2	\$4,680	\$4,728	\$0.08	\$0.11	16	17.1
3	\$7,950	\$9,450	\$0.17	\$0.21	19	17.8
4	\$9,300	\$8,271	\$0.18	\$0.12	19	25.4
5	\$9,600	\$11,219	\$0.25	\$0.38	20	20.1
6	\$10,700	\$9,145	\$0.35	\$0.28	21	18.3
7	\$11,500	\$6,956	\$0.35	\$0.32	22	18.5
8	\$11,980	\$11,957	\$0.38	\$0.44	22	22.8
9	\$12,000	\$12,653	\$0.44	\$0.21	23	25.9
10	\$12,092	\$20,778	\$0.48	\$0.24	32	36.8
11	\$12,200	\$13,029	\$0.59	\$0.57	33	38.7
12	\$14,300	\$17,962	\$0.91	\$0.75	40	44.5
13	\$16,250	\$13,882	\$0.98	\$0.79	42	42.1
14	\$17,500	\$18,040	\$1.06	\$0.82	43	34.6
15	\$18,050	\$18,735	\$1.79	\$1.71		
16	\$28,000	\$31,235				
17	\$3,390	\$35,902				
18	\$33,900	\$24,570				
19	\$34,800	\$41,337				
20	\$38,750	\$38,547				
21	\$43,500	\$48,427				
22	\$63,000	\$52,543				
23	\$69,000	\$76,613				
24	\$72,000	\$76,613				

TABLE 8.

EFFECT OF MATERIAL SELECTION ON COOLING TIME

	Equal Wall	Equal Stiffness	Equal Strength
	Rel. Cool Time	Rel. Cool Time	Rel. Cool Time
<hr/>			
HIGH-DENSITY POLYETHYLENE	1.00	1.00	1.00
HIGH-IMPACT POLYSTYRENE	0.89	0.58	1.66
POLYPROPYLENE 40% TALC FILLED	0.98	0.53	0.77
ABS (general purpose)	0.86	0.51	0.31
ACETAL (homopolymer)	0.77	0.43	0.13
NYLON 6/6	0.91	0.91	0.12
NYLON 40% MINERAL FILLED	0.50	0.22	0.10
POLYCARBONATE (general purpose)	0.78	0.50	0.16
POLYCARBONATE 30% GLASS FILLED	0.76	0.22	0.04
MODIFIED PPO (general purpose)	0.87	0.57	0.30
MODIFIED PPO 30% GLASS FILLED	0.83	0.24	0.05
PET 30% GLASS FILLED	0.46	0.12	0.01

TABLE 9.
MOLDABILITY PARAMETERS

	Melt Flow Index g/10 min	Mold Shrink in/in	Thermal Diffusivity, $\times 10^{-4}$ in ² /sec	Weather- ability	Solvent Resistance	Ease of Molding
HIGH-DENSITY POLYETHYLENE	17.0	0.017	1.90	P	E	E
HIGH-IMPACT POLYSTYRENE	10.5	0.006	0.95	F	P	E
POLYPROPYLENE 40% TALC FILLED	4.5	0.010	0.82	F	E	E
ABS (general purpose)		0.005	1.75	G	P	G-E
ACETAL (homopolymer)	6.5	0.020	1.03	P	E	E
NYLON 6/6	12.3	0.015	1.35	F	E	E
NYLON 40% MINERAL FILLED		0.008	2.34	F	E	E
POLYCARBONATE (general purpose)	9.5	0.006	1.58	E	F	G-E
POLYCARBONATE 30% GLASS FILLED	6.5	0.002	1.70	E	F	VG
MODIFIED PPO (general purpose)		0.006	1.75	E	G	E
MODIFIED PPO 30% GLASS FILLED		0.002	1.21	E	G	VG
PET 30% GLASS FILLED	8.0	0.002	2.38	E	F	E

TABLE 10a
Cover Plate Cost (Steel)

Mat'l: C1010 Steel Mat'l Cost [\$/lb]: 0.45
Modulus [psi]: 30×10^6 Labor Rate [\$/hr]: 30.00

MATERIAL COST	1"	2"	4"	6"	9"	12"	16"
Gauge	22	22	22	20	18	16	14
Thickness [in]	0.030	0.030	0.030	0.036	0.048	0.060	0.071
Part Area [in ²]	0.944	3.900	15.85	35.80	80.75	143.5	257.0
Part Volume [in ³]	0.028	0.117	0.476	1.289	3.876	8.609	18.25
Vol. w/ Scrap [in ³]	0.043	0.150	0.579	1.728	5.760	10.80	25.56
Part Weight [lb]	0.008	0.033	0.135	0.365	1.097	2.436	5.164
Wt. w/ Scrap [lb]	0.012	0.042	0.164	0.489	1.630	3.056	7.233
Material Cost [\$/pc]	\$0.01	\$0.02	\$0.07	\$0.22	\$0.73	\$1.38	\$3.26
PROCESSING COST							
Turret Press [min/pc]	0.234	0.234	0.239	0.252	0.494	0.550	0.757
Deburr [min/pc]	0.164	0.174	0.194	0.250	0.270	0.305	0.325
Prime, Paint [min/pc]	0.263	0.328	0.440	0.700	1.110	1.570	2.210
Total [min/pc]	0.661	0.736	0.873	1.202	1.874	2.425	3.292
Process cost [\$/pc]	\$0.33	\$0.37	\$0.44	\$0.60	\$0.94	\$1.21	\$1.65
Total Cost [\$/pc] (w/o set-up)	\$0.34	\$0.39	\$0.51	\$0.82	\$1.67	\$2.59	\$4.90
SET UP	1"	2"	4"	6"	9"	12"	16"
Turret Press [min]	39.0	39.0	39.0	39.0	52.0	52.0	52.0
Deburr [min]	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Prime, Paint [min]	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Ttl S.U. Cst (4X) [\$]	\$114	\$114	\$114	\$114	\$140	\$140	\$140

TABLE 11d

12" Cover Plate Cost (Zinc)

