PRIMARY FABRICATION METHODS AND COSTS
IN POLYMER PROCESSING FOR AUTOMOTIVE APPLICATIONS

by

JOHN VICTOR BUSCH

B.E., Vanderbilt University (1979)

Submitted to the Department of Materials Science and Engineering in Partial Fulfillment of the Requirements of the Degree of

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Signature of Author

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May 6, 1983

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1.0 ABSTRACT

The substitution of plastics for conventional materials,
primarily steel, in automobiles, is governed by engineering
constraints and cost competitiveness. The latter of these was
studied in depth and a cost model was constructed to estimate
the cost of fabrication for plastic components for the
automotive industry. Estimation involves two phases,
1) fabrication process selection, 2) elemental cost
estimation.

Ten primary fabrication processes were identified. Feasible
methods of fabrication for a specified component were
determined from the component geometry and material of
construction or, alternately, by external selection from the
user of the model. All of the processes identified as
feasible were evaluated by elemental cost analysis to
determine the least cost method of fabrication.

Cost elements were separated into two categories: variable and
fixed costs. The variable cost elements were raw materials,
direct labor and utilities. The fixed cost elements were
equipment, overhead labor, installation, maintenance, and the
capital recovery cost of invested capital.

Sensitivity analysis was performed on a sample automotive
component (cooling fan blade) and it showed that fabrication
costs were most sensitive to raw material price, production
volume, and the period for capital recovery. The cost was
relatively insensitive to the price of utilities, the wages of
direct labor, and the interest rate on capital recovery.

Thesis Supervisor: Dr. Joel P. Clark

Title: Associate Professor of Materials Systems
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First, I would like to acknowledge my grandfather, Dr. John Chipman, for instilling in me the desire for, and purpose of a higher education. I might easily have stopped at the undergraduate level if it was not for his influence on my life.

Second, I must thank my advisor, Prof. Joel Clark, for supporting a research topic that was interesting to me and for giving me considerable freedom to pursue this topic as I saw fit. Also, Prof. Clark has provided many of the key insights which I needed to overcome the obstacles to research.

Next, I would like to thank my colleagues Frank Field and Jay Wadekar, whose contributions to my project have rivaled my own. I would especially like to thank Frank for sharing his genius in the area of computer programming and thank Jay for the advice he has given regarding the methodology of my research.

I must also thank my fiancee, Marcy McCain, for her unselfish contributions to all of the other facets of my life and for enduring the long hours which arise during graduate studies.

Finally, I must acknowledge my family who also instilled the goals of higher education in me and who provided the emotional support that these goals demand.
2.0 INTRODUCTION

Synthetic plastics are relatively new materials. They were first utilized in novelty applications such as billiard balls or piano keys. Even then, they were substitutes for a more costly material, natural ivory. In these early applications, as is often the case today, the need for cost reduction was the driving force for the substitution process.

Automotive applications date back to the 1930's and include distributor caps and steering wheel encasements. In these applications, plastics were not chosen because of cost effectiveness but rather because they were the materials which best provided the desired physical properties (e.g. electrical resistivity) Applications such as these may be considered to be "natural" applications for plastics.

The consumption of plastics by the automotive industry prior to the 1970's was dominated by "natural" applications (1). Examples include distributor caps, safety glass (the inner ply) and foam padding. In these uses, cost was not the primary consideration since in many cases the plastic component was more expensive than the conventional analog. "Natural" applications were justified by improved performance and they accounted for the early growth of plastics, from less than 1% to more than 4% of the weight of automobiles, over the period 1960 to 1970 (2).
In the early 1970's, several factors changed. As the polymers industry matured, the rate at which new and substantially different polymers were developed and brought to market declined (only two of the materials studied in conjunction with this model were introduced after 1960 (3)). Without new materials, automotive engineers quickly satisfied the "natural" applications.

Second, as the economic prosperity of the 50's and 60's ended, it became increasingly difficult to justify applications on the basis of improved performance. In the new market, performance was required to be cost effective since the consumer's willingness to pay had declined.

The use of plastics, however, continued to grow and cost effectiveness replaced improved performance as the reason. One attribute of plastics which emerged in the 70's was the ease of processing these materials. Large semi-automated production facilities were built which could produce high quality parts with minimal secondary processing and minimal labor costs.

A second attribute of plastics were the opportunities offered for parts consolidation, often eliminating secondary assembly processes entirely. An example is the dash-board assembly which has been molded as a single piece of plastic. Previously, it was built from as many as 13 bolted or welded metal substructures (4).
Perhaps the single largest boost to plastics utilization was the need for weight reduction, which arose from the escalating cost of fuel. Plastics offered a good balance of light weight and low cost and increasingly were substituted for steel.

Weight reduction and parts consolidation may be considered to be "cost" reasons for using plastics. Driven by the need for cost reduction, the utilization of plastics in automobiles grew to as much as 10% of the total weight for certain models in 1980 (5).

The potential for continued growth also seems promising. Engineering studies have demonstrated that almost the entire automobile can be built from plastics; if cost is not considered. Exterior body panels, fuel tanks, suspension parts, even engines have been successfully prototyped and utilization of plastics for these applications awaits only a favorable shift of the relative costs of the competing materials.

The importance which cost plays in current decisions to substitute one material for another cannot be overstressed. Most of the physical limitations which prevented the use of plastics have disappeared. A new generation of high strength, high temperature plastics are available to the automotive engineer. Application of these materials depends on the cost of utilizing them. To predict the success of a material
substitution, detailed analysis of costs is therefore required.

It is the intent of this thesis to present a systematic and comprehensive method for estimating primary fabrication costs and for performing sensitivity analysis on the results. The method developed herein provides dollar estimates of the costs of production and, for a sample case, these estimates are analyzed to demonstrate the impact of production volume, cycle time, interest rate, wages, etc. on fabrication costs. This type of analysis allows plastics processors to identify and focus on the critical production parameters while allowing less critical ones to stray from their optimum values without major adverse effects.

The global topic of material substitution lies outside of the scope of this work. This study will, however, be incorporated into a larger project entitled, "The Future of Automotive Materials" which will deal directly with the issues of material substitution in automobiles. Effort has been made to facilitate this incorporation.
3.0 FABRICATION PROCESSES

The diversity of plastic materials and applications have lead to the development of numerous methods for processing them. One major reference describes 15 different processes (6). Ten of these fabrication processes are included within this model. These are,

1) injection molding,
2) extrusion,
3) blow molding,
4) sheet forming,
5) compression molding,
6) reaction injection molding (RIM),
7) thermoplastic foam molding,
8) pultrusion,
9) filament winding, and
10) SMC compression molding.

As there are no universally accepted definitions of each of these processes and since some overlap among them exists, a brief description of each follows. These descriptions define the context in which each process is considered in the model.

Process selection is made by the model on the basis of the material being processed and the geometry of the component being produced. The material and geometry are supplied as inputs and must be entered separately for each component undergoing cost estimation. A fabrication process is selected
undergoing cost estimation. A fabrication process is selected as feasible if it satisfies, simultaneously, the material and geometry requirements. These requirements are a part of the model data and can be modified by the user if new materials, geometries or processes are to be added to the model. The following process descriptions include a listing of the types of materials and geometries which meet the constraints of each process.

(Alternately, process selection can be specified directly by the model's users, since they may know which of the processes are feasible or optimal from previous experience.)

Finally, within each process description, the relative importance of the process in current automotive production is given. For those processes where this is not provided, it may be assumed that the process accounts for less than 5% of the plastics consumption in automobiles.

3.1 Injection Molding - Injection molding (see figure 1) is a cyclic process that can be considered in terms of four distinct phases. First, solid plastic, usually as pellets, is transferred into a heating chamber and caused to melt by the application of both thermal and mechanical energies. The plastic melt is forced through a nozzle at the end of the chamber and into a closed, cool mold. The melt cools and solidifies within the mold in the desired shape. Finally, the finished part is ejected from the mold.
Figure 1
In-line Reciprocating Screw Injection Molder
(source: Plastics Engineering Handbook)

Injection molding (within the context of this model) is limited to thermoplastic materials. It can be used to process either unreinforced or reinforced thermoplastics and can be used to produce components with any geometry except those with large internal volumes (e.g., containers or hollow columns). Internal volumes cannot be produced by injection molding because a portion of the mold would be trapped within the component.

Injection molding currently is the most widely used method of processing plastics for automobiles. It accounts for roughly 50% of the plastics consumed in automobiles (7).
3.2 Extrusion - Extrusion (see figure 2) is a continuous process that can be considered as a sequence of five operations. In the first, solid plastic material, usually pellets, is transferred into a heating chamber and caused to melt through the application of thermal and mechanical energies. The melting material is conveyed down the length of the chamber by the action of a continuously rotating screw. At the end of the chamber, the molten plastic is forced through a forming die which shapes it into the desired profile. Finally, as the plastic extrusion emerges, it is cooled and solidified by a water quench or by forced cool air.

Figure 2
Single Screw Extruder
(source: Plastics Engineering Handbook)
Extruders are accompanied by either a cut-off device which cuts the profile into the desired lengths or by a take-up reel which winds the profile onto a spool. This is necessary because the formed profile emerges continuously.

Extrusion is limited to thermoplastic materials but can be used with either unreinforced or reinforced thermoplastics. Extrusion can only be used to produce components with constant cross-sectional areas.

Extrusion currently accounts for 11% of the plastics consumed in automobiles (8).

3.3 Blow Molding - Blow molding (see figure 3) is a cyclic process used to produce hollow components. The process can be considered as a sequence of four distinct phases. The first phase involves forming a prestructure or preform that is tube-like in shape with one sealed end. Formation of this prestructure is accomplished either through an injection molding process or through a discontinuous extrusion process. In the next phase, the sealed end of the preform is inserted through an opening into a female mold. This is done while the preform is still soft and hot. An air injector is inserted into the open end of the preform and air is blown into it causing it to expand like a balloon. The expanding "balloon" contacts the cool walls of the mold and the plastic solidifies, taking the shape of the mold cavity. Finally,
when the plastic has solidified, the finished component is removed from the mold and trimmed.

Figure 3
Extrusion Blow Molders
(source: Plastics Engineering Handbook)

Blow molding is limited to use with thermoplastic materials. It is generally used with unreinforced resins although it has been used successfully with a number of reinforced resins. Blow molding is limited to geometries which are hollow or which were hollow prior to trimming.

3.4 Thermoplastic Foam Molding - Thermoplastic foam molding is a cyclic process that is a subset of injection molding. The principle difference is that in foam molding a blowing agent which releases gas is added to the plastic resin and it
causes the plastic froth and expand during processing. When the molten plastic solidifies, it contains significant amounts of trapped gas and porosity.

The advantages to foam molding over regular injection molding include lower material costs (for the same part volume), reduced weight, higher specific stiffness, larger maximum wall thickness, and lower molding pressure (therefore reduced mold costs). The disadvantages include longer cycle times, lower maximum strengths, and higher scrap rates (9).

Foam molding can be used with most of the unreinforced thermoplastics. It is possible, but not common, to use foam molding with reinforced thermoplastics. Foam molding is constrained to the production of those geometries which could also be injection molded.

3.5 Sheet Forming - Sheet forming is a cyclic process that involves three steps. In the first step, a sheet of plastic is heated to its softening point in a large convective or radiant oven. In the second step, the softened sheet is transferred onto one side of a matched mold set and the halves of the mold are brought together under pressure. The temperature of the mold is kept below the softening point of the plastic and this causes the sheet to solidify and assume the shape of the mold. Finally, the finished piece is removed and trimmed of excess material.
In the context of this model, sheet forming is restricted to thermoplastic materials. A similar process for thermosets (SMC molding) is considered separately. Sheet forming can be used with both unreinforced or reinforced thermoplastics. Sheet forming can produce geometries which have relatively uniform wall thickness and which do not have included volume.

3.6 Compression Molding – Compression molding is a cyclic process used for processing thermosetting materials. It can be analyzed as a sequence of three phases. The first phase involves the transfer of chemically reactive prepolymer material into a heated mold. The prepolymer may exist in a number of initial forms including liquid, paste or sheet. In the second phase, the mold is closed under pressure causing the material to flow until it assumes the shape of the mold. When the material contacts the heated surfaces of the mold, the chemical reaction (polymerization) occurs and the material hardens. After the material is sufficiently hardened, the finished part is removed from the mold and trimmed.