Mat'l: ASTM AG40A Mat'l Cost [\$/lb]: 0.54

Modulus [psi]: 10.8×10^6 Density [lb/in³]: 0.237

MATERIAL COST	Concentrated load, [lb]						
	10.0	20.0	40.0	60.0	80.0	100.0	120.0
Wall Required [in]	0.082	0.104	0.131	0.150	0.165	0.178	0.189
Projected Area [in ²]	143.5	143.5	143.5	143.5	143.5	143.5	143.5
Slab Volume [in ³]	11.8	14.9	18.8	21.5	23.7	25.5	27.1
Ribbed Volume [%]	69	69	69	69	69	69	69
Ribbed Volume [in ³]	8.2	10.3	13.0	14.8	16.3	17.6	18.7
Part Weight [lb]	1.94	2.44	3.07	3.51	3.87	4.17	4.43
Material Cost [\$/pc]	\$1.04	\$1.32	\$1.66	\$1.90	\$2.09	\$2.25	\$2.39
PROCESSING COST							
Cycle Time [sec]	22.0	25.0	26.0	28.0	29.0	30.0	31.0
Mach-Hr Rt [\$/hr]	37.16	37.16	37.16	37.16	37.16	37.16	37.16
Molding Cost [\$/pc]	\$0.23	\$0.26	\$0.27	\$0.29	\$0.30	\$0.31	\$0.32
Trimming Cost [\$/pc]	\$0.03	\$0.03	\$0.03	\$0.03	\$0.03	\$0.03	\$0.03
Plating Cost [\$/pc]	\$0.72	\$0.75	\$0.78	\$0.82	\$0.86	\$0.91	\$0.96
Cast+Finish [\$/pc]	\$0.98	\$1.04	\$1.08	\$1.14	\$1.19	\$1.25	\$1.31
Total Cost [\$/pc] (w/o set-up,tooling)	\$2.02	\$2.35	\$2.74	\$3.04	\$3.28	\$3.50	\$3.70
FIXED COSTS							
	1"	2"	4"	6"	9"	12"	16"
Mach. Setup (4X) [\$]	\$297	\$297	\$297	\$297	\$297	\$297	\$297
Mold Cost [K\$]	\$29.5	\$29.5	\$29.5	\$29.5	\$29.5	\$29.5	\$29.5
Ttl Fixed Cost [K\$]	\$29.8	\$29.8	\$29.8	\$29.8	\$29.8	\$29.8	\$29.8

TABLE 11c

12" Cover Plate Cost (TP Polyester)

Mat'l: 30% GR Polyester Mat'l Cost [\$/lb]: 1.64
 Flex. Mod. [psi]: 13.0×10^5 Density [lb/in³]: 0.056

MATERIAL COST	Concentrated load, [lb]						
	10.0	20.0	40.0	60.0	80.0	100.0	120.0
Wall Required [in]	0.167	0.210	0.264	0.303	0.333	0.359	0.381
Projected Area [in ²]	143.5	143.5	143.5	143.5	143.5	143.5	143.5
Slab Volume [in ³]	23.9	30.1	37.9	43.4	47.8	51.5	54.7
Ribbed Volume [%]	69	69	69	69	69	69	69
Ribbed Volume [in ³]	16.5	20.8	26.2	30.0	33.0	35.5	37.7
Part Weight [lb]	0.92	1.16	1.47	1.68	1.85	1.99	2.11
Material Cost [\$/pc]	\$1.51	\$1.91	\$2.40	\$2.75	\$3.03	\$3.26	\$3.47
PROCESSING COST							
Nominal Wall [in]	0.083	0.105	0.132	0.151	0.166	0.179	0.191
Overall Height [in]	0.292	0.367	0.463	0.529	0.583	0.628	0.667
Clamp Force [tons]	431	431	431	431	431	431	431
Cycle Time [sec]	13.8	18.1	23.4	28.6	33.2	37.1	40.8
Mach-Hr Rt [\$/hr]	37.16	37.16	37.16	37.16	37.16	37.16	37.16
Molding Cost [\$/pc]	\$0.14	\$0.19	\$0.24	\$0.30	\$0.34	\$0.38	\$0.42
Total Cost [\$/pc] (w/o set-up, tooling)	\$1.66	\$2.09	\$2.65	\$3.05	\$3.37	\$3.64	\$3.89
FIXED COSTS							
	1"	2"	4"	6"	9"	12"	16"
Mach. Setup (4X) [\$]	\$297	\$297	\$297	\$297	\$297	\$297	\$297
Mold Cost [K\$]	\$24.6	\$24.6	\$24.6	\$24.6	\$24.6	\$24.6	\$24.6
Ttl Fixed Cost [K\$]	\$24.9	\$24.9	\$24.9	\$24.9	\$24.9	\$24.9	\$24.9

TABLE 11b

12" Cover Plate Cost (Polypropylene)

Mat'l: Talc-filled Polypro Mat'l Cost [\$/lb]: 0.57

Flex. Mod. [psi]: 4.3×10^5 Density [lb/in³]: 0.044

MATERIAL COST	Concentrated load, [lb]						
	10.0	20.0	40.0	60.0	80.0	100.0	120.0
Wall Required [in]	0.242	0.304	0.383	0.439	0.483	0.520	0.553
Projected Area [in ²]	143.5	143.5	143.5	143.5	143.5	143.5	143.5
Slab Volume [in ³]	34.7	43.7	55.0	63.0	69.3	74.6	79.3
Ribbed Volume [%]	69	69	69	69	69	69	69
Ribbed Volume [in ³]	23.9	30.1	38.0	43.4	47.8	51.5	54.7
Part Weight [lb]	1.05	1.33	1.67	1.91	2.10	2.27	2.41
Material Cost [\$/pc]	\$0.60	\$0.76	\$0.95	\$1.09	\$1.20	\$1.29	\$1.37
PROCESSING COST							
Nominal Wall [in]	0.121	0.152	0.192	0.219	0.241	0.260	0.276
Overall Height [in]	0.423	0.532	0.671	0.768	0.845	0.910	0.967
Clamp Force [tons]	431	431	431	431	431	431	431
Cycle Time [sec]	28.7	39.6	58.2	71.3	86.7	99.2	110.9
Mach-Hr Rt [\$/hr]	37.16	37.16	37.16	37.16	37.16	37.16	37.16
Molding Cost [\$/pc]	\$0.30	\$0.41	\$0.60	\$0.74	\$0.89	\$1.02	\$1.14
Total Cost [\$/pc] (w/o set-up, tooling)	\$0.90	\$1.16	\$1.55	\$1.83	\$2.09	\$2.32	\$2.52
FIXED COSTS							
	1"	2"	4"	6"	9"	12"	16"
Mach. Setup (4X) [\$]	\$297	\$297	\$297	\$297	\$297	\$297	\$297
Mold Cost [K\$]	\$24.6	\$24.6	\$24.6	\$24.6	\$24.6	\$24.6	\$24.6
Ttl Fixed Cost [K\$]	\$24.9	\$24.9	\$24.9	\$24.9	\$24.9	\$24.9	\$24.9

TABLE 11a

12" Cover Plate Cost (Steel)

Mat'l: C1010 Steel Mat'l Cost [\$/lb]: 0.45
 Modulus [psi]: 30×10^6 Labor Rate [\$/hr]: 30.00

MATERIAL COST	Concentrated load, [lb]						
	10.0	20.0	40.0	60.0	80.0	100.0	120.0
Gauge	16	14	13	12	11	10	9
Thickness [in]	0.060	0.071	0.090	0.105	0.120	0.135	0.150
Part Area [in ²]	143.5	143.5	143.5	143.5	143.5	143.5	143.5
Part Volume [in ³]	8.61	10.19	12.92	15.07	17.22	18.51	20.81
Vol. w/ Scrap [in ³]	10.80	12.78	16.20	18.90	21.60	24.30	27.00
Part Weight [lb]	2.44	2.88	3.65	4.26	4.87	5.24	5.89
Wt. w/ Scrap [lb]	3.06	3.62	4.58	5.35	6.11	6.88	7.64
Material Cost [\$/pc]	\$1.38	\$1.63	\$2.06	\$2.41	\$2.75	\$3.09	\$3.44
PROCESSING COST							
Turret Press [min/pc]	0.550	0.550	0.550	0.550	0.550	0.550	0.550
Deburr [min/pc]	0.305	0.305	0.305	0.305	0.305	0.305	0.305
Prime, Paint [min/pc]	1.570	1.570	1.570	1.570	1.570	1.570	1.570
Total [min/pc]	2.425	2.425	2.425	2.425	2.425	2.425	2.425
Process cost [\$/pc]	\$1.21	\$1.21	\$1.21	\$1.21	\$1.21	\$1.21	\$1.21
Total Cost [\$/pc] (w/o set-up)	\$2.59	\$2.84	\$3.28	\$3.62	\$3.96	\$4.31	\$4.65
SET UP	1"	2"	4"	6"	9"	12"	16"
Turret Press [min]	52.0	52.0	52.0	52.0	52.0	52.0	52.0
Deburr [min]	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Prime, Paint [min]	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Ttl S.U. Cst (4X) [\$]	\$140	\$140	\$140	\$140	\$140	\$140	\$140

TABLE 10d

Cover Plate Cost (TP Polyester)

Mat'l: 30% GR Polyester Mat'l Cost [\$/lb]: 1.64
 Flex. Mod. [psi]: 13.0×10^5 Density [lb/in³]: 0.056

MATERIAL COST	1"	2"	4"	6"	9"	12"	16"
Wall Required [in]	0.050	0.050	0.074	0.102	0.135	0.167	0.203
Projected Area [in ²]	0.944	3.900	15.85	35.80	80.75	143.5	257.0
Slab Volume [in ³]	0.047	0.195	1.177	3.659	10.92	24.00	52.26
Ribbed Volume [%]	--	--	--	68	66	66	66
Ribbed Volume [in ³]	--	--	--	2.488	7.21	15.84	34.49
Part Weight [lb]	0.002	0.009	0.052	0.109	0.317	0.697	1.518
Material Cost [\$/pc]	\$0.00	\$0.01	\$0.08	\$0.18	\$0.52	\$1.14	\$2.49
PROCESSING COST							
Nominal Wall [in]	0.050	0.050	0.074	0.050	0.065	0.080	0.097
Overall Height [in]	0.250	0.250	0.274	0.080	0.240	0.297	0.361
Clamp Force [tons]	3	11	44	100	226	402	720
Cycle Time [sec]	7.1	7.2	10.1	8.4	9.8	13.1	17.4
Mach-Hr Rt [\$/hr]	22.70	22.70	22.70	24.61	29.39	36.07	48.15
Molding Cost [\$/pc]	\$0.04	\$0.05	\$0.06	\$0.06	\$0.08	\$0.13	\$0.23
Total Cost [\$/pc] (w/o set-up, tooling)	\$0.05	\$0.06	\$0.15	\$0.24	\$0.60	\$1.27	\$2.72
FIXED COSTS	1"	2"	4"	6"	9"	12"	16"
Mach. Setup (4X) [\$]	\$182	\$182	\$182	\$197	\$235	\$289	\$385
Mold Cost [K\$]	\$3.1	\$3.8	\$5.6	\$10.6	\$16.4	\$24.6	\$37.7
Ttl Fixed Cost [K\$]	\$3.3	\$3.9	\$5.8	\$10.8	\$16.6	\$24.9	\$38.0

TABLE 10c

Cover Plate Cost (Polypropylene)

Mat'l: Talc-filled Polypro Mat'l Cost [\$/lb]: 0.57

Flex. Mod. [psi]: 4.3×10^5 Density [lb/in³]: 0.044

MATERIAL COST	1"	2"	4"	6"	9"	12"	16"
Wall Required [in]	0.050	0.064	0.107	0.148	0.196	0.242	0.294
Projected Area [in ²]	0.944	3.900	15.85	35.80	80.75	143.5	257.0
Slab Volume [in ³]	0.047	0.250	1.701	5.288	15.79	34.69	75.54
Ribbed Volume [%]	--	--	72	72	66	66	69
Ribbed Volume [in ³]	--	--	1.225	3.808	10.42	22.89	52.12
Part Weight [lb]	0.002	0.011	0.054	0.168	0.459	1.007	2.293
Material Cost [\$/pc]	\$0.00	\$0.01	\$0.03	\$0.10	\$0.26	\$0.57	\$1.31
PROCESSING COST							
Nominal Wall [in]	0.050	0.064	0.056	0.077	0.094	0.116	0.147
Overall Height [in]	0.250	0.264	0.182	0.252	0.349	0.410	0.514
Clamp Force [tons]	3	12	48	107	242	430	771
Cycle Time [sec]	8.5	10.1	20.7	13.3	18.3	25.1	37.8
Mach-Hr Rt [\$/hr]	22.70	22.70	22.70	24.88	30.01	37.16	50.10
Molding Cost [\$/pc]	\$0.05	\$0.06	\$0.13	\$0.09	\$0.15	\$0.26	\$0.53
Total Cost [\$/pc] (w/o set-up,tooling)	\$0.05	\$0.07	\$0.16	\$0.19	\$0.41	\$0.83	\$1.83
FIXED COSTS	1"	2"	4"	6"	9"	12"	16"
Mach. Setup (4X) [\$]	\$182	\$182	\$182	\$199	\$240	\$297	\$401
Mold Cost [K\$]	\$3.1	\$3.8	\$5.6	\$10.6	\$16.4	\$24.6	\$37.7
Ttl Fixed Cost [K\$]	\$3.3	\$3.9	\$5.8	\$10.8	\$16.6	\$24.9	\$38.1

TABLE 10b

Cover Plate Cost (Alum.)