Compression molding, as presented in this study, is limited to thermosetting materials which do not have continuous reinforcement. Materials with continuous reinforcement that are processed in a similar manner, are considered as SMC moldings. Compression molding can be used to produce components with geometries that do not contain included volume.
or large undercuts since these would impede removal of the finished piece from the mold.

3.7 Reaction Injection Molding - Reaction injection molding and reinforced reaction injection molding (RIM & RRIM) are cyclic processes that are similar to conventional injection molding in many respects. The principle difference is that in the RIM or RRIM processes, chemically reactive polymer precursors are injected into the mold in place of molten thermoplastics. The precursors polymerize within the mold and harden in the shape of the mold cavity.

Because RIM and RRIM involve chemical reactions, they require specialized storage, mixing, metering and temperature control equipment that is not needed for conventional injection molding. The polymer precursors (usually two or three components) must be stored separately and they must be protected from external contamination such as moisture or dust. During processing, the precursors must be mixed in exact proportions and heat control equipment is needed to regulate the rate of the chemical reaction.

RIM and RRIM are currently feasible with three classes of materials: urethanes,nylons and epoxies. Of these, only the first two are included within this model since they are the only ones presently targeted for large-scale commercialization. Either process can be used to fabricate any geometry which otherwise could be injected molded.
3.8 Pultrusion - Pultrusion is a continuous process that can be analyzed as a sequence of six distinct operations: filament dispensing, resin wet-out, excess resin removal, die forming or shaping, gripping/pulling, and part cut-off. The process is similar to extrusion in many respects.

In pultrusion, continuous reinforcing filaments are pulled from dispensing creels through a bath which coats the filaments with a thin film of thermosetting resin. The filaments are pulled through progressively smaller shaping dies to remove the excess resin. The final die forms the wetted filaments into the shape of the desired profile and it contains banks of imbedded heaters. As the filaments are pulled through it, the heat causes the resin to polymerize and harden. The cured profile is pulled from the forming die and cut into the appropriate lengths.

Pultrusion is used to process epoxy and polyester thermosetting resins and in this model, the filaments may be either glass or graphite. The pieces produced by this process are, of course, reinforced. Pultrusion can be used to fabricate components which have constant and uniform cross-sections.

3.9 Filament Winding - Filament winding is a cyclic process which may be analyzed as a sequence of four phases. In the first phase, filaments are drawn through a resin bath and coated with a thin film of thermosetting resin. (Alternately,
the filaments may be pre-coated). The coated filaments are wound around a forming mandrel (similar to the way thread is wound on a spool) to form the desired part. Generally, the filaments are wound in the form of bundles or as tapes to expedite the wrapping procedure. When the appropriate thickness of filaments have been wound onto the mandrel, the assembly is transferred to an oven for curing. Finally, after the resin has cured, the forming mandrel may be removed leaving only the cured outer wrapping or it may remain as an integral part of the finished structure.

Filament winding can be used to process epoxy and polyester thermosetting resins and in this model, the filaments may be either glass or graphite. Filament winding can be used to produce components with hollow geometries such as box beams, columns, and containers.

3.10 SMC Molding - SMC (sheet molding compound) molding is a cyclic process that is similar to the sheet forming of thermoplastics in many respects. The principle difference is that reinforced thermosetting sheet materials are used. In SMC molding, the sheet is placed between the halves of a split mold and the halves are pressed together causing the sheet to assume the shape of the mold cavity. The mold halves are kept hot and this causes the resin to polymerize and harden in the desired shape. When sufficiently polymerized, the finished piece is removed from the mold and trimmed of excess material.
By convention, SMC molding implies the processing of glass reinforced polyester resin. This restriction is arbitrary since the process could be used with other materials. In essence, SMC molding is a subset of compression molding, restricted to the use of a single class of material. It seems justifiable to consider it as a separate process, however, because SMC accounts for 59% of the thermosetting materials currently used in automobiles (10).

SMC molding can be used to form any of the geometries which could also be sheet formed. This restricts the process to fabricating components with no included volume and relatively uniform wall thickness.
4.0 MODEL DESCRIPTION

The model developed within this study uses a digital computer to estimate the production costs of making plastic automotive components. The model is programmed in Fortran and is configured for operation on IBM VM systems. Adaptation of the model to other operating systems is considered elementary.

The methodology of the model consists of a sequence of four operations:

1) inputs to the model by the user of the model,
2) selection of feasible fabrication processes by the model (if not directly specified),
3) estimation of the costs of production for each of the feasible processes, and
4) tabulation and output of the estimation results.

Each of these operations is described in detail in the following sections.

The model developed herein does not consider the engineering feasibility of the plastic components which are input for estimation. For example, it will estimate the costs of producing plastic exhaust pipes without considering the technical barriers to such an application. To assure meaningful results, engineering analysis should precede the use of this model.

Finally, the model does not judge the absolute economic feasibility of producing plastic components, it only estimates
the production costs. Decisions regarding the economic attractiveness of the various alternatives are left of the user of the model.

4.1 Inputs to the Model - The inputs to the model are provided by the user as they pertain to the component which is to be fabricated/cost estimated. The inputs provide the basis for selection of feasible processes and for estimation of the production costs.

The inputs are made by the user in response to queries issued by the computer program. The following inputs must be supplied for each component which is estimated:

1) material,
2) geometry,
3) weight,
4) production number,
5) wall thickness and,
6) cross sectional area.

The material and geometry inputs are selected from menus and the contents of these menus are described in sections 4.1.1 and 4.1.2. The other inputs are entered as numbers and the dimensions and bounds on these inputs are described in sections 4.1.3 to 4.1.6.

4.1.1 Material Inputs - Twenty-three materials appear on the menu for use with this model and the user must select the one
from which the component will be fabricated. These materials are divided into a two by two matrix which characterizes them according to their physical nature. The elements of the matrix are: thermoplastics, thermosets, unreinforced and reinforced materials. The names of the specific materials and their placement within the matrix appears in Table 1. A brief description of the utilization, processing and properties of each category follows.

4.1.1.1 Thermoplastics — Fifteen of the twenty-three materials on the menu are thermoplastics and they currently account for 70.6% of the plastics consumed in automobiles (11).

Thermoplastics are characterized by their ability to transform reversibly from solids at low temperatures to viscous liquids at elevated temperatures. Generally they have high deformability, relatively low strengths, strengths which decline with increasing temperature and low maximum service temperatures (typically less than 275 F). Thermoplastics are used in applications such as interior trim pieces, door handles, window cranks, dashboard panels, grills and fender liners.

Processing thermoplastics involves raising the temperature until the material melts, shaping the melt into the desired configuration, and cooling the material until it resolidifies.
<table>
<thead>
<tr>
<th></th>
<th>THERMOPLASTICS</th>
<th>THERMOSETS</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNREINFORCED</td>
<td>POLYPROPYLENE</td>
<td>POLYURETHANE (RIM)</td>
</tr>
<tr>
<td></td>
<td>POLYPHENYLENE OXIDE</td>
<td>PHENOLIC</td>
</tr>
<tr>
<td></td>
<td>PVC (RIGID)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ABS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>POLYSTYRENE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NYLON</td>
<td></td>
</tr>
<tr>
<td></td>
<td>POLYCARBONATE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ACETAL (HOMOPOLYMER)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>POLYETHYLENE (HIGH DENS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>THERMOPLASTIC POLYESTER</td>
<td></td>
</tr>
<tr>
<td></td>
<td>THERMOPLASTIC POLYIMIDE</td>
<td></td>
</tr>
<tr>
<td>REINFORCED</td>
<td>NYLON/30% MILLED GLASS</td>
<td>POLYESTER SMC</td>
</tr>
<tr>
<td></td>
<td>POLYCARBONATE/30% GLASS</td>
<td>POLYESTER BMC</td>
</tr>
<tr>
<td></td>
<td>ABS/20% MILLED GLASS</td>
<td>PHENOLIC/MILLED GLASS</td>
</tr>
<tr>
<td></td>
<td>ACETAL/25% MILLED GLASS</td>
<td>EPOXY/50% CONT GLASS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>POLYESTER/50% CONT GLASS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EPOXY/CONT GRAPHITE</td>
</tr>
</tbody>
</table>
Six of the processes considered in this model may be used to process thermoplastics.

Thermoplastics can be processed easily and rapidly thereby lending themselves to process automation. Also, thermoplastic scrap can be reprocessed to minimize material costs. These reasons promote utilization of thermoplastics and account for the variety of available processing methods.

4.1.1.2 Thermosets - Nine of the materials listed on the menu are thermosets. These materials currently account for 15% of the plastics consumed in automobiles (12).

Thermosets are made from chemically reactive prepolymer which, when processed together, undergo an irreversible chemical change (polymerization). The prepolymer is usually viscous liquids which transform into solids as the chemical reaction proceeds. Usually heat must be added to initiate and accelerate the reaction.

In general, thermosets are high strength, high service temperature materials which are used in conjunction with reinforcing filaments. The combination of high strength (especially when reinforced) and high temperature resistance make them useful for applications such as distributor caps, body panels, engine parts and brake pads.

Processing thermosets involves mixing and shaping the prepolymer materials into the desired form, causing the
material to react and solidify, and finally, removing and trimming the finished part.

Processing thermosets is more difficult than processing thermoplastics because of the complexities associated with polymerization. Normally the prepolymer must be combined in precise proportions and the temperature must be carefully controlled. Also, because thermosets are usually reinforced, there are problems of mixing, orienting, and handling the abrasive nature of the reinforcing material. As a final drawback, the scrap trimmed from the finished part cannot be recycled. For these reasons, thermosets are usually used only where thermoplastics are inadequate.

Five of the processes which appear in this model are used with thermosets and they produce 19% of the plastics consumed in automobiles (13). One process which has been purposefully excluded from this study is thermoset foam molding. While this process accounts for 10% of the plastics consumed in automobiles, it is not included because foam padding is considered to be a "natural" application of a polymeric material with little flexibility for substitution.

4.1.1.3 Unreinforced Plastics - Thermoplastics or thermosets which are unreinforced do not contain reinforcing filaments or fibers. They are always less stiff and less strong than their reinforced analogs (14) and are typically used in applications
which are not subjected to high levels of stress (trim pieces, interior paneling, etc.).

Processing unreinforced materials is comparatively easy and rapid. Processing costs (excluding raw material) are generally lower than for the comparable reinforced materials. For these reasons, unreinforced plastics are generally selected in favor of reinforced plastics whenever they meet the strength requirements.

4.1.1.4 Reinforced Plastics - Reinforced plastics consist of a two phase mixture of a polymeric resin and a fiberous reinforcing material. They are frequently referred to as composite materials. Reinforced plastics combine the properties of the materials from which they are made to yield a composite material which has better properties than either one taken alone. The reinforcement contributes strength and stiffness to the composite and the resin contributes resilience, abrasion resistance and cohesiveness.

Glass is the only reinforcement which is currently used in significant quantities in automobiles. Other reinforcements which may have applications in the future include graphite fibers and polyaramid fibers. All three of these can be used with a variety of resins including both thermoplastics and thermosets.

Processing reinforced materials is comparatively difficult. Reinforced resins are more viscous than unreinforced resins,
so more power is required to transport and shape them. For thermoplastics, the reinforcement raises melt processing temperatures which also increases power consumption. Also, all reinforced plastics have the additional problems associated with obtaining a uniform and intimate mixture of resin and filaments. Finally, in the case of glass, the mixture of glass and resin is abrasive and this increases the wear-rate on the equipment and the costs of maintainence.

4.1.2 Geometry Inputs - Component geometry is the second model input which the user must supply. Sixteen geometries appear on the second menu and the user is expected to select the one which best describes the component of interest. A listing of these geometries appears in Table 2 along with a diagram and example of each.

Categorizing geometries is difficult since real components rarely occur as simple categorical shapes. The geometry of a component is one of the principle factors used to determine the feasible methods of fabrication within this model. In addition, production parameters such as the cycle time and mold cost are effected by the geometry of the part. Within this model, these influences are accounted for through the use of adjustment factors, a complete explanation of which appears in a later section of this thesis.
<table>
<thead>
<tr>
<th>Geometry</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMPLE CURVED PANELS</td>
<td>Roof, Outer door</td>
</tr>
<tr>
<td>COMPLEX CURVED PANELS</td>
<td>Fenders, Firewall</td>
</tr>
<tr>
<td>OPEN BOX BEAMS (STRAIGHT)</td>
<td>Door beams</td>
</tr>
<tr>
<td>CLOSED BOX BEAMS (STRAIGHT)</td>
<td>Radiator support</td>
</tr>
<tr>
<td>HOLLOW COLUMNS (STRAIGHT)</td>
<td>Drive shaft</td>
</tr>
<tr>
<td>SOLID COLUMNS (STRAIGHT)</td>
<td>Steering linkage</td>
</tr>
<tr>
<td>OPEN BOX BEAMS (CURVED)</td>
<td>Bumpers</td>
</tr>
<tr>
<td>CLOSED BOX BEAMS (CURVED)</td>
<td>Passenger cage</td>
</tr>
<tr>
<td>HOLLOW COLUMNS (CURVED)</td>
<td>Chassis frame</td>
</tr>
<tr>
<td>SOLID COLUMNS (CURVED)</td>
<td>Torsion bars</td>
</tr>
<tr>
<td>SIMPLE HOLLOW CONTAINERS</td>
<td>Fuel tank</td>
</tr>
<tr>
<td>COMPLEX HOLLOW CONTAINERS</td>
<td>Fuel tank</td>
</tr>
<tr>
<td>COILS</td>
<td>Springs</td>
</tr>
<tr>
<td>OPEN BOXES</td>
<td>Valve cover</td>
</tr>
<tr>
<td>COMPLEX SOLID (FLAT SURFACES)</td>
<td>A/C bracket</td>
</tr>
<tr>
<td>COMPLEX SOLID (INTERNAL PASSAGES)</td>
<td>Carburetor housing</td>
</tr>
</tbody>
</table>
4.1.3 **Weight** - The user must input a numerical value for the weight of the component of interest. The component weight refers to the weight in pounds of the as-molded product after it is trimmed of the initial fabrication scrap (i.e., flashing, runners, etc.). It does not include the weight loss which results from the removal of material in secondary operations such as drilling or machining. Nor does it include additional weight which is added in secondary joining or inserting operations. The range of weight which is acceptable to the model is from 0.1 to 40 lbs.

4.1.4 **Maximum Wall Thickness** - The user must input the numerical value of the thickest wall section in the component of interest. The maximum wall thickness is twice the maximum distance to the nearest surface from within the body of the material. The value is entered in inches and must fall in the range of 0.1 to 1.0 inches.

Maximum wall thickness is an important parameter for polymer processing since it affects the limiting rate of heating or cooling. In turn, this affects the cycle time which affects the cost of production.

4.1.5 **Cross Sectional Area** - The user must input a numerical value for the cross sectional area for those components which have uniform and constant cross sections. These components can be produced by continuous processes such as extrusion or
pultrusion. In these processes, the cross section effects the production rate and ultimately, the cost. The cross sectional area is entered in square inches and must be in the range from 0.1 to 5.0 sq.in.

4.1.6 Yearly Production Volume - The user inputs a value for the number of components which will be produced during one year. The acceptable range of entries is from 1,000 to 1,000,000
4.2 PROCESS SELECTION

Process selection is made on the basis of the material being processed and the geometry of the component which is being produced. The material/geometry constraints for each fabrication process appear in the preceding section of this report. Both constraints must be satisfied simultaneously for a process to be selected.

This approach to process selection works well for determining which processes are technically feasible. It does not, however, take advantage of the experience which the model user may possess. To do so, the model is equipped with a subroutine which gives the user the option to select, from a menu, the desired fabrication process. The program checks this selection to verify that it is technically feasible. If it is not, the program issues a warning but continues the cost estimation procedure. For such instances, the results that are produced should be carefully reviewed.
4.3 MODEL DATA

To estimate the production costs for a specified component, the cost estimation model utilizes four "types" of variables. These are:

1) process variables,
2) exogeneous variables,
3) adjustment factors, and
4) regression variables.

The first three of these are described in this section and the values and sources are listed. The regression variables are described in the following section on cost estimation.

To change the default values of any of the first three variable types, the user must edit the model program and alter the appropriate data files or data statements. To change the values of the regression variables, it is necessary to collect data on the elements of interest and to correlate them by standard least squares regression techniques.

4.3.1 Process Variables - Process variables are taken to be dependent only upon the fabrication process used for production. For example, it is assumed that scrap rate is a process variable and that the scrap rate for injection molding may be different from the rate for compression molding. Ten process variables have been identified and a brief description of each appears below. Within the program, the value of each of these is stored in a data file. These values appear in
Table 3. For a complete understanding of the function of each variable, the reader must refer to the cost equations in section 4.4.

1) (MLF) The capital recovery life of the machine: This is length of time over which the capital investment is recovered by distribution of the recovery burden onto the parts being produced. Ideally, it should correspond to the expected physical life of the equipment (to minimize the burden on each part).

2) (OLF) The capital recovery life of the mold: Similar to MLF except OLF is expressed as the logarithm of the number of production cycles over which the capital recovery is distributed.

3) (AUX) The cost of auxiliary equipment: This is any equipment which is necessary to the process in addition to the main machine. It should include such equipment as dryers, chillers, raw material storage and handling equipment, etc. but should not include items such as fork lifts (which are part of overhead) or robotics which are considered as a substitute for labor.

4) (INS) The installation cost: This includes the cost of preparing the building for the installation of the main machine and auxiliary equipment (electrical, plumbing, etc.) as well as the actual cost of setting up the equipment.
Table 3

Process Variables

<table>
<thead>
<tr>
<th>Process</th>
<th>MLF</th>
<th>OLF</th>
<th>AUX</th>
<th>INS</th>
<th>DLB</th>
<th>OLH</th>
<th>MNT</th>
<th>PRD</th>
<th>SCR</th>
<th>UTL</th>
</tr>
</thead>
<tbody>
<tr>
<td>INJECTION MOLDING</td>
<td>6</td>
<td>5.1</td>
<td>.10</td>
<td>.10</td>
<td>1.4</td>
<td>.35</td>
<td>.03</td>
<td>.58</td>
<td>.03</td>
<td>.46</td>
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<tr>
<td>EXTRUSION</td>
<td>6</td>
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<td>.30</td>
<td>.15</td>
<td>1.2</td>
<td>.35</td>
<td>.03</td>
<td>.75</td>
<td>.03</td>
<td>.26</td>
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<td>.20</td>
<td>.25</td>
<td>1.4</td>
<td>.35</td>
<td>.03</td>
<td>.72</td>
<td>.03</td>
<td>.34</td>
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<tr>
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<td>.15</td>
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<td>.35</td>
<td>.03</td>
<td>.57</td>
<td>.05</td>
<td>.34</td>
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<td>5.2</td>
<td>.10</td>
<td>.10</td>
<td>1.4</td>
<td>.35</td>
<td>.03</td>
<td>.46</td>
<td>.15</td>
<td>.32</td>
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<tr>
<td>RIM &amp; RRIM</td>
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<td>5.2</td>
<td>.15</td>
<td>.10</td>
<td>1.5</td>
<td>.35</td>
<td>.04</td>
<td>.62</td>
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<td>.40</td>
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<td>1.5</td>
<td>.35</td>
<td>.03</td>
<td>.69</td>
<td>.20</td>
<td>.46</td>
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<tr>
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<td>.15</td>
<td>1.2</td>
<td>.35</td>
<td>.03</td>
<td>.50</td>
<td>.10</td>
<td>.40</td>
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<tr>
<td>FILAMENT WINDING</td>
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<td>.35</td>
<td>.03</td>
<td>.50</td>
<td>.10</td>
<td>.40</td>
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<tr>
<td>SMC MOLDING</td>
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<td>.10</td>
<td>.10</td>
<td>1.8</td>
<td>.35</td>
<td>.03</td>
<td>.50</td>
<td>.10</td>
<td>.40</td>
</tr>
</tbody>
</table>
5) (DLB) The direct laborer requirements per machine: This is the number of hourly laborers needed to operate the machine plus any additional labor involved directly in the production of components. It includes labor needed for initial trimming and handling of the parts but should not include labor for janitorial services, quality control, maintenance, etc.

6) (OVR) Overhead costs: Overhead costs include the wages of labor such as managerial, quality control, shipping, receiving, janitorial, etc., plus the costs of overhead equipment like fork lifts, conveyors, office equipment, etc. It does not include the cost of the buildings or any of the other cost elements which are calculated separately.

7) (MNT) Maintenance cost: This is the cost of maintaining the main machine and auxiliary equipment including the required labor and capital costs. It does not include the cost of maintaining the molds or other tooling.

8) (PRD) The productivity of the process: Productivity is defined, within this model, to be productive machine hours divided by available machine hours. Machine hours are considered to be "productive" only when acceptable quality parts are being produced.

9) (SCR) The scrap rate of the process: The scrap rate includes all non-recyclable material which is lost during trimming as well as material which is lost due to the
production of parts which do not meet the design specifications.

10) (UTL) The utilities consumption rate of the process: This is a measure of the power consumed by the main machine during the processing of parts. It includes the power consumed in heating, cooling, and in mechanical transport of the material during processing.

Values for the process variables were obtained from literature (15, 16, 17, 18, 19, 20) and from conversations with processing equipment manufacturers (21, 22, 23, 24).

4.3.2 Exogeneous Variables - Exogenous variables are taken to be factors which effect the cost of production directly but which have no inherent statistical error caused by limitations of the model methodology. For example, the price of utilities (in $ per kwh) is an exogeneous variable. The value may vary from one region to another, however, it is assumed that in any given location, it will be fixed and it will be accurately known. Exogeneous variables provide information on the structure of the industry and on the economic environment in which the industry operates. The following exogeneous variables are included:

1) (PDLB) the wages of direct laborers (including employee benefits),

2) (DAYS) the number of working days per calendar year,

3) (SHFT) the number of shifts per working day,
4) (HORS) the hours worked per shift,
5) (PUTL) the price of utilities ($/kwh electrical),
6) (PBLD) the price of factory floor space ($/sqft.),
7) (BLIF) the capital recovery life of buildings (yrs),
8) (R) the capital recovery rate on investments (%),
9) (PRI(mat)) the price of the raw material ($/lb.).

The default values for these variables appear in Table 4 (except for the raw material prices which appear in section 4.4.1.1) The exact usage of these variables is better understood with reference to section 4.4 on cost analysis. Values for the exogeneous variables were obtained from literature sources (25, 26, 27, 28, 29, 30), and from conversations with members of the plastics processing industry (31, 32, 33).

4.3.3 Adjustment Factors - Adjustment factors account for variations in cost or variations in other processing parameters which arise from two sources: the material being processed, and the geometry of the part being produced. For example, tooling costs for processing abrasive, glass-reinforced materials are known to be greater than those for unreinforced materials. An adjustment factor is used to account for this difference. Adjustment factors appear in the model as multipliers which increase or decrease a given parameter by a specified proportion.
Table 4
Exogenous Variables

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDLB</td>
<td>Wages of direct labor</td>
<td>14.00 $/hr</td>
</tr>
<tr>
<td>DAYS</td>
<td>Working days per calendar year</td>
<td>220</td>
</tr>
<tr>
<td>SHFT</td>
<td>Shifts per day</td>
<td>3</td>
</tr>
<tr>
<td>HORS</td>
<td>Hours per shift</td>
<td>8</td>
</tr>
<tr>
<td>PULT</td>
<td>Price of utilities</td>
<td>0.60 $/kwh</td>
</tr>
<tr>
<td>PBLD</td>
<td>Price of factory floor space</td>
<td>18.00 $/sqft</td>
</tr>
<tr>
<td>BLIF</td>
<td>Depreciation life of buildings</td>
<td>25 yrs</td>
</tr>
<tr>
<td>R</td>
<td>Rate of return on capital recovery</td>
<td>10 %</td>
</tr>
</tbody>
</table>

Eight material adjustment factors were identified. These are:

1) adjustment to utilities consumption (XUT),
2) adjustment to the life of the mold (XML),
3) adjustment to the scrap rate (XSC),
4) adjustment to the cost of auxiliary equipment (XAU),
5) adjustment to the cost of the main machine (XMA),
6) adjustment to the cycle time (XCY),
7) adjustment to the life of the main machine (XLF), and
8) adjustment to the cost of the mold (XMO).