Mat'l: 5052-H32 Alum Mat'l Cost [\$/lb]: 1.75
 Modulus [psi]: 10×10^6 Labor Rate [\$/hr]: 30.00

MATERIAL COST	1"	2"	4"	6"	9"	12"	16"
Thickness [in]	0.031	0.031	0.031	0.062	0.062	0.093	0.125
Part Area [in ²]	0.944	3.900	15.85	35.80	80.75	143.5	257.0
Part Volume [in ³]	0.029	0.121	0.491	2.220	5.007	13.34	32.13
Vol. w/ Scrap [in ³]	0.045	0.155	0.598	2.976	7.440	16.74	45.00
Part Weight [lb]	0.003	0.012	0.048	0.218	0.491	1.308	3.148
Wt. w/ Scrap [lb]	0.004	0.015	0.059	0.292	0.729	1.641	4.410
Material Cost [\$/pc]	\$0.01	\$0.03	\$0.10	\$0.51	\$1.28	\$2.87	\$7.72
PROCESSING COST							
Turret Press [min/pc]	0.234	0.234	0.239	0.252	0.494	0.550	0.757
Deburr [min/pc]	0.164	0.174	0.194	0.250	0.270	0.305	0.325
Anodize [min/pc]	0.198	0.308	0.489	0.680	1.030	1.310	1.640
Total [min/pc]	0.596	0.716	0.922	1.182	1.794	2.165	2.722
Process cost [\$/pc]	\$0.30	\$0.36	\$0.46	\$0.59	\$0.90	\$1.08	\$1.36
Total Cost [\$/pc] (w/o set-up)	\$0.31	\$0.38	\$0.56	\$1.10	\$2.17	\$3.95	\$9.08
SET UP	1"	2"	4"	6"	9"	12"	16"
Turret Press [min]	39.0	39.0	39.0	39.0	52.0	52.0	52.0
Deburr [min]	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Anodize [min]	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Ttl S.U. Cst (4X) [\$]	\$96	\$96	\$96	\$96	\$122	\$122	\$122

TABLE 12
FASTENING SYSTEM COSTS

Estimated cost of installing a simple 6" cover plate
with 4 of the following fastening elements

	Sheetmetal Screws	Mch. Screw & "Pemsert	Screw, Nut & Washer	Snap Elements
Place/Install Cover	\$0.07	\$0.07	\$0.07	\$0.03
Install Fasteners	\$0.32	\$0.61	\$0.73	---
Cost of Fasteners	\$0.08	\$0.20	\$0.20	---
TOTAL	\$0.47	\$0.88	\$1.00	\$0.03

Table 13.
Heater Component Cost Comparison

Estimated Costs	Original Design	Proposed Re-Design
Material Cost	\$0.078	\$0.076
Processing Cost	\$0.121	\$0.086
Mold Cost	\$34,780 (6 cavity)	\$22,875 (2 cavity)
Amortized Mold Cost (1 million pcs.)	\$0.035	\$0.023
PART COST	\$0.234	\$0.185

FIGURE 1. Components of the injection molding cycle

FIGURE 2. Injection unit of typical reciprocating screw molding machine (from ref. 8)

FIGURE 3. Typical cavity pressure profile. Note that the timing of sealing (the point where the gate(s) freeze off) is difficult to determine. Therefore the determination of when to release packing pressure is also uncertain, as ideally, packing pressure should be held just until sealing takes place.

Figure 4a.
Mechanical (Toggle) Clamp Unit

Figure 4b.
Hydraulic Clamp Unit

Figure 4c.
Hydro-mechanical Clamp Unit

FIGURE 4a. thru 4c. Clamp unit configurations typical of modern molding machines (from ref. 8.)

Two-plate mold. Generally used with conventional runner system, with single drop from sprue to distributing channels. Basically for simple parts requiring limited cam actions and movements in tool. Generally used with edge-gated parts, so pieces stay attached to runner on removal. Least cost, compared with three-plate or hot-runner molds. Easy to maintain. Runner size dictates cycle requirements because of necessary cooling time.

FIGURE 5. Cross-section of typical 2 plate mold (from ref 47.)

SPRUELESS MOLDING
MAKES SENSE!
SAVES DOLLARS!
SEE D-M-E
HOT SPRUE BUSHINGS
SECTION P

17 $\frac{7}{8}$ x 18"

D-M-E Standard A-Series Mold Bases

A	B	C	H	CATALOG NUMBER	PRICE			NET WT.
					D-M-E NO. 1 STEEL	D-M-E NO. 2 STEEL	D-M-E NO. 3 STEEL	
1 $\frac{3}{8}$	1%	3	10%	1818A-13-13	\$2130.00	\$2600.00	\$2849.00	850
	1%	3	10%	1818A-13-17	2178.00	2682.00	2948.00	895
	2%	3½	11%	1818A-13-23	2226.00	2763.00	3048.00	951
	2%	3½	12%	1818A-13-27	2273.00	2844.00	3147.00	996
	3%	4	13%	1818A-13-33	2322.00	2926.00	3246.00	1051
	3%	4	13%	1818A-13-37	2370.00	3007.00	3346.00	1097
	4%	4½	15%	1818A-13-47	2465.00	3170.00	3543.00	1188
	5%	4½	16%	1818A-13-57	2562.00	3332.00	3742.00	1289
1 $\frac{7}{8}$	1%	3	10%	1818A-17-13	2178.00	2682.00	2948.00	895
	1%	3	11%	1818A-17-17	2226.00	2763.00	3048.00	941
	2%	3½	12%	1818A-17-23	2273.00	2844.00	3147.00	996
	2%	3½	12%	1818A-17-27	2322.00	2926.00	3246.00	1042
	3%	4	13%	1818A-17-33	2370.00	3007.00	3346.00	1097
	3%	4	14%	1818A-17-37	2418.00	3088.00	3444.00	1142
	4%	4½	15%	1818A-17-47	2513.00	3251.00	3643.00	1243
	5%	4½	16%	1818A-17-57	2610.00	3414.00	3841.00	1334
2 $\frac{3}{8}$	1%	3½	11%	1818A-23-13	2226.00	2763.00	3048.00	951
	1%	3½	12%	1818A-23-17	2273.00	2844.00	3147.00	996
	2%	3½	12%	1818A-23-23	2322.00	2926.00	3246.00	1042
	2%	4	13%	1818A-23-27	2370.00	3007.00	3346.00	1097
	3%	4	14%	1818A-23-33	2418.00	3088.00	3444.00	1142
	3%	4	14%	1818A-23-37	2465.00	3170.00	3543.00	1188
	4%	4½	16%	1818A-23-47	2562.00	3332.00	3742.00	1289
	5%	4½	17%	1818A-23-57	2657.00	3495.00	3939.00	1380
2 $\frac{7}{8}$	1%	3½	12%	1818A-27-13	2273.00	2844.00	3147.00	996
	1%	3½	12%	1818A-27-17	2322.00	2926.00	3246.00	1042
	2%	3½	13%	1818A-27-23	2370.00	3007.00	3346.00	1087
	2%	4	14%	1818A-27-27	2418.00	3088.00	3444.00	1142
	3%	4	14%	1818A-27-33	2465.00	3170.00	3543.00	1188
	3%	4	15%	1818A-27-37	2513.00	3251.00	3643.00	1234
	4%	4½	16%	1818A-27-47	2610.00	3414.00	3841.00	1334
	5%	4½	17%	1818A-27-57	2705.00	3576.00	4039.00	1426