The values used for the material adjustment factors appear in Table 5. Values were obtained from surveys of industry (34, 35, 36, 37), literature (38), and for XCY and XAU by analytical estimation based on heat transfer and heat capacity considerations.

Four geometry adjustment factors were identified. These are:

1) adjustment to the cost of the mold (YMO),
2) adjustment to the scrap rate (YSC),
3) adjustment to the cycle time (YCY), and
4) adjustment to the life of the mold (YML).

The values used for the geometry adjustment factors appear in Table 6. Values were obtained from surveys of industry (39, 40, 41, 42, 43).
<table>
<thead>
<tr>
<th>Material</th>
<th>XUT</th>
<th>XML</th>
<th>XSC</th>
<th>XAU</th>
<th>XMA</th>
<th>XCY</th>
<th>XLF</th>
<th>XMO</th>
</tr>
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<tbody>
<tr>
<td>POLYPROPYLENE</td>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.14</td>
<td>1.00</td>
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<tr>
<td>POLYURETHANE (HIGH MOD)</td>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>PVC (RIGID)</td>
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<td>1.14</td>
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<tr>
<td>ABS</td>
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<td>1.00</td>
<td>1.30</td>
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<td>1.12</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<td>2.82</td>
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<td>1.00</td>
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<td>1.00</td>
<td>0.66</td>
<td>1.00</td>
<td>1.05</td>
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<tr>
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<tr>
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<td>1.06</td>
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<tr>
<td>NYLON 6/30% MILLED GLASS</td>
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<td>1.30</td>
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<td>1.25</td>
<td>1.30</td>
<td>1.30</td>
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<td>0.65</td>
<td>1.70</td>
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<tr>
<td>ABS/20% MILLED GLASS</td>
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<td>0.75</td>
<td>1.20</td>
<td>1.30</td>
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<td>PHENOLIC/MILLED GLASS</td>
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<td>EPOXY/50% CONT GLASS</td>
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Table 6
Geometry Adjustment Factors

<table>
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<th>YCY</th>
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<td>1.00</td>
<td>1.00</td>
<td>1.10</td>
<td>1.00</td>
</tr>
<tr>
<td>COMPLEX SOLID (FLAT SURFACES)</td>
<td>1.15</td>
<td>1.10</td>
<td>0.95</td>
<td>1.10</td>
</tr>
<tr>
<td>COMPLEX SOLID (INTERNAL PASSAGES)</td>
<td>1.20</td>
<td>0.90</td>
<td>1.30</td>
<td>0.90</td>
</tr>
</tbody>
</table>
4.4 COST ESTIMATION

The overall elemental cost estimation equations are,

(1) Fabrication cost = Variable costs + Fixed costs

(2) Variable costs = Raw materials + Utilities +
    Direct labor

(3) Fixed = Main machine + Mold or die + Installation +
    Maintenance + Building + Auxiliary equip +
    Overhead + Capital recovery

An explanation of each of the cost elements and a description
of how it is calculated appears below.

In the first cut, the elements are separated into two
categories: fixed costs and variable costs. Variable cost
elements are those elements which vary directly with the pro-
duction volume. Fixed cost elements remain constant regard-
less of the quantity that is being produced. There are
difficulties with overlap which arise when catagorizing cost
elements as "fixed" or "variable". For instance, some of the
direct labor costs should be considered as fixed since, when
production levels are small, a minimum number of laborers are
required and this number cannot be reduced. Similarly, tool-
ing costs can be considered as variable when the production
volume is sufficiently large to cause one or more sets of
tools to be consumed. These problems are not serious to the
model since they arise at the limits and rarely affect the
accuracy of the estimates.
4.4.1 Variable Costs - Three variable cost elements are estimated, these are: material, utilities, and direct labor. Variable costs are calculated on the basis of cost per component.

Other variable costs which are not considered within this model are the costs of inserts or specialty operations such as in-mold coatings which may be part of the fabrication process in special instances. These costs are not included since they vary greatly from one component to the next, making it exceedingly difficult to estimate an "average" production cost.

4.4.1.1 Raw Material Costs - Raw material costs per component are estimated as,

\[ \text{Material} = \text{Weight} \times \text{Price/lb.} \times (1 - \text{Scrap}) \]

"Weight" is the weight of the component as described in section 4.1.3. Material prices ($/lb) are regularly published and the value used for each type of material appears in Table 7. These values were obtained in June 1982 (44). No effort is made to distinguish between the prices of a raw material which is used with several fabrication processes. For instance, injection molding grade nylon is considered to have the same price as extrusion grade nylon. The implications and possible remedies for this assumption are discussed in section 4.6.3.
<table>
<thead>
<tr>
<th>Material</th>
<th>Price/lb.</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLYPROPYLENE</td>
<td>$ 00.42</td>
</tr>
<tr>
<td>POLYURETHANE (HIGH MOD)</td>
<td>$ 01.45</td>
</tr>
<tr>
<td>PVC (RIGID)</td>
<td>$ 00.24</td>
</tr>
<tr>
<td>ABS</td>
<td>$ 01.10</td>
</tr>
<tr>
<td>POLYSTYRENE (IMPACT GRD)</td>
<td>$ 00.45</td>
</tr>
<tr>
<td>NYLON 6</td>
<td>$ 01.66</td>
</tr>
<tr>
<td>POLYCARBONATE</td>
<td>$ 01.65</td>
</tr>
<tr>
<td>ACETAL (HOMOPOLYMER)</td>
<td>$ 01.48</td>
</tr>
<tr>
<td>POLYETHYLENE (H DENSITY)</td>
<td>$ 00.44</td>
</tr>
<tr>
<td>NYLON 6/30% MILLED GLASS</td>
<td>$ 01.66</td>
</tr>
<tr>
<td>POLYCARB/30% MILL GLASS</td>
<td>$ 02.20</td>
</tr>
<tr>
<td>ABS/20% MILLED GLASS</td>
<td>$ 01.08</td>
</tr>
<tr>
<td>ACETAL/25% MILLED GLASS</td>
<td>$ 01.73</td>
</tr>
<tr>
<td>THERMOPLASTIC POLYESTER</td>
<td>$ 00.75</td>
</tr>
<tr>
<td>THERMOPLASTIC POLYIMIDE</td>
<td>$ 05.00</td>
</tr>
<tr>
<td>POLYPHENYLENE OXIDE</td>
<td>$ 01.50</td>
</tr>
<tr>
<td>PHENOLIC</td>
<td>$ 00.55</td>
</tr>
<tr>
<td>POLYESTER SMC</td>
<td>$ 01.00</td>
</tr>
<tr>
<td>POLYESTER BMC</td>
<td>$ 00.95</td>
</tr>
<tr>
<td>PHENOLIC/MILLED GLASS</td>
<td>$ 00.65</td>
</tr>
<tr>
<td>EPOXY/50% CONT GLASS</td>
<td>$ 01.75</td>
</tr>
<tr>
<td>POLYESTER/50% CONT GLASS</td>
<td>$ 01.25</td>
</tr>
<tr>
<td>EPOXY CONT GRAPHITE</td>
<td>$ 06.00</td>
</tr>
</tbody>
</table>
"Scrap" is calculated from the process variable (SCR) which has been adjusted for both the material and the geometry. "Scrap" is a measure of the amount of raw material which does not become incorporated in the final product including that which is trimmed as offal and that which is lost due to the production of parts which do not meet the design specifications. "Scrap" is reduced substantially if the offal and out of spec parts can be recycled.

4.4.1.2 Utilities Costs - Utilities costs per component are estimated as,

\[
(5) \quad \text{Utilities} = \text{Weight} \times \text{UTL} \times \text{PUTL} \times \text{Mtl adj}
\]

"UTL" is a process variable which specifies the average amount of energy consumed per pound of material that is processed and it includes energy consumed for heating, cooling, and mechanical transport of the material. "PUTL" is an exogeneous variable which specifies the cost of energy in dollars per kilowatt hour. Within this study, it is implicitly assumed that all of the energy consumed is electrical. If alternate sources of energy are used (i.e., thermal, mechanical, etc.), the costs relative to electricity must be calculated and "PUTL" must be adjusted, appropriately. "Mtl adj" is the appropriate material adjustment factor dependent on the material being processed.
4.4.1.3 Direct Labor Cost - Direct labor costs per component are estimated on the basis of the cycle time required to produce the components.

(6) \( \text{Direct Labor} = \text{Cycle time} \times \text{PDLB} \times \text{DLB} \div \text{PRD} \)

"PDLB" is an exogenous variable which defines the wage rate of the direct laborers in dollars per hour including the costs of employee benefits. "DLB" is a process variable which defines the number of laborers required per main machine for the production, trimming and handling of the component. "PRD" is a process variable which defines the productivity of the process (see section 4.3.1).

"Cycle time" for most of the cyclic molding processes is estimated as,

(7) \( \log(\text{Cycle time}) = (\text{CYC1} \times \log(\text{Weight}) + \text{CYC2}) \times \text{Mtl adj} \times \text{Geo adj} \)

where "CYC1" and "CYC2" are regression variables obtained by regressing cycle time on to part weight in a log-log model for a variety of molding conditions. Values for "CYC1" and "CYC2" for the cyclic processes appear in Table 8. Data for these regressions were obtained from various sources (45, 46, 47, 48, 49) including literature surveys, manufactures data, and previous work on this subject (50, 51).
Table 8
Cycle Time Regression Parameters

<table>
<thead>
<tr>
<th>Process</th>
<th>CYC1</th>
<th>CYC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>INJECTION MOLDING</td>
<td>.45</td>
<td>1.50</td>
</tr>
<tr>
<td>BLOW MOLDING</td>
<td>.45</td>
<td>1.50</td>
</tr>
<tr>
<td>SHEET FORMING</td>
<td>.54</td>
<td>1.36</td>
</tr>
<tr>
<td>COMPRESSION MOLDING</td>
<td>.29</td>
<td>2.48</td>
</tr>
<tr>
<td>RIM &amp; RRIM</td>
<td>.30</td>
<td>1.95</td>
</tr>
<tr>
<td>TP FOAM MOLDING</td>
<td>.45</td>
<td>2.00</td>
</tr>
</tbody>
</table>

For extrusion and pultrusion (continuous processes) an "equivalent cycle time" in terms of output in lbs/hr can be estimated through the following assumptions.

For extrusion it has been suggested that the lineal output in feet per minute is approximately constant for most typical automotive profiles (52). The value reported for simple profile extrusion is 1 ft/s. The output in lbs/hr can be estimated from the cross sectional area by the following formula:
(8) \[ \text{Output} = \text{Weight} + (\text{Density} \times \text{Area} \times 1 \text{ ft/s}) \]

Where "Weight" is the weight of the part being fabricated, "Density" is the density of the material being processed (assumed to be 1 g/cc for all extrude-able plastics) and "Area" is the cross sectional area of the profile. For pultrusion, the same set of assumptions can be used except the constant lineal output should be reduced to 10 ft/min (53).

The product of the density, the area and the lineal output yields the mass output (lbs. per second). The mass output is used in place of the component weight in regression analysis of the continuous processes. For example, the correlation between mass output and machine cost has been established for extruders (54).

For filament winding, the equivalent cycle time is estimated from the winder output as measured in pounds per second. The output has been found to be a function of the wall thickness (inches) of the component (55) by the equation:

(9) \[ \log(\text{Output}) = 0.58 \log(\text{Thickness}) + 3.00 \]

The cycle time for filament winding is calculated from the ratio of the component weight (not including the forming mandrel) to the output.

Finally, for SMC molding the cycle time has been found to be a function of wall thickness based on heat transfer consid-
erations. It was found that 2.5 minutes were required per each 0.10 inches of wall thickness (56).

4.4.2 Fixed Costs - Eight fixed costs elements are estimated. These are:

1) main machine cost,
2) mold or die cost,
3) installation cost,
4) maintenance cost,
5) building cost,
6) auxiliary equipment cost,
7) overhead cost, and
8) the cost of capital recovery.

Fixed costs are estimated on the basis of dollars per year. The main machine, mold and building costs, each have characteristic lifetimes over which the cost is spread evenly.

4.4.2.1 Machine Costs - The cost of the main machine (or machines) required for a given fabrication method is estimated as,

(10) \[ \text{Machine} = \text{NMCH} \times \exp(\text{MCH1} \times \log(\text{Weight}) + \text{MCH2}) \times \text{Mtl adj} + \text{Machine life} \]

"MCH1" and "MCH2" are regression variables whose values appear in Table 9. These values were obtained from regression analysis of price data obtained from industry (57, 58, 59, 60, 61,
62, 63) and from literature (64, 65). For continuous processes (i.e. extrusion and pultrusion) machine output in pounds per hour is substituted into equation 10 in place of part weight.

Table 9
Main Machine Regression Parameters

<table>
<thead>
<tr>
<th>Process</th>
<th>MCH1</th>
<th>MCH2</th>
</tr>
</thead>
<tbody>
<tr>
<td>INJECTION MOLDING</td>
<td>.66</td>
<td>4.93</td>
</tr>
<tr>
<td>EXTRUSION</td>
<td>.51</td>
<td>4.01</td>
</tr>
<tr>
<td>BLOW MOLDING</td>
<td>.49</td>
<td>5.07</td>
</tr>
<tr>
<td>SHEET FORMING</td>
<td>.48</td>
<td>4.41</td>
</tr>
<tr>
<td>COMPRESSION MOLDING</td>
<td>.61</td>
<td>4.75</td>
</tr>
<tr>
<td>RIM &amp; RRIM</td>
<td>.61</td>
<td>4.84</td>
</tr>
<tr>
<td>TP FOAM MOLDING</td>
<td>.64</td>
<td>4.83</td>
</tr>
<tr>
<td>PULTRUSION</td>
<td>.78</td>
<td>4.22</td>
</tr>
<tr>
<td>FILAMENT WINDING</td>
<td>.50</td>
<td>4.17</td>
</tr>
<tr>
<td>SMC MOLDING</td>
<td>.78</td>
<td>4.82</td>
</tr>
</tbody>
</table>
Machine life is estimated as,

(11) Machine life = MLF \times \text{Mtl adj}

"MLF" is a process variable which defines the life of the machine in years. It is adjusted for the material which is being processed since certain materials are either abrasive or corrosive and tend to shorten the life of the equipment.

"Machine life" is used in equation 10 for straight-line amortization of the equipment costs. It is not actually a measure of the physical life of the equipment, but rather it is a measure of the depreciation life. This distinction is important since the two lives may be significantly different.

"NMCH" is the number of machines operating in parallel which are required to produce the specified number of parts per year. "NMCH" is calculated as,

(12) \[ \text{NMCH} = \frac{\text{Yearly production number} \times \text{Cycle time}}{\text{(PRD} \times \text{DAYS} \times \text{SHFT} \times \text{HORS)}} \]

where "PRD" is the process productivity as defined in section 4.3.1. and "DAYS", "SHFT", and "HORS" are exogenous variables which define the number of working days per year, the number of shifts per day and the number of hours per shift, respectively.

4.4.2.2 Mold or Die Cost - The cost of the mold or die required to form the desired component is estimated as,
(13) Mold or Die = NMCH • exp(MOL1 • log(Weight) + MOL2) • Geo adj + Mold life

"MOL1" and "MOL2" are regression variables whose values appear in Table 10. Values were obtained from regression analysis of data from literature and industry (66, 67, 68, 69, 70, 71) and from previous work in this area (72, 73).

The cost of the mold or die is multiplied by a geometry adjustment factor to account for cost differences which arise from the various possible shapes of components considered herein. Shape differences effect the cost of the tooling dramatically since for certain shapes cam-action or slides are required in the tool. This increases the complexity and expense of the tooling, greatly.

Regression parameters for filament winding do not appear because in this process the mold or forming mandrel may remain as a part of the fabrication. In general, it is not reusable and its cost are not correlated with the weight of the finished component.

Mold life is estimated as,

(14) Mold life = exp(OLF) x Mtl adj x Geo adj / Yearly production number

where "OLF" is a process variable that is the logarithm of the expected life of the mold (in cycles). The quantity "exp(OLF)" therefore, is the total unadjusted number of cycles over which the cost of the mold is distributed. This number
Table 10

Mold or Die Regression Parameters

<table>
<thead>
<tr>
<th>Process</th>
<th>MOL1</th>
<th>MOL2</th>
</tr>
</thead>
<tbody>
<tr>
<td>INJECTION MOLDING</td>
<td>.57</td>
<td>4.61</td>
</tr>
<tr>
<td>EXTRUSION</td>
<td>.99</td>
<td>0.70</td>
</tr>
<tr>
<td>BLOW MOLDING</td>
<td>.34</td>
<td>3.97</td>
</tr>
<tr>
<td>SHEET FORMING</td>
<td>.27</td>
<td>3.82</td>
</tr>
<tr>
<td>COMPRESSION MOLDING</td>
<td>.57</td>
<td>4.61</td>
</tr>
<tr>
<td>RIM &amp; RRIM</td>
<td>.57</td>
<td>4.61</td>
</tr>
<tr>
<td>TP FOAM MOLDING</td>
<td>.57</td>
<td>3.78</td>
</tr>
<tr>
<td>PULTRUSION</td>
<td>.74</td>
<td>3.30</td>
</tr>
<tr>
<td>FILAMENT WINDING</td>
<td>---</td>
<td>----</td>
</tr>
<tr>
<td>SMC MOLDING</td>
<td>.76</td>
<td>4.19</td>
</tr>
</tbody>
</table>

is adjusted for both the material and the geometry since either abrasive materials or complex mold configurations can shorten the life of the mold appreciably.
As with machine life, the mold life is the capital recovery period for the investment. Ideally, this should roughly equal the physical life to minimize the accounted cost of production.

4.4.2.3 Installation Costs - The cost of installation is estimated as,

\[(15) \text{Installation} = \text{INS} \times \text{Machine cost}\]

where "INS" is a process variable which defines the percent of the main machine cost which must be added to the total cost to account for installation (see section 4.3.1). Installation costs are distributed uniformly over the life of the main machine.

4.4.2.4 Maintenance Costs - The cost of maintenance for all of the equipment is,

\[(16) \text{Maintenance} = \text{MNT} \times \text{machine cost}\]

where "MNT" is a process variable which defines the percent of the main machine cost which must be added to account for maintenance. Maintenance costs are considered to occur uniformly over the life of the equipment.

4.4.2.5 Building Costs - The cost of the buildings which are required to house the operation is estimated as,
(17) Building = Area × PBLD + BLIF

"PBLD" and "BLIF" are exogeneous variables which define the price of factory floor space in dollars per square foot and the straight-line depreciation life of the building in years. "Area" is the floor space in square feet required for the manufacture and warehousing of the component. "Area" is estimated as,

(18) Area = \exp(BLD1 \times \log(Weight) + BLD2) \times 
           \left(1 + 0.3(NMCH - 1)\right)

"BLD1" and "BLD2" are regression variables whose values appear in Table 11. These values were obtained from Sanada (74).

The second term in equation 18 estimates the floor space required for additional, parallel processing streams. It has been shown that only thirty percent of the area required for the first machine is required for each additional station (75).

4.3.2.6 Auxiliary Equipment Costs - The cost of auxiliary equipment such as dryers, material handling equipment, grinders, etc. is estimated as,

(19) Auxiliary = AUX × Machine cost × Mtl adj

where "AUX" is a process variable which defines the percent of the main machine cost which must be added to account for expenditures on auxiliary equipment. The auxiliary equipment cost is adjusted to compensate for the type of material which
Table 11

Building Cost Regression Parameters

<table>
<thead>
<tr>
<th>Process</th>
<th>BLD1</th>
<th>BLD2</th>
</tr>
</thead>
<tbody>
<tr>
<td>INJECTION MOLDING</td>
<td>.71</td>
<td>2.92</td>
</tr>
<tr>
<td>EXTRUSION</td>
<td>.50</td>
<td>1.87</td>
</tr>
<tr>
<td>BLOW MOLDING</td>
<td>.71</td>
<td>2.66</td>
</tr>
<tr>
<td>SHEET FORMING</td>
<td>.71</td>
<td>2.88</td>
</tr>
<tr>
<td>COMPRESSION MOLDING</td>
<td>.71</td>
<td>2.47</td>
</tr>
<tr>
<td>RIM &amp; RRIM</td>
<td>.71</td>
<td>2.47</td>
</tr>
<tr>
<td>TP FOAM MOLDING</td>
<td>.71</td>
<td>2.67</td>
</tr>
<tr>
<td>PULTRUSION</td>
<td>.50</td>
<td>3.47</td>
</tr>
<tr>
<td>FILAMENT WINDING</td>
<td>.71</td>
<td>2.92</td>
</tr>
<tr>
<td>SMC MOLDING</td>
<td>.71</td>
<td>2.40</td>
</tr>
</tbody>
</table>

is being processed since certain materials (eg. PET) require special handling or preconditioning prior to processing.
Implicitly, the auxiliary equipment is assumed to have the same working life as the main machine. Auxiliary equipment costs are distributed uniformly over this time.

4.4.2.7 Overhead Costs - The cost of overhead labor such as management, marketing, sales, engineering, etc. as well as the cost of overhead equipment like office supplies, fork lifts, etc. is estimated as,

\[ (20) \quad \text{Overhead} = OVR \times \text{Fixed costs} \]

where "OVR" is a process variable that defines the fraction of the other fixed costs which must be added to the total cost to account for the overhead expenses. Values of "OVR" were obtained from industry-wide averages (76). The "fixed costs" which are multiplied by "OVR" are the six aforementioned cost elements (main machine, mold or die, installation, maintenance, building, and auxiliary equipment).

4.4.2.8 Capital Recovery Costs - The recovery cost of the capital investment is estimated as,

\[ (21) \quad \text{Recovery cost} = \text{Capital} \times (-1 + (1 + R)\exp(\text{Life}) \times \log(1 + R) + (1 + R)\exp(\text{Life} - 1)) \]

where "R" is the rate of capital recovery, "Life" is the recovery life of the investment and "\exp" and "\log" are the natural exponentiation and logarithm operators, respectively. Equation 21 is a modified continuous interest capital recovery
formula. It has been modified such that the payback of the investment principal is subtracted from the capital recovery. The remainder corresponds to the recovery cost of the capital, alone.

Capital costs are estimated for the main machine, mold or die, building and auxiliary equipment. In addition, they are estimated for working capital which is assumed to be three months of expenditures on the variable costs and overhead.
4.4.3 Multi-cavity Optimization - For all of the cyclic molding processes, an optional iterative technique may be employed to optimize the number of cavities per mold. To accomplish this, the model first computes the cost elements for a single cavity mold. These values are saved in buffer memory. The number of cavities is incremented by two and the cost estimation is repeated. A comparison is made to determine if the total cost is reduced. If it is, the iteration is repeated. If not, the previous values are taken as the optimum.

When the number of cavities is incremented, the weight of a molding is increased proportionally and the total number of molding cycles required to produce the yearly production volume is decreased proportionally. Effectively, this increases the equipment costs but decreases the labor costs of producing the component.

Several restraints are imposed on the cavities optimization routine. First, the number of cavities must be even. This restraint reflects current design practice for mold construction (77, 78). Second, the combined weight of the parts in all cavities cannot exceed 15 pounds if multi-cavity molds are to be utilized. This is considered to be the maximum weight that a single operator could be expected to handle continuously (79) and also corresponds to the maximum capacity of the main machine for many processes (80, 81). The
final constraint is that the number of cavities is not allowed to exceed sixteen. This constraint is imposed on the basis of typical present day industrial practice (82, 83).

It is recognized that all of the constraints are somewhat arbitrary. Provisions have been made such that they may be easily relaxed or eliminated if desired. The two latter constraints, maximum number of cavities and maximum weight, are controlled through the variables "MAXCAV" and "MAXWGT" which appear in data statements within the program.

Discussions with members of the plastics industry (84, 85) indicate that although this procedure does define the least cost method, molders often will not operate in this manner. This occurs because large capital investments are required to purchase the main machine and since these machines are frequently used to produce a variety of components, molders favor the purchase of mid-sized machines which offer the greatest versatility.
4.5 MODEL OUTPUT

The final operation of the model is the output of cost estimates for the component of interest. Samples of this appear in figures 4, 5, 6, and 7 (see section 5.1). As seen, the output is divided into three sections: variable cost elements, fixed cost elements, and total fabrication cost. Each element in each section is presented on the basis of cost per component, cost per year, and percent of total cost.