WHEN ORDERING, PLEASE SPECIFY:

1. Quantity & Catalog Number
2. No. 1, No. 2 or No. 3 Steel
3. Locating Ring Catalog Number
4. E, O and R Dimensions

A	B	C	H	CATALOG NUMBER	PRICE			NET WT.
					D-M-E NO. 1 STEEL	D-M-E NO. 2 STEEL	D-M-E NO. 3 STEEL	
3 $\frac{3}{8}$	1%	4	13%	1818A-33-13	\$2322.00	\$2926.00	\$3246.00	1051
	1%	4	13%	1818A-33-17	2370.00	3007.00	3346.00	1097
	2%	4	14%	1818A-33-23	2418.00	3088.00	3444.00	1142
	2%	4½	15%	1818A-33-27	2465.00	3170.00	3543.00	1198
	3%	4½	15%	1818A-33-33	2513.00	3251.00	3643.00	1243
	3%	4½	16%	1818A-33-37	2562.00	3332.00	3742.00	1289
	4%	4½	17%	1818A-33-47	2657.00	3495.00	3939.00	1380
	5%	4½	18%	1818A-33-57	2754.00	3659.00	4138.00	1471
3 $\frac{7}{8}$	1%	4	13%	1818A-37-13	2370.00	3007.00	3346.00	1097
	1%	4	14%	1818A-37-17	2418.00	3088.00	3444.00	1142
	2%	4½	15%	1818A-37-23	2465.00	3170.00	3543.00	1198
	2%	4½	15%	1818A-37-27	2513.00	3251.00	3643.00	1243
	3%	4½	16%	1818A-37-33	2562.00	3332.00	3742.00	1289
	3%	4½	16%	1818A-37-37	2610.00	3414.00	3841.00	1334
	4%	4½	17%	1818A-37-47	2705.00	3576.00	4039.00	1426
	5%	4½	18%	1818A-37-57	2802.00	3740.00	4237.00	1517
4 $\frac{7}{8}$	1%	4	14%	1818A-47-13	2465.00	3170.00	3543.00	1198
	1%	4	15%	1818A-47-17	2513.00	3251.00	3643.00	1234
	2%	4½	16%	1818A-47-23	2562.00	3332.00	3742.00	1289
	2%	4½	16%	1818A-47-27	2610.00	3414.00	3841.00	1334
	3%	4½	17%	1818A-47-33	2657.00	3495.00	3939.00	1380
	3%	4½	17%	1818A-47-37	2705.00	3576.00	4039.00	1426
	4%	4½	18%	1818A-47-47	2802.00	3740.00	4237.00	1517
	5%	4½	19%	1818A-47-57	2897.00	3903.00	4436.00	1608
5 $\frac{7}{8}$	1%	4	15%	1818A-57-13	2562.00	3332.00	3742.00	1279
	1%	4½	16%	1818A-57-17	2610.00	3414.00	3841.00	1334
	2%	4½	17%	1818A-57-23	2657.00	3495.00	3939.00	1380
	2%	4½	17%	1818A-57-27	2705.00	3576.00	4039.00	1426
	3%	4½	18%	1818A-57-33	2754.00	3659.00	4138.00	1471
	3%	4½	18%	1818A-57-37	2802.00	3740.00	4237.00	1517
	4%	4½	19%	1818A-57-47	2897.00	3903.00	4436.00	1608
	5%	4½	20%	1818A-57-57	2994.00	4065.00	4634.00	1699

NOTES:

1. D-M-E steels are described on page A-3
2. Catalog numbering system is described on page A-6
3. To reinforce support plate, use Support Pillars (pages K2-3)
4. For identical assembly without support plate and top clamping plate, see "B" Series Mold Bases (page C-88)

FIGURE 6. Representative page of mold base catalog (from ref. 23.). Also see Fig. 7.

D = DIAMETER OF LOCATING RING
 Cat. No. 6501 (D = 3.990) Standard
 Cat. No. 6504 (D = 3.990) Clamp Type
 (For other rings, see pages K16-18)

C	3"	3½	4"	4½
S	1⅝	1⅞	2⅝	2⅞

VIEW X-X

VIEW Y-Y

SECTION Z-Z

END VIEW

TABLE OF DIMENSIONS

Dimension	Value	Tolerance
A	1 3/4	± .001
B	1 3/4	± .001
C	2.375	± .001
D	1 3/4	± .001
E	1 3/4	± .001
F	1 3/4	± .001
G	1 3/4	± .001
H	1 3/4	± .001
I	1 3/4	± .001
J	1 3/4	± .001
K	1 3/4	± .001
L	1 3/4	± .001
M	1 3/4	± .001
N	1 3/4	± .001
O	1 3/4	± .001
P	1 3/4	± .001
Q	1 3/4	± .001
R	1 3/4	± .001
S	1 3/4	± .001
T	1 3/4	± .001
U	1 3/4	± .001
V	1 3/4	± .001
W	1 3/4	± .001
X	1 3/4	± .001
Y	1 3/4	± .001
Z	1 3/4	± .001

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FIGURE 8. Examples of runner systems. Right views show balanced systems. Top left view is also balanced, while middle and lower left views are unbalanced. (from ref. 19.)

FIGURE 9. Cross-sectional views of common runner systems. (from ref. 19.)

Three-plate mold. Uses separate plate for runner and cavity/core systems. Melt can be injected through plate into part cavity. Usually used for center pinpoint gating. Parting line for runner and part permit automatic degating or ejection. Gating in center of part provides even fill of material and reduces stresses, weld and knit lines. Size of runner dictates cycle time. Design uses pin ejection when part has flanges for adequate bearing surface.

FIGURE 10a. Cross-sectional view of typical 3 plate mold (from ref. 47.)

Stripper mold. Movable stripper plate in conjunction with stripper ring pushes molded part out after mold opens. Generally used on round parts for uniform ejection. Simple, easy to maintain, and relatively wear-free. More expensive than pin ejection.

FIGURE 10b. Cross-sectional view of typical stripper mold (from ref. 47.)

FIGURE 10c. Cross-sectional view of typical hot runner (runnerless) mold (from ref. 47.)

FIGURE 11. Effect of regrind on mechanical properties (from ref. 19.)

FIG. 12a. Effect on tensile strength

FIG. 12b. Effect on impact strength

FIGURES 12a. and 12b. Effect of regrind on the tensile strength and impact strength of thermoplastic polyester. (from ref 19.)

FIGURE 13. Components of material cost

RUNNER SYSTEM VOLUME

vs. PART VOLUME

FIGURE 14. Sprue and runner volume vs. part volume.