Additional information utilized in calculating the cost elements is also included. This information is either derived during the course of computation (e.g., cycle time, number of cavities, etc.) or it is data which is imbedded within the model (e.g., raw material price, interest rate, etc.).

Finally, at the top of each output sheet, there is a brief description of the component for which the estimates apply.
4.6 MAJOR ASSUMPTIONS

Several major assumptions were made in constructing this model. The ones with the greatest significance are presented herein.

4.6.1 Dedicated Equipment - It is assumed, implicitly, that the fabrication of a component is accomplished using dedicated equipment. The cost of the equipment is distributed totally and uniformly onto the components being produced.

This assumption has only minor significance in large production volumes, where the equipment is fully utilized in the production of a single component. For very large volumes (or for components which require long cycle times) several machines may be required to operate in parallel. Under these circumstances, the assumption that the equipment is dedicated to the production of a single component becomes completely valid.

For smaller production volumes and rapid cycle times, the assumption of dedicated equipment can be very serious. Fortunately, the automotive industry operates with large volumes. In addition, there is a trend within the industry to minimize parts inventories (86). To do this, production is spread evenly over the course of a year and, because there is considerable lost time associated with changing molds, materials, etc., the equipment is more likely to remain dedicated to the production of a single component.
If the user feels this assumption is inappropriate, one solution is to distribute only a fraction of the equipment cost on to the component which is being fabricated. This fraction might be calculated as the ratio of the cumulative cycle time to the time available for processing during the year.

4.6.2 Variable Labor - It is assumed that the availability of direct labor is infinitely flexible. Under this assumption, laborers can be switched from the production of one component to the production of another without penalty. Therefore, direct labor costs are incurred only for the time in which components are being fabricated (i.e., the cycle time).

The validity of this assumption depends on the production volume and on the nature of the production facility. For large volumes, the assumption is valid because labor is always needed, just to complete the production quota. For large integrated production facilities, as are typical in the automotive industry, the assumption is also valid since many different components are being fabricated at the same time. In such cases; it becomes possible to transfer a laborer to the production of another component once the quota for the first has been met.

This assumption can become unrealistic when the automotive industry is seriously depressed. In these situations, under-utilization and idle capacity can exist and the ability
to transfer laborers to other production lines may not exist. It may become necessary to add an idle labor cost on to the components which are produced. Of course, if this situation persists, lay-offs will occur and the cost of idle labor will diminish.

4.6.3 Fixed Raw Material Prices - It is assumed that the price of the raw material is independent of the way it is processed. For most materials this is appropriate. In some cases (eg. RIM nylon vs. injection nylon) the price of the material is greatly affected by the process. For such instances, the model output should be modified to reflect the true raw material price. This is especially true for large production volumes since in these instances, the raw material cost dominates all other costs.

4.6.4 Cavities Optimization - It is assumed that the optimal number of cavities is that number which produces at minimum cost. No attempt is made to maximize the utilization of equipment. This assumption often leads to the selection of large multi-cavity molds and large but under-utilized equipment (because of the assumption of variable labor, section 4.6.2). Production costs can be minimized by using large multi-cavity molds because they reduce the time necessary to produce a given number of components and thereby reduce the labor costs.
If the user of the model feels this assumption is not applicable to the specific circumstances, it is possible to select the number of cavities externally or to impose other constraints which change the number of cavities used during cost estimation. One such constraint is to require a minimum level of utilization on the equipment. Another is to change the maximum number of cavities constraint (MAXCAV) until the desired level of utilization is achieved.
5.0 RESULTS AND DISCUSSION

The cost estimation model developed herein can be used to accomplish two ends. First, it can and has been used to generate precise production cost estimates for specific automotive components. Examples of this application of the model follow and these examples provide a detailed analysis of primary fabrication costs and provide a basis for comparison when more than one fabrication process is feasible.

Second, the model is useful as a tool for performing sensitivity analysis on the cost estimates. Sensitivity analysis is performed by varying one element of the cost structure or of the underlying cost equations and observing the impact that it has upon the other elements or upon the total cost of fabrication. One of the example components, a cooling fan blade, is analyzed by detailed sensitivity analysis to study the effects of changes in ten variables or inputs on the cost of fabrication. The results of this analysis are presented and discussed in section 5.2.

5.1 Sample Output - The cost of producing a nylon cooling fan blade and a SMC front fender are estimated and these estimates provide an example of the model output. The inputs that were used for each of these examples are given below. The input values correspond to a hypothetical 1978 Dodge Omni with the assumption that the components (fan and fenders) are made from the specified materials (87).
5.1.1 Fan Blade

Material: nylon/30% milled glass;
Geometry: complex solid (w/ flat surfaces);
Weight: 0.90 lbs.;
Maximum wall thickness: 0.15 in.;
Yearly production number: 500,000

The cost estimates for the fan blade appear in Figures 4, 5 and 6, one for each of the feasible fabrication methods. The methods which are selected as feasible by the model are injection molding, sheet forming, and reaction injection molding.

According to the results, sheet forming is the least cost method of production, followed by injection molding and RIM. Careful examination reveals that sheet forming is least because of low capital investment costs, especially the main machine and mold, and because of the low direct labor costs which are the result of the extremely rapid cycle time. It must be considered, however, that this analysis assumes that nylon sheet is no more expensive than nylon pellets (for injection molding). If the raw material price is corrected to reflect the price differential between these starting materials, quite likely injection molding will become the most cost effective.

Injection molding is more expensive than sheet forming primarily because of higher equipment costs. This is somewhat
There is no text material missing here. Pages have been incorrectly numbered.

pg. 69
METHOD OF FABRICATION: INJECTION MOLDING

Material: NYLON/30% MILLED GLASS
Component Geometry: COMPLEX SOLID (FLAT SURFACES)
Component Weight (lbs): 0.90
Annual Production Number: 500000

VARIABLE COST ELEMENTS: per component ($) per year ($) fraction of total cost

Material Cost: 1.551 775403.  .563
Utilities Cost: 0.052 25958.  .019
Direct Labor Cost: 0.063 31707.  .023
Total Variable Cost: 1.666 833067.  .605

FIXED COST ELEMENTS: per component ($) per year ($) fraction of total cost

Main Machine Cost: 0.209 104404.  .076
Mold or Die Cost: 0.443 221484.  .161
Overhead Labor Cost: 0.254 126872.  .092
Building Cost: 0.199 9459.  .007
Installation Cost: 0.021 10440.  .008
Auxiliary Equip Cost: 0.027 13573.  .010
Maintenance Cost: 0.006 3132.  .002
Cost of Capital: 0.111 55481.  .040
Total Fixed Cost: 1.090 544845.  .395

TOTAL FABRICATION COST: per component ($) per year ($) fraction of total cost

2.756 1377912.  1.000

ADDITIONAL INFORMATION:

Raw Material Price ($/lb): 1.66
Scrap Rate on Material Usage (%): 0.04
Utilities Price ($/kw hr): 0.060
Direct Labor Wage Rate ($/hr): 14.00
Man-hours of Direct Labor (per yr): 2264
Number of Direct Laborers: 4.2
Number of Cavitys in Mold: 8
Cycle Time (s): 54.0
Number of Parallel Production Streams: 1
Run-time for one machine (%): 30.6
Mold Life (yrs): 1.11
Required Building Space (sq ft): 3378
Interest Rate (%): 10.0

Figure 4
Injection Molded Fan Blade Fabrication Costs
**METHOD OF FABRICATION: SHEET FORMING**

Material: NYLON/30% MILLED GLASS  
Component Geometry: COMPLEX SOLID (FLAT SURFACES)  
Component Weight (lbs): 0.90  
Annual Production Number: 500000

**VARIABLE COST ELEMENTS:** per component ($) per year ($) fraction of total cost

<table>
<thead>
<tr>
<th>Cost Element</th>
<th>per component ($)</th>
<th>per year ($)</th>
<th>fraction of total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Cost</td>
<td>1.591</td>
<td>795569.</td>
<td>.829</td>
</tr>
<tr>
<td>Utilities Cost</td>
<td>0.038</td>
<td>19186.</td>
<td>.020</td>
</tr>
<tr>
<td>Direct Labor Cost</td>
<td>0.086</td>
<td>43248.</td>
<td>.045</td>
</tr>
<tr>
<td>Total Variable Cost</td>
<td>1.716</td>
<td>858003.</td>
<td>.894</td>
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</table>

**FIXED COST ELEMENTS:** per component ($) per year ($) fraction of total cost

<table>
<thead>
<tr>
<th>Cost Element</th>
<th>per component ($)</th>
<th>per year ($)</th>
<th>fraction of total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Machine Cost</td>
<td>0.038</td>
<td>19250.</td>
<td>.020</td>
</tr>
<tr>
<td>Mold or Die Cost</td>
<td>0.039</td>
<td>19469.</td>
<td>.020</td>
</tr>
<tr>
<td>Overhead Labor Cost</td>
<td>0.041</td>
<td>20729.</td>
<td>.022</td>
</tr>
<tr>
<td>Building Cost</td>
<td>0.014</td>
<td>7033.</td>
<td>.007</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>0.006</td>
<td>2887.</td>
<td>.003</td>
</tr>
<tr>
<td>Auxillary Equip Cost</td>
<td>0.020</td>
<td>10010.</td>
<td>.010</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>0.001</td>
<td>577.</td>
<td>.001</td>
</tr>
<tr>
<td>Cost of Capital</td>
<td>0.043</td>
<td>21386.</td>
<td>.022</td>
</tr>
<tr>
<td>Total Fixed Cost</td>
<td>0.203</td>
<td>101343.</td>
<td>.106</td>
</tr>
</tbody>
</table>

**TOTAL FABRICATION COST** per component ($) per year ($) fraction of total cost

|                       | 1.919             | 959346.      | 1.000                  |

**ADDITIONAL INFORMATION:**

- Raw Material Price ($/lb): 1.66
- Scrap Rate on Material Usage (%): 0.06
- Utilities Price ($/kw hr): 0.060
- Direct Labor Wage Rate ($/hr): 14.00
- Man-hours of Direct Labor (per yr): 3089
- Number of Direct Laborers: 5.7
- Number of Cavities in Mold: 6
- Cycle Time (s): 40.0
- Number of Parallel Production Streams: 1
- Run-time for one machine (%): 30.8
- Mold Life (yrs): 1.05
- Required Building Space (sq ft): 2511
- Interest Rate (%): 10.0

**Figure 5**
Sheet Formed Fan Blade Fabrication Costs
METHOD OF FABRICATION: REACTION INJECTION MOLDING

Material: NYLON/30% MILLED GLASS
Component Geometry: COMPLEX SOLID (FLAT SURFACES)
Component Weight (lbs): 0.90
Annual Production Number: 500000

VARIABLE COST ELEMENTS: per component ($) per year ($) fraction of total cost

<table>
<thead>
<tr>
<th>Element</th>
<th>Per Component ($</th>
<th>Per Year ($)</th>
<th>Fraction of Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Cost</td>
<td>1.829</td>
<td>914488.</td>
<td>.644</td>
</tr>
<tr>
<td>Utilities Cost</td>
<td>0.045</td>
<td>22572.</td>
<td>.016</td>
</tr>
<tr>
<td>Direct Labor Cost</td>
<td>0.114</td>
<td>56980.</td>
<td>.040</td>
</tr>
<tr>
<td>Total Variable Cost</td>
<td>1.988</td>
<td>994040.</td>
<td>.700</td>
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FIXED COST ELEMENTS: per component ($) per year ($) fraction of total cost

<table>
<thead>
<tr>
<th>Element</th>
<th>Per Component ($</th>
<th>Per Year ($)</th>
<th>Fraction of Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Machine Cost</td>
<td>0.176</td>
<td>88098.</td>
<td>.062</td>
</tr>
<tr>
<td>Mold or Die Cost</td>
<td>0.320</td>
<td>159835.</td>
<td>.113</td>
</tr>
<tr>
<td>Overhead Labor Cost</td>
<td>0.197</td>
<td>98482.</td>
<td>.069</td>
</tr>
<tr>
<td>Building Cost</td>
<td>0.008</td>
<td>3933.</td>
<td>.003</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>0.018</td>
<td>8810.</td>
<td>.006</td>
</tr>
<tr>
<td>Auxiliary Equip Cost</td>
<td>0.034</td>
<td>17179.</td>
<td>.012</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>0.007</td>
<td>3524.</td>
<td>.002</td>
</tr>
<tr>
<td>Cost of Capitol</td>
<td>0.092</td>
<td>45817.</td>
<td>.032</td>
</tr>
<tr>
<td>Total Fixed Cost</td>
<td>0.851</td>
<td>425677.</td>
<td>.300</td>
</tr>
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TOTAL FABRICATION COST per component ($) per year ($) fraction of total cost