FIGURE 15. Components of processing cost

FIGURE 16. Viscosity vs. shear rate of thermoplastics at molding temperature (from ref. 8.)

FIGURE 17. Mechanics of injection

INJECTION POWER vs. CLAMP FORCE

FIGURE 18. Empirical relationship describing injection power. Based on product literature of machine manufacturers.

FIGURE 19. Time to conduct 1 cal. of heat through 1 cm³ of material with a temperature difference of one degree Celsius (from ref. 8.)

COMPARITIVE COOLING TIMES

FIGURE 20. Comparison of cooling time predictions for general purpose ABS.

DRY CYCLE TIME vs. CLAMP FORCE

From manufacturer's data sheets

Figure 21. Empirical relationship describing machine dry cycle time with the data points used to derive it.

MAX. CLAMP STROKE vs. CLAMP FORCE

From manufacturer's data sheets

Figure 22. Empirical relationship used to describe maximum machine clamp stroke, along with the data points used to derive it.

Figure 23. Empirical relationship used to describe machine-hour rates, along with the data points (Plas. Tech.) used to derive it. Another independent report has been included for comparison.

View A

View B

View C

Figure 24. The effect of part design and orientation on the shape of the mold's parting line. A part molded as in View A requires a mold with a stepped parting line, but no core pulls, while View B eliminates the stepped parting line, but requires core pulls. Finally, adding sides to the part permits molding without a stepped parting line or core pulls.

FIGURE 25.

MATRIX OF CAVITY/CORE COMPLEXITY
(from Sors et al. [36])

Intersection of cavity and core complexity yields
mfg. hours associated with geometric complexity

		CORE COMPLEXITY (inner surface)					
		1	2	3	4	5	6
CAVITY COMPLEXITY (outer surface)	1	13	26	40	60	80	120
	2	25	50	80	120	170	230
	3	50	80	120	170	230	290
	4	80	120	170	230	290	360
	5	120	170	230	290	360	440
	6	170	230	290	360	440	540

FIGURE 26

COMPLEXITY CALCULATOR

1. Identify the part's outer surface.
2. Count the number of times each of the following appears on the outer surface. Multiply this number by the respective feature's relative cost factor.

A. Depressions	4.0
B. Free-Forms	4.0
C. Holes	3.0
D. All others	1.0
3. Total each of the four products of the number of occurrences and relative cost from step 2. This figure is the total number of complexity points for the outer surface (CP_o).
4. Calculate the number of hours associated with geometric complexity of the outer surface, (CH_o), as follows.
5. Repeat steps 1-4 for the parts inner surface, replacing CP_o and CH_o with CP_i and CH_i , respectively.
6. Add CH_o and CH_i to arrive at the total number of hours associated with geometrical complexity, X_{gc} .
7. Convert the number of hours to a complexity rating as follows.

$$AGC = ((CH_o + CH_i)/12.3)^{.48}$$

AGC is an overall complexity rating defined as the average of the geometrical complexity of the inner and outer surfaces. It is used in the calculation of finishing cost and as a relative index of part complexity.

NOTES

1. The outer surface can be described as that which is essentially convex, while the opposite inner surface is concave. The assignment of inner and outer surfaces is arbitrary for flat parts.
2. All surfaces that be differentiated as separate are to be counted. The intent is to represent the number of motions required in metal removal. In this regard, the following are exceptions for counting: 1.) Surfaces broken up by other features that can be machined in a single pass. An example of this is an egg-crate pattern of ribs, where the intersection of ribs does not preclude machining each one full length. Two surfaces should be counted for each rib. 2.) Radii whose function is to blend features, thus avoiding stress risers or sharp edges. In general, small blend radii of approximately .06" or less.
3. An identical surface that occurs multiple times should be factored to reflect the savings of not having to change tools or re-program. The same index is used as was used for over-all cavity and core costs, .8. The effective number of occurrences for a particular feature is therefore calculated as $n^{.8}$, where n is the number of identical occurrences on any plane. It is not necessary to use this relationship for surfaces occurring less than four times. Note that the surfaces must be identical, not just similar, and they should be grouped by the number that can be completed in a single machining setup. For example, if an identical cylindrical feature occurs ten times in the same orientation on each outer wall of an open box, its total number of effective occurrences is $5(10^{.8}) = 32$, not $50^{.8} = 23$.
4. When counting depressions, do not count the number of surfaces on the depression, but simply the number of times that depressions occur. A depression is defined as a surface or group of surfaces which is sunk into the nominal wall of the part. When trying to determine whether a group of surfaces represents a single large depression, or several smaller adjacent depressions, judge whether it appears likely that all the features could have been included on a single piece of tool steel inserted in the mold wall. If this is likely, then it should be considered a single depression.
5. For free-form surfaces count as separate each segment that can be delineated by a change in curvature, or in general, by a discontinuity. As discussed in 5.3.8, standard features can also fall into this category. When they do, each surface should be counted as outlined in Note 2.

WIDGET

Mat'l: ABS

OUTER SURFACE

	# of Occurrences	Relative Cost	# of points
A. Depressions	1	4	4
B. Free-forms	4	4	16
C. Holes	0	3	0
D. All Others	24	1	24

Total Points 44

Complexity hrs. for outer surface: $.38(44)^{1.27} = 46$

INNER SURFACE

	# of Occurrences	Relative Cost	# of points
A. Depressions	1	4	4
B. Free-forms	1	4	4
C. Holes	4	3	12
D. All Others	63	1	63

Total Points 83

Complexity hrs. for inner surface: $.38(83)^{1.27} = 104$

Average Part Complexity: $((46 + 104)/12.3)^{.48} = 3.3$

FIGURE 27. Sample complexity calculation

MOLD COST COMPARISON

FIGURE 28. Comparison of the quoted cost of 24 different injection molds with costs estimated using the described methodology.

PART COST COMPARISON

FIGURE 29. Comparison of the quoted cost of 15 different injection molded parts with costs estimated using the described methodology.

CYCLE TIME COMPARISON

FIGURE 30. Comparison of the actual cycle time of 14 different injection molded parts with cycle times estimated using the described methodology.

FIGURE 32. Breakdown of total costs for single cavity molds producing a total production volume of 100,000 parts. All parts in polypropylene.

FIGURE 33. Proposed scheme of weighting the desirability of a particular polymer's engineering properties with respect to established target levels.

Fig 34a. Relative cooling time for equal wall thickness

Fig 34b. Relative cooling time for equal stiffness

Fig 34c. Relative cooling time for equal strength

COVER PLATE

Figure 35. Design of cover plate for sheetmetal application (top), and for injection molding and die-casting (bottom).

PLATE COST vs TOTAL PRODUCTION

PLATE COST vs TOTAL PRODUCTION

Figure 36. Estimated cost of cover plates at various production volumes. The cost of tooling for the injection molded components has been amortized into the cost estimate.

PLATE COST vs. SIZE

Figure 37. Estimated cost of producing cover plates in a total production quantity of 10,000. Tooling cost has been amortized into the estimate for the injection molded components.

PLATE COST vs. APPLIED LOAD

Figure 38. Estimated cost of producing cover plates for various levels of loading. Tooling cost has been amortized into the estimate of the injection molded components.

FASTENING SYSTEM COSTS

Figure 39. Estimated cost of assembly labor and fasteners to secure 6 inch cover plate by various means. The cost of core pulls has been amortized into the estimate of the snap fit assembly.

EFFECT OF PART ATTRIBUTES ON MOLD COST

FIGURE 40. The increase in mold cost of increasing the average value of the part attributes by 20%. These average values are listed in Table 6. For tolerance, finish, parting surface, and complexity the added cost was calculated based on increasing the index for that attribute by one.

FIGURE 41. Original design

FIGURE 42. Proposed design

REFERENCES

1. Monroe, S. 1987. "Design for Manufacture Activities at Ford Motor Company". Presentation at Rhode Island Technology Symposium, (Oct. 19)
2. Daetz, D. 1987. "The Effect of Product Design on Product Quality and Product Cost". Quality Progress (June): 63-67
3. Boothroyd, G. 1987. "Estimating the Cost of Machined Components". Report No. 15, Product Design for Manufacture Series, University of Rhode Island (May).
4. Stewart, S. and Wyskkida, R.. 1980. Cost Estimators Reference Manual. New York: J. Wiley & Sons.
5. Park, W. 1973. Cost Engineering Analysis. New York: J. Wiley & Sons.
6. Clark, Forest D. and Lorenzo, A.B.. 1985. Applied Cost Engineering. New York: Marcel Dekker.
7. Dym, J. B.. 1979. Injection Molds and Molding. New York: Van Nostrand Reinhold.
8. Bown, John. 1979. Injection Moulding of Plastic Components. Maidenhead: McGraw Hill (UK).
9. Dallas, Daniel, ed. 1976. Tool and Manufacturing Engineers Handbook. 3d ed. New York: McGraw Hill
10. Mold-Tech Co. Chicopee, Ma. Technical Data Sheet
11. Machine Design 1988 Reference Issue Series-Materials (Apr. 14)
12. "Concepts in Engineering Plastics". 1978. Promotional literature of E.I. duPont de Nemours & Co., Wilmington, DE.
13. Product literature from Negri Bossi S.p.A., Milan Italy, a division of John Brown Plastics Machinery.

14. Product literature from Reed Co., East Longmeadow Ma., a division of Package Machinery Co.
15. Product literature from HPM Corporation, Mount Gilead, OH.
16. Product literature from Battenfeld Maschinenfabriken GmbH, Meinerzhagen W. Germany
17. Carslaw, H.S. and Jaeger, J.C.. 1959. Conduction of Heat in Solids. Cambridge: Oxford University Press.
18. Ballman, P. and Shusman, R.. 1959. "Easy Way to Calculate Injection Molding Setup Time". Modern Plastics (Nov): 126-131
19. Rosato, Dominick V. and Rosato, Donald V., ed. 1986. Injection Molding Handbook. New York: Van Nostrand Reinhold.
20. Whelan, A. and Craft, J.L., ed. 1979. Developments in Injection Molding - 1. London: Applied Science Publishers.
21. Whelan, A. and Craft, J.L., ed. 1979. Developments in Injection Molding - 2. London: Applied Science Publishers.
22. Ostwald, P.F., ed. 1985. AM Cost Estimator. New York: McGraw-Hill.
23. Product catalogue (1986) of the D-M-E Company, Madison Heights, MI, a division of Fairchild Industries.
24. Dewhurst, P. and Kuppurajan, K.. 1987. "Optimum Processing Conditions for Injection Molding". Report No. 12, Product Design for Manufacture Series, University of Rhode Island (Feb).
25. Diaz, A., DI-Mo Development Co, Middleboro, Ma, personal communication, June 1987.
26. Mathrin, E., Elmwood Plastics, Providence, RI, personal communication, June 1987.
27. Russo, T.D., Anthony Tool and Die, Leominster, MA, personal communication, June 1987.
28. St. Louis, Bud, Windsor Mold, Windsor, Ontario, response to questionnaire, July 1988.
29. Dimatic Die & Tool Co., Omaha, NE, response to questionnaire, June 1988.

30. "Custom Molders Hourly Rate Survey". 1987. Plastics Technology. (Apr): 125-126
31. Fontaine, O., Fall River Tool and Die, Fall River, MA, personal communication, May 1987.
32. Smith, V., Ford Motor Co., Dearborn, MI, personal communication, June 1987.
33. Erwin, Timothy R., Pitney Bowes, Danbury, CT, personal communication, Sept 1987.
34. Weber, J., Prince Co., Holland, MI, personal communication, Aug 1988.
35. Schuster, A., "Injection Mold Tooling", Society of Plastics Engineers Seminar, New York, NY, Sept 30-Oct 1, 1987.
36. Sors, L., Bardocz, L., and Radnoti, I.. 1981. Plastic Molds and Dies. New York: Van Nostrand Reinhold.
37. Crici, P., Acro-Matic Plastics Corp., Leominster, MA, personal communication, July, 1988.
38. American Society for Testing and Materials, 1916 Race St, Philadelphia, Pa.
39. Harper, Charles.,ed. Handbook of Plastics and Elastomers. New York: McGraw-Hill, 1975.
40. MacDermott, Charles P. 1984. Selecting Thermoplastics for Engineering Applications. New York: Marcel Dekker.
41. Modern Plastics Encyclopedia '88. 1987. New York: McGraw Hill
42. Birch, J.M., Zinc Development Assn., London, correspondence, Dec, 1987.
43. Blum, C. "Early Cost Estimation for Die-Cast Components". Master's Thesis in preparation, University of Rhode Island.
44. Boothroyd, G., and Dewhurst, P. 1987. "Product Design for Assembly". Boothroyd Dewhurst, Inc., Wakefield, RI
45. "General Design Principles" Module 1 Design Handbook, DuPont Co, Wilmington DE.