<table>
<thead>
<tr>
<th>Total Cost</th>
<th>Per Component ($)</th>
<th>Per Year ($)</th>
<th>Fraction of Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.839</td>
<td>1419716.</td>
<td>1.000</td>
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ADDITIONAL INFORMATION:

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<thead>
<tr>
<th>Item</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Raw Material Price ($/lb)</td>
<td>1.66</td>
</tr>
<tr>
<td>Scrap Rate on Material</td>
<td>0.18</td>
</tr>
<tr>
<td>Usage (%)</td>
<td></td>
</tr>
<tr>
<td>Utilities Price ($/kw hr)</td>
<td>0.060</td>
</tr>
<tr>
<td>Direct Labor Wage Rate</td>
<td>14.00</td>
</tr>
<tr>
<td>($/hr)</td>
<td></td>
</tr>
<tr>
<td>Man-hours of Direct</td>
<td>4069</td>
</tr>
<tr>
<td>Labor (per yr)</td>
<td></td>
</tr>
<tr>
<td>Number of Direct</td>
<td>4.5</td>
</tr>
<tr>
<td>Laborers (per yr)</td>
<td></td>
</tr>
<tr>
<td>Number of Cavities in</td>
<td>10</td>
</tr>
<tr>
<td>Mold</td>
<td></td>
</tr>
<tr>
<td>Cycle Time (s)</td>
<td>121.1</td>
</tr>
<tr>
<td>Number of Parallel</td>
<td>1</td>
</tr>
<tr>
<td>Production Streams</td>
<td></td>
</tr>
<tr>
<td>Run-time for one machine</td>
<td>51.4</td>
</tr>
<tr>
<td>(%)</td>
<td></td>
</tr>
<tr>
<td>Mold Life (yrs)</td>
<td>1.74</td>
</tr>
<tr>
<td>Required Building Space</td>
<td>1404</td>
</tr>
<tr>
<td>(sq ft)</td>
<td></td>
</tr>
<tr>
<td>Interest Rate (%)</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Figure 6
Reaction Injection Molded Fan Blade
Fabrication Costs
compensated for by lower material costs ($1.55/piece vs. $1.59/piece) which are the result of lower process scrap rates and by lower direct labor costs ($0.063/piece vs $0.086/piece) which result from the high degree of process automation.

The most expensive method is RIM. The two cost elements which account for most of this difference are the material cost and the direct labor cost.

The high material cost is a result of the high process scrap rate (18%). In general, large scrap rates are typical in RIM because the process involves a chemical reaction and, once reacted, the raw material cannot be re-used. The exception is nylon RIM where the product is a thermoplastic and can be recycled for use with another process (e.g. extrusion, injection molding). This advantage of nylon RIM has not been encorporated into the the estimate since the value of the scrap is unknown.

The RIM estimates do not reflect the price differential which exists between injection grade nylon and RIM nylon. The estimates should be adjusted to reflect this difference as discussed in section 4.6.3.

For all three estimates, the single largest cost element is the raw material, averaging 67% of the total cost of fabrication. The costs of the main machine, tooling, direct labor, and overhead are also quite significant. Together, they are 25% of the total cost or 75% of the remaining cost
once the raw material has been accounted. The cost of installation, maintenance, and the building are insignificant, accounting for less than 2% of the total fabrication cost.

5.1.2 Front Fender

Material: polyester SMC;
Geometry: complex curved panel;
Weight: 21.5 lbs.;
Maximum wall thickness: 0.125 in.;
Yearly production number: 100,000

The estimate for the cost of producing SMC fenders appears in Figure 7. By definition, only one fabrication method is feasible for producing this component, since SMC defines not only the material, but also the process.

As seen from the results, SMC molding is a comparatively slow process (cycle time 187 s). This compares with cycle times of less than one minute for producing the equivalent part in metal stamping presses (88). The long cycle time results in large direct labor costs, in this case, $2.63 for the fabrication of each fender.

The combination of the long cycle time and the relatively large production number (100,000/yr) causes the need for parallel production streams, doubling the requirement for capital equipment. This increases fabrication costs substantially.
METHOD OF FABRICATION: SMC COMPRESSION MOLDING

Material: POLYESTER SMC
Component Geometry: COMPLEX CURVED PANELS
Component Weight (lbs): 21.50
Annual Production Number: 100000

VARIABLE COST ELEMENTS: per component ($) per year ($) fraction of total cost

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Per Component ($)</th>
<th>Per Year ($)</th>
<th>Fraction of Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Cost</td>
<td>23.882</td>
<td>2388223</td>
<td>.589</td>
</tr>
<tr>
<td>Utilities Cost</td>
<td>0.831</td>
<td>83076</td>
<td>.020</td>
</tr>
<tr>
<td>Direct Labor Cost</td>
<td>2.625</td>
<td>262500</td>
<td>.065</td>
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<tr>
<td>Total Variable Cost</td>
<td>27.338</td>
<td>2733798</td>
<td>.674</td>
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FIXED COST ELEMENTS: per component ($) per year ($) fraction of total cost

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Per Component ($)</th>
<th>Per Year ($)</th>
<th>Fraction of Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Machine Cost</td>
<td>3.482</td>
<td>348240</td>
<td>.086</td>
</tr>
<tr>
<td>Mold or Die Cost</td>
<td>4.242</td>
<td>424250</td>
<td>.105</td>
</tr>
<tr>
<td>Overhead Labor Cost</td>
<td>3.012</td>
<td>301231</td>
<td>.074</td>
</tr>
<tr>
<td>Building Cost</td>
<td>0.081</td>
<td>8075</td>
<td>.002</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>0.348</td>
<td>34824</td>
<td>.009</td>
</tr>
<tr>
<td>Auxiliary Equip Cost</td>
<td>0.348</td>
<td>34824</td>
<td>.009</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>0.104</td>
<td>10447</td>
<td>.003</td>
</tr>
<tr>
<td>Cost of Capital</td>
<td>1.584</td>
<td>158432</td>
<td>.039</td>
</tr>
<tr>
<td>Total Fixed Cost</td>
<td>13.203</td>
<td>1320322</td>
<td>.326</td>
</tr>
</tbody>
</table>

TOTAL FABRICATION COST per component ($) per year ($) fraction of total cost

<table>
<thead>
<tr>
<th>Cost Items</th>
<th>Per Component ($)</th>
<th>Per Year ($)</th>
<th>Fraction of Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40.541</td>
<td>4054119</td>
<td>1.00</td>
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ADDITIONAL INFORMATION:

<table>
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<tr>
<th>Cost Item</th>
<th>Unit Cost ($)</th>
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<tbody>
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<td>Scrap Material Price ($/lb)</td>
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</tr>
<tr>
<td>scrap rate on material usage</td>
<td>0.10</td>
</tr>
<tr>
<td>Utilities Price ($/kw hr)</td>
<td>0.060</td>
</tr>
<tr>
<td>Direct Labor Wage Rate ($/hr)</td>
<td>14.00</td>
</tr>
<tr>
<td>Man-hours of Direct Labor (per yr)</td>
<td>18750</td>
</tr>
<tr>
<td>Number of Direct Laborers</td>
<td>10.8</td>
</tr>
<tr>
<td>Cycle Time (s)</td>
<td>187.5</td>
</tr>
<tr>
<td>Number of Parallel Production Streams</td>
<td>2</td>
</tr>
<tr>
<td>Run-time for one machine (%)</td>
<td>197.3</td>
</tr>
<tr>
<td>Mold Life (yrs)</td>
<td>0.95</td>
</tr>
<tr>
<td>Required Building Space (sq ft)</td>
<td>2883</td>
</tr>
<tr>
<td>Interest Rate (%)</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Figure 7
SMC Compression Molded
Front Fender
Again, the single largest cost element is the raw material, accounting for 59% of the total cost of production. Much of the raw material cost is due to the high scrap rate (10%) which is the result of the irreversible chemical reaction which occurs during processing. Successful SMC processing involves minimizing these costs through careful mold design and manufacturing control.

5.2 Sensitivity Analysis - Sensitivity analysis is a method for evaluating the impact that changes in one parameter have upon the values of other parameters. For example, sensitivity analysis can be used to quantify the effect that changes in cycle time have upon the direct labor cost.

Sensitivity analysis is applied to case examples since the impact of a given parameter will vary depending on the specifics of the example. Within this study, all of the sensitivity analysis has been performed on the previously mentioned nylon fan blade (section 5.1.1). It cannot be expected that these results would also apply to the front fender (section 5.1.2).

The sensitivity analysis which is presented herein can be divided into two groups. The first group evaluates the precision of the model with regards to variables which have known statistical uncertainty. These include the regression variables and some of the process variables. Analysis of this
type can be considered as a measure of the goodness of the model.

The second group of sensitivity analyses measure the impacts that external or exogenous parameters have upon other parameters or upon the results. Essentially, this is a form of "what if" analysis where the user measures the impact of factors like labor wages, energy prices, raw material prices, etc. This type of analysis is most useful when coupled with realistic forecasts and can be extremely useful to fabricators and their suppliers (ie, equipment manufacturers, raw material suppliers, etc.) for evaluating cost competitiveness, identifying critical processing parameters, etc.

5.2.1 Regression Variables (MCH1 & MCH2) - Sensitivity analysis of the main machine regression variables appears in Figures 8 and 9. In both figures, the abscissa of the graph measures the absolute value of the variable (MCH1 & MCH2) and the ordinate measures percent change in the total fabrication cost (for producing fan blades). The origin is located at the current default values for the variables MCH1 & MCH2.

The banded region of each graph corresponds to the 95% confidence interval obtained from statistical analysis of the regression results. The variation in total cost which arises from this uncertainty is 1% for MCH1 and 3% for MCH2.

The confidence intervals depend on the implicit assumption that the size of the main machine is appropriately matched to
the weight of the component. Appropriate sizing in this model means the machines are operated at 90% of their rated output capacity. This assumption is reasonable if the production facility is large and contains a variety of main machine sizes or if one assumes the facility does not exist, but is being built from the ground up with knowledge of the size of the components which are to be produced.

5.2.2 Process Variables - The sensitivity of total cost of fabricating fan blades to variations in three process variables - productivity, main machine life and mold life - are presented graphically. The abscissa of each graph shows the absolute value of the process variable and the ordinate corresponds to the percent change in total fabrication cost. The origin is located at the currently accepted values for each process variable.

5.2.2.1 Productivity (PRD) - The effect of productivity on the cost of production appears in Figure 10. As seen, fabrication costs for the reference case are relatively insensitive to changes in productivity. Increasing productivity from 60% to 90% decreases the total cost by less than one percent. This insensitivity occurs for two reasons.

The first reason is that the share of cost due to direct labor is extremely small. Productivity effects cost by changing the amount of time required to produce a given number
of components. Time translates into direct labor costs and in situations where labor costs are already low, productivity has little influence.

The second reason for insensitivity is that the equipment is not fully utilized but is still assumed to be dedicated to the production of fan blades. Dedicated equipment influences the cost of production by distributing all of the yearly depreciation costs on to the component being fabricated (see section 4.6.1). This cost is fixed regardless of the productivity of the process. (Unless the yearly quota cannot be produced without purchasing parallel equipment).

5.2.2.2 Machine Life (MLF) - The sensitivity of production cost to machine life appears in Figure 11. Machine life is seen to have a strong influence upon total cost when it is reduced below the default value of 6 years. If the machine life is reduced to 1 year, the cost of producing fan blades increases by 32 percent.

Short machine life is the same as rapid recovery of the capital investment and it strongly influences the accounted cost of production. This practice has been cited as a problem with current American industrial policy (89). It is clear that extending the capital recovery period to be in accord with the physical life of the equipment, reduces the cost ascribed to each component, substantially. Also, extending the recovery period encourages investment in new capital.
Figure 11
Total Cost vs Machine Life
equipment, thereby helping to alleviate the problems associated with the antiquated machinery.