46. "Snap Fit Joints in Plastics". 1986. Mobay Corporation, Pittsburgh, PA

47. Plastics Engineering, Nov, 1985

BIBLIOGRAPHY

1. Ballman, P. and Shusman, R.. "Easy Way to Calculate Injection Molding Setup Time". Modern Plastics (Nov 1959): 126-131
2. Barrie, Ian. "Understanding How an Injection Mold Fills". SPE Journal (August 1971): 64-69
3. Beck, Ronald. Plastic Product Design. New York: Van Nostrand Reinhold, 1970.
4. Bernhardt, Ernest. Processing of Thermoplastic Materials. New York: Van Nostrand Reinhold, 1959.
5. Birch, J.M., Zinc Development Assn., London, correspondence, Dec, 1987.
6. Blum, C. "Early Cost Estimation for Die-Cast Components". Master's Thesis in preparation, University of Rhode Island.
7. Boothroyd, G.. "Estimating the Cost of Machined Components". Report No. 15, Product Design for Manufacture Series, University of Rhode Island (May 1987).
8. Boothroyd, G., and Dewhurst, P. "Product Design for Assembly". , Wakefield, RI: Boothroyd Dewhurst, Inc., 1987
9. Bown, John. Injection Moulding of Plastic Components. Maidenhead: McGraw Hill (UK), 1979.
10. Carslaw, H.S. and Jaeger, J.C.. Conduction of Heat in Solids. Cambridge: Oxford University Press, 1959.
11. Clark, Forest D. and Lorenzo, A.B.. Applied Cost Engineering. New York: Marcel Dekker, 1985.
12. Coates, J.B.. "Tool Costs and Tool Estimating". The Production Engineer (April 1976)
13. Crici, P., Acro-Matic Plastics Corp., Leominster, MA, personal communication, July, 1988.

14. Daetz, D. "The Effect of Product Design on Product Quality and Product Cost". Quality Progress (June 1987): 63-67
15. Dallas, Daniel, ed. Tool and Manufacturing Engineers Handbook. 3d ed. New York: McGraw Hill, 1976.
16. Dewhurst, P. and Kuppurajan, K.. "Optimum Processing Conditions for Injection Molding". Report No. 12, Product Design for Manufacture Series, University of Rhode Island (Feb 1987).
17. Diaz, A., DI-Mo Development Co, Middleboro, Ma, personal communication, June 1987.
18. Dourlet, Ernest. "Selecting Plastics". Machine Design (12 December 1968): 4-8
19. DuBois, J. H., and John, F. W.. Plastics. 5th ed. New York: Van Nostrand Reinhold, 1970.
20. Dym, J. B.. Injection Molds and Molding. New York: Van Nostrand Reinhold, 1979.
21. Erwin, Timothy R. Pitney Bowes, Danbury, CT, personal communication, Sept 1987.
22. Fontaine, O., Fall River Tool and Die, Fall River, MA, personal communication, May 1987.
23. Fritch, L.W.. "Honing Molding Parameters by Measuring Flow Length". Plastics Engineering. (June 1986): 41-44
24. Gascott, Michael. "How Tool Steel Shapes Product Design". Design News (22 June 1987): 54-55
25. Harper, Charles., ed. Handbook of Plastics and Elastomers. New York: McGraw-Hill, 1975.
26. Litman, A., Chthampally, M., Fowler, N.. "Selecting Plastic Parts for CAE Analysis". From the proceedings of Regional Technical Conference, Society of Plastics Engineers held in Rochester New York, Oct 1985
27. MacDermott, Charles P. Selecting Thermoplastics for Engineering Applications. New York: Marcel Dekker, 1984.
28. Mathrin, E., Elmwood Plastics, Providence, RI, personal communication, June 1987.

29. Monroe, S. "Design for Manufacture Activities at Ford Motor Company". Presentation at Rhode Island Technology Symposium, Oct. 19, 1987.
30. Ostwald, P.F., ed. AM Cost Estimator. New York: McGraw-Hill, 1985.
31. Park, W. Cost Engineering Analysis. New York: J. Wiley & Sons, 1973.
32. Paro, T., Fredrickson, E., Minnichelli, M., and Pageau, K. "Eliminating Warp in Molded Plastics". Machine Design (21 August 1987): 69-73
33. Pauplis, W.J.. "Design Guide for Determining the Cost of Injection Molded Parts" Inter-office memo, Sippican Ocean Systems Inc (18 December 1986)
34. Rosato, Dominick V. and Rosato, Donald V., ed. Injection Molding Handbook. New York: Van Nostrand Reinhold, 1986.
35. Russo, T.D., Anthony Tool and Die, Leominster, MA, personal communication, June 1987.
36. Schuster, A., "Injection Mold Tooling", Society of Plastics Engineers Seminar, New York, NY, Sept 30-Oct 1, 1987.
37. Sors, L., Bardocz, L., and Radnoti, I.. 1981. Plastic Molds and Dies. New York: Van Nostrand Reinhold, 1981.
38. Smith, V., Ford Motor Co., Dearborn, MI, personal communication, June 1987.
39. St. Louis, Bud, Windsor Mold, Windsor, Ontario, response to questionnaire, July 1988.
40. Stewart, S. and Wyskida, R.. Cost Estimator's Reference Manual. New York: J. Wiley & Sons, 1980.
41. Stoeckert, Klaus, ed. Mold-Making Handbook. New York: McMillian, 1983.
42. Van Krevelen, D.W.. Properties of Polymers, their estimation and correlation with chemical structure. London: Elsevier, 1976.
43. Weber, J., Prince Co., Holland, MI, personal communication, Aug 1988.

44. Whelan, A. and Craft, J.L., ed. Developments in Injection Molding - 1. London: Applied Science Publishers, 1979.
45. Whelan, A. and Craft, J.L., ed. Developments in Injection Molding - 2. London: Applied Science Publishers, 1979.
46. American Society for Testing and Materials, 1916 Race St, Philadelphia, Pa.
47. "Concepts in Engineering Plastics". Promotional literature of E.I. duPont de Nemours & Co., Wilmington, DE. 1978.
48. "Custom Molders Hourly Rate Survey". Plastics Technology. (Apr 1987): 125-126
49. Dimatic Die & Tool Co., Omaha, NE, response to questionnaire, June 1988.
50. "General Design Principles" Module 1 Design Handbook, DuPont Co, Wilmington DE
51. Machine Design 1988 Reference Issue Series-Materials (Apr. 14)
52. Modern Plastics Encyclopedia '88. New York: McGraw Hill, 1987
53. Mold-Tech Co. Chicopee, Ma. Technical Data Sheet
54. "Multinational Producability - Plastic Molded Parts", Xerox Corporation, Webster, NY, 1987
55. Plastics Engineering, November, 1985
56. Product catalouge (1986) of the D-M-E Company, Madison Heights, MI, a division of Fairchild Industries.
57. Product literature from Battenfeld Maschinenfabriken GmbH, Meinerzhagen W. Germany
58. Product literature from HPM Corporation, Mount Gilead, OH.
59. Product literature from Negri Bossi S.p.A., Milan Italy, a division of John Brown Plastics Machinery.
60. Product literature from Reed Co., East Longmeadow Ma., a division of Package Machinery Co.
61. "Snap Fit Joints in Plastics", Mobay Corporation, Pittsburg, PA, 1986.