Extending the machine life beyond 6 years however, does not reduce the cost of production, significantly. This suggests that old equipment should be sold or traded for new equipment, regularly. This is especially true if the old equipment requires large maintenance expenditures and if the replacement equipment is technologically superior and offers advantages of improved scrap management, labor requirements or energy efficiency.

5.2.2.3 Mold Life – The effect of the life of the mold on the cost of production appears in Figure 12. The mold life has a strong influence on the cost of production in the reference case and significant cost reductions can be realized by extending it.

For the reference case, the mold life is extremely short because glass reinforced nylon (the material being processed) is extremely abrasive. The variable used to define mold life (OLF, sec. 4.4.2.2) is an average value obtained from a variety of molding conditions. Effectively, it corresponds to carbon tool steel molds used with nonabrasive materials. An adjustment factor corrects for the differences in the expected life when this type of mold is used to process abrasive materials.
Mold life can be extended by changing the material of the mold from carbon steel to a special hardened alloy steel. These materials are more expensive and cost analysis is required to determine whether they result in a net decrease in the cost of fabrication.

The benefit of extending the mold life can be evaluated by use of Figure 12. Doubling the life from 70,000 to 140,000 cycles (doubling the reference case value) reduces the cost by 9%. Extending the life beyond 200,000 cycles, however, does not reduce the cost substantially. This represents the upper limit to profitable mold life prolongation.

Not shown in Figure 12 is the effect of mold life on the optimum number of cavities. It was found, however, that reducing the life from 70,000 to 50,000 cycles shifts the optimum from 8 to 10 cavities. This occurs because the additional expense of purchasing a 10 cavity mold is less than the cost of purchasing two 6 or 8 cavity molds, and having one of them wear out.

5.2.3 Exogeneous Variables - The sensitivity of fabrication cost to four exogeneous variables (price of raw materials, wages of direct laborers, price of utilities, and interest rates) is examined in this section.

5.2.3.1 Raw Material Price - The sensitivity of production cost to changes in the price of the raw material appears in
Figure 13. As seen, cost is extremely sensitive to material price. An increase of 50% in the raw material price produces a 30% increase in the cost. This high sensitivity results from the high share of total cost which is due to the raw material.

In the reference case, raw material is 58% of the total. Overall, for automotive production, the average share is 48% (90). Clearly, manufacturers must work to minimize these costs through effective manufacturing control, scrap management and material selection.

From the perspective of this study, raw material prices are considered to be exogeneous. In practice, the automotive industry can influence them since their suppliers are usually willing to lower prices when large volumes are purchased. This is especially true for specialty materials, like graphite/epoxy composites, where the potential demand by the automobile industry is large compared with the total amount of the material that is currently produced.

5.2.3.2 Direct Laborer Wages – The sensitivity of production costs to direct laborer wages appears in Figure 14. As seen, production costs for the reference case are not very sensitive to wage changes. Raising wages from 14 to 25 dollars per hour increases costs by only 2 1/4 percent.

This insensitivity, in part, is due to the high degree of automation in the injection molding process. Only 1.4
laborers are needed to operate each molding station and this greatly reduces the impact of labor salaries. Also, the cycle time of injection molding is extremely rapid and because labor costs are only incurred during the time when the equipment is cycling, this minimizes labor costs.

A minor inflection appears in Figure 14 where wages are 8 dollars per hour. This results from a change in the optimum number of cavities from 8 to 6. Reducing the number of cavities reduces the mold and machine costs but increases the production time and labor costs. When wages are below 8 dollars, the savings on the equipment are greater than the additional labor expense. The least cost optimum shifts to a lesser number of cavities.

5.2.3.3 Price of Utilities - The sensitivity of cost to variations in the price of utilities appears in Figure 15. As seen, utilities do not influence production costs significantly in the reference case. Doubling the default value from $0.06/kwh to $0.12/kwh increases the total cost of fabrication by only 2 percent.

Utilities prices are expressed in dollars per kilowatt-hour because the majority of the energy consumed by polymer processing equipment is electrical. When other sources of energy are used (e.g. steam, internal combustion), conversion to electrical equivalence is required.
In recent years, attention has focused on energy conservation as a means of cost reduction, inspite of the small contribution of energy to the total cost. This emphasis may have arisen from the explosive and erratic increases in energy prices which occurred in the 1970's. Escalating energy costs concerned all energy consumers, even when the actual impact was small. Equipment manufacturers responded to the perceived problem by designing new equipment which was more efficient. Some of the energy savings were achieved with little additional expense and these improvements were certainly justified. It is clear from Figure 15, however, that very little expense can be justified to attain further improvements.

5.2.3.4 Capital Recovery Rate - Production costs are moderately sensitive to recovery rates (Figure 16). Doubling the recovery rate from the accepted value of 10% increases the total production cost by 4 percent.

A change in the slope appears in Figure 16 for interest rates greater than 15 percent. This results from a shift to more labor intensive production through a reduction in the optimum number of cavities in the mold. When interest rates are high, labor intensive processing is favored over capital intensive processing.

High interest rates (which lead to high recovery rates) have been cited as the cause of the current economic
recession. The impact of high rates on production costs does not fully explain this position. It appears that instead of effecting production, high rates affect the availability of capital for consumption. This indirectly effects production by reducing consumer demand. In view of this analysis, "supply-side" stimulation appears questionable as a means of economic recovery.

5.3.1 Cycle Time - The sensitivity of the cost to the cycle time appears in Figure 17. Cycle time has a moderate impact on the cost of production for the same reasons similar to those applied to productivity. In the reference case, both of these parameters affect only the direct labor cost and this cost is already minimal. Cycle time has a large impact on production costs only when changing it causes a change in the number of parallel production paths. In the reference case, this does no occur because the equipment is not fully utilized. Enough idle capacity is available to compensate for longer cycle times.

The discontinuities which appear in Figure 17 are the result of changes in the optimum number of cavities. As the cycle time is increased, additional cavities are utilized. With additional cavities, producing a given number of components requires less time and less labor costs. This cost reduction is partially offset by an increase in equipment costs.

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Each increase in the number of cavities causes a decrease in the slope of the sensitivity graph because it causes a decrease in the cost share of labor. Decreasing the share of labor reduces the sensitivity of cost to cycle time for the reasons previously cited.

5.3.2 Number of Cavities - The cost of production appears as a function of the number of cavities and the yearly production volume in Figure 18. Each solid line contains a minimum and these minima indicate the optimum trade off between labor costs and equipment costs. To the left of the minima, labor costs are excessive, while to the right, equipment costs are excessive.

A dashed line connects the least cost optimums. The dashed line demonstrates the effect of production volume on the minimum production cost and is, therefore, an indication of the expected returns to scale.

A trade off between the number of cavities and the number of molds that are required to complete the production quota, influences the location of each minimum. Because of the short mold life, several single cavity molds may be required to produce the yearly quota whereas one multicavity mold may be sufficient. The latter is usually more cost effective.

Finally, a trade off between the number of cavities and the number of parallel processing streams affects the minima. Decreasing the number of cavities can require the addition of
Figure 18
Total Cost vs Number of Cavities

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parallel streams to complete the production quota, especially for large quotas. The least cost solution usually minimizes the number of parallel streams.
6.0 CONCLUSIONS

1) Estimating the total cost of fabricating automotive components can be accomplished by systematically estimating the elements which contribute to the cost. When using a systematic approach (and because of the need for extensive data management) elemental cost estimation is best accomplished with the use of a digital computer. This is the approach that was successfully employed within this study.

2) The contribution of cost elements such as the cost of the main machine or of the mold can be estimated by using regression analysis to find the correlation between cost and weight. The inherent uncertainty that arises from this technique varies dependent upon the specifics of the component which is being estimated. For the case of a 1978 Dodge Omni cooling fan (injection molded nylon) the uncertainty in the estimate within the 95% confidence interval is four percent.

3) By using a digital computer for the cost estimation, sensitivity analysis on the parameters which effect the estimate can be easily performed. Using this approach it is shown that the cost of fabricating 500,000/yr. nylon fan blades by injection molding (under the assumptions of dedicated equipment and variable labor) is extremely sensitive to variations in the price of the raw material. It is also sensitive to variations in the period for capital recovery and
in the yearly production volume. For the three above mentioned parameters, a 50% decrease in the parameter causes a 30%, 8%, and 10% variation in the fabrication cost, respectively. Similarly, it is shown that the fabrication cost is not very sensitive to the wages of the direct laborers, the price of energy, and the interest rate for capital recovery.

4) By an iterative solution it is possible to determine the optimal (least cost) number of cavities for molding a given quantity of a specified component.
Bibliography

1. Wark, Donald T., "Impacts of the Automobile on the U.S. Chemical Industry", American Chemical Society Symposium, Aug. 29, 1977, Chicago, Ill., pg. 221

2. Ibid


5. Radermacher, Dr. K., "Plastics in Cars", Kunststoffe, 1980


7. "Road to Detroit Still Smooth, but S-curves Ahead", Plastics Engineering, Nov, 1980, pg. 35

8. Ibid

9. Conversations with Mr. Steve Elliott, FCM Middleville, Structural Foam, Cost Estimator

10. Op. Cit., "Road to Detroit", pg. 34

11. Op. Cit., "Road to Detroit", pg. 34

12. Op. Cit., "Road to Detroit", pg. 34


15. Sanada, Mashiko, Economics of Plastic Molding Processes Thesis Master of Science, Lowell Technological Institute, May, 1973


21. Conversations with Mr. K. Coulter, Davis Standard, Pawcatuck, Ct., Aug. 7, 1982

22. Conversations with Mr. Garret Peters, Battenfeld, E. Providence, RI, June 7, 1982

23. Conversations with Mr. R. Burton, Cincinnati Milacron, June 7, 1982

24. Conversations with Mr. R. Hogue, Admiral Equipment Co., Akron, Ohio, June 7, 1982


32. Conversations with Mr. J. Horne, Polymer Machinery Corp., Berlin, Ct.

33. Conversations with Mr. M. Goldin, Celanese Corporation, Summit, N.J.
34. Op. Cit., Horne
37. Conversations with Mr. D. Guillon, Vetrotex St. Gobain, Parris, France, March 30, 1983
42. Op. Cit., Guillon
45. "Prospects Improve for Automotive Composites", Automotive Engineering, Dec. 1979, pg. 46
47. Modern Plastics, Mar. 1981, pg. 43
49. Modern Plastics, May 1981, pg. 44
52. Conversations with Mr. Ghoul, Davis Standard, Pawcatuck, Ct., Aug 29, 1982
56. Op. Cit., ECON, pg. 128

57. Conversations with Mr., Van Dorn Plastics Machinery Co., Strongsville, Ohio, Aug., 1982


60. Op. Cit., Guillon


64. Op. Cit., ECON


66. Conversations with Mr. Ross E. Rockenaugh, D-M-E Co., Madison Heights, Wi

67. Conversations with Mr. Ernie Csaszar, Empire Enterprises, Boundbrook, N.J.

68. "Fiberglass/Plastic Door Study", Owens/Corning Fiberglass

69. Conversations with Mr. Frank Kaiser, Michigan Plastic Products, July 7, 1982

70. "Plastiscope", Modern Plastics, Nov. 1982, pg. 18


73. Op. Cit., Sanada

74. Op. Cit., Sanada

75. Op. Cit., Sanada

77. Conversations with Mr. Jim Horne, Polymer Machinery Corp., Berlin, Ct., Dec. 10, 1982

78. Conversations with Mr. R. Linstrum, Arthur D. Little Inc., Cambridge, Ma.

79. Conversations with Mr. Steve Elliott, FCM Middleville Nov. 26, 1982

80. "Plastics Injection Molding Machines", Cincinnati Milacron, Promotional Flyer

81. "Reciprocating Screw Injection Machines", Van Dorn Plastic Machinery Co., Promotional Flyer

82. Op. Cit., Horne


84. Conversations with Mr. M. Goldin, Celanese Corporation Summit, N.J., March 18, 1983

85. Conversations with Mr. M. Wilson, Celanese Corporation Summit, N.J., March 18, 1983

86. Op. Cit., Linstrum


88. Conversations with Mr. Terri Suyama, Toyota Motor Corp., Feb, 1983

89. Conversations with Mr. D. Howell, Arthur D. Little Inc., Cambridge, Ma., June 6, 1